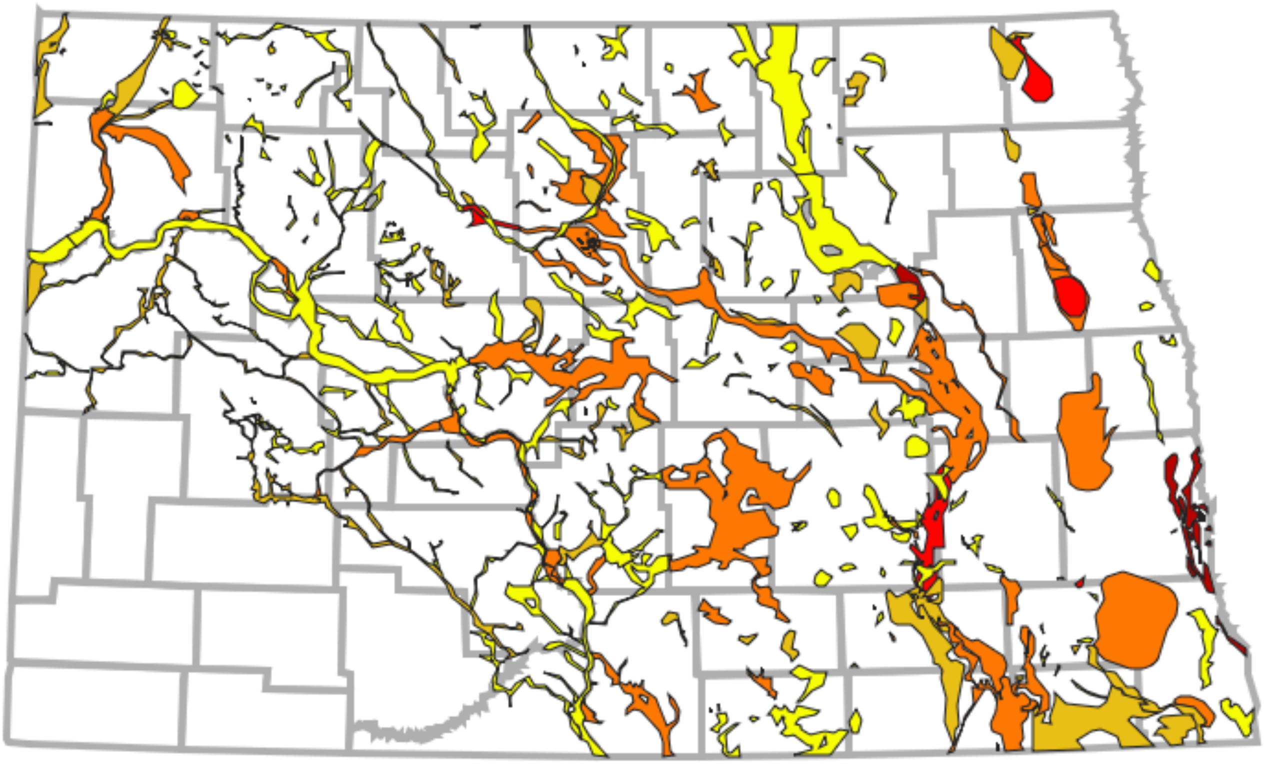
Assessment of

Managed Aquifer Recharge (MAR) Potential for Glacial Drift Aquifers in North Dakota



by Jon C. Patch, P.E.

2024

Prepared under the direction of the
North Dakota Department of Water Resources
Bismarck, ND

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[1] See "about the author" section

Interactive Map: https://mar.dwr.nd.gov

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INTRODUCTION

Managed Aquifer Recharge (MAR) involves capturing a portion of excess or abundant surface water flows from rivers and streams (often in the spring) and storing that volume of water in an aquifer for later use. MAR projects are also referred to as artificial recharge (AR), Aquifer Storage and Recovery (ASR), and Aquifer Recharge and Recovery (ARR). MAR has also been referred to as "water banking." Much like surface reservoirs mitigate transient river and stream flow conditions, MAR allows aquifers to be used as reservoirs. Groundwater supplies are less prone than surface water to extreme variations in quantity from short-term changes in climate, which is why groundwater is often used as a source for irrigation, municipal, rural-water, and industrial supplies. However, even aquifers are eventually affected by long-term climate trends, where extended droughts can reduce available groundwater. Mitigating these drought impacts and increasing the confidence that water supply remain dependable can be accomplished through MAR.

MAR can be accomplished generally through two means: surface infiltration or well injection. Surface infiltration is accomplished where water is placed in excavated basins and allowed to infiltrate through a vadose zone to the aquifer. This type of recharge is best suited to unconfined or "water table" aquifers where no substantial low-permeability materials preclude the direct infiltration of the water to the aquifer. Well injection involves using a well to place the water into the aquifer through pumping or gravity. This type of recharge is required where there are low-permeability materials overlying the confined aquifer preventing direct infiltration from the surface.

PURPOSE AND OBJECTIVES

The purpose of this investigation is to evaluate the feasibility for the use of MAR to North Dakota's glacial drift aquifers to extend and enhance their resiliency. The objective is to create a map, using reasoned criteria and considerations, of the state's glacial drift aquifer's MAR potential and to identify candidate aquifers for successful MAR application. For an aquifer to be considered as having the best potential for MAR, a minimum threshold of 1,000 acre-feet of annual recharge was established. The map, along with the currently available information and tool sets, such as the North Dakota Department of Water Resources (DWR) GIS platform, provides a broader base from which decision makers and individuals can leverage the past knowledge with the currently available information. The map and information in this report is intended to maximize efficient conjunctive use of the state's water supply while increasing its dependability and reliability.

HISTORY OF MAR IN NORTH DAKOTA

In North Dakota MAR has previously been used or tested in several instances. Beginning in 1932, Valley City recharged Sheyenne River water into an abandoned gravel pit overlying a surficial aquifer where their hand dug municipal well was located (Kelly, 1967 and Appendix 1). The simple and elegant design is still in operation today with no major changes to the original conception.

In the mid-1960s, the city of Minot supplemented water in a local aquifer with water from the Souris River (Pettyjohn and Fahy, 1968). In 1968, the Civil Engineering Department of North Dakota State University did a laboratory analysis that scale-tested the use of gravity shafts for groundwater recharge into the declining West Fargo aquifer (d'Errico and Skodje, 1968).

The U.S. Bureau of Reclamation (USBR) and the Garrison Conservancy District supplemented groundwater in the Oakes aquifer using springtime infiltration of water pumped from the James River during the late 1980s and early 1990s. Water was pumped to low areas of the landscape, or applied through irrigation pivots (Frietag and Esser, 1986).

In the late 1980s, the North Dakota State Water Commission (SWC), in cooperation with the USBR, conducted studies on a pilot recharge basin, infiltrating water from the James River to the Oakes aquifer in Dickey County, southeastern North Dakota (Schuh and Shaver, 1988; Shaver and Schuh, 1988; Shaver and Schuh, 1989a; Shaver and Schuh, 1989b).

The feasibility of augmenting groundwater in the Englevale Aquifer (Ransom and Sargent Counties, southeastern North Dakota) was explored, and results published by Cline and others (1993).

In 1992, the Forest River Hutterian Colony began development of an artificial recharge project to enhance and expand their irrigation capabilities in Grand Forks County (Schuh and others, 2009; and Schuh and Patch, 2009).

In 2010, the USBR considered artificial recharge as part of an integrated plan for stabilizing water supplies in the Red River Valley.

An investigation was done in 2017 on the potential geochemical effects of storing James River water in the Spiritwood Aquifer using PHREEQC Simulations of pe-pH (Korom and Hisz, 2018).

While extensive research and investigation of MAR has been conducted in North Dakota, there have been limited large-scale projects implemented. However, three noteworthy long-term MAR projects have successfully been realized: Valley City's municipal water supply, Minot's municipal water supply, and Forest River Colony's irrigation supply in Grand Forks County. These projects demonstrate the potential for further implementation and success of MAR in the region.

Valley City project

Prior to 1932, Valley City obtained its municipal supply from a single hand-dug municipal well that was 15 feet in diameter and 30 feet deep (Kelly, 1966). The supply was located in the small (approximately 1 square mile) Valley City aquifer, a glacial outwash deposit. The Valley City recharge system was built in 1932 as the result of prolonged drought, during which there was a rapid decline in water levels in the municipal well. The project was the subject of a feature article in the February 2, 1932 edition of the Fargo Forum (Appendix 1). The recharge project, which operates to this day, involved piping water from the nearby Sheyenne River through a ½ mile long, 18" tile pipeline to an excavated pit into the small surficial aquifer where the municipal well was located. Water flows from the river to the pit under the influence of gravity as the floor of the excavated pit was 6 feet below the river level. The inlet of the pipeline was approximately 2 feet below the normal river level. The maximum measured rate of free flow was 2,600 gpm. The river level was maintained by a 12-foot dam located approximately a half mile downstream from the pipeline. Steady flow in the river is now maintained by Baldhill Dam, constructed in 1949 on the Sheyenne River approximately 13 miles upstream. Valley City has a water-right to a portion of the water stored in the reservoir behind Baldhill dam (Lake Ashtabula). Releases from the Lake Ashtabula are captured downstream in the river adjacent to the recharge pit, and ultimately recaptured in wells completed in the Valley City aquifer.

In 1957, the city installed a pump and valve system on the pipeline. The valve system allowed the water-level in the pit to be raised approximately 5 feet above river level. At present, no pumping from the river to the recharge pit is needed as the water-level is held fairly steady in the Sheyenne River due to the steady releases from Lake Ashtabula. The gravity-feed system provides the necessary volumes to the recharge system; thus, a constant supply of recharge is available to the aquifer, and decline of the piezometric surface is minimal. However, occasional cleaning of the recharge pit floor is necessary due to the buildup of silt and clay bought in with the river water (Hesch, 2023). At present, about 1,000 acre-feet per year is used by Valley City for municipal use (Figure 1). All water pumped is essentially recaptured Sheyenne River Water that has be artificially recharged the Valley City aquifer.

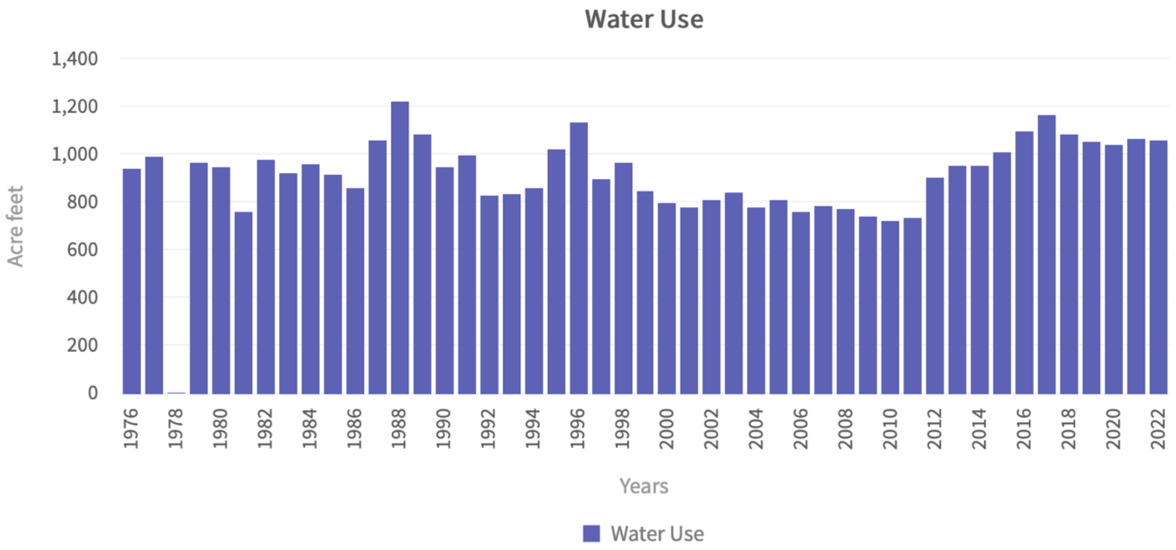


Figure 1. Reported Municipal Water Usage in Valley City. Equals the amount recharged from Sheyenne River to the Valley City Aquifer.

Since the Valley City recharge project began in 1932, the water quality in the aquifer is identical to the Sheyenne River's chemical composition. Starting around 2005, the river's quality began to deteriorate following the infusion of lower quality water from Devils Lake, introduced via two emergency outlets situated upstream of Valley City. These outlets were constructed as a response to the chronic flooding caused by the rising Devils Lake. While the outlets have assisted in lowering Devils Lake's levels, preventing disastrous floods, they have inadvertently increased the total dissolved solids in the Sheyenne River, shifting the water type from predominantly sodium-bicarbonate to sodium-sulfate. To counteract the declining water quality sourced from the river, Valley City has, since 2009, implemented advanced ultra- and nano-filtration treatment processes.

Minot project

In 1965, the city of Minot constructed an artificial recharge facility to place water from the Souris River into the Minot aquifer. The project was the subject of an article published in *Public Works* periodical in September, 1968 authored by Wayne A. Pettyjohn, Ph.D. Associate Professor of Geology, The Ohio State University, Columbus, Ohio and Vernon Fahy, P.E., City Manager. Minot, ND. The article is included in its entirety as Appendix 2. The facility consisted of a settling basin connected to a y-shaped canal system. Along the centerline of the canals are gravel-filled bored holes, called hydraulic connectors, that perforate the poorly permeable material that overlies the Minot aquifer. The hydraulic connectors range in diameter from 30 to 72 inches and from 28 to 34 feet in depth. The lower part of the hydraulic connectors taps sand and gravel in the dewatered upper part of the Minot aquifer.

Water was pumped from the Souris River into a settling basin. When the settling basin filled to a specified level, water flowed into the recharge basin and downward in the hydraulic connectors. During the period 1965 to 1975, it was estimated that as much as 2.6 billion gallons of water (7,979 acre-feet total or about 725 acre-feet per year) were recharged into the Minot aquifer (Pusc, 1994 and City of Minot, 1991). The recharge facility was destroyed during flooding events in the mid 1970's and no attempts to artificially recharge the Minot aquifer have been made since. Additional information on the artificial recharge facility constructed by the city of Minot is found in Pettyjohn (1967), Pettyjohn and Hutchinson (1971), and Pettyjohn (1968B).

In 1992, the City of Minot formulated a Water Management Plan advocating for the revival of an artificial recharge system for the Minot aquifer and the initiation of a similar system for the Sundre aquifer (City of Minot, 1991). The strategy included budget allocations for preliminary projects and additional research. However, the emergence of the Northwest Area Water Supply (NAWS) project, aimed at piping Missouri River water to the region, led to the shelving of the initial plan. Despite this, water levels in both the Minot and Sundre aquifers continued to plummet to critical points until a sudden rise following the flood of 2011, temporarily alleviating concerns over water scarcity. Nevertheless, subsequent years saw the resurgence of low water levels, with the Minot aquifer experiencing even more severe declines than before the 2011 flood.

It is anticipated at the time of this report that the NAWS system will achieve a significant milestone by delivering treated water from the Missouri River to the region within the 2024/2025 period.

Forest River Project

In 1992, the Forest River Hutterite Community (FRHC), near Fordville, ND in eastern North Dakota, began the planning, testing, and operation of an ARR basin and well field facility. The project, which is still being operated today, was developed in close consultation with the SWC (Schuh and Patch, 2009). SWC hydrologists provided assistance to ensure that all of the necessary scientific instrumentation was put into place to measure the effectiveness of the process, to confirm that all of the appropriate SWC permits were acquired and that the project would not impact prior water permits, and to ensure that groundwater was adequately protected from contamination. The project examined the feasibility of taking Forest River water during higher spring flows for injection into the Inkster aquifer for irrigation when needed.

The FRHC recharge project, includes two infiltration basins, each about 3.5 acres in area. Topsoil was removed from both basins to two feet below grade, with that removed soil being used to build a berm around the infiltration basins. The excavated topsoil, which was high in the less water-permeable clay, exposed a bed material of fine and medium sand, which is more permeable to water.

This project takes water from the Forest River during high flows in the spring and early summer, flows that would otherwise have been unavailable to beneficial use, for storage in a shallow aquifer. The water is pumped from the river into the two basins, allowing gravity to move that water into an aquifer through infiltration. Water stored in the aquifer through artificial recharge is short-term storage, meaning that water cannot be “banked” long-term due to losses to evaporation and seepage. That stored water is extracted from the aquifer for irrigation, typically June through September, when the normal flows in the river are too low to support direct pumping from the river for irrigation.

In order to quantify the amount of water that could be reliably withdrawn from the Forest River for aquifer injection, an analysis based upon two climate scenarios, a “dry” and a “wet” cycle was developed by the SWC. The dry cycle allowed for 200 acre-feet of aquifer recharge annually, and the wet cycle allowed 600 acre-feet of aquifer recharge annually. During the time the project was being contemplated, the region was in a multi-year severe drought. Since the project began, the region has been in an extended wet cycle. After a few years of operation, the restrictions on the amount that could be pumped from the river to recharge the aquifer have increased. Volumes pumped from the river for the recharge project are now based on approval of an annual operating plan which set the limits of the amount to be recharged on the projected crop plan and probable water usage based on crop types to be irrigated. FRHC water permits set conditions requiring a minimum flowrate past the USGS gaging station at Fordville, ND. Since beginning the operation of the recharge basin, the FRHC has obtained three water appropriations from the Forest River that now total 1820 acre-feet annually. The maximum annual pumpage from the Forest River to the infiltration basin was 1610 acre-feet in 2021 (Figure 2). This has allowed up to 2,200 acres of irrigation that would not have been possible through direct water appropriation from the aquifer due to the fact that the Inkster aquifer was at or near full appropriation prior to 1992 when the recharge project began.

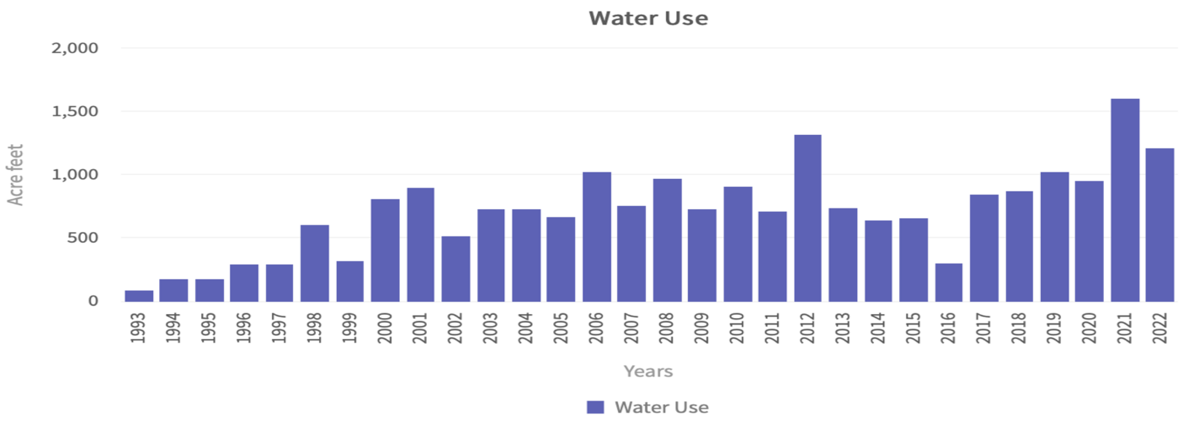


Figure 2. Reported Water Usage from Water Permits 4561 and 4980 approximately equal the amount recharged from to the Inkster Aquifer from the Forest River.

The project has operated continuously for 30 years. Over that period, approximately 83% of the water injected into the aquifer was recovered for irrigation and 17% of the water injected was lost through various natural processes (evaporation, plant use, seepage from the aquifer to adjacent springs, etc.). Basin infiltration raised the water-level elevation at the basin sites, creating a “mound” in the water table. The ability of water to infiltrate the sand at the bottom of the recharge basins is limited by the buildup of the suspended solids in the river water and forms a “filter cake,” or a layer of sediment and organic materials that reduces the permeability to the more-permeable underlying sands, lowering the ability of water to pass through. It was discovered, that a basin floor composed of fine to medium sand is better at trapping the suspended solid load and allowing the filter cake layer to form. This filter cake prevents deep infiltration of the fine-grained materials brought in by the river water. After the basin infiltration is completed for the season, the basin bottoms are allowed to dry out exposing the filter cake material, usually less than 1” thick. Once it is completely dried out and cracked, a road grader is used to windrow the material and an earthmoving scraper removes of material. Annual removal of the filter cake has allowed the Forest River Project to operate effectively for the entire 30 years history without a loss of infiltration capability. No major renovations of the basin floors have been required at the current rate of surface removal, although it is expected that replacement of bottom sands with nearby materials may be needed at some time in the future.

No adverse impacts to groundwater quality were detected as a result of the Forest River Project. Normal depth to water in the vicinity of the recharge basin is approximately 30 feet. It was discovered that the water-table mound that developed under the recharge basin at times nearly intersected the bottom of the basin, which would effectively stop the infiltration. From this it was learned that basin infiltration type aquifer recharge works best in unconfined aquifers with relatively deep (greater than 20’) water tables, or with aquifers composed of large hydraulic conductivity materials (coarse sands or coarser). Aquifers with shallow water tables (less than 20’) and smaller hydraulic conductivity materials (medium sand or finer) will not work as well due to higher evaporation and plant use and a lack of storage volume in the aquifer.

The average long-term estimated cost of recharging the aquifer, including amortized construction costs, maintenance costs and pumping costs was about $100 to $130 per acre-foot. The cost to pump the water from the aquifer for irrigation is not included in that estimate. The stable sources of irrigation water allowed the Forest River Colony to expand into the production of high value, water intensive crops, such as potatoes. The recharge facility continues to operate to this day.

METHODS OF ANALYSIS

In order to properly evaluate the MAR potential for the states glacial drift aquifers, it was necessary to assemble basic aquifer data such as location, areal extent, thickness, hydraulic conductivity, degree of confinement, depth, water-level trends, water quality, water usage, nearby streamflow data duration hydrographs. These data were then used in conjunction to develop a set of criteria and considerations to assess and rank the MAR potential for each aquifer.

Assemblage of Aquifer Basic Data

A comprehensive list of all of the glacial drift aquifers in the state was assembled from various sources. Primarily, the list of aquifers and aquifer names found in the DWR *mapservice* website (https://mapservice.dwr.nd.gov) was used as the de-facto standard. Modifications were made to the list the further define segments of aquifer systems, complexes, segments, or sub-aquifers. A complete listing of aquifers evaluated in this investigation are found in Appendix 3. Basic data were gathered on all of the aquifers and, where available, hyperlinks compiled to directly link to the page of the County Ground Water Study report or to other prominent reports where the aquifer is defined and described. Analysis of the hydrogeologic setting and size, water-level trends in the aquifer, aquifer water-usage, and water quality was completed on those aquifers, aquifer segments, or sub-aquifers. In addition, surface water sources that could serve as potential sources of supply to recharge the aquifers were assessed for mean quantity of flow, chemical quality, and distance to the target aquifer.

Aquifer water-level trends

To better understand the history of use and impact of climatic effects to groundwater levels in the state, a water-level trend analysis was undertaken on all of the aquifer systems where water levels have been monitored. A 4D™ algorithm designed to operate within the water-level database environment was implemented. The algorithm termed “Trends” (Bader, 1993) compiles all of the water levels from selected wells in the database and creates a daily array of incremental water-level changes (daily delta) for each well with two or more water-level measurements recorded in the database. A cumulative average daily delta array is created based on the summation of all of the daily delta values for each well divided by the number of wells included on that day. Because the algorithm is based solely on the change in water level, the elevation of the water-level measured is not relevant, nor is the frequency or period of record. The algorithm is housed within the Well Inventory Client software interface to the NDWR site inventory database A subjective point on which to base the water-level change delta relative to the assumed average water-level prior to major development was selected. For the most part, the average water-level in about 1970 was used as the zero-change basis. Most of the water-level monitoring of these aquifers has occurred since the 1960’s with the widespread advent of center-pivot irrigation systems and regional rural water system development. Aquifer systems that were analyzed for water-level trends using the “Trends” program are listed in Appendix 5 which have hyperlinks to the hydrographs.

Aquifer water-usage assessment

Most of the substantial use of groundwater that has taken place in the state has been since the wide-spread implementation of center-pivot irrigation systems and regional rural water system development beginning mainly in the 1960s. A few notable exceptions of large-scale groundwater usage for municipalities date back to the 1930s, one of which is the West Fargo aquifer system that was used as a regional municipal/rural water supply since the 1930s. An assessment of aquifer water usage was accomplished through the querying of water usage data in the DWR's water permit database, accessible through the web and mapservice interfaces. The 2022 reported water usage from all aquifers is listed in Appendix 4 (source: NDDWR water permit database). A summary of the highest 2022 water-use totals from aquifers in each of the categories of: total use, irrigation usage, municipal and rural water usage, and industrial use is shown in Table 1. An analysis of the 10-year average annual municipal and rural water usage from aquifers is displayed in the pie diagram in Figure 3. It should be noted that although the West Fargo aquifer system appears in the top twenty suppliers of water in the 10-year average

Table 1. Highest 2022 Reported Water Use from Aquifers in Categories of Use Type (not including temp permits)

	Top Total Use	acre-feet
1	Central Dakota	26,125
2	Oakes	12,442
3	Spiritwood	12,310
4	Elk Valley	11,077
5	Englevale	10,115
6	Sheyenne Delta	9,405
7	Page	6,976
8	Milnor Channel	6,548
9	Lodgepole	5,620
10	LaMoure	5,424
11	Missouri River	5,080
12	Hofflund	4,789
13	Little Muddy	4,766
14	Jamestown	4,417
15	Sundre	3,868
16	New Rockford	3,796
17	Minot	3,437
18	Knife River	2,889
19	Karlsruhe	2,753
20	Lake Nettie	2,597

	Top Irrigation Use	acre-feet
1	Central Dakota	25,717
2	Oakes	12,250
3	Englevale	10,114
4	Elk Valley	8,943
5	Spiritwood	8,367
6	Sheyenne Delta	8,347
7	Milnor Channel	5,816
8	Page	5,707
9	LaMoure	4,794
10	Little Muddy	3,741
11	New Rockford	3,328
12	Hofflund	2,799
13	Karlsruhe	2,744
14	Knife River	2,394
15	Charbonneau	2,363
16	Lake Nettie	2,299
17	Streeter	2,231
18	Lake Souris	2,157
19	Carrington	1,728
20	Skjermo Lake	1,584

	Top Municipal + Rural Water Use	acre-feet
1	Jamestown	3,884
2	Sundre	3,811
3	Spiritwood	3,437
4	Minot	3,427
5	Missouri River	2,974
6	Elk Valley	2,134
7	Shell Valley	1,513
8	Page	1,269
9	Sheyenne Delta	1,058
10	Wahpeton Buried Valley	906
11	Hankinson	904
12	Icelandic	862
13	Enderlin	847
14	Fordville	841
15	Voltaire	670
16	McVille	643
17	LaMoure	631
18	New Town	523
19	Pleasant Lake	510
20	Knife River	495
21	West Fargo South	451
22	NewRockford	424
23	Fox Hills	420
24	Ray	418

	Top Industrial Use	acre-feet
1	Lodgepole	5,620
2	Hofflund	1,984
3	Little Muddy	1,024
4	Missouri River	966
5	New Town	915
6	Dakota Group	914
7	Shell Creek	884
8	Milnor Channel	732
9	Ray	709
10	Hankinson	685
11	Tobacco Garden Cr.	535
12	Spiritwood	505
13	Jamestown	486
14	Central Dakota	408
15	Wahpeton Buried Val	399

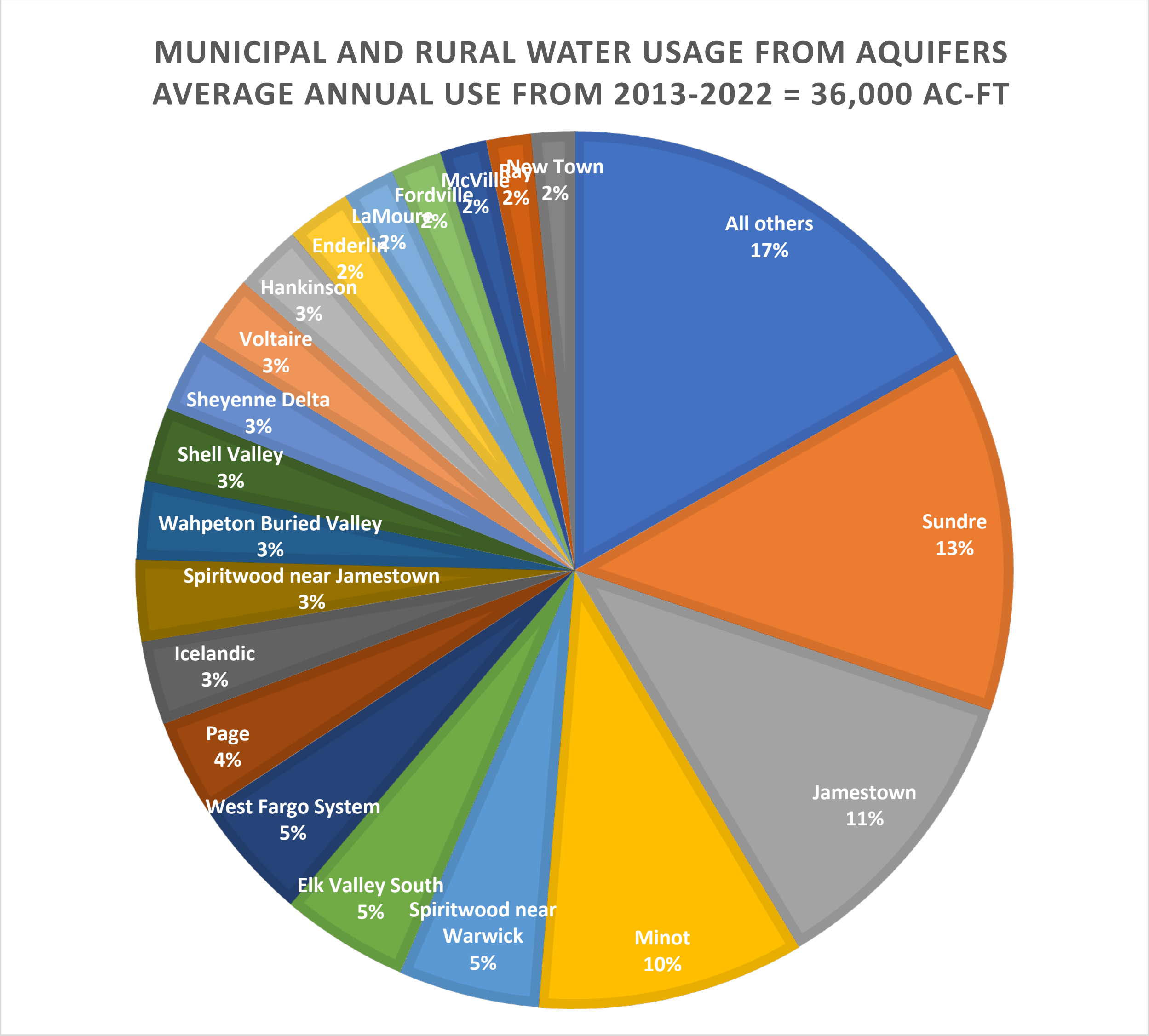


Figure 3. Average Annual Municipal and Rural Water Usage From 2013-2022 from Aquifers.

annual municipal and rural water use in Figure 3, it was discontinued as the source for the City of West Fargo in 2016 and is no longer one of the top 20 municipal and rural water use suppliers.

A chart of the long-term water-level change of the top 20 aquifers supplying municipal and rural water use is presented in Table 2. The chart contains the following information:

1. **Aquifer Use and Ranking**: The data contains information on different aquifers or segments, with a 10-year average use measured in acre-feet (ac-ft), and a rank based on water use where 1 represents the highest use.
2. **Size and Volume**: Each aquifer is described by its size in square miles and average thickness in feet, which when combined give the total volume of the aquifer in acre-

feet. A specific yield value (drainable pore space) of 0.25 was used in the volume calculation.

3. **Type**: The aquifers are classified by type (confined, semi-confined, or unconfined).
4. **Annual use/Volume**: Percentage of aquifer storage used annually.
5. **Long-Term Water-Level (WL) Change**: The long-term change in water-level in feet is shown, which can indicate the sustainability of water use.

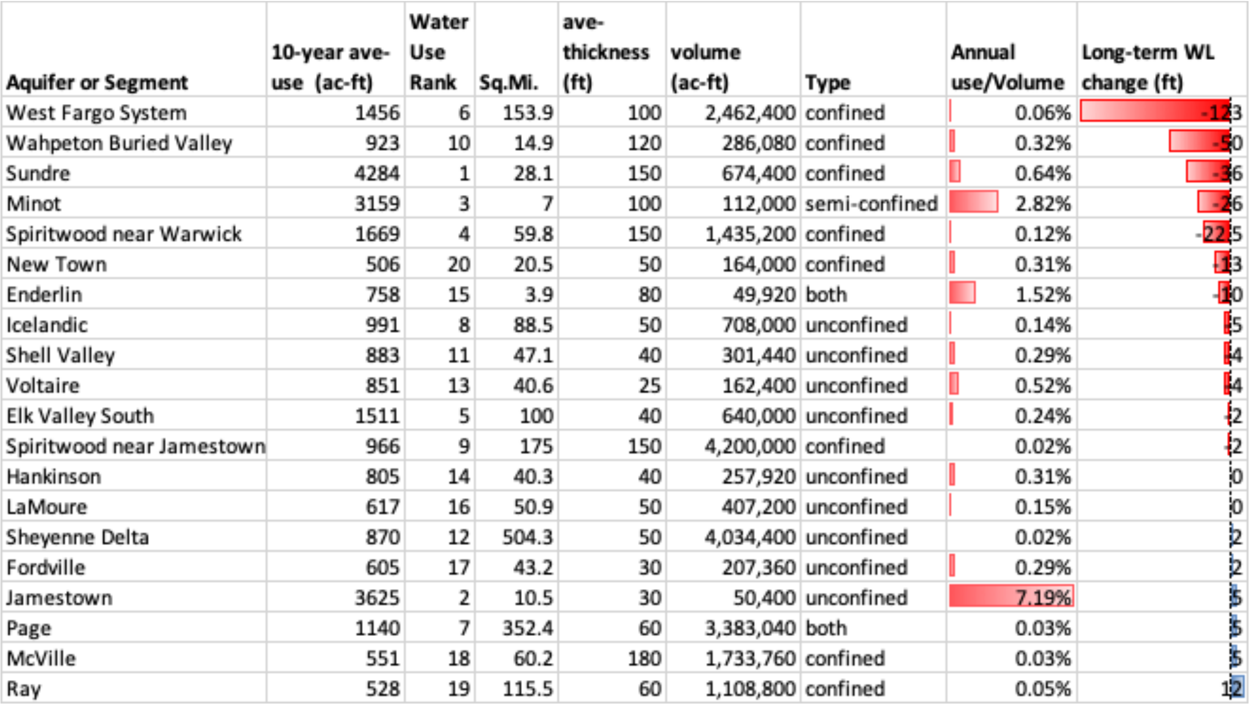
From the data, we can note several points:

- The **Sundre** aquifer has the highest water use rank with 4284 ac-ft, and it also has a relatively high annual use/volume percentage (0.64%) compared to other aquifers.
- The **Minot** aquifer has the highest annual use/volume percentage (2.82%) of aquifers that have a negative long-term water-level change (decline).
- The **West Fargo System** and **Wahpeton Buried Valley** have significant long-term water-level drops of -123 ft and -50 ft, respectively, which could be concerning for sustainability.
- The **Jamestown** aquifer has the highest annual use/volume percentage at 7.19%, which is substantially higher than the other listed aquifers, and it shows an increase in water level, which is unusual compared to others.
- **McVille** and **Ray** aquifers show an increase in water levels, with Ray having the most significant rise at 12 feet, which might suggest there is sufficient replenishment through natural recharge.
- The aquifer sizes vary greatly, with **Sheyenne Delta** being the largest in area (504.3 sq.mi.) and **New Town** being one of the smallest (20.5 sq.mi.).
- Larger annual use/volume percentage may indicate more vulnerability to drought cycles should natural recharge not be able to keep up with the demand given the relatively small amount of storage in relation to the demand.

These data can be used to help assess the need for consideration of MAR in the overall water resource management of the aquifers and identify trends in water usage. It's clear that some aquifers are under more stress than others, and the long-term water-level changes provide critical feedback on the sustainability of current water usage practices.

Reported water usage plots for selected aquifers are listed in Table 3 which has hyperlinks to the plots. Appendix 6 contains the graphical representations of annual water usage, categorized by type. These visual aids are designed to facilitate the identification of any discernible patterns or trends in water utilization across different categories.

Table 2. Long Term Water-Level Change of the Top 20 Aquifers Supplying Municipal and Rural Water Use.



Aquifer or Segment	10-year ave-use (ac-ft)	Water Use Rank	Sq.Mi.	ave-thickness (ft)	volume (ac-ft)	Type	Annual use/Volume	Long-term WL change (ft)
West Fargo System	1456	6	153.9	100	2,462,400	confined	0.06%	-123
Wahpeton Buried Valley	923	10	14.9	120	286,080	confined	0.32%	-50
Sundre	4284	1	28.1	150	674,400	confined	0.64%	-36
Minot	3159	3	7	100	112,000	semi-confined	2.82%	-26
Spiritwood near Warwick	1669	4	59.8	150	1,435,200	confined	0.12%	-22.5
New Town	506	20	20.5	50	164,000	confined	0.31%	-13
Enderlin	758	15	3.9	80	49,920	both	1.52%	-10
Icelandic	991	8	88.5	50	708,000	unconfined	0.14%	-5
Shell Valley	883	11	47.1	40	301,440	unconfined	0.29%	-4
Voltaire	851	13	40.6	25	162,400	unconfined	0.52%	-4
Elk Valley South	1511	5	100	40	640,000	unconfined	0.24%	-2
Spiritwood near Jamestown	966	9	175	150	4,200,000	confined	0.02%	-2
Hankinson	805	14	40.3	40	257,920	unconfined	0.31%	0
LaMoure	617	16	50.9	50	407,200	unconfined	0.15%	0
Sheyenne Delta	870	12	504.3	50	4,034,400	unconfined	0.02%	2
Fordville	605	17	43.2	30	207,360	unconfined	0.29%	2
Jamestown	3625	2	10.5	30	50,400	unconfined	7.19%	5
Page	1140	7	352.4	60	3,383,040	both	0.03%	5
McVille	551	18	60.2	180	1,733,760	confined	0.03%	5
Ray	528	19	115.5	60	1,108,800	confined	0.05%	12

Table 3. Reported Water Usage Plots for Selected Aquifers in Appendix 6

- Elk Valley South
- Enderlin
- Fordville
- Hankinson
- Icelandic
- Jamestown
- Lake Nettie
- Lake Souris
- Lamoure
- Lignite City
- Mcville
- Minot
- Missouri River
- New Town
- Page
- Ray
- Shell Valley
- Sheyenne Delta
- Spiritwood Near Jamestown
- Spiritwood-Warwick
- Sundre
- Voltaire
- Wahpeton Buried Valley
- West Fargo

Water quality assessment of aquifers and rivers

An assessment of the water quality was made on key aquifers which have high potential to be target aquifers for MAR consideration and their potential MAR surface water sources of supply. The primary indicator used to generalize the water quality was the parameter of calculated total dissolved solids (TDS) of samples collected with results stored in the NDDWR site inventory database. TDS plots for selected aquifers are listed in Table 4, which has hyperlinks to the plots and displayed in Appendix 7. Selected river TDS plots are listed in Table 5 and displayed in Appendix 8.

Table 4. TDS Plots for Selected Aquifers Included in Appendix 7.

- Elk Valley South
- Enderlin
- Fordville
- Icelandic
- Minot
- New Town
- Shell Valley
- Spiritwood Near Jamestown
- Spiritwood-Warwick
- Sundre
- Voltaire
- Wahpeton buried valley
- West Fargo
- West Fargo North
- West Fargo South

Table 5. TDS Plots for Selected Rivers Included in Appendix 8.

- Forest River near Fordville
- James River (4 stations)
- Maple River near Enderlin
- Red River (Wahpeton, Hickson)
- Red River (All)
- Sheyenne River near Warwick
- Sheyenne River near West Fargo
- Souris River (Foxholm and Bantry)
- Tongue River near Akra
- Turtle River near State Park
- Wild Rice (Abercrombie and Rutland)
- Willow Creek near Willow City

Assessment of Surface water sources of supply

An assessment of surface water sources of supply that could be used in MAR applications was made by querying the streamflow gage network operated by the US Geological Survey (USGS). The long-term mean flowrate was obtained from each of the 106 gages. These gaging stations with their long-term mean (categorized) are displayed in Figure 4. The streamflow duration hydrographs for selected gaging stations on streams which could be considered as sources of supply are also presented in Appendix 9.

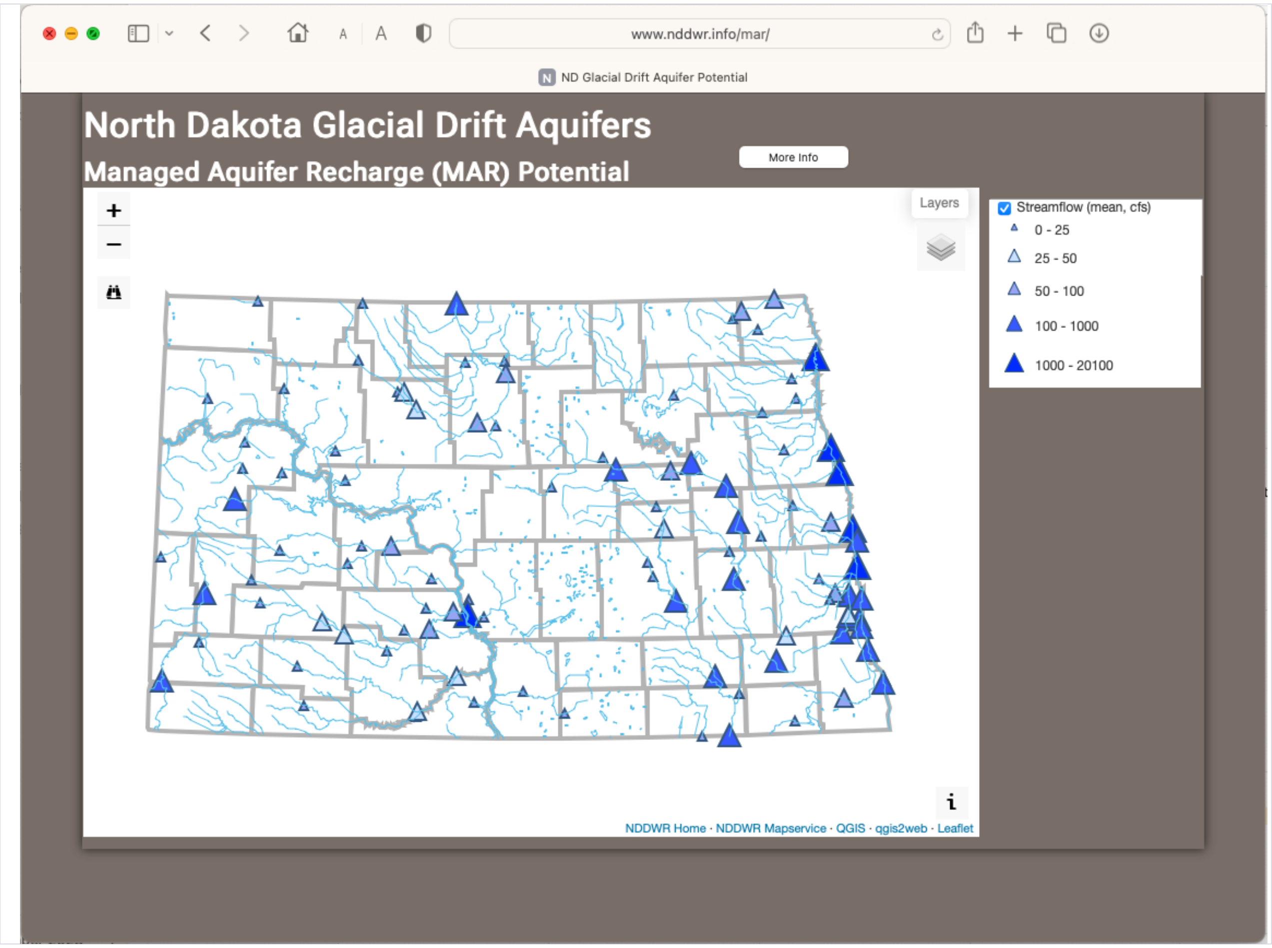


Figure 4. USGS Stream Gaging Stations Showing the Long-Term Mean Streamflow.

RANKING CRITERIA AND CONSIDERATIONS

The potential for MAR can be determined based on multiple criteria, considerations, and factors.

A. Need-based Considerations:

- **Need for the Stabilization of Water Levels:** Aquifers that have previously experienced over usage or where current withdrawals may be exceeding the long-term sustainability may benefit from water-level stabilization and recovery through the use of MAR. Identification of these aquifers can be made through an aquifer system trend analysis using the DWR's water-level trends program described earlier in this report. High ranking aquifers under this consideration include the West Fargo aquifer system, the Fox Hills aquifer, and the Spiritwood aquifer near Warwick.
- **Need to Allow Future Appropriation:** The implementation of MAR in areas where aquifers are fully appropriated may allow for additional appropriation to occur without fear of over-appropriation and violation of the duty of the prior appropriation doctrine to protect prior appropriators. MAR can mitigate the challenges of water scarcity, particularly during dry periods when the natural replenishment of aquifers is often insufficient to keep pace with the ongoing extraction for agricultural, industrial, and domestic use. Having a MAR process in-place can prevent or respond to this imbalance. MAR offers a strategic approach to counteract this issue by moving available surface flows into the aquifer during these dry periods. Aquifers that need supplementary water to provide for additional water appropriations include Central Dakota aquifer.
- **Water Storage Needs:** This considers aquifers that could be used as a reservoir for water storage offering protection to drinking water supply availability especially during extended drought periods. The stored water in these aquifers increase the resilience to these critical groundwater supplies. The Spiritwood Aquifer near Warwick segment is a prime example.
- **Need to "Free-up" Groundwater Supplies:** There are aquifers that currently face a higher threshold of allowable appropriation due to the need to mitigate the impact of seasonal drawdown and ensure adequate drinking water supplies through those times. This is essential to safeguard these drinking water supplies during peak seasonal demand especially during prolonged droughts. The Elk Valley aquifer, a major groundwater source for regional rural water systems, stands out in this regard.

B. Hydrogeological Considerations

When considering MAR as a solution for enhancing water availability, a thorough understanding of the hydrogeological characteristics of the potential target aquifer is crucial. These characteristics fundamentally influence the aquifer's ability to accept, store, and transmit the recharged water efficiently. Key factors such as the extent, thickness, degree of confinement, depth to water, hydraulic conductivity and their ability to hold stored water before escaping to springs, seeps and evapotranspiration are all pivotal components in determining the feasibility and effectiveness of MAR projects.

The extent and thickness of an aquifer are essential in determining its storage capacity. A larger and thicker aquifer can potentially hold more recharged water, making it a more suitable candidate for MAR. This factor is particularly important in regions where significant quantities of water need to be stored to meet the demands during dry periods. The degree of confinement of an aquifer, whether it is unconfined, semi-confined, or confined, also plays a vital role. Generally speaking, artificial recharge is easier and more economically feasible to unconfined aquifers. However, not all aquifers are simply confined or unconfined, or deeply or shallowly confined. Most aquifers vary in status and depth of confinement. For this reason, discretionary adjustments of MAR potential are made based on aquifer depths as indicated on drill logs, and on information provided in County Study reports and other sources.

Unconfined aquifers are easier to recharge as water can percolate directly from the surface. Confined aquifers, with their overlying impermeable layers, may require more sophisticated methods such as direct injection through constructed wells or deep excavation and installation of high hydraulic conductivity materials to flow downward under the force of gravity.

Depth to water, or the distance from the ground surface to the water table or piezometric surface is another critical factor. Shallow depths to water in combination with lower hydraulic conductivity sands may create a water table mound that intersects the floor of the recharge basin, thereby slowing or stopping the infiltration rate. Deeper depths to water in an unconfined aquifer, typically 20 feet or more, are a more desirable setting when considering a site for basin infiltration type recharge. But, deeper water levels can also often mean less saturated thickness of aquifer in which to screen recovery wells and allow for cones of influence to develop.

Hydraulic conductivity, the ability of the aquifer materials to transmit water, is perhaps one of the most critical factors. High hydraulic conductivity means water can move more freely through the aquifer, making it more suitable for rapid recharge and recovery. However, in aquifers with low hydraulic conductivity, water moves more slowly, create higher mounds, and limit the efficiency of MAR operations.

Understanding these hydrogeological factors is essential not only for the initial assessment of an MAR project's feasibility but also for its ongoing management. This includes determining the optimal locations for recharge, the best methods to use (such as surface spreading, direct injection and the quantity of water that can be safely recharged.

C. Available Source Water Considerations

When developing a MAR project, one of the key considerations is the identification and evaluation of available source water. The viability and cost-effectiveness of a MAR project largely depend on the ability to secure an adequate, sustainable, and suitable source of water for recharge. This involves a comprehensive assessment of various factors related to potential water sources, such as their availability, proximity to recharge sites, quality, and compatibility with the target aquifer.

Initially, the evaluation process often includes looking at nearby river systems or treated wastewater as potential sources. River water, especially during periods of high flow, can provide a substantial and renewable supply of water for recharge. However, it is essential to consider the seasonal variability and the legal or environmental constraints associated with diverting river water. On the other hand, using treated wastewater offers a dual benefit: it provides a consistent water source and helps in wastewater management. This option is particularly relevant in urban areas where wastewater is continuously generated and needs sustainable disposal or reuse methods.

The feasibility of delivering these potential recharge sources to MAR sites is another critical aspect. This involves analyzing the logistical and infrastructural requirements, such as constructing pipelines or channels, and their associated costs and environmental impacts. The proximity of the water source to potential recharge sites is a crucial factor in this assessment. Closer sources generally mean lower conveyance costs and reduced energy usage, making the project more sustainable and economically viable.

When considering surface water sources such as rivers or streams, it is imperative to evaluate their potential suspended solids sediment load. High levels of suspended solids in the water can pose challenges for MAR projects. Sediments can clog the recharge basins, infiltration galleries, or injection wells, leading to reduced infiltration rates and increased maintenance costs. Clogging can also create anaerobic conditions that may lead to undesirable biological and chemical changes in the recharged water and the aquifer. Therefore, understanding the sediment dynamics of the source water is essential. This includes assessing seasonal variations in suspended solids load, especially during periods of high flow which are often associated with increased sediment transport.

In cases where sediment load is a concern, pre-treatment of the source water might be necessary before it can be used for recharge. Pre-treatment methods like sedimentation basins, filtration systems, or constructed wetlands can be employed to reduce the sediment content to acceptable levels. This not only helps in maintaining the efficiency of the MAR system but also extends its operational lifespan and reduces maintenance costs.

D. Suitability of the Aquifer to Accept the Various Methods of Recharge

Evaluating the suitability of an aquifer for MAR involves a detailed assessment of how effectively it can accept water through various recharge methods. Two primary methods typically considered are surface infiltration and the use of injection wells, each with its own set of parameters that need to be thoroughly analyzed to determine their feasibility.

1. **Surface Infiltration Feasibility**: This method involves spreading water over a large area (such as recharge basins or through infiltration galleries) allowing it to percolate down through an unsaturated zone (vadose zone) and into the aquifer. The feasibility of surface infiltration is largely dependent on the permeability of the vadose zone above the aquifer. Vadose zones consisting of course sand and gravel are ideal as they allow easy percolation of water. Conversely, silty or clayey vadose zones with low permeability can hinder the infiltration process. The depth of the unsaturated zone is also a factor; a shallower unsaturated zone can lead to quicker water table mound intersection with the basin floor but deeper water tables can also mean less saturated thickness of aquifer material. Additionally, the land area available for creating recharge basins or infiltration systems and its proximity to the source water are important logistical considerations.
2. **Injection Well Feasibility**: This method involves directly injecting water into the aquifer through wells. Key factors in assessing the feasibility of injection wells include the depth of the well and the geologic characteristics of the aquifer. The depth to groundwater is crucial as it determines the head space available for injecting water under pressure. Additionally, the presence of confining layers above or within the aquifer needs to be considered. These layers can either aid in containing the recharged water within specific aquifer zones or pose challenges by restricting the flow of water. High aquifer hydraulic conductivity facilitates the dispersion of water within the aquifer, while adequate storage capacity ensures that the aquifer can accommodate the additional volume.

Both methods require careful monitoring and management to ensure effective recharge and to avoid potential issues such as clogging in injection wells or the formation of impermeable layers due to sedimentation in surface infiltration systems.

In summary, assessing the suitability of an aquifer for different MAR methods requires a detailed understanding of its hydrogeological characteristics. This includes the depth to groundwater, confining layers, hydraulic conductivity, storage capacity, soil permeability, and the depth of the unsaturated zone. Such a comprehensive evaluation ensures that the chosen recharge method is not only feasible but also efficient and sustainable in the long term.

E. Water Quality Considerations

Water quality considerations are a central aspect of planning and implementing MAR projects. Ensuring that the quality of the source water is compatible with the existing groundwater is vital primarily to prevent deterioration of water quality within the aquifer or contamination of the groundwater resource.

1. **Compatibility of Water Quality**: The chemical and biological makeup of the source water needs to be thoroughly analyzed and matched with the characteristics of the groundwater. Factors such as pH, salinity, dissolved organic and inorganic compounds, and the presence of microbes and nutrients must be considered. This is important to prevent chemical reactions that could lead to clogging, especially in methods like injection wells, where fine pores can easily become blocked by precipitates or entrapped gases. Similarly, biological growth stimulated by organic compounds or nutrients in the recharge water can lead to biofouling, affecting the efficiency of the recharge process.
2. **PHREEQC Analysis**: Tools like USGS's PHREEQC (derived from the terms PH, REaction, and EQuilibrium in C language), a geochemical modeling software, are invaluable in assessing the chemical interactions between the recharge water and the aquifer material. This software can simulate a variety of chemical reactions, including dissolution, precipitation, ion exchange, and adsorption processes that might occur during and after the recharge. By using such models, project planners can predict potential problems and adjust the treatment of the source water or the recharge method accordingly to avoid adverse effects. PHREEQC analysis can also ensure that unintended consequences, such as the mobilization of lead or arsenic do not occur by introducing source water into an aquifer matrix where those interactions may occur.
3. **Vulnerability of the Aquifer to Contamination**: The intrinsic characteristics of the aquifer, such as its hydrogeological features and existing quality of groundwater, determine its vulnerability to contamination. Assessing this vulnerability is crucial, especially when considering the recharge of treated wastewater or urban runoff, which may carry a range of pollutants. Understanding how contaminants move and degrade within the aquifer, and how quickly they can reach drinking water wells, is essential for safeguarding the quality of the groundwater.

F. Environmental Impact Considerations

Environmental impact considerations are an integral part of planning and executing MAR projects. The artificial introduction of water into an aquifer can have a range of effects on the hydrogeologic flow systems, local ecosystems, land use, and even farming practices. It is crucial to conduct comprehensive environmental impact assessments to anticipate, mitigate, and manage these effects.

1. **Alteration of Hydrogeologic Flow Systems**: MAR can significantly modify the natural flow of groundwater. This alteration may affect not only the aquifer being recharged but also interconnected water systems. Changes in flow patterns can lead to unintended consequences such as the migration of contaminants within the aquifer, changes in the direction of groundwater flow, or alterations in the discharge patterns to springs and

streams. A detailed hydrogeological study is essential to understand these potential impacts and to design recharge systems that minimize negative consequences.

2. **Impact on Ecosystems**: Ecosystems that depend on groundwater, such as wetlands, springs, and riparian habitats, can be profoundly affected by changes in groundwater levels and flow patterns. For example, increasing the groundwater-level through MAR might enhance wetland habitats in some cases, but it could also lead to waterlogging in other areas, adversely affecting terrestrial ecosystems. Additionally, changes in water quality due to recharge activities could impact aquatic life, particularly if the recharge water contains pollutants or nutrients.
3. **Land Use Changes**: The implementation of MAR projects often requires physical infrastructure like recharge ponds, wells, or conveyance systems. This infrastructure can lead to changes in land use, potentially impacting local landscapes and land values. In agricultural areas, such changes could affect farming practices and land availability for cultivation.

Addressing the potential environmental impacts of MAR is essential for the successful and sustainable implementation of these projects. Thorough evaluation and careful planning can help mitigate adverse effects, ensuring that MAR projects contribute positively to water resource management without compromising environmental integrity and the well-being of local communities and existing water supply systems.

G. Regulatory Considerations

Navigating the regulatory landscape is a critical aspect of planning and implementing MAR projects. A comprehensive understanding of the existing regulatory framework and permitting prerequisites is essential to ensure compliance and to facilitate a smooth project development process. These regulations are often multi-faceted, involving different state agencies and sometimes local jurisdictions, each with its own set of rules and areas of authority.

1. **State Agencies' Jurisdiction**: Typically, two primary state agencies are involved in the oversight of groundwater-related activities. The Department of Environmental Quality (DEQ) usually holds the primary authority over water quality concerns. This agency is responsible for ensuring that MAR projects do not negatively impact the quality of groundwater and adhere to environmental protection standards. They regulate aspects like the permissible levels of contaminants in the recharge water, monitoring requirements, and the impact of the project on existing water quality. Compliance with DEQ regulations is essential for obtaining project approvals and for the ongoing monitoring and management of MAR projects.

   On the other hand, the DWR oversees water rights and appropriation. This agency ensures that the water used for recharge is legally available and that the project does not infringe upon the water rights of other users.
2. **Local Jurisdictions and Land Use Regulations**: Beyond state agencies, local jurisdictions like counties and cities may also play a significant role, especially when it comes to land use and zoning regulations. The siting of surface facilities for a MAR project, such as

recharge basins or infrastructure for water conveyance, must comply with local zoning laws and land use policies. This might involve obtaining special permits, adhering to specific construction standards, or engaging in public consultation processes. Local jurisdictions may also have specific environmental protection rules or water management plans that need to be considered.

3. **Navigating Regulatory Overlaps**: Often, MAR projects may fall under the purview of multiple regulatory bodies, each with its own set of requirements. Navigating these overlapping jurisdictions can be complex and requires careful planning and coordination. Ensuring that the project complies with all relevant regulations is not just a legal necessity but also crucial for maintaining the project's legitimacy and public acceptance.
4. **Engaging with Regulatory Agencies**: Early and proactive engagement with regulatory agencies can facilitate a smoother permitting process. This involves understanding their requirements, seeking their guidance during the planning phase, and keeping them informed throughout the project lifecycle. Building a positive relationship with these agencies can also be beneficial in addressing any regulatory challenges that may arise during the project.
5. **Keeping Abreast of Regulatory Changes**: Regulatory frameworks are not static; they can evolve in response to new scientific findings, policy shifts, or changes in public priorities. Keeping abreast of these changes and understanding their implications for MAR projects is important for ongoing compliance and for adapting project management strategies as necessary.

Regulatory considerations are required for successful implementation of MAR projects. A comprehensive assessment of the regulatory environment, adherence to the requirements of various agencies, and proactive engagement with regulatory bodies are key to navigating the complexities of water resource management and ensuring the sustainability and legal compliance of MAR initiatives. As an example, an aquifer storage and recovery (ASR) project was conceived in the early 1990s to help resolve an impending municipal water supply crisis in the Lakehaven Utility District in Federal Way, Washington. The project was intended to store enough water to annually serve the summertime needs of more than 100,000 people. The OASIS (optimization of aquifer storage for increased supply) project was finally completed in 2007 after finally receiving the necessary state permits. The original feasibility study for OASIS occurred in 1994. For several years the OASIS Project was not pursued due to a lack of clear law regarding the ownership of artificially recharged water. In 2000, the state Legislature clarified the issue by expanding the definition of a reservoir to include aquifers, largely as a direct response to the OASIS Project. Later that year, Lakehaven submitted a reservoir application for the project. It took an additional three years, as a result of a rule-making process, for the Washington State Department of Ecology to begin processing the application. Ecology provided the district with a draft report of examination for the application in September 2005. Following negotiations with the district and tribal interests, an amended draft report of examination was written in May 2006. A final approved reservoir permit for the project was received by the district in September 2006, more than a decade after the project was deemed feasible and a full six years after the application was submitted.

H. Cost-effectiveness Evaluation

Evaluating the cost-effectiveness of a MAR project is essential for determining its economic viability. This process involves a careful assessment of both the initial and ongoing costs against the potential benefits the project offers.

1. **Initial Capital Costs**: The upfront investment is significant, covering the construction of recharge wells or basins, and any necessary infrastructure like pipelines or treatment facilities. Costs vary depending on the project's scale, the recharge method, and local geological conditions.
2. **Operational and Maintenance Costs**: Ongoing expenses include the costs of operating the system, maintaining infrastructure, monitoring water quality and aquifer levels, and administrative tasks. Regular maintenance is key to maintaining system efficiency and longevity.
3. **Water Delivery Costs**: The expense of transporting water to the recharge site, influenced by the distance and the mode of transportation, is an important factor, especially if the water source is far from the recharge area.
4. **Cost-Benefit Analysis**: It's crucial to weigh these costs against the project's benefits, which can range from increased water security and agricultural support to environmental protection. Quantifying these benefits, although challenging, provides a more comprehensive view of the project's value.
5. **Long-Term Financial Sustainability**: Assessing the project's long-term financial sustainability involves considering future changes in water demand, potential regulatory shifts, and ongoing maintenance needs.
6. **Funding and Financing**: Exploring diverse funding and financing options, like government grants, public-private partnerships, or water trading credits, is part of the economic assessment.

Overall, a thorough cost-effectiveness evaluation helps in understanding the full financial implications of a MAR project, ensuring that it is not only feasible initially but remains viable and beneficial over the long term.

I. Stakeholder Considerations

Stakeholder support is essential for the success of MAR projects. Effectively engaging with and gaining the backing of various groups impacted by the project is crucial:

1. **Landowners**: Their cooperation is vital, especially when projects require land for infrastructure. Transparent dialog over land use concerns, property values, and disruptions is essential.
2. **Community Members**: Open communication with local communities is key to addressing concerns about environmental changes, water quality, and impacts on local amenities.

3. **Water Users**: Farmers, industries, and municipal suppliers have a vested interest in the project. Engaging with them helps understand and accommodate their water needs and quality concerns.
4. **Regulatory Agencies**: Their approval is critical. Regular communication and adherence to regulations are essential for smooth project approval and implementation.
5. **Building Support**: Educate stakeholders about the benefits, like improved water security and environmental protection, and address concerns to build broad-based support.
6. **Ongoing Engagement**: Maintain a dialogue, provide updates, and be responsive to feedback throughout the project's lifecycle to sustain support and trust.

Stakeholder engagement in MAR projects involves continuous dialogue and responsiveness to the concerns and needs of landowners, local communities, water users, and regulatory bodies, ensuring broad acceptance and support for the project.

APPLICATION OF THE RANKING CRITERIA AND CONSIDERATIONS

With the ultimate goal of this project to rank and map North Dakota's glacial drift aquifers for their MAR potential and identify the best candidates, it's paramount to properly apply and weight each of the comprehensive set of criteria and considerations listed above. To this end, a systematic approach was employed to develop a comprehensive map of the aquifers, each annotated with a quantified level of suitability for becoming candidates for MAR. This process involved the implementation of a stratified evaluation framework, comprising five distinct tiers. Each tier represents a gradation in the likelihood of an aquifer being deemed an appropriate and promising candidate for MAR project to be able to artificially recharge a significant amount of water into the aquifer. This tiered system allows for a nuanced and detailed assessment of each aquifer's potential, facilitating informed decision-making in the selection of optimal candidates for MAR projects. These five tiers are:

Tier 1 – (Excellent MAR Potential): This is the highest rating, signifying that MAR could be exceptionally effective, and sustainable when integrated into the overall water management system.

Tier 2 – (Very Good MAR Potential): This rating indicates that MAR could be highly effective and well-suited to the local hydrogeological conditions.

Tier 3 – (Good MAR Potential): This rating is given when MAR could be generally effective and appropriate in limited site-specific areas.

Tier 4 – (Fair MAR Potential): This rating suggests that MAR may provide some level of aquifer recharge potential or benefit, but there are significant limitations or inefficiencies.

Tier 5 – (Poor MAR Potential): This rating indicates that MAR would likely be ineffective or unsuitable given hydrogeological context.

A systematic ranking approach was applied to the aquifers listed in Appendix 3. Application of the ranking criteria and considerations were applied to each of the aquifers with emphasis given to higher ranking for aquifers with the ability to accommodate 1,000 acre-feet annually or more through a MAR project. A review was made of published reports describing the aquifers, mostly from the County Ground Water Studies Series, where favorable conditions exist for the likelihood of a successful recharge through a MAR project. Favorable hydrogeological conditions for successful MAR projects would be in environments where aquifers are either in unconfined conditions and have sufficient depth to the water table to allow a mound to form yet not intersect the recharge basin floor, and have high enough transmissivity to allow recapture by high capacity production wells.

The highest rating (*Tier 1, excellent*) denotes those aquifers with the highest level of need for artificial recharge to the aquifer to help solve past or ongoing over-appropriation effects, such as an unsustainable downward trend in water-levels or potential prior-appropriation conflicts. Also, aquifers where there is a perceived major future water need but lack existing capacity to serve the need without MAR support. Aquifers in this category also have the hydrogeologic characteristics to enable large quantities to be put into storage to provide needed resilience to critical drinking water supplies through municipal and rural water systems.

A *Tier 2 (very good)* rating was given to aquifers where MAR could be highly effective and well-suited to the local hydrogeological conditions. These aquifers may also be highly appropriated and future appropriation limited because of the need to ensure the rights of the prior appropriators are protected. These aquifers could easily accommodate the storage of water added through a MAR project especially in areas where there is a high level of demand on the aquifer.

Aquifers where there is significant development but no current need for substantial MAR enhancement are considered *Tier 3 (good)*. This rating is given when MAR could be generally effective and appropriate in limited site-specific areas and during drought cycles. Aquifers in this category typically have stable (or rising) water-level trends but may be susceptible if future large-scale development may lead to downward water-level trends. Also, MAR enhancement may allow additional appropriation to occur without violating the prior appropriation doctrine.

Named unconfined aquifers with little or no significant development were ranked as *Tier 4 (fair)* potential simply because geologic conditions exist for success for successful MAR and if development were to occur in the future, they could become higher ranked and considered better candidates for MAR to occur. These are aquifers are not currently moderately or heavily developed but may have the capacity to accept and store water either due to their high transmissivities or deeper water levels and could be used as transitory reservoirs to store water captured from surface water sources in times of abundant flow in those sources. The existing water quality may not be suitable for supply to irrigation or drinking water but could possibly be improved with the addition of higher quality surface water sources.

Buried aquifers where there is no significant past, current, or imminent development rank the lowest *(Tier 5, poor)* for their MAR potential. This rating indicates that MAR would likely be ineffective or unsuitable given their hydrogeological context. Attempts at MAR may lead to minimal or no recharge, or inefficient use of resources. In addition to buried (confined) aquifers with no significant development, unnamed aquifers, or other small aquifers with minimal or no existing or potential development were put into this category.

Ranking Tier	Number of Aquifers in Tier
1. (Excellent)	3
2. (Very good)	6
3. (Good)	46
4. (Fair)	55
5. (Poor)	175
Grand Total	**285**

AQUIFERS BY RANK

Tier 1 (Excellent potential for MAR consideration)

- Spiritwood-Warwick
- Wahpeton Buried Valley
- West Fargo

Tier 2 (Very good potential for MAR consideration)

- Elk Valley South
- Enderlin
- Icelandic
- Minot
- Spiritwood near Jamestown
- Sundre

Tier 3 (Good potential for MAR consideration)

- Bismarck
- Carrington
- Cattail
- Central Dakota
- Edgeley
- Elk Valley
- Elk Valley middle
- Elk Valley north
- Englevale
- Englevale Lower
- Englevale Middle
- Englevale Upper
- Fordville
- Glencoe Channel
- Guelph
- Hankinson
- Hofflund
- Inkster
- Jamestown
- Karlsruhe
- Knife River
- Lake Nettie
- Lake Souris
- LaMoure
- Little Muddy
- McVille
- Missouri River
- Napoleon
- New Rockford
- New Town
- Oakes
- Page
- Pleasant Lake - Int. Chan.
- Pleasant Lake - N Deep Chan
- Pleasant Lake - S Deep Chan
- Ray
- Sand Prairie
- Shell Valley
- Sheyenne Delta
- Spiritwood-Griggs
- Spiritwood-LaMoure SE
- Spiritwood-Oakes
- Strasburg
- Streeter
- Voltaire
- Warwick Aquifer
- Winona
- Wishek

Tier 4 (Fair potential for MAR consideration)

- Adrian
- Antelope Creek
- Apple Creek
- Beaver Lake
- Braddock
- Brightwood
- Cherry Creek
- Crete
- Crosby
- Dead Colt
- Denbigh-Lake Souris
- Douglas
- Edinburg
- Ellendale
- Elm Creek
- Esmond
- Grenora
- Heimdal
- Hillsburg
- Horseshoe Valley

James River
Juanita Lake
Karlsruhe Deep Channel
Keene
Killdeer
Lignite City
Little Missouri River
Medford
Medina South
Milnor Channel
Mohall
Munich
North Burleigh
Northwest Buried Channel
Painted Woods Creek
Pembina Delta
Pembina River
Pipestem Creek
Pleasant Lake
Rugby Aquifer
Rusland
Skjermo Lake
Spiritwood - Grand Rapids
Spiritwood-Berlin
Spiritwood-SE
Spiritwood-Sheyenne River
Square Butte Creek
Strawberry Lake
Tiffany Flats
Tobacco Garden
Tokio
Trappers Coulee
West Wildrose
Yellowstone
Yellowstone River Channel

Tier 5 (Poor potential for MAR consideration)

Austin
Bantel
Battle Creek
Beaver Creek
Beaver Creek2
Belmont
Bennie Peer
Bicker
Big Bend
Big Coulee
Buffalo Creek
Burnt Creek
Butte
Charbonneau
Cherry Lake
Clayton
Clearwater
Cleary
Colfax
Columbus
Cottonwood Creek
Courtenay
Crane Creek
Cut Bank Creek
Deer Lake
Denbigh Buried Channel
Des Lacs River
Dry Fork Creek
Dunseith
East Fork Shell Creek
Eastman
Edgemont
Elliot
Estevan
Fairmount
Fillmore
Foothills
Foothills South
Fort Mandan
Fox Haven
Garrison
Glenburn
Glenview
Goodman Creek
Grand Forks
Gwinner
Heart River
Hiddenwood Lake
Hillsboro
Homer
Horse Nose Butte
Kenmare
Kilgore
Koble
Lake Ilo
Landa
Leeds
Little Heart
Little Knife River Valley
Little Stoney
Long Lake
Lost Lake
Lower Wishek
Lucy
Maddock
Manfred
Martin
McClusky
McIntosh
McKenzie
Medina North
Middle James
Midway
Missouri River - Lake Sak
Missouri River-Oahe
Montpelier
Oberon
Otter Creek
Painted Woods Lake
Pony Gulch
Random Creek
Renner
Riverdale
Rocky Run
Rolla
Roosevelt
Rosefield
Russell Lake
Ryder
Ryder Ridge
Sanish
Seven Mile Coulee
Shealy
Sheldon
Shell Creek-Central
Shell Creek-East Branch
Shell Creek-White Lake
Shields
Smoky Butte
Snake Creek
Soo Channel
Souris River
South Branch Beaver Creek
South Fessenden
Spiritwood-Devils Lake
Spiritwood-Rogers
Spiritwood-Towner County
Spring Creek
Squaw Creek
St. James

- Starkweather
- Stoneview
- Stoney Creek
- Sydney
- Thompson
- Tolgen
- Tolgen North
- Tower City
- Trenton
- Turtle Lake
- Upper Apple Creek
- Upper Buffalo Creek
- Vang
- Wagonsport
- Weller Slough
- White Earth
- White Shield
- Wildrose
- Wimbledon
- Windsor
- Wing Channel
- Wolf Creek
- Ypsilanti
- Zap
- Zeeland
- Wahpeton Complex
- Wahpeton sand plain
- Wahpeton shallow sand
- West Fargo North
- West Fargo South

CREATION OF THE MAP SHOWING THE MAR POTENTIAL

An interactive map showing a color-coded ranking of MAR Potential for each aquifer was created using a combination of geographical information system (GIS) tools and web mapping technologies. The aim was to enhance accessibility and user engagement with aquifer data through an interactive web-based platform. The interactive map is available through the web at the web at https://mar.dwr.nd.gov. A static images of the webpage are shown in Figures 5 and 6.

Data Sources and Initial Setup

The foundational layer for the map was sourced from the DWR map service (mapservice.dwr.nd.gov), specifically the aquifer basemap. This layer provided crucial spatial information about the aquifers and aquifer names. The basemap was downloaded and imported into a QGIS project, a popular open-source GIS software. In addition to the aquifer basemap, several other layers were incorporated to enrich the map's usefulness:

- County Boundaries: To give spatial context within well-known political bounds.
- Rivers and Streams: For a better understanding of the hydrological context and distance to aquifers if desired to be used as recharge sources to them.
- Water Permits: Showing areas with active water rights.
- Long-term Stream Flow Data: To give insight into surface water flow trends, quantity and quality.

The aquifer layer was the focal point of this project. To maximize its utility, several fields were added to its attribute table:

- County Study Hyperlinks: Linking to detailed studies or reports on aquifers within specific counties.
- Composite Hydrograph Hyperlinks: Directing users to hydrograph data illustrating water-level changes over time.
- Water Quality Hyperlinks: Offering quick access to water quality reports and data.
- Areal Size and Approximate Thickness: Quantitative data providing a sense of the scale and capacity of each aquifer.
- Calculated Volume: Estimating the total water volume contained within each aquifer.
- MAR Rank: A qualitative measure based on various factors such as size, recharge rate, and water quality.

Web Map Creation and Deployment

With the data layers enriched and organized, the next phase involved converting the QGIS project into a web-accessible format. For this, the opensource plugin, qgis2web (https://github.com/qgis2web/qgis2web), was employed. This tool facilitated the creation of an interactive web map directly from the QGIS interface. The resulting web map offered several interactive features:

- Layer Toggling: Users can choose which layers to display, tailoring the map to their specific interests or needs.
- Pop-up Windows: Clicking on an aquifer triggers a pop-up window, presenting the user with detailed information and hyperlinks to external resources.
- Zoom and Pan: Intuitive navigation controls for exploring different regions of the map.
- Rank Filtering
- Aquifer Search
- More info button and icon
- Related links

Accessibility and User Interaction

The interactive web map can be accessed at mar.dwr.nd.gov. The interactive aquifer map uses a combination of GIS technologies and web mapping tools to bring static data together into an engaging and informative web-based platform. This approach significantly expands the reach of the map, allowing all users – researchers, policymakers, educators and the general public – to interact with aquifer MAR ranking data along with existing pertinent datasets allowing informed decision-making regarding water resources management with respect to managed aquifer recharge.

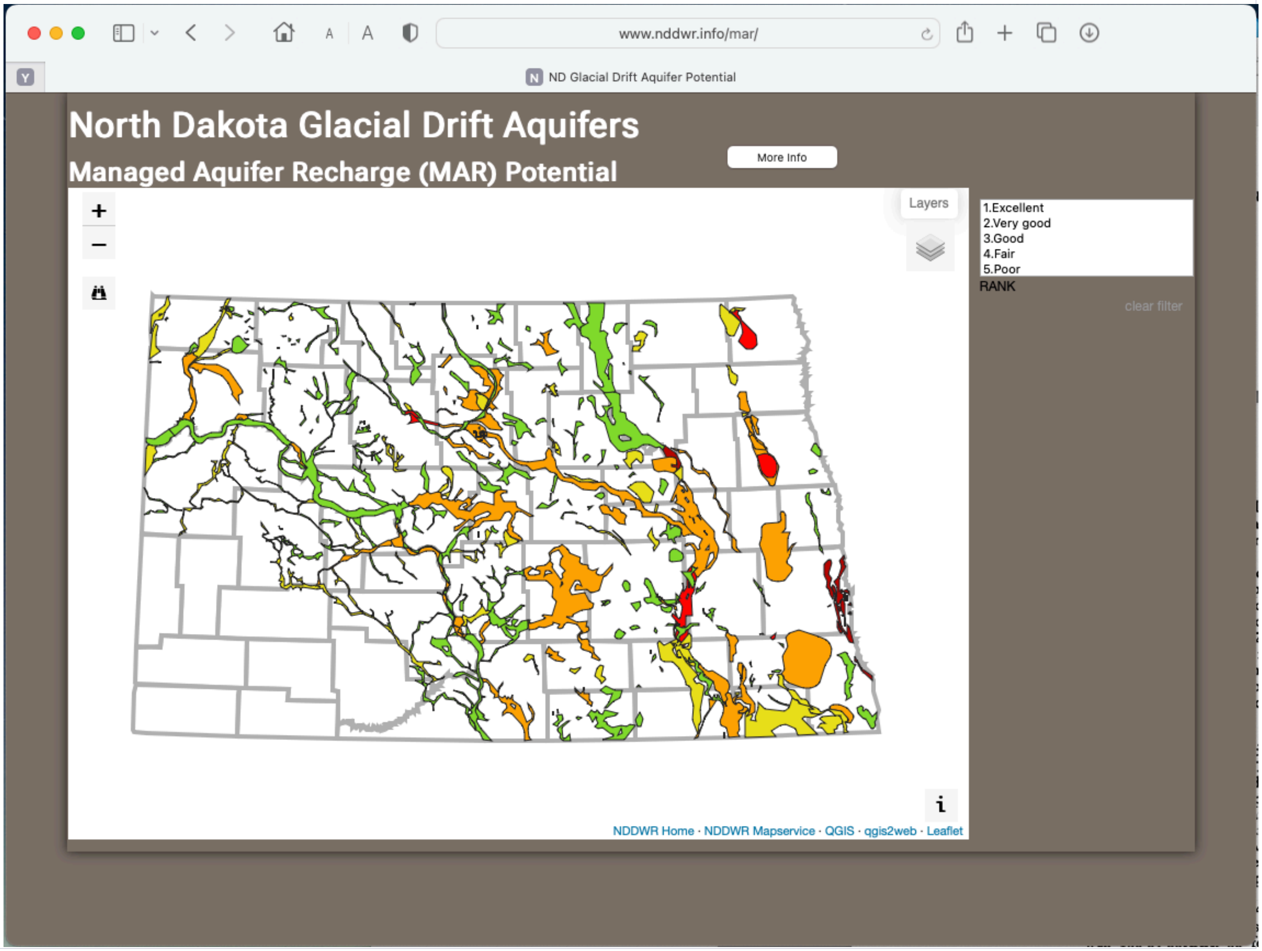


Figure 5. Interactive website displaying the ranking of MAR Potential for ND Glacial Drift aquifers.

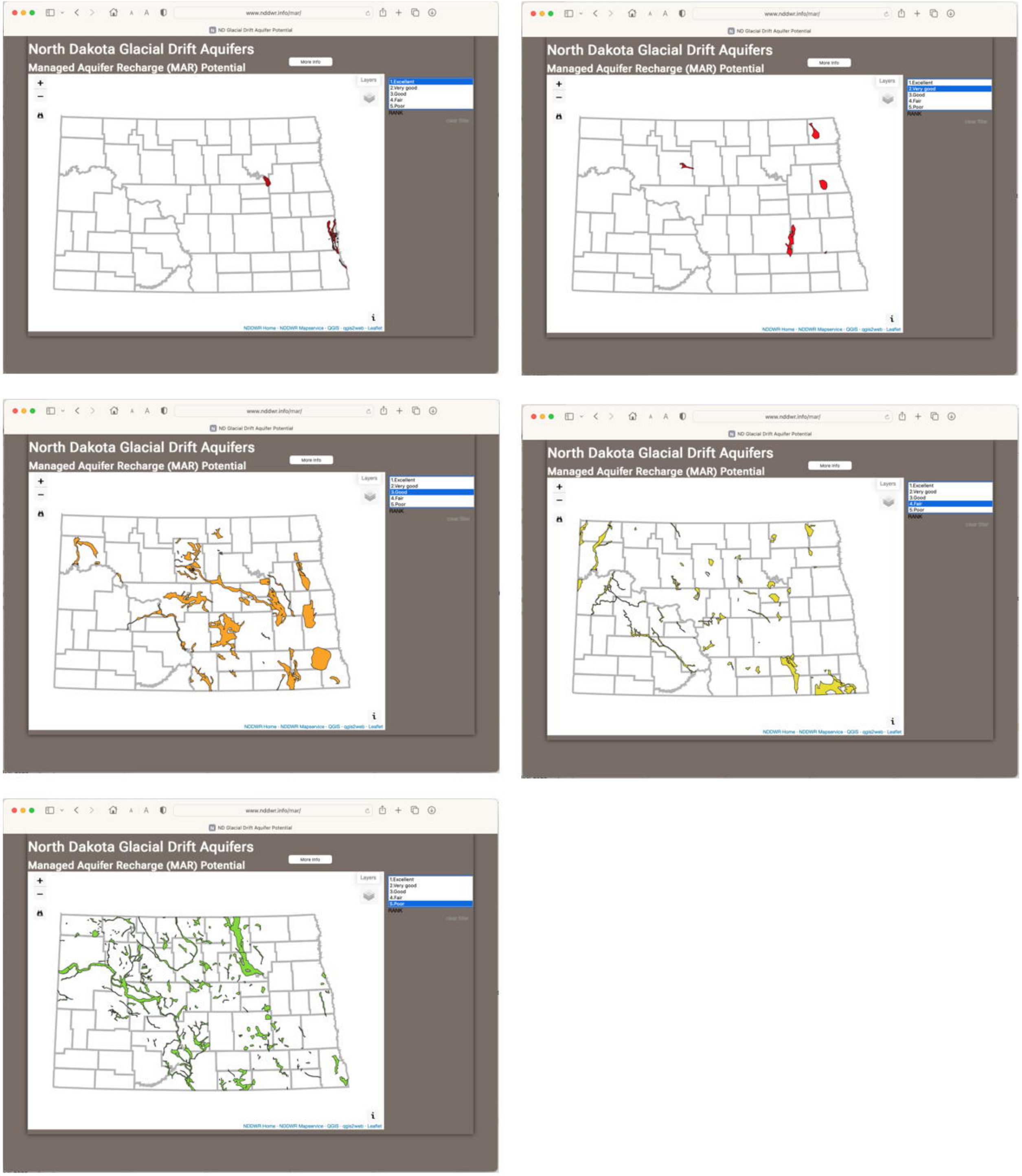


Figure 6. Interactive website displaying the individual ranking tiers of MAR Potential for ND Glacial Drift aquifers.

DISCUSSION OF AQUIFERS WITH BEST MAR POTENTIAL

There are nine distinct aquifers within the state which have been classified within the Tier 1 (excellent) and Tier 2 (very good) categories, thereby signifying their strong potential suitability for successful MAR application. An in-depth analysis of the three aquifers within the Tier 1 category is presented below. Following that, a concise overview of the six aquifers in the Tier 2 category is also provided.

Tier 1 – Excellent Potential for MAR

The West Fargo aquifer system

West Fargo aquifer is actually a system of aquifers with a similar depositional environment in and around the cities of Fargo and West Fargo (Figure 7). Stated by Ripley (2000), "the spatial

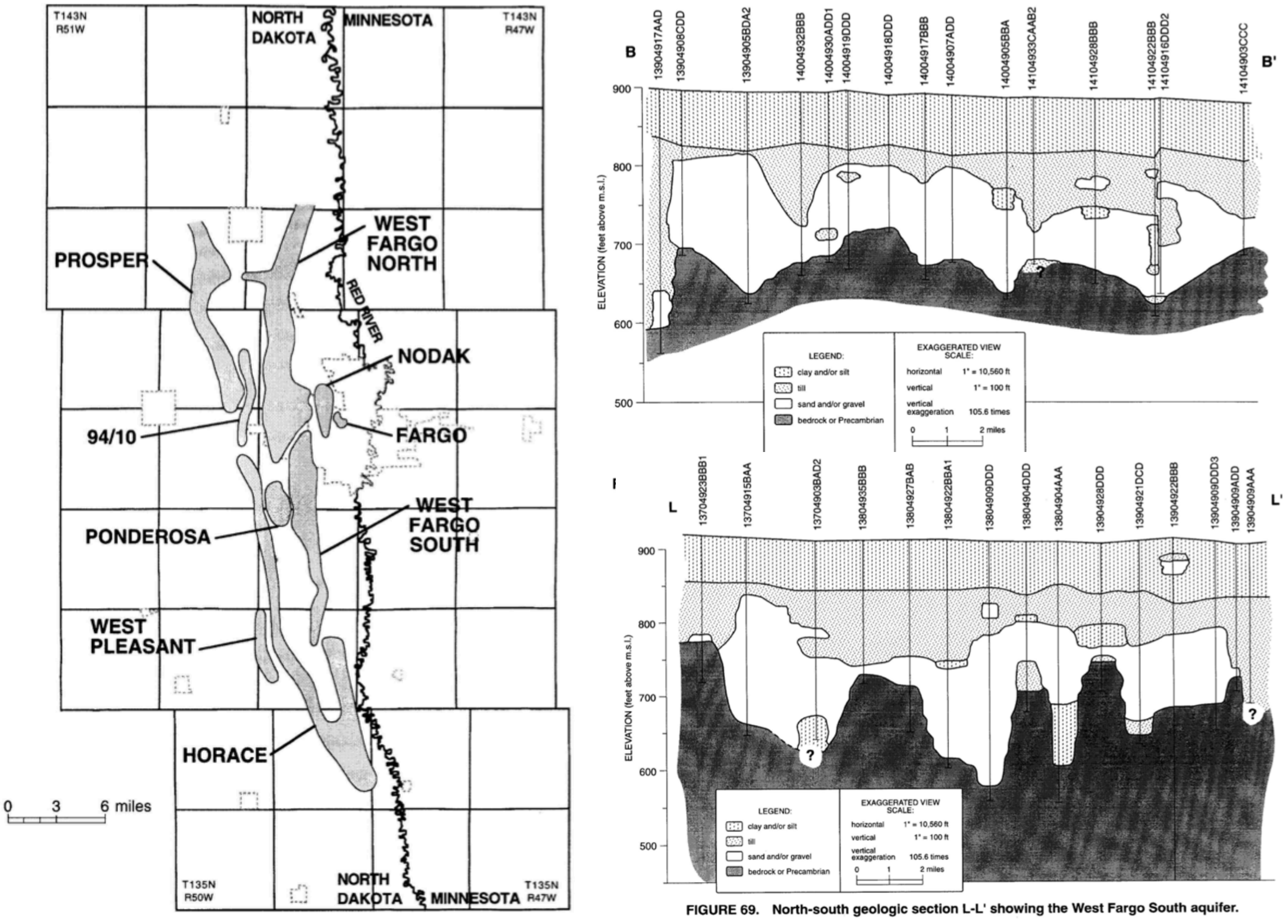


FIGURE 69. North-south geologic section L-L' showing the West Fargo South aquifer.

Figure 7. Figures from Ripley (2000) showing the map of aquifers making up the West Fargo Aquifer System and geologic sections of the West Fargo North and West Fargo South aquifers.

distribution of the glacial sediments (approximately 200 to 400+ feet thick) is extremely complex. It is within these sediments that the West Fargo Aquifer System (WFAS) is found." The two primary sub units of the WFAS are the West Fargo North and West Fargo South aquifers. The geologic setting for each of these aquifers is similar: about 50 to 100 feet of sand and gravel buried under approximately 80 feet of tight lacustrine clay and silt. The tight lacustrine clay overlying the aquifer restricts any significant recharge from natural precipitation from making its way into the aquifer system hence, the water levels have declined over 100 feet since the 1930s when significant water supply development began for municipal and industrial supply began (Figure 8).

The decline in water-level in the aquifer was apparently enough even in 1968 that an investigation was initiated by the SWC to investigate artificial recharge to the aquifer which was then referred to as the Southwest Fargo aquifer. In 1968, the Civil Engineering Department of North Dakota State University, did a laboratory analysis that scale-tested the use of gravity shafts for groundwater recharge into the declining Southwest Fargo aquifer. The laboratory investigation is described in a report entitled "The Use Of Gravity Shafts For Ground Water Recharge." To summarize the conclusions of the report, the number of 48" gravity shafts composed of uniform sands with different sizes with much higher permeabilities than the aquifer itself (U.S. Standard Sieves sizes 20, 30 and 40), would be 6, 18 or 25 shafts, respectively, to recharge 1MGD (million gallons per day) under water-table conditions. Larger sand sizes reduce the number of shafts but may increase the risk of clogging sediment or other detrimental elements entering the aquifer. Theoretically, the maximum permeability of the shaft should be provided for flow considerations, but the minimum permeability should be equal to that of the aquifer to prevent sediment from entering the aquifer.

In laboratory tests, clogging occurred in the top few inches of the shaft, and in field conditions, it is possible that air binding or bacteriological clogging could occur, but it might be prevented by chlorination. Measures to prevent clogging by algae would need to be determined in field tests. Two shaft designs are feasible: (a) for shaft restoration and (b) for shaft replacement. Both designs include a minimum sand size to prevent sediment penetration into the aquifer. The shaft restoration design has a coarse gravel and sand at the bottom, reducing to a pea gravel and medium sand in the upper 10 feet, with a uniform fine sand in the top portion. The shaft replacement design is the reverse of this, with the minimum sand size equal to No. 20 sand throughout the full depth. The reduction in clogging rate of the upper layers of the shafts under reduced sediment concentration shows that the life expectancy of the shaft can be extended and the permeability retained by a reduction in turbidity or sediment loading.

Where land is available, simple detention or lagooning may reduce the necessary turbidity for highly turbid water. A sedimentation basin will also result in a reduction of particle size of the sediment. The shaft test results show a definite reduction in clogging rate in the upper level of the shaft with the use of recharge water having lower levels of turbidity. Turbidity levels in the Sheyenne River at Southwest Fargo at various flow rates were estimated, and the results of the laboratory tests were found to be applicable to future field experiments in the Southwest Fargo area using recharge water from the Sheyenne River. Sedimentation experiments using river water during higher river stages would be required to determine the physical and economic value of sedimentation for pre-treatment of recharge water during periods of high flows.

The composite hydrograph of observation wells in the West Fargo Aquifer system shows there has been over 120 feet of water-level decline in the aquifer system as a result of municipal, industrial, and rural-water water supply development since the 1930s. The reason for the large decline is the lack of significant natural recharge to the system due to the overlying tight lake clay layer. Most of the water in the aquifer is thought to be connate water placed in the aquifer at the time of deposition during the Pleistocene, hence the “cold” signature in the stable isotopic analyses described by Ripley (2000). The pre-development aquifer water-level was at or near land surface. After several decades of pumping it appears the aquifer broke into unconfined conditions in approximately 1963 based on the inflection in slope of the water-level decline. A more gentle decline in water-levels occurred until about 1983 where a steeper decline began. It does not appear there was a dramatic increase in water usage to cause the decline so it is speculated that the decline may have been caused by a reduction in the areal size of the saturated portion of the unconfined aquifer. The water-level decline tapered off until about 2016 when water levels began to increase. This is due to the City of West Fargo abandoning the West Fargo aquifer as their primary source of supply and transitioning to purchasing their municipal water from the City of Fargo which uses the Red River as their supply source.

Recorded Water Usage from the WFAS since 1977 is shown in Figure 9. The City of West Fargo was the primary municipal user until 2016, Cass County Water District is the primary rural water supply, and Cargil, Inc. is the primary industrial user from WFAS.

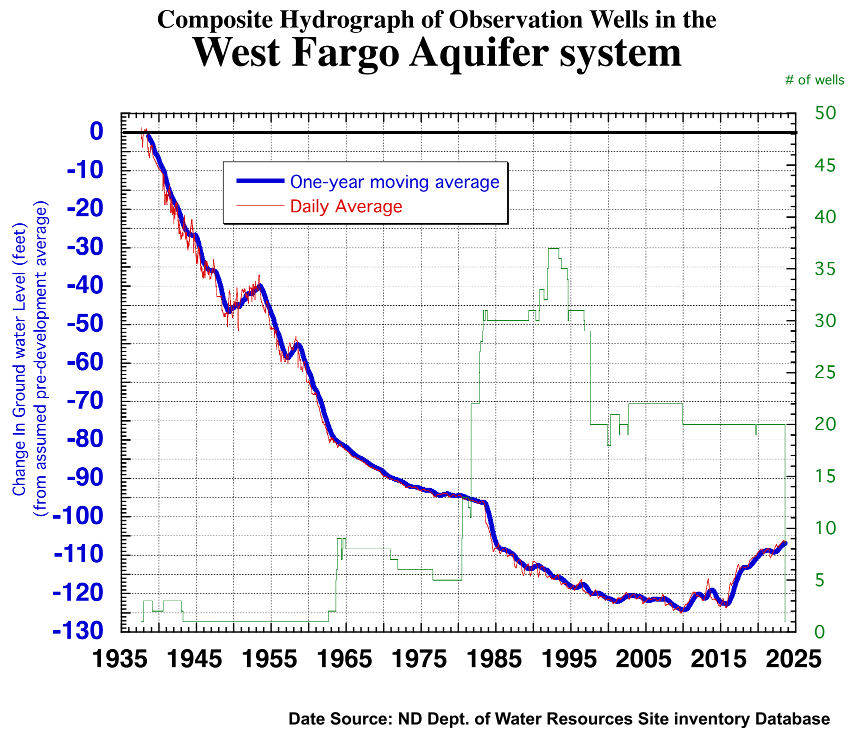


Figure 8. Composite Hydrograph of Wells in the West Fargo Aquifer System.

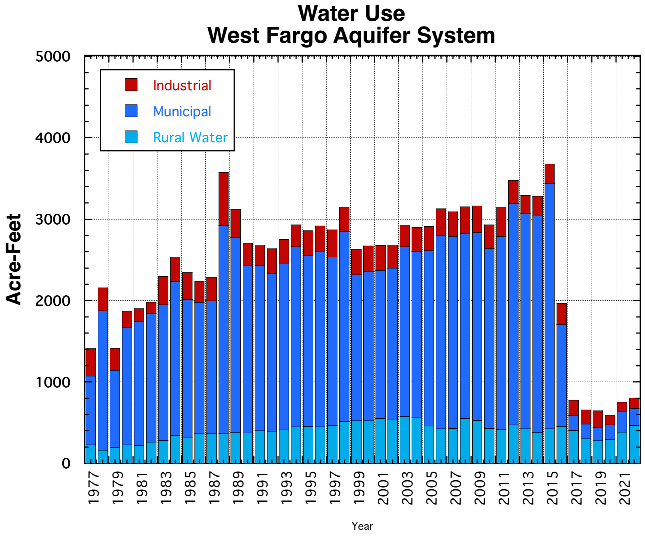


Figure 9. Reported water usage from the West Fargo Aquifer System.

The overall water quality of the West Fargo aquifer can be characterized by the total dissolved solids (TDS). The mean TDS trend of all samples from the West Fargo aquifer is shown in Figure 10. The trendline of the mean TDS shows the water quality has improved over the period of record from approximately 1,000 mg/l in 1962 to approximately 600 mg/l in 2022.

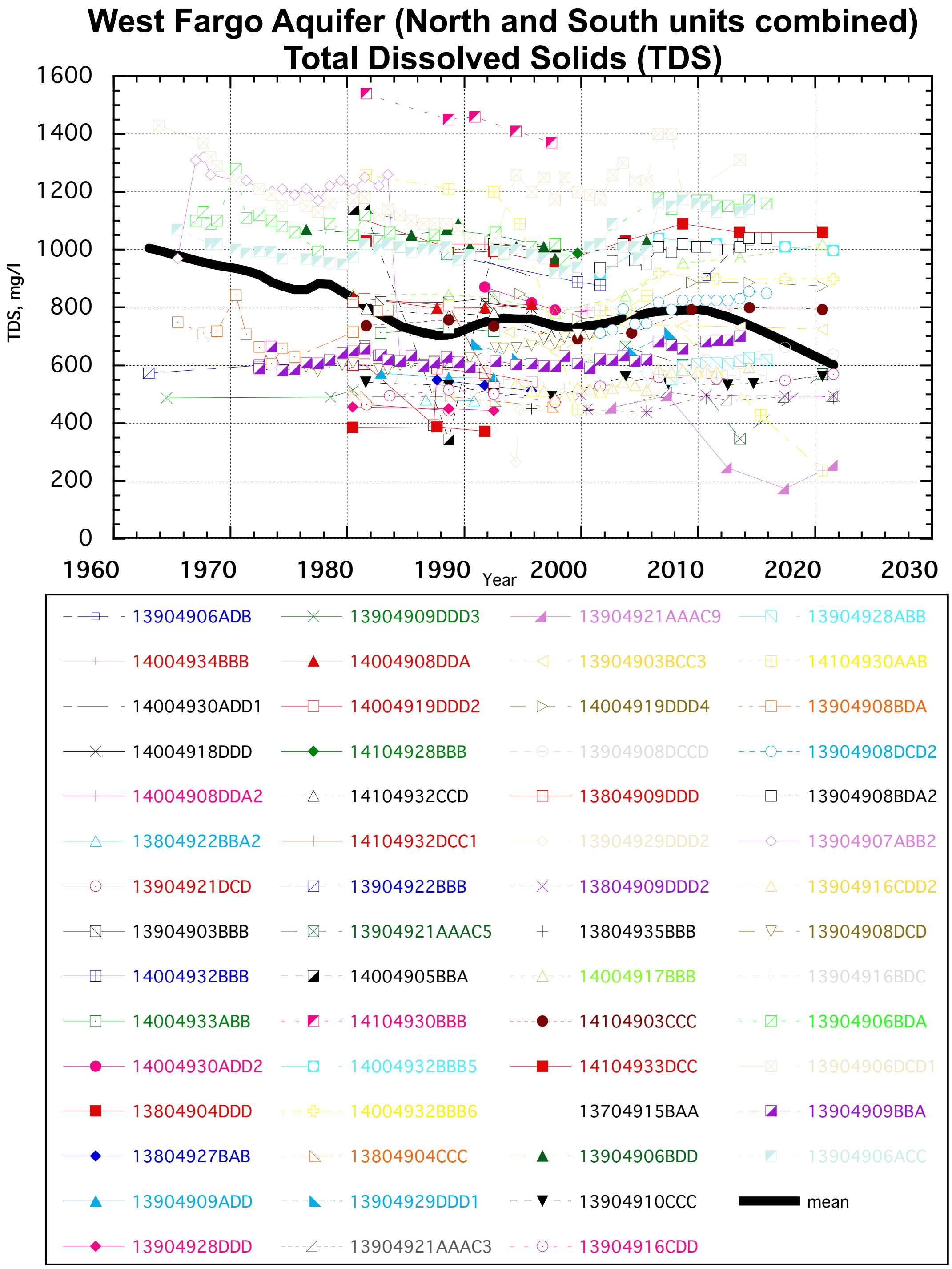


Figure 10. Spatial and Temporal TDS Analyses from the West Fargo Aquifer System.

Nearby surface water sources that could be used as sources of supply include the Sheyenne and Red rivers. The mean TDS trends of these sources are show in Figures 11. The Red River mean TDS is less than 500 mg/l which indicates excellent water quality and would improve the in-situ water quality of the aquifer if used as a MAR source. The Sheyenne River has an average TDS of approximately 900 mg/l which has been improving since about 2016 when the TDS was averaging approximately 1,150 mg/l (Figure 11). At present, use of the Sheyenne River as the source of supply for MAR to the West Fargo aquifer system would slightly degrade the in-situ quality of the aquifer, however, if the trend of improving water quality in the Sheyenne River continues as it as for the last several years, it would become a very viable source of supply for MAR to the WFAS.

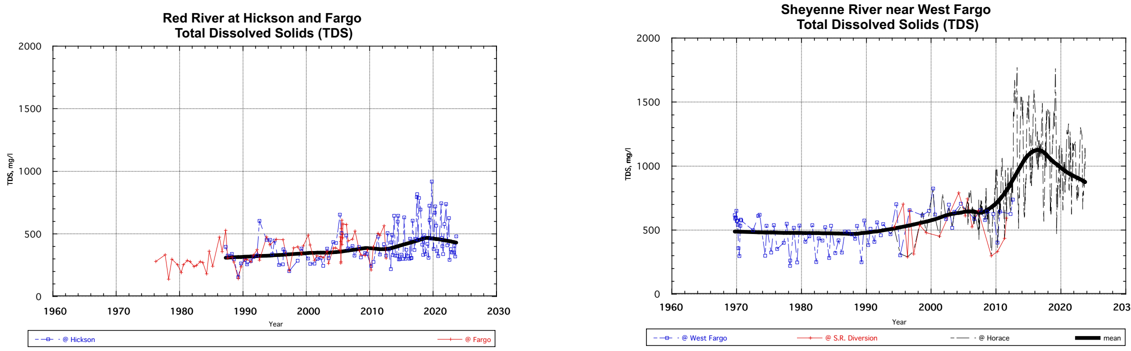


Figure 11. Mean TDS of samples collected from the Red River at Hickson and Fargo and the Sheyenne River near West Fargo.

The long-term mean flow is 468 cubic feet per second (cfs) in the Red River at Fargo and 192 cfs in the Sheyenne River at West Fargo. Streamflow duration hydrographs for these two sources are shown below in Figure 12.

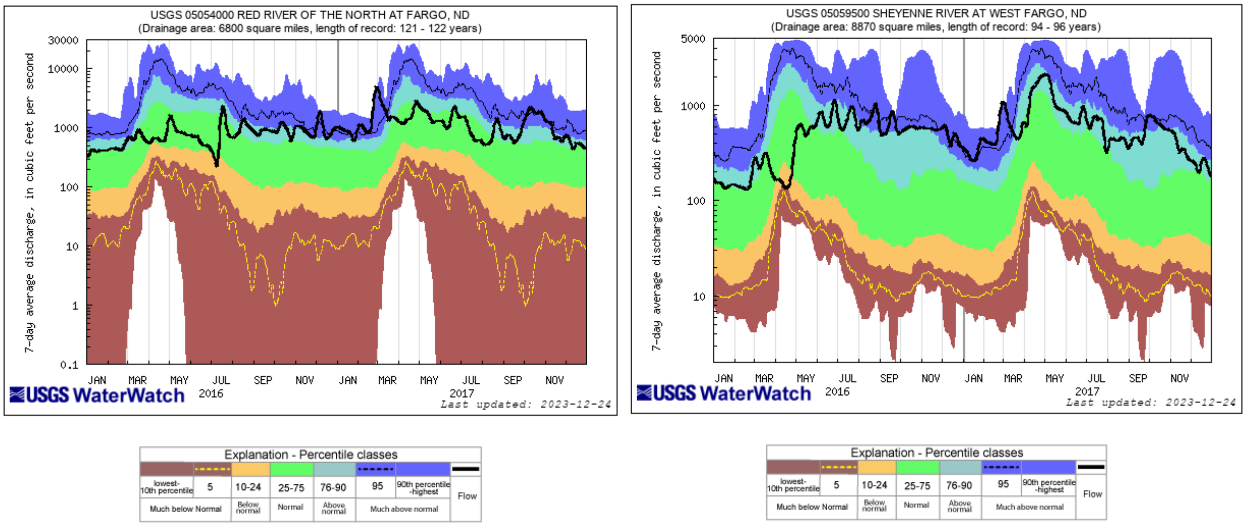


Figure 12. Streamflow Duration Hydrographs from the Red River at Fargo and the Sheyenne River near West Fargo.

Pros and Cons of the West Fargo Aquifer as a candidate for MAR

Pros:

- Over 100 feet of water-level decline has occurred from development
- Large reservoir for water to be stored due to past dewatering
- Suitable fresh water supply nearby (Red and Sheyenne Rivers)
- Could easily accommodate 1,000+ acre-feet per year in MAR
- Could provide resiliency to the greater Fargo area water supplies.
- Continued dewatering may result in some land subsidence if not addressed

Cons:

- Buried confined system
- More sophisticated recharge method required
- No immediate need for recharged water to be put to beneficial use

Wahpeton Buried Valley aquifer

The Wahpeton Buried Valley aquifer system is a complex of aquifers which occur at three distinct levels: the Wahpeton Shallow Sand (WSS) aquifer, the Wahpeton Sand Plain, (WSP) and the Wahpeton Buried Valley (WBV) aquifer (Ripley, 1992). From Ripley (1992): "The WBV aquifer is at least 12 to 15 miles long, about a mile wide, and has an average thickness of about 125 feet. The aquifer terminates to the north somewhere near Abercrombie, and to the south the aquifer continues to at least several miles into Minnesota. The WBV aquifer crosses the Red River a mile southeast of Minn-Dak Farmers' Cooperative beet plant.

The top of the aquifer is generally about 150 feet below land surface, although in places overlying sand units that are in direct connection with the sand of the WBV aquifer are found at depths of 75 feet or less in some places. The bottom of the WBV aquifer is generally about 250 to 300 feet below land surface in the deepest part of the channel. The bottom of the aquifer in some areas is as little as 150 feet below land surface.

The material found in the WBV aquifer is generally sand or sand and gravel. The sand is generally well sorted medium to coarse, subangular to subrounded sand. The pore space between the sand and gravel grains is where the water in the Wahpeton Buried Valley aquifer is stored. This space is approximately about 35 percent of the volume of the aquifer. Not all of the water in the pore space is retrievable. The actual retrievable volume of water stored is about 25 percent of the aquifer volume."

Honeyman (2021), provided updated information of the aquifer system in his Recommended Decision on an amendment to Water Permit Nos. 1822 and 1898 (Figure 13). The amendment allows the City of Wahpeton to move their well field to a new location in the vicinity of 133-048-02DDD. Should the city pump their maximum allocation at this location, an additional 40.5 feet of drawdown could occur on top of the current developmental decline which the aquifer has already sustained in the decades since development began. Total drawdown of approximately 80 feet at this location would put the water-level below the top of the aquifer at this location. Generally, the water-level decline in the aquifer as a whole has been 40 to 45 feet due to the demand of the municipal and industrial development in the aquifer (Figure 14).

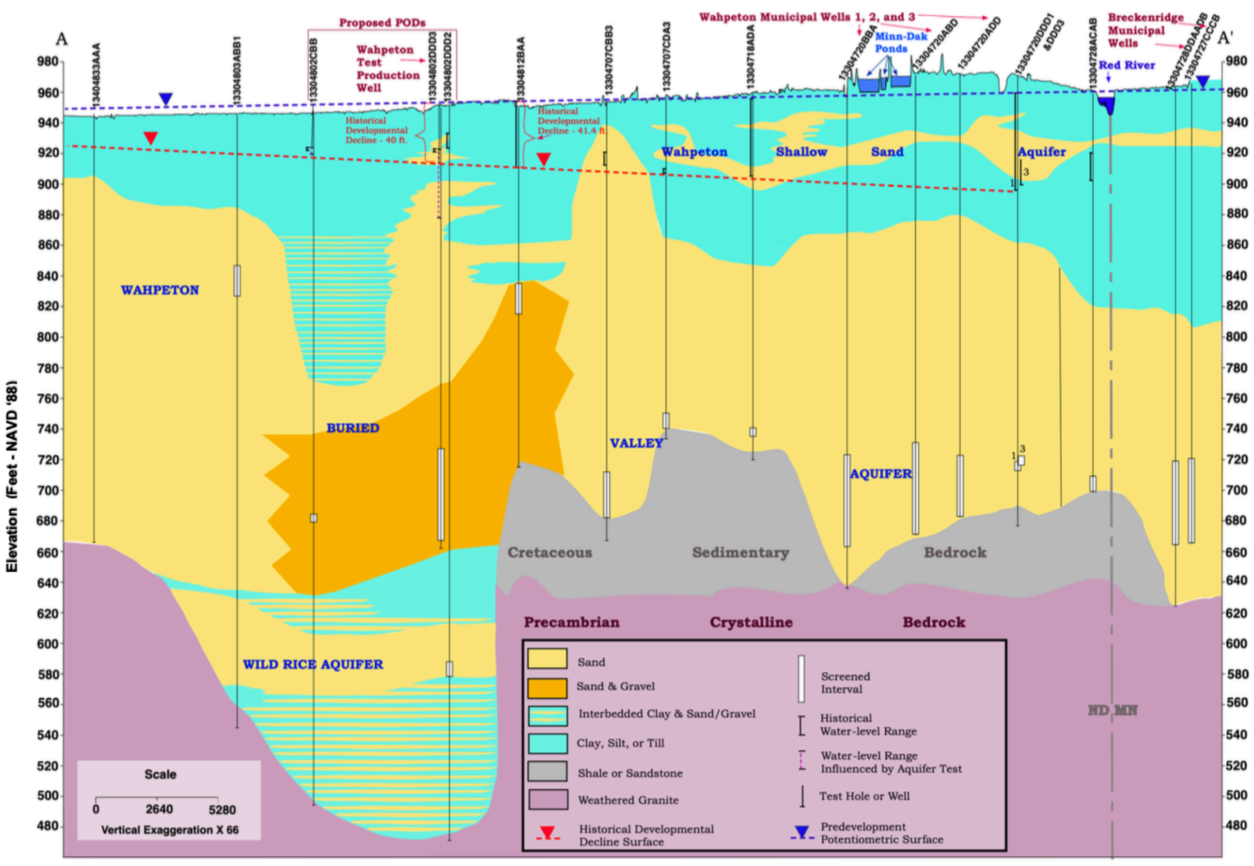
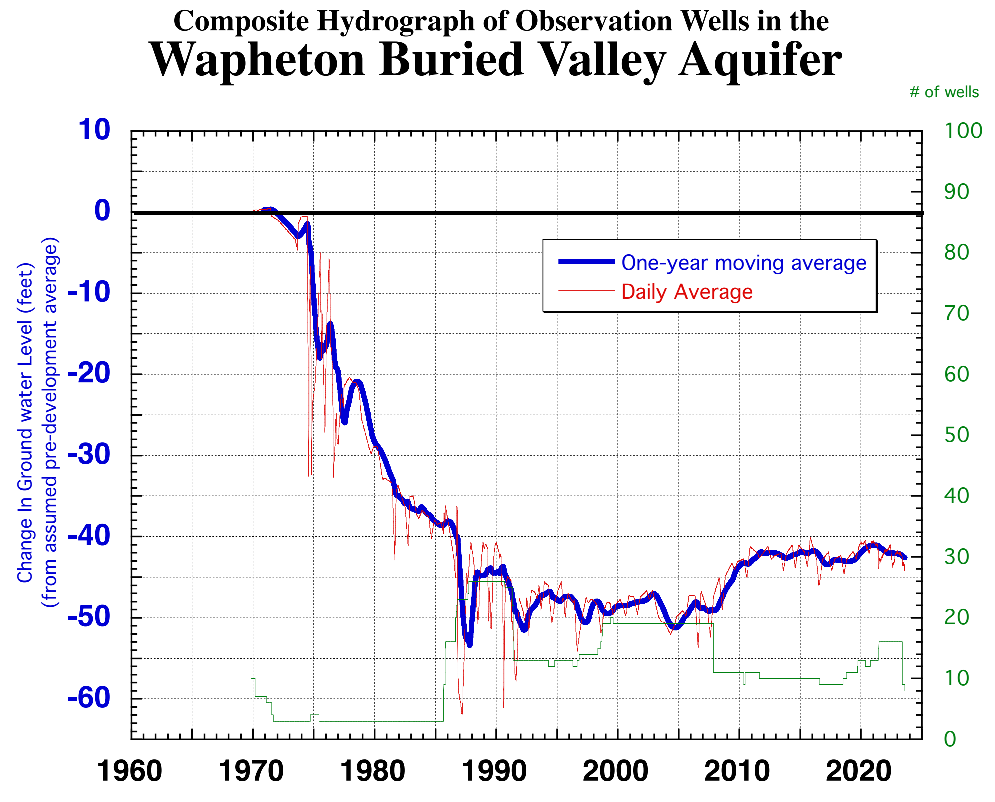


Figure 6. Hydrogeologic Section A-A' (NAVD '88 – North American Vertical Datum of 1988).

Figure 13. From Honeyman (2021), Amendment to Water Permit Nos. 1822 and 1898 - Aquifer Test Results



Date Source: ND Dept. of Water Resources Site inventory Database

Figure 14. Composite Hydrograph of Wells in the Wahpeton Buried Valley Aquifer.

Recorded Water Usage (from Permits in North Dakota) from the Wahpeton Buried Valley aquifer since 1977 is shown in Figure 15. The primary municipal user is the City of Wahpeton and the primary industrial user is Minn-Dak Farmers Cooperative. Honeyman (2021) provide a thorough description of historical use in the aquifer including water-use by the City of Breckenridge, MN which pumps water from the WBV for their municipal use.

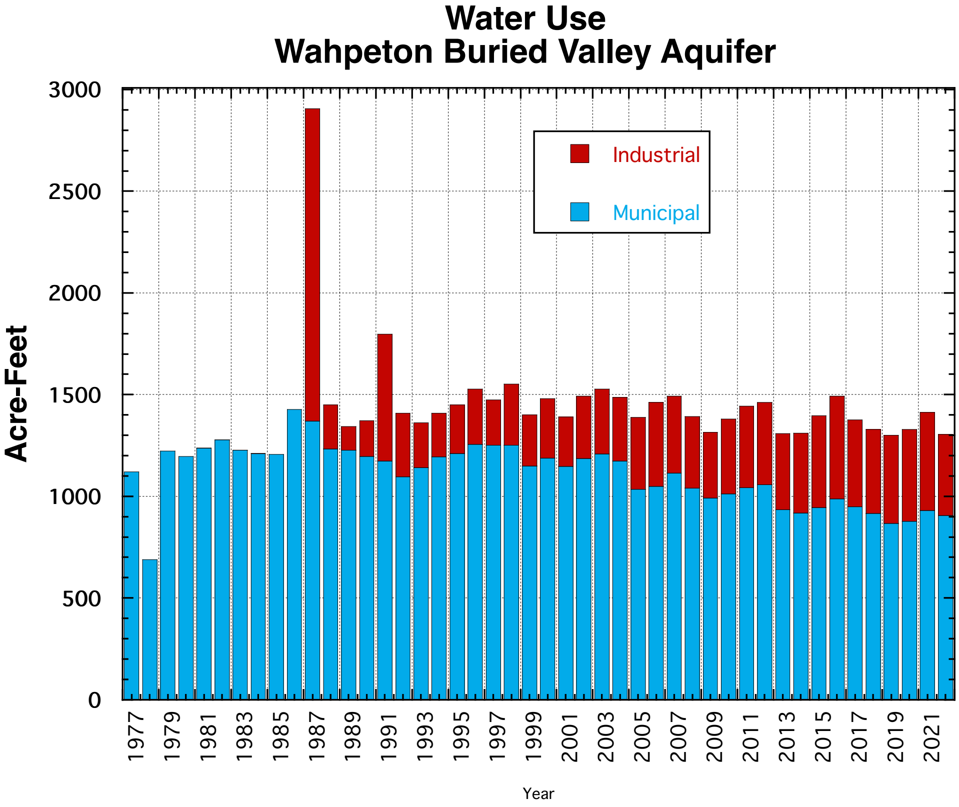


Figure 15. Reported water usage from the Wahpeton Buried Valley Aquifer.

The overall water quality of the WBV aquifer as characterized by the mean total dissolved solids (TDS) trend of all samples from the WBV aquifer is shown in Figure 16. The trendline of the mean TDS shows the water quality has held steady over the period of record at approximately 650 to 700 mg/l.

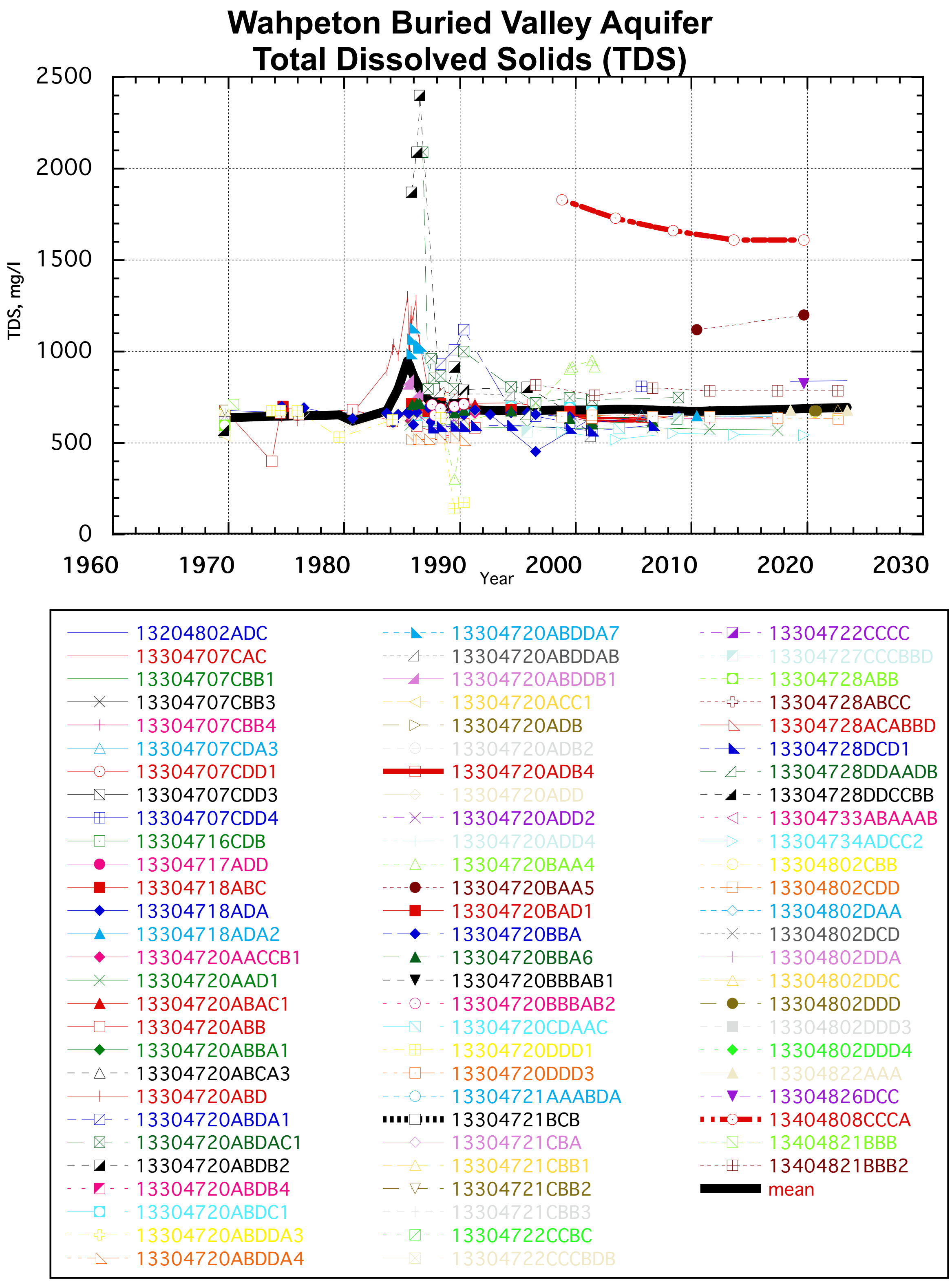


Figure 16. Spatial and Temporal TDS Analyses from the Wahpeton Buried Valley Aquifer.

Nearby surface water sources that could be used as sources of supply include the Wild Rice and Red rivers. The mean TDS trends of these sources are show in Figure 17. The Red River mean TDS is less than 500 mg/l which indicates excellent water quality and would improve the in-situ water quality of the aquifer if used as a MAR source. The Wild Rice River average TDS trends from near 500 mg/l in 1970 to over 1,000 mg/l in 2020, however, appears to be in a declining trend to around 900mg/l in 2023 . Use of the Wild Rice River as the source of supply for MAR to the Wahpeton aquifer system would degrade the in-situ quality of the aquifer at the present time but if the trend of improving water quality continues it may become a viable source of water for MAR to the WBV aquifer.

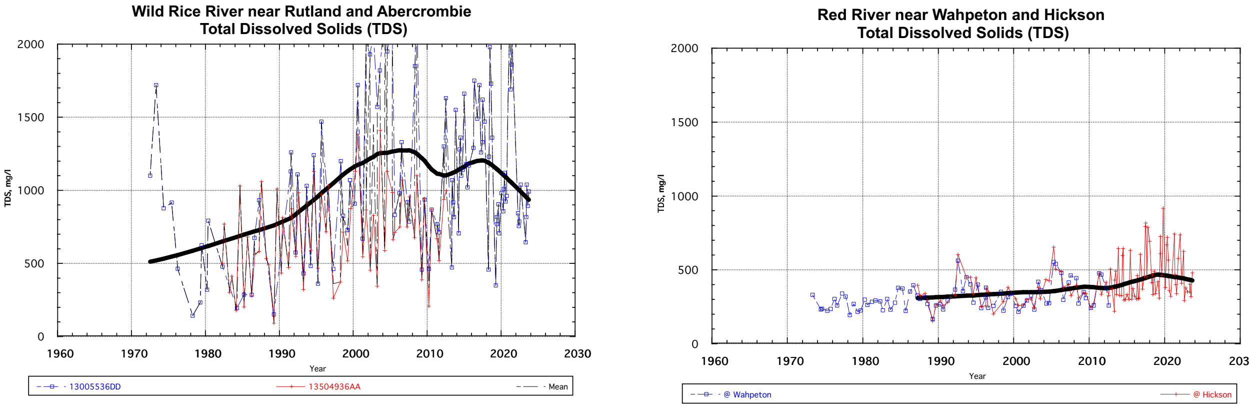


Figure 17. Mean TDS of samples collected from the Red River at Wahpeton and Hickson and Wild Rice River near Rutland and Abercrombie.

The long-term mean flow is 468 cubic feet per second (cfs) in the Red River at Fargo and 192 cfs in the Sheyenne River at West Fargo. Streamflow duration hydrographs for these two sources are shown below in Figure 18.

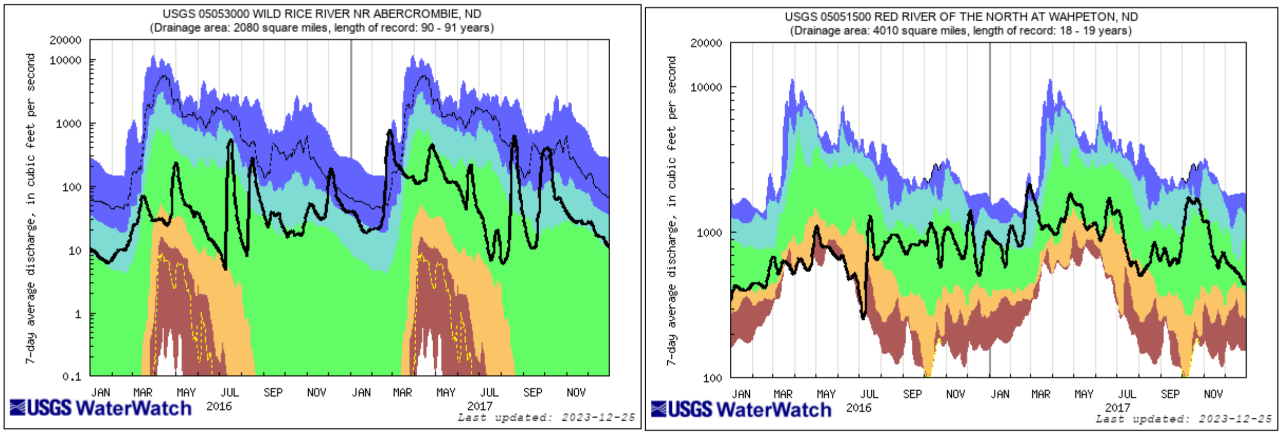


Figure 18. Streamflow Duration Hydrographs from the Red River at Fargo and the Sheyenne River near West Fargo.

Pros and Cons of the Wahpeton Aquifer as a candidate for MAR:

Pros:

- Over 45 feet of water-level decline has occurred from development
- Large reservoir for water to be stored due to past dewatering
- Suitable fresh water supply nearby (Red and Wild Rice Rivers)
- Could easily accommodate 1,000+ acre-feet per year in MAR
- Could provide resiliency to the Wahpeton area water supplies.
- An additional 40 feet of decline could occur without the addition or artificial recharge
- Immediate need
- Would allow additional appropriation for beneficial use

Cons:

- Buried confined system
- More sophisticated recharge method required

Spiritwood aquifer near Warwick

The Spiritwood aquifer near Warwick (SPW-WAR) is a segment of the Spiritwood aquifer that is for the most part hydraulically separated from the segment to the north, the Spiritwood aquifer near Devils Lake, and the segment to the south, the Spiritwood aquifer near the Sheyenne River. The SPW-WAR is a buried confined aquifer that varies from 3 to 8 miles wide and is about 13 miles long and covers about 60 sq. miles. The aquifer is 150 to 200 feet thick along its axis in this segment. The aquifer is composed of sand and gravel ranging from fine sand to very coarse gravel and cobbles with a large portion of the aquifer consisting of coarse sand to fine gravel. Much of this segment of the Spiritwood aquifer is overlain by the Warwick aquifer. The Warwick aquifer is a surficial outwash deposit. The aquifer thickness ranges from 20 to 200 feet and is for the most part unconfined. For the most part, the Spiritwood and Warwick aquifers are separated by a layer of either till or glacio-lacustrine clay and silt. In some places, there is nearly continuous sand and gravel from the surface to the bottom of the SPW-WAR with just small interruptions of low-K material. One such area is depicted on the Geologic section C-C’ from Patch and Honeyman, 2003 shown in Figure 19.

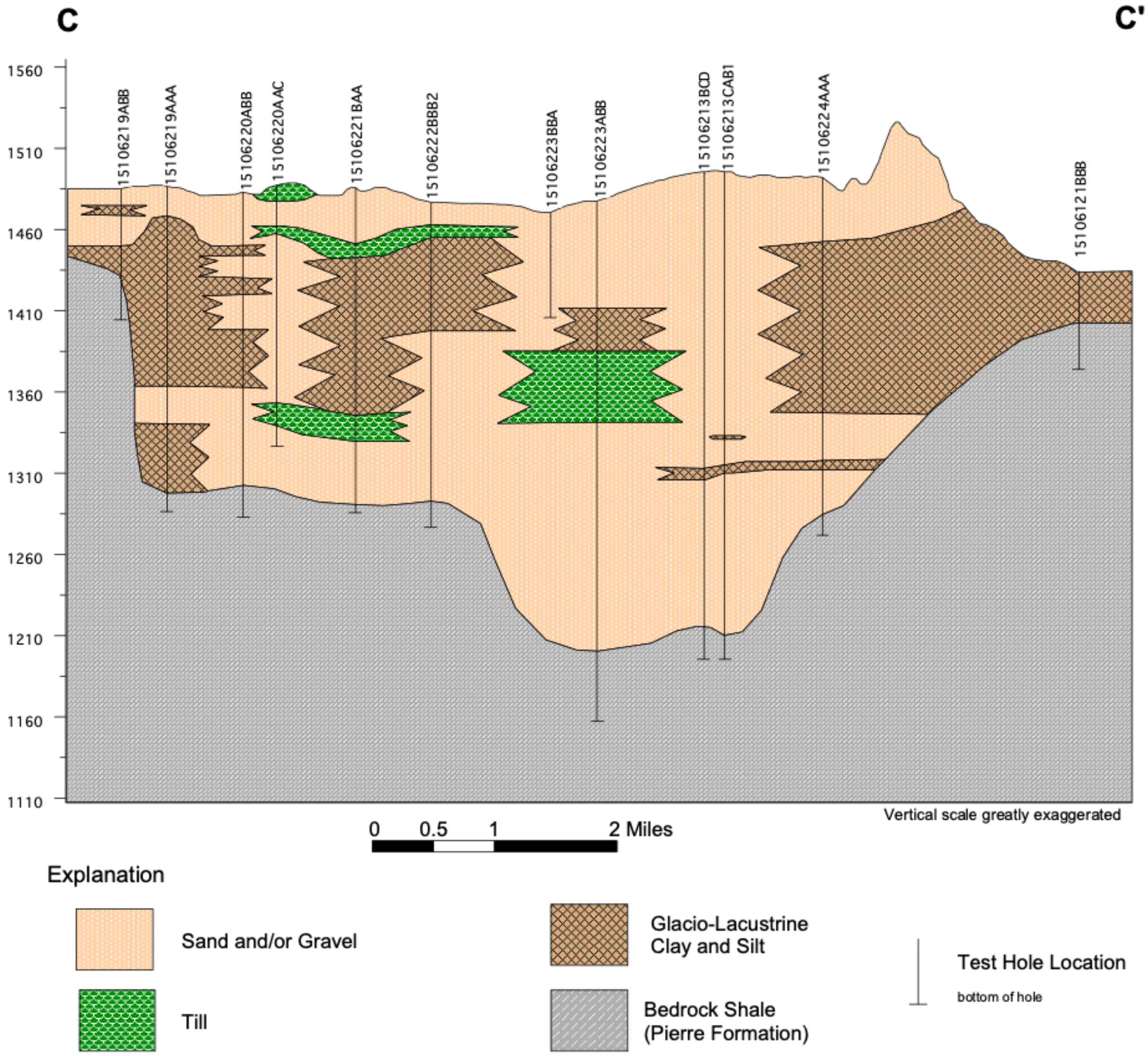


Figure 6. Geologic section C-C'.

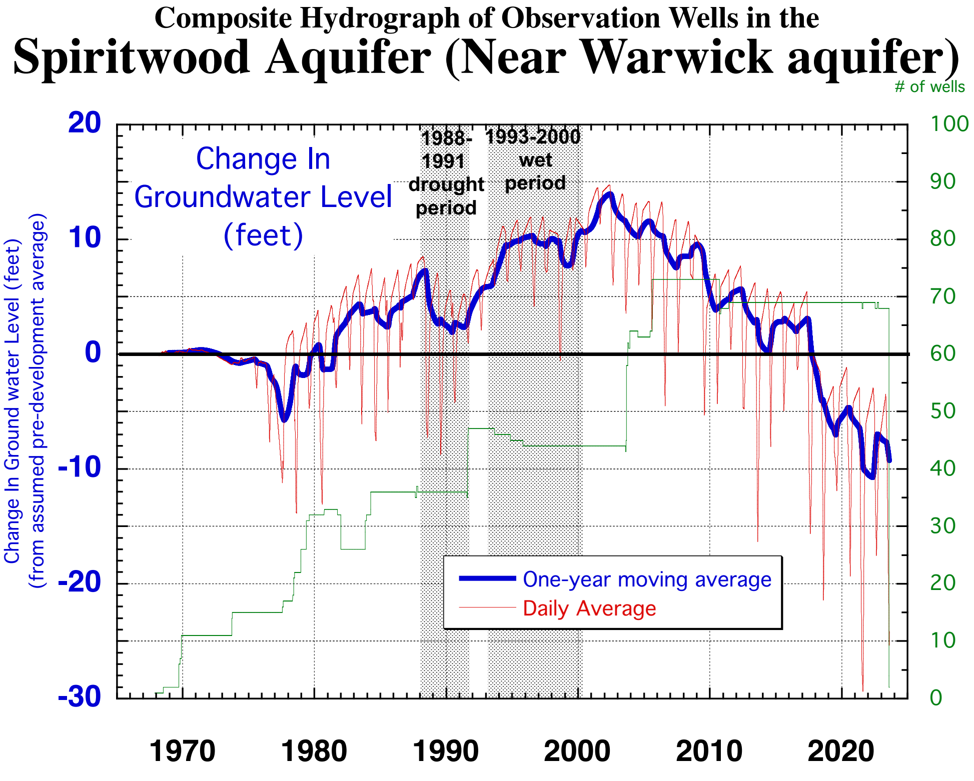
Figure 19. Geologic section C-C’ from Patch and Honeyman, 2003 showing the nearly continuous sand and gravel from land surface to the bottom of the Spiritwood aquifer in this area.

There is a downward vertical gradient of flow at all locations where nested piezometers screen both the Warwick and Spiritwood aquifers (Table 6). This indicates that MAR water loaded into the Warwick aquifer will infiltrate downward to the Spiritwood aquifer thereby allowing the use of recharge basins as the practical methodology for MAR into the SPW-WAR.

Table 6. Warwick and Spiritwood aquifer Water-Level Elevation Difference at Well Nest Sites

Well Nest Location	Aquifer Screened	Screened Interval	Water-Level	Difference (ft)
15006201DDD2	Warwick	5-15'	1465	
15006106CCC2	Spiritwood	198-203'	1446.05	18.95
15006118BBB2	Warwick	0-15'	1455.59	
15006118BBB3	Spiritwood	292-302'	1444.39	11.20
15006203DDD2	Warwick	5-15'	1471	
15006203DDD	Spiritwood	168-173'	1448.24	22.76
15006210DDD2	Warwick	0-10'	1471.65	
15006210DDD	Spiritwood	168-173'	1447.62	24.03
15006213CCC	Warwick	0-10.4'	1459.18	
15006224CBB*	Spiritwood	158-163'	1375.37	83.81
15106203DDD1	Warwick	62-65'	1499.59	
15106203DDD4	Spiritwood	258-268'	1454.3	45.29
15106220DAD2	Warwick	55-58'	1464.53	
15106220DAD1	Spiritwood	143-146'	1464.5	0.03
15106223ABB3	Warwick	48-53'	1466.53	
15106223ABB2	Spiritwood	148-153'	1439.72	26.81
15106223ABB	Spiritwood	228-231'	1439.69	26.84
15106224CCC3	Warwick	18-23'	1473.45	
15106224CCC	Spiritwood	258-261'	1435.19	38.26
15106224DDC3	Warwick	18-23'	1469.97	
15106224DDC2	Spiritwood	148-153'	1434.78	35.19
15106224DDC1	Spiritwood	218-223'	1434.82	35.15
15106225DAA3	Warwick	18-23'	1472.33	
15106225DAA2	Spiritwood	148-153'	1432.87	39.46
15106225DAA1	Spiritwood	218-223'	1432.48	39.85
15106227AAA3	Warwick	6-11'	1464.85	
15106227AAA2	Spiritwood	198-204'	1437.26	27.59
* Well is screened in the Spiritwood aquifer near the Sheyenne River segment			min	0.03
			mean	31.68
			median	27.59
			max	83.81

The composite hydrograph of observation wells in the SPW-WAR aquifer (Figure 20) shows there has been over 20 feet of water-level decline since 2002 in the aquifer system as a result of municipal, rural-water, irrigation development. Since 2002, the decline rate has been approximately 1 foot per year. The reason for the large decline rate is the deficit in the natural recharge to the system compared with the demand placed by the various use types. Although there is sufficient available drawdown at present, the unabated rate of decline could put these water supplies in jeopardy in the future. Especially if the drought cycle were to exacerbate the rate of decline.



Date Source: ND Dept. of Water Resources Site inventory Database

Figure 20. Composite Hydrograph of Wells in the Spiritwood aquifer near Warwick.

Recorded Water Usage from the SPW-WAR since 1977 is shown in Figure 21. The aquifer supports about 3,000 acres of irrigation, the City of Devils Lake municipal supply, and Greater Ramsey Water District. Both Greater Ramsey and the City of Devils Lake have agreements to supply water to neighboring water districts including Northeast Water District and Tri-County water users. Over 15,000 people rely on these public water supplies according to annual use reports of these entities.

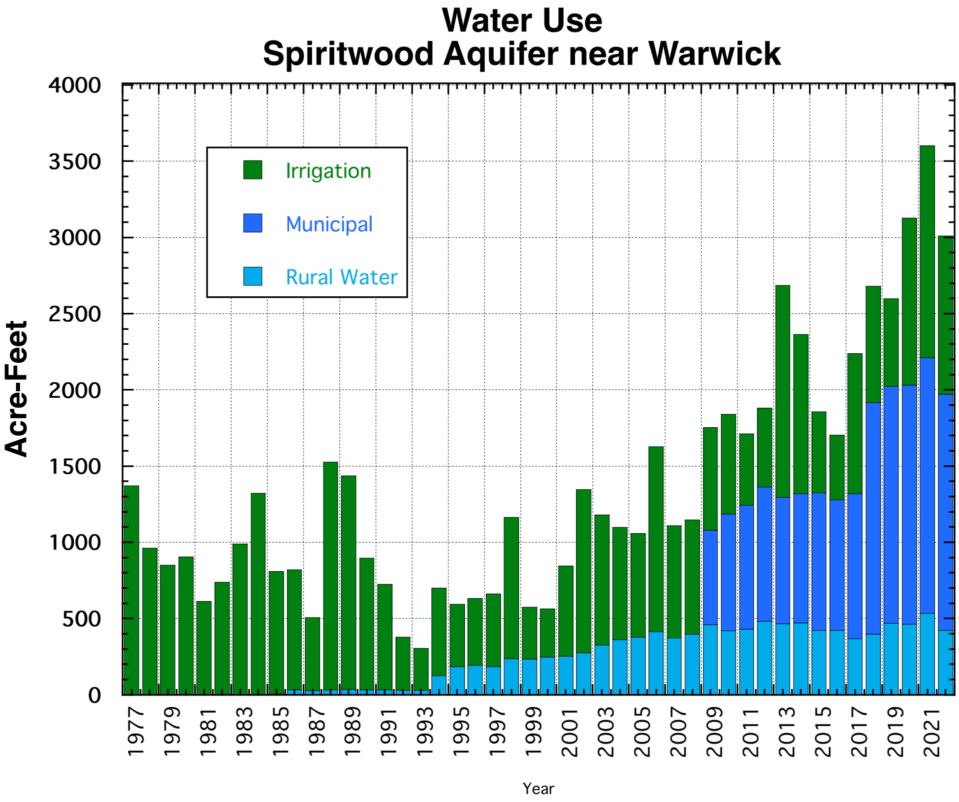


Figure 21. Reported water usage from the Wahpeton Buried Valley Aquifer.

The overall water quality of the SPW-WAR aquifer as characterized by the mean total dissolved solids (TDS) trend of all samples from the SPW-WAR aquifer is shown in Figure 22. The trendline of the mean TDS shows the water quality has held steady over the period of record at approximately 450 to 500 mg/l.

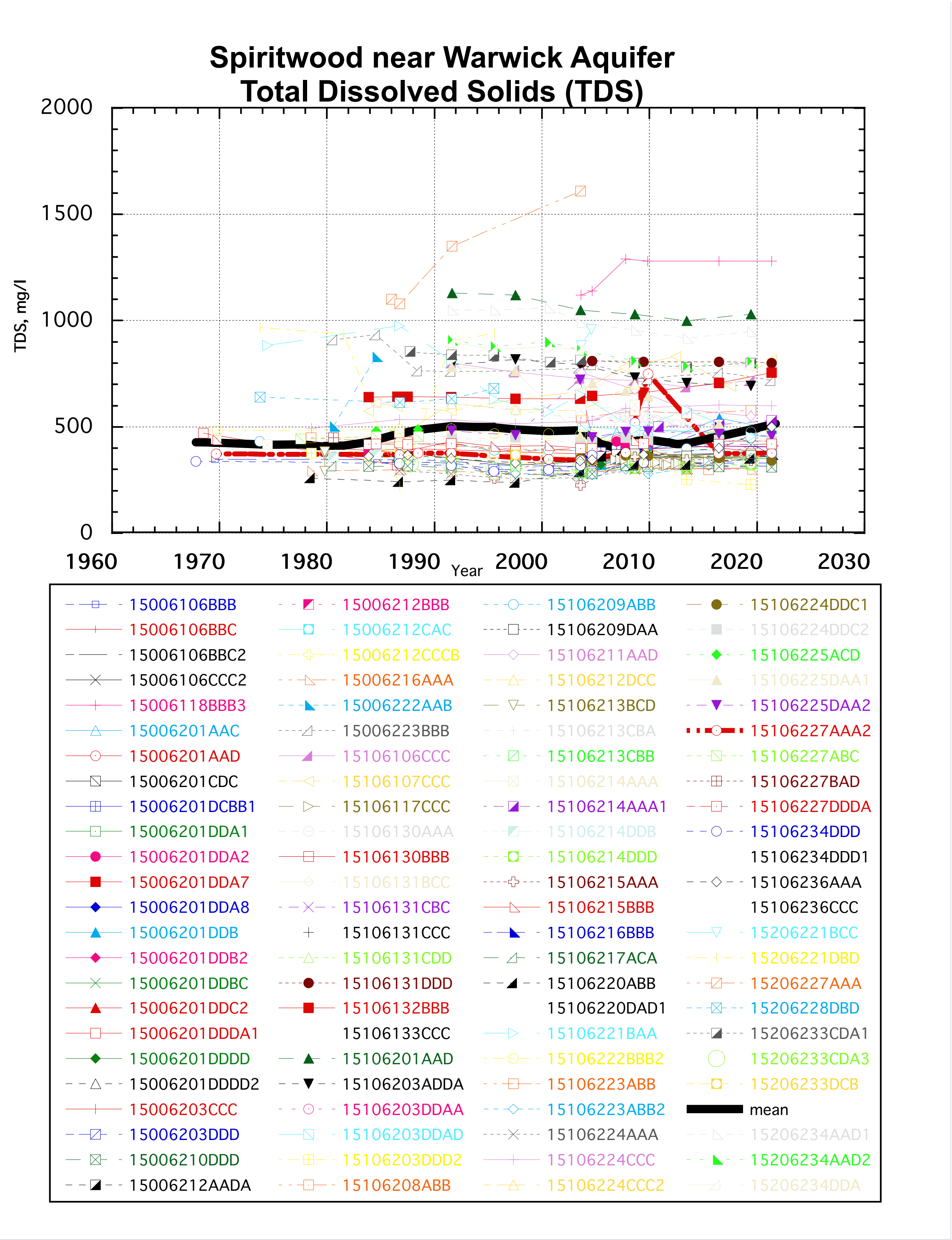


Figure 22. Spatial and Temporal TDS Analyses from the Spiritwood aquifer near Warwick.

The only existing nearby surface water source that could be used as source of supply for MAR is the Sheyenne River located approximately 7 miles south of the aquifer. The mean TDS trends of the source is shown in Figure 23. Presently, the mean TDS is 900 to 1000 mg/l which indicates it would not be a suitable source since the aquifer has much fresher water and would degrade in quality with the addition of the Sheyenne River water. If the water quality were to return to the pre-1995 level of under 500 mg/l TDS, it could be considered an excellent source of supply. The only known potential alternative source would be Missouri River water via a pipeline shunt from the planned Red River Valley Water Supply project should that ever be considered to bring that water into the region.

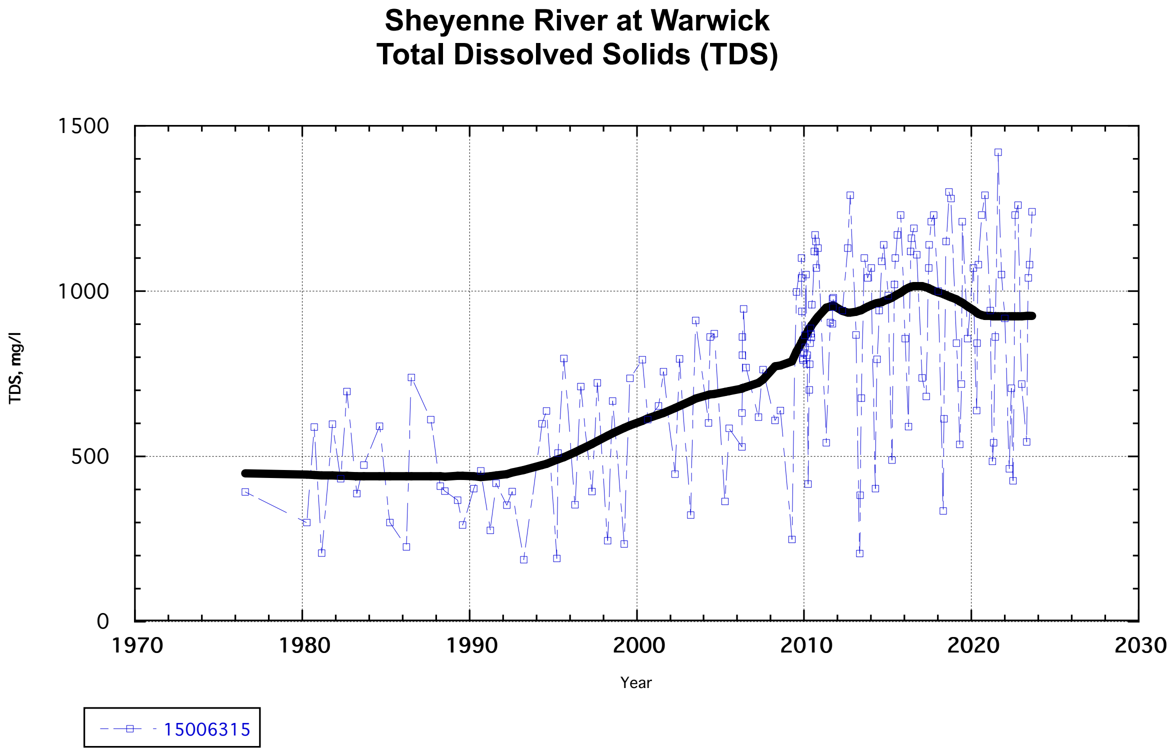


Figure 23. Mean TDS of samples collected from the Sheyenne River near Warwick.

The long-term mean flow is 57 cubic feet per second (cfs) in the Sheyenne River near Warwick. Streamflow duration hydrograph for this location is shown below in Figure 24.

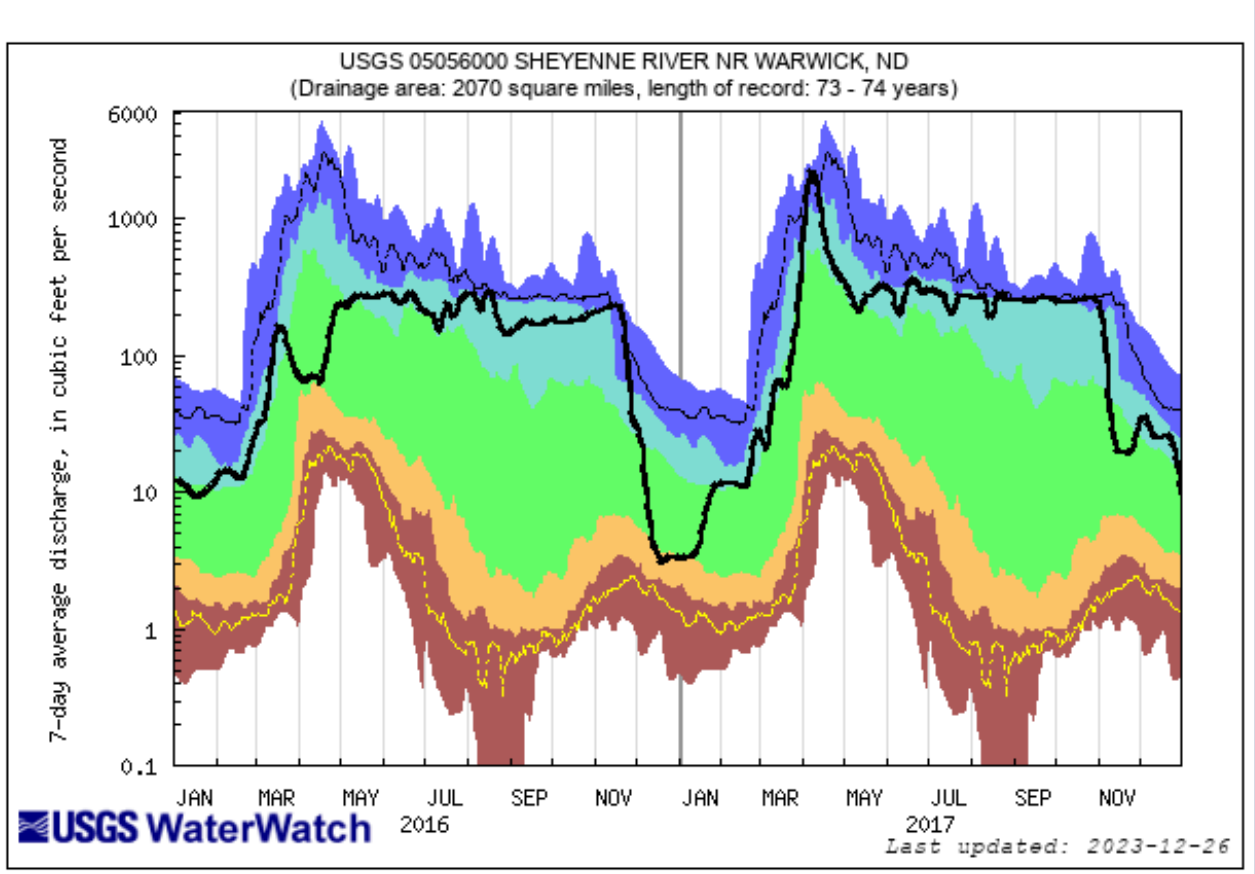


Figure 24. Streamflow Duration Hydrographs from the Sheyenne River near Warwick.

Pros:

- Over 20 feet of water-level decline has occurred in the past 20 years
- Large reservoir for water to be stored due to past dewatering
- Water levels are declining at a rate of 1 foot per year on average
- Aquifer could easily accommodate 1,000+ acre-feet per year in MAR
- Could provide resiliency to several rural water systems throughout the region.
- Unique geology would allow basin infiltration to the overlying Warwick aquifer which will infiltrate down to the Spiritwood aquifer
- Would allow for additional appropriation for beneficial use

Cons:

- No current nearby water source of equal or better quality than in-situ aquifer water

Aquifers in Tier 2 - Very good potential for MAR consideration

Elk Valley South aquifer

Pros:

- Shallow unconfined system with limited resilience during extended drought periods
- Supplies fresh drinking water to over 15,000 people in east central North Dakota
- MAR would allow the appropriation of water to multiple pending permits
- Water levels are declining slightly even through the recent 30-year wet cycle
- Aquifer could accommodate 1,000+ acre-feet per year in MAR
- Could provide resiliency to several rural water systems throughout the region.
- Geology would allow basin infiltration method
- Would allow for additional appropriation for beneficial use

Note: The nearest source is the Turtle River which may not support 1,000 acre-feet per year of MAR water.

Enderlin aquifer

Pros:

- The aquifer has sustained over 10 feet of water-level decline that has occurred in the past 12 years, yet water-use has been declining during that time
- Aquifer could accommodate 1,000 acre-feet per year in MAR
- Could provide resiliency to municipal and critical industrial water need in the region.
- Geology would allow basin infiltration method
- Maple River flows could support recharge project and in located nearby
- Water quality of the aquifer and Maple River are similar

Note: MAR implementation would benefit the City of Enderlin and the nearby sunflower seed crushing plant which are the only two major users of the Enderlin aquifer.

Icelandic

Pros:

- The aquifer is shallow unconfined, geology would allow basin infiltration method
- Aquifer could accommodate 1,000 acre-feet per year in MAR due to demand
- Water levels have declined over 5 feet and are continuing to declining slightly even through the recent 30-year wet cycle
- Without MAR the aquifer the fairly thin, unconfined system could be susceptible to negative effects of an extended drought period
- Could provide needed resiliency to a major rural water system, North Valley Water District

- Would allow for additional appropriation for beneficial use from the aquifer

Note: The closest nearby source is the Tongue River which has adequate water quality by may lack a constant enough flowrate to be a viable MAR source especially during drought periods

Minot aquifer

Pros:

- The aquifer has sustained over 25 feet of water-level decline since 2011 high
- Due to declines, the aquifer has a large reservoir for water to be stored
- Water levels are declining at a rate of about 2.5 feet per year
- Aquifer could easily accommodate 1,000+ acre-feet per year in MAR
- Could provide resiliency to the City of Minot and Northwest Area Water Supply System.
- Has a proven track record for use in a past successful artificial recharge project
- Would allow for additional appropriation for beneficial use especially industrial use
- In-situ water quality could be dramatically improved with Souris River Water which has an average TDS of 600 mg/l

Cons:

- Poor in-situ aquifer water quality – average TDS is around 1,300 mg/l

Note: Demand on the aquifer will essentially cease once the NAWS system in fully operational

Sundre

Pros:

- The aquifer has sustained over 40 feet of water-level decline since 1975 high
- Due to declines, the aquifer has a large reservoir for water to be stored
- Water levels are declining at a rate of about 1.5 feet per year in the past decade
- Aquifer could easily accommodate 1,000+ acre-feet per year in MAR
- Could provide resiliency to the City of Minot and Northwest Area Water Supply System.
- Has a proven track record for use in a past successful artificial recharge project
- Would allow for additional appropriation for beneficial use especially industrial use
- In-situ water quality could be dramatically improved with Souris River Water which has an average TDS of 600 mg/l

Cons:

- Poor quality in-situ aquifer water – average TDS is around 1,100 mg/l

Note: Demand on the aquifer will essentially cease once the NAWS system in fully operational

Spiritwood near Jamestown

Pros:

- Could provide resiliency to two a rural water systems in the region.
- Would allow for additional appropriation for beneficial use especially as industrial hub
- Water quality is compatible with the James River, about three to seven miles distant

Cons:

- Buried confined system
- More sophisticated recharge method required

Aquifers in Tier 3 - Good potential for MAR consideration

Tier 3 aquifers, classified as having good potential for MAR, possess a unique combination of characteristics that make them suitable for this purpose. However, there are also some limitations to consider when evaluating these aquifers.

Pros:

- Generally have favorable hydrogeological properties, such as high transmissivity, storage capacity, and unconfined setting which allow for efficient water storage and recovery during MAR operations.
- There is significant demand on these aquifers justifying the need or potential use of MAR water.
- The water quality in these aquifers is typically suitable for MAR, with good or adequate water quality for most beneficial uses.

Cons:

- Currently no overriding need for a MAR project due to current adequate water supply
- Cost-effectiveness of a MAR project can not be justified under current conditions.
- Water level trends indicate a stable or rising water-level
- Limited surface water availability for use in a MAR project

Aquifers in Tier 4 and 5 – Fair or Poor potential for MAR consideration

Typically, the cons outweigh the pros for aquifers classified in these tiers. They lack the need for MAR consideration or their hydrogeologic settings would not lend themselves to effective MAR implementation.

SUMMARY AND CONCLUSIONS

This project aimed to develop a comprehensive understanding of the potential for MAR in North Dakota. The project included four stages, with deliverables such as the development of a ranking criteria and considerations for MAR potential, a comprehensive database of existing aquifers, an interactive web-based map showing MAR potential, and a comprehensive report identifying the top potential MAR candidates and recommendations.

This investigation has shown there are many potential candidates for successful MAR among the nearly 300 glacial drift aquifers, segments, or sub-units identified and mapped in North Dakota. The project provides valuable insights into the use of MAR in state's aquifers. The ranking considerations allows for an assessment of each aquifer's potential for MAR. The data collected provides a comprehensive understanding of the baseline conditions of the aquifers and other water sources in the state.

Ranking criteria were applied to each aquifer, resulting in detailed profiles and water-level trend analysis. The top-ranked aquifers with high MAR potential were identified for further study or implementation. Finally, a high-resolution interactive web-based MAR map was created. This report also provided recommendations for future MAR initiatives, pilot and/or production projects, and multiple scenario hydrological modeling of potential MAR.

The completion of this project has laid a solid foundation for further exploration and implementation of MAR in North Dakota, which can contribute to the state's water management and sustainability efforts.

RECOMMENDATIONS

Based on the results of this project, the following recommendations are made to further advance the understanding and implementation of MAR in North Dakota:

1. Establish a dedicated MAR program: Create a dedicated program responsible for overseeing the development and implementation of MAR projects in the state. This will ensure that resources and expertise are effectively allocated to maximize the benefits of MAR for North Dakota's water management and sustainability efforts.
2. Foster collaboration and partnerships: Engage stakeholders, including local communities, water users, other government agencies, and research institutions, in the planning and implementation of MAR projects. This will help to build support for the projects and ensure that the needs and concerns of all parties are addressed.
3. Develop multi-scenario hydrogeological models of selected Tier 1 and Tier 2 candidates: Utilize the comprehensive data collected in this project to develop multi-scenario hydrogeological models that can simulate various MAR scenarios. This will help to identify the most effective and sustainable approaches to MAR in the state.
4. Conduct pilot and/or production projects: Select the top-ranked aquifers identified in the project and initiate pilot or production projects to test the feasibility and effectiveness of MAR in these areas. This will provide valuable real-world data and insights into the practical aspects of implementing MAR in North Dakota.
5. Continue research and monitoring: Invest in ongoing research and monitoring to refine the understanding of the state's aquifers and improve the effectiveness of MAR techniques. This will enable the state to adapt to changing conditions and make informed decisions about the future of its water resources.

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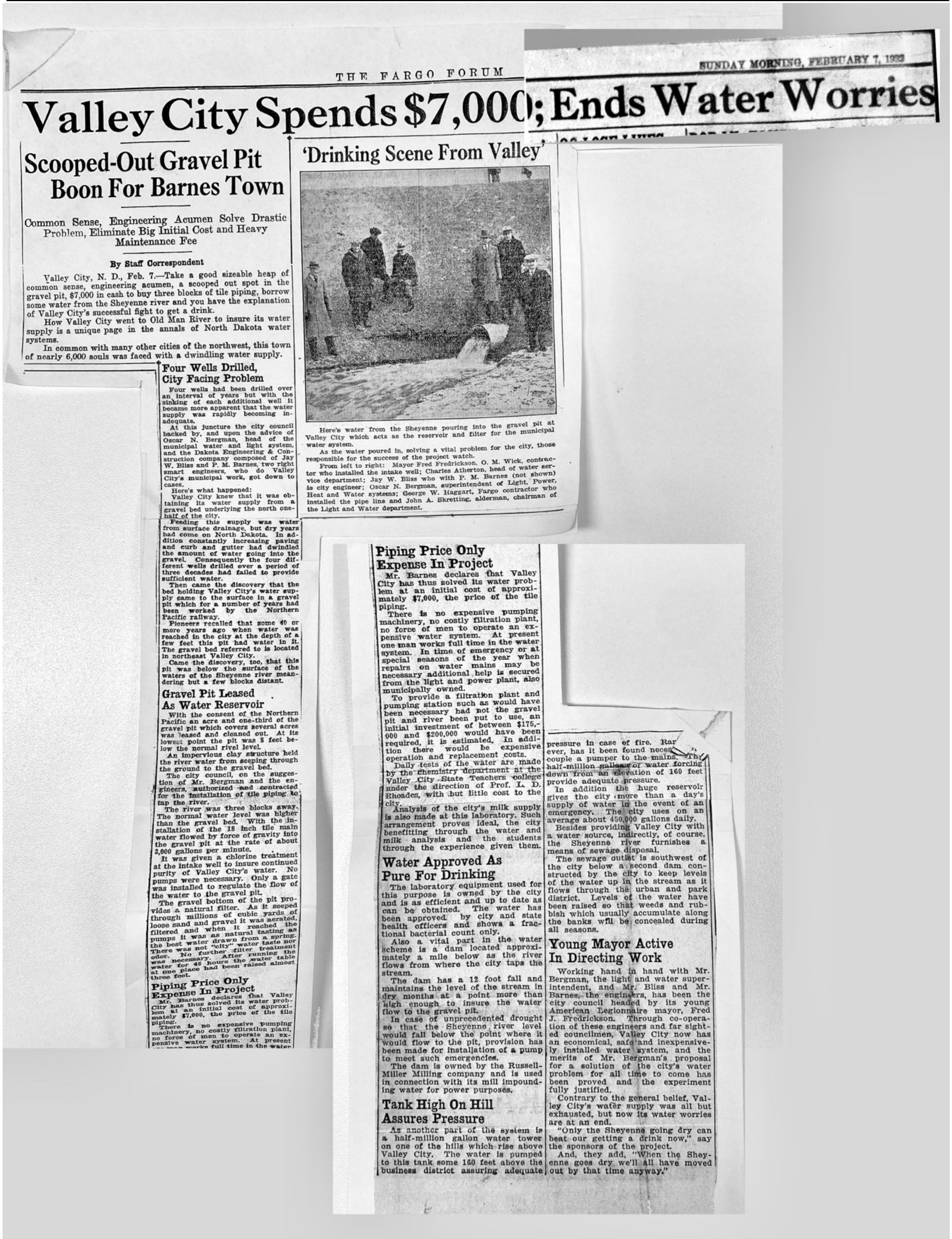
APPENDICES

Appendix 1. Valley City Project – Fargo Forum Article -1932.



THE FARGO FORUM

SUNDAY MORNING, FEBRUARY 7, 1932

Valley City Spends $7,000; Ends Water Worries

Scooped-Out Gravel Pit Boon For Barnes Town

Common Sense, Engineering Acumen Solve Drastic Problem, Eliminate Big Initial Cost and Heavy Maintenance Fee

By Staff Correspondent

Valley City, N. D., Feb. 7.—Take a good sizeable heap of common sense, engineering acumen, a scooped out spot in the gravel pit, $7,000 in cash to buy three blocks of tile piping, borrow some water from the Sheyenne river and you have the explanation of Valley City's successful fight to get a drink.

How Valley City went to Old Man River to insure its water supply is a unique page in the annals of North Dakota water systems.

In common with many other cities of the northwest, this town of nearly 6,000 souls was faced with a dwindling water supply.

Four Wells Drilled, City Facing Problem

Four wells had been drilled over an interval of years but with the sinking of each additional well it became more apparent that the water supply was rapidly becoming inadequate.

At this juncture the city council backed by, and upon the advice of Oscar N. Bergman, head of the municipal water and light system, and the Dakota Engineering & Construction company composed of Jay W. Bliss and P. M. Barnes, two right smart engineers, who do Valley City's municipal work, got down to cases.

Here's what happened:

Valley City knew that it was obtaining its water supply from a gravel bed underlying the north one-half of the city.

Feeding this supply was water from surface drainage, but dry years had come on North Dakota. In addition constantly increasing paving and curb and gutter had dwindled the amount of water going into the gravel. Consequently the four different wells drilled over a period of three decades had failed to provide sufficient water.

Then came the discovery that the bed holding Valley City's water supply came to the surface in a gravel pit which for a number of years had been worked by the Northern Pacific railway.

Pioneers recalled that some 40 or more years ago when water was reached in the city at the depth of a few feet this pit had water in it. The gravel bed referred to is located in northeast Valley City.

Came the discovery, too, that this pit was below the surface of the waters of the Sheyenne river meandering but a few blocks distant.

Gravel Pit Leased As Water Reservoir

With the consent of the Northern Pacific an acre and one-third of the gravel pit which covers several acres was leased and cleaned out. At its lowest point the pit was 8 feet below the normal rivel level.

An impervious clay structure held the river water from seeping through the ground to the gravel bed.

The city council, on the suggestion of Mr. Bergman and the engineers, authorized and contracted for the installation of tile piping to tap the river.

The river was three blocks away. The normal water level was higher than the gravel bed. With the installation of the 18 inch tile main water flowed by force of gravity into the gravel pit at the rate of about 3,000 gallons per minute.

It was given a chlorine treatment at the intake well to insure continued purity of Valley City's water. No pumps were necessary. Only a gate was installed to regulate the flow of the water to the gravel pit.

The gravel bottom of the pit provides a natural filter. As it seeped through millions of cubic yards of loose sand and gravel it was aerated, filtered and when it reached the pumps it was as natural tasting as the best water drawn from a spring. There was not "city" water taste nor odor. No further filter treatment was necessary. After running the water for 46 hours the water table at one place had been raised almost three feet.

Piping Price Only Expense In Project

Mr. Barnes declares that Valley City has thus solved its water problem at an initial cost of approximately $7,000, the price of the tile piping.

There is no expensive pumping machinery, no costly filtration plant, no force of men to operate an expensive water system. At present

'Drinking Scene From Valley'

Here's water from the Sheyenne pouring into the gravel pit at Valley City which acts as the reservoir and filter for the municipal water system.

As the water poured in, solving a vital problem for the city, those responsible for the success of the project watch.

From left to right: Mayor Fred Fredrickson, O. M. Wick, contractor who installed the intake well; Charles Atherton, head of water service department; Jay W. Bliss who with P. M. Barnes (not shown) is city engineer; Oscar N. Bergman, superintendent of Light, Power, Heat and Water systems; George W. Haggart, Fargo contractor who installed the pipe line and John A. Skretting, alderman, chairman of the Light and Water department.

Piping Price Only Expense In Project

Mr. Barnes declares that Valley City has thus solved its water problem at an initial cost of approximately $7,000, the price of the tile piping.

There is no expensive pumping machinery, no costly filtration plant, no force of men to operate an expensive water system. At present one man works full time in the water system. In time of emergency or at special seasons of the year when repairs on water mains may be necessary additional help is secured from the light and power plant, also municipally owned.

To provide a filtration plant and pumping station such as would have been necessary had not the gravel pit and river been put to use, an initial investment of between $175,000 and $200,000 would have been required, it is estimated. In addition there would be expensive operation and replacement costs.

Daily tests of the water are made by the chemistry department at the Valley City State Teachers college under the direction of Prof. L. D. Rhoades, with but little cost to the city.

Analysis of the city's milk supply is also made at this laboratory. Such arrangement proves ideal, the city benefitting through the water and milk analysis and the students through the experience given them.

Water Approved As Pure For Drinking

The laboratory equipment used for this purpose is owned by the city and is as efficient and up to date as can be obtained. The water has been approved by city and state health officers and shows a fractional bacterial count only.

Also a vital part in the water scheme is a dam located approximately a mile below as the river flows from where the city taps the stream.

The dam has a 12 foot fall and maintains the level of the stream in dry months at a point more than high enough to insure the water flow to the gravel pit.

In case of unprecedented drought so that the Sheyenne river level would fall below the point where it would flow to the pit, provision has been made for installation of a pump to meet such emergencies.

The dam is owned by the Russell-Miller Milling company and is used in connection with its mill impounding water for power purposes.

Tank High On Hill Assures Pressure

As another part of the system is a half-million gallon water tower on one of the hills which rise above Valley City. The water is pumped to this tank some 160 feet above the business district assuring adequate pressure in case of fire. Rar ever, has it been found neces couple a pumper to the mains. Th half-million gallons of water forcing down from an elevation of 160 feet provide adequate pressure.

In addition the huge reservoir gives the city more than a day's supply of water in the event of an emergency. The city uses on an average about 450,000 gallons daily.

Besides providing Valley City with a water source, indirectly, of course, the Sheyenne river furnishes a means of sewage disposal.

The sewage outlet is southwest of the city below a second dam constructed by the city to keep levels of the water up in the stream as it flows through the urban and park district. Levels of the water have been raised so that weeds and rubbish which usually accumulate along the banks will be concealed during all seasons.

Young Mayor Active In Directing Work

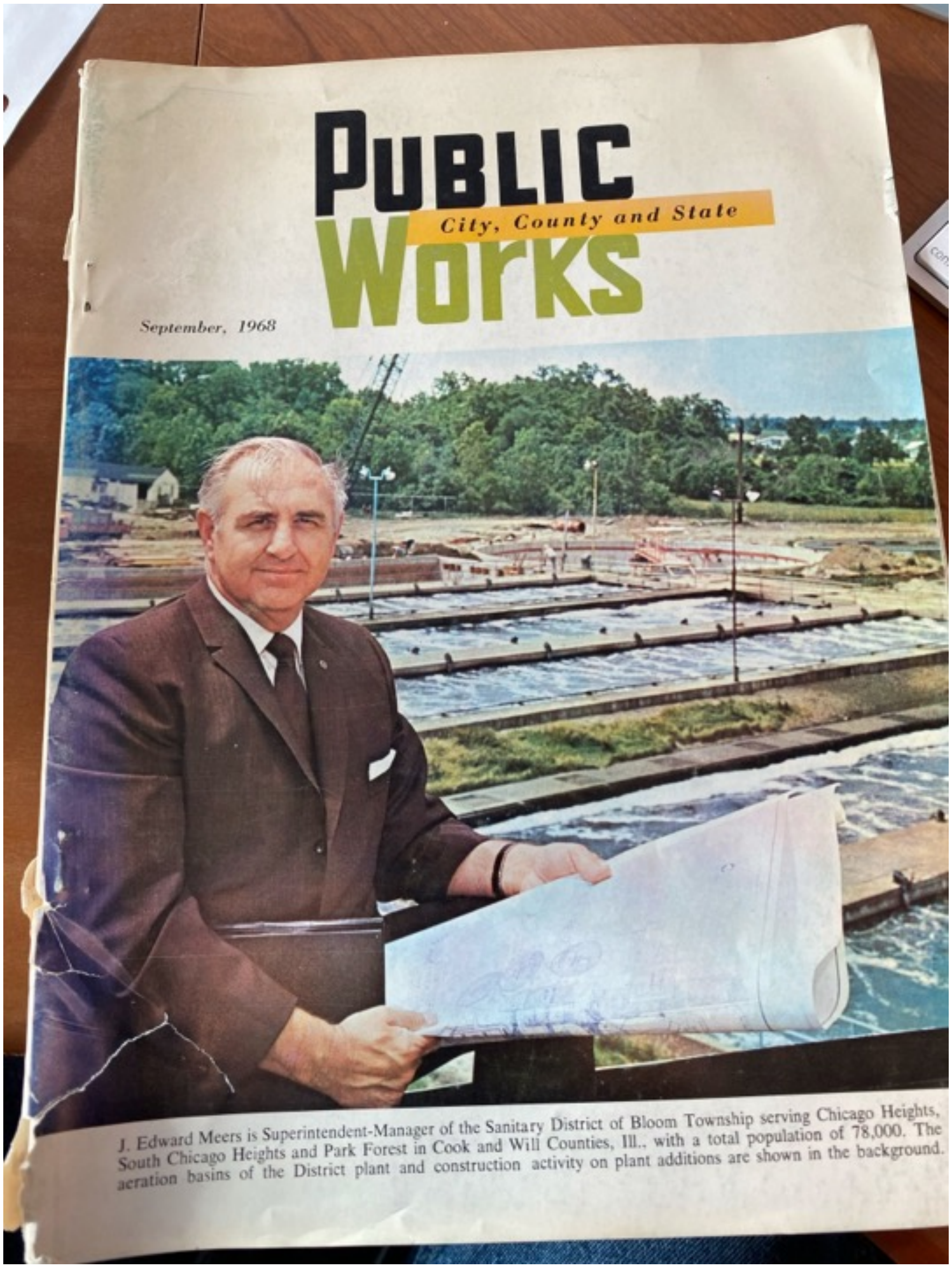
Working hand in hand with Mr. Bergman, the light and water superintendent, and Mr. Bliss and Mr. Barnes, the engineers, has been the city council headed by its young American Legionnaire mayor, Fred J. Fredrickson. Through co-operation of these engineers and far sighted councilmen, Valley City now has an economical, safe and inexpensively installed water system, and the merits of Mr. Bergman's proposal for a solution of the city's water problem for all time to come has been proved and the experiment fully justified.

Contrary to the general belief, Valley City's water supply was all but exhausted, but now its water worries are at an end.

"Only the Sheyenne going dry can beat our getting a drink now," say the sponsors of the project.

And, they add, "When the Sheyenne goes dry we'll all have moved out by that time anyway."

Appendix 2. Minot Aquifer Article in *Public Works* Periodical, 1968
Artificial Recharge Solves Water Problem



PUBLIC WORKS

City, County and State

September, 1968

J. Edward Meers is Superintendent-Manager of the Sanitary District of Bloom Township serving Chicago Heights, South Chicago Heights and Park Forest in Cook and Will Counties, Ill., with a total population of 78,000. The aeration basins of the District plant and construction activity on plant additions are shown in the background.

Artificial Recharge Solves Water Problem

WAYNE A. PETTYJOHN, Ph.D.
Associate Professor of Geology
The Ohio State University
Columbus, Ohio
and
VERNON FAHY, P.E.
City Manager
Minot, North Dakota

AN INTENSIVE ground-water investigation in 1963-64 by the U.S. Geological Survey, made in cooperation with the North Dakota State Water Commission and the city of Minot, served to forewarn of an impending shortage of water supply for the nearly 50,000 people. The Minot ground-water reservoir (aquifer), which in 1963 supplied the city's entire water supply, was being depleted faster by pumping, about 4 mgd, than it was being replenished by natural recharge, about 3 mgd, from the Souris River and adjacent buried glacial deposits. Consequently, the drilling of additional wells in the already overdeveloped aquifer would only accelerate the depletion. Extensive test drilling indicated that other larger-yielding aquifers are not present in the Minot area.

The Souris River had been used as a source for part of the municipal water requirements for many years. Although the annual average flow of the river is about 136 cfs, or 89 mgd, during dry weather there is often no flow at all. Moreover, much of the annual discharge is appropriated to water rights preceding those of the city of Minot. Hence, much of the time the river is not a reliable source of direct supply. However, the relatively large peak flows indicated that the Souris River is a potential source of water for recharge to the aquifer, particularly if surface-water control or retaining structures could be built.

Two plans were considered to alleviate the forthcoming water shortage for the city of nearly 50,000 people:

1) A pipeline about 50 miles long, connecting Minot with Garrison Reservoir. The cost of the facility in 1959 was estimated at $12 million and because of the urgency of the need, the time factor was considered critical. Funding was not immediately available and time for planning, fund-raising and construction was inadequate.

2) Artificial recharge of the Minot ground-water reservoir as suggested by the U.S. Geological Survey on the basis of a cooperative investigation with the North Dakota State Water Commission.

The ground-water recharge facility described herein was designed and constructed by the city of Minot. The facility, located at the west end of Minot, is referred to as a dual recharge system because natural infiltration of surface water from a spreading basin through a surface layer of sandy clay is supplemented by flow through gravel-filled perforations, called "hydraulic connectors," in the clay layer. It covers a small area of city-owned land and permits maximum water infiltration at nominal cost. The artificial-recharge system, which required relatively little time for construction, has been successful both in an engineering and economic sense and, no doubt, could be used in other regions with similar problems.

About 7.5 acres of land were purchased by the city in an area where investigations indicated maximum infiltration rates probably could be achieved. The long, narrow, wedge-shaped plot trends east-west; it is about 1,800 feet long and 260 feet wide at the west end (Fig. 1). It is bordered on the south by a railroad track, on the north by a housing development, and on the west by a section-line road. Because of the size and location of the area, the land was of little economic value for other purposes.

Prior to construction, several test holes were drilled at the site to determine the subsurface conditions. The upper 7 to 20 feet of the strata consist of sandy clay and a few thin layers of sand. At greater depths a bed of coarse sand and gravel is present. About 45 feet of the deeper sand and gravel were unsaturated at the time of test drilling. The sand and gravel bed is directly connected to the Minot aquifer; in fact, it represents the dewatered upper part of the aquifer.

Facilities

Storage reservoir and sediment basin. A pit was constructed at the west end of the site to provide a sediment basin because water from the Souris River contains a large concentration of sediment, especially during periods of peak discharge. The dimensions of the pit at land surface are 180 feet by 210 feet. It is 35 feet deep and the walls have a 2 to 1 slope. The bottom of the pit measures approximately 60 feet by 90 feet. The upper part of the pit is constructed in clay, but the lower 15 to 23 feet are in unsaturated fine to coarse gravel.

Although the sediment basin was designed as a holding structure so that the clay and silt would settle out of the water before it flowed into the canals, observations showed that initially the basin would recharge at least 2 mgd. As expected, the rate has since decreased, owing to a buildup of fine material on the floor of the basin, which requires periodic cleaning. The basin, when full, holds about 300 million gallons of water.

Recharge channel system. A Y-shaped canal system was excavated in the overlying clay to a depth of about 10 feet, with a bottom width of 12 feet and side slopes of 3 to 1. The wide bottom of the canal permits entry of maintenance equipment. The bottom area of the canals is covered with 12 inches of coarse gravel overlaid with 6 inches of fine washed sand, forming a filter bed. Although some infiltration (leakage) will occur through the upper layer of sandy clay, the rates were considered to be too small to be effective. The filter bed removes sediment from the water and is most effective when the water level in the canals is just below the top of the filter bed. Although it has not been done as yet, the water level in the canals could be maintained just below the top of the filter during the summer to inhibit the growth of algae.

The major function of the canal system is to transport water from the sediment basin to the hydraulic connectors that are bored along the centerline in the bottom of the canals as shown in Figure 1. The total length of the canal system is approximately 2,460 feet; it can store about 270 million gallons of water when full.

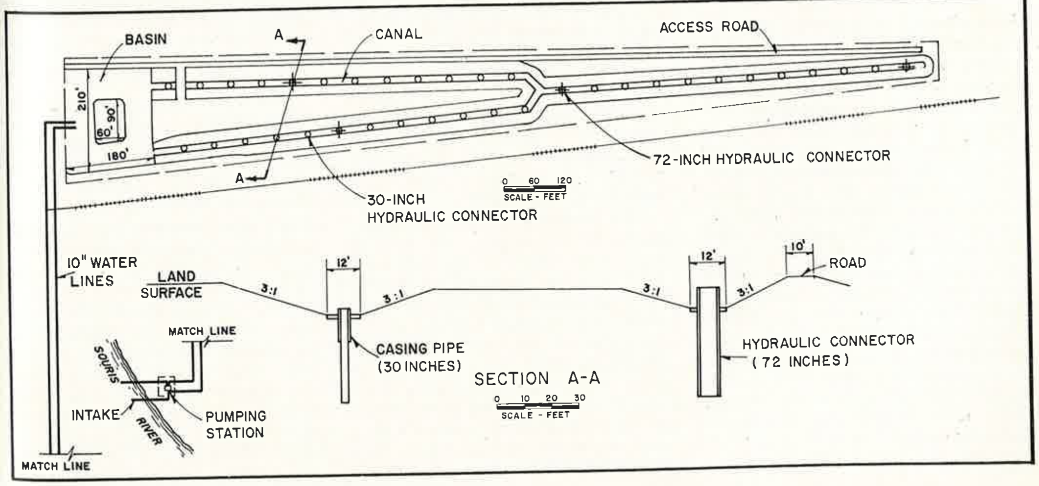
Hydraulic connectors. The purpose of the hydraulic connectors, large-diameter perforations bored through the clay aquiclude and backfilled with permeable material, is to provide high-permeability conduits through which the aquifer can be readily recharged with surface water from the canals. This system allows much larger volumes of water to be recharged than natural conditions would have permitted, requires a minimum of excavation, and eliminates the need for such things as costly slope protection and excessive land acquisitions. By use of hydraulic connectors, therefore, the volume of water recharged to an aquifer from a very small facility may be equal or greater than the volume recharged from a much larger area by natural leakage through confining beds.


■ **AERIAL** view of the recharge facility, showing how it is arranged on a narrow, wedge-shaped piece of land bounded by railroad and housing near the Souris River.

Originally 36 hydraulic connectors 30 inches in diameter were bored along the canal centerline through the overlying clay into the unsaturated sand and gravel (Fig. 1). The holes range in depth from 28 to 32 feet, for a total of slightly more than 1,000 linear feet. They were cased to their full depth with 30-inch diameter corrugated metal culvert during the boring operation. Following completion of each boring, a 1¼-inch diameter plastic pipe was inserted in the center of each hole to permit measurement of water levels. While the casing was being withdrawn, the holes were backfilled with coarse, washed gravel. A 7-foot section of the culvert, including 18 inches extending above the base of the canal, was left in the upper part of the hole. The casing was perforated and covered with a mound of coarse gravel that acts as a sediment filter.

Tests indicated that the hydraulic connectors have an average infiltration rate of 60 gpm. It was assumed, therefore, that a total of about 3 mgd of river water could

■ **FIGURE 1.** Plan and section of Minot's artificial recharge facility. Connectors link canals with the subsurface gravel aquifer.



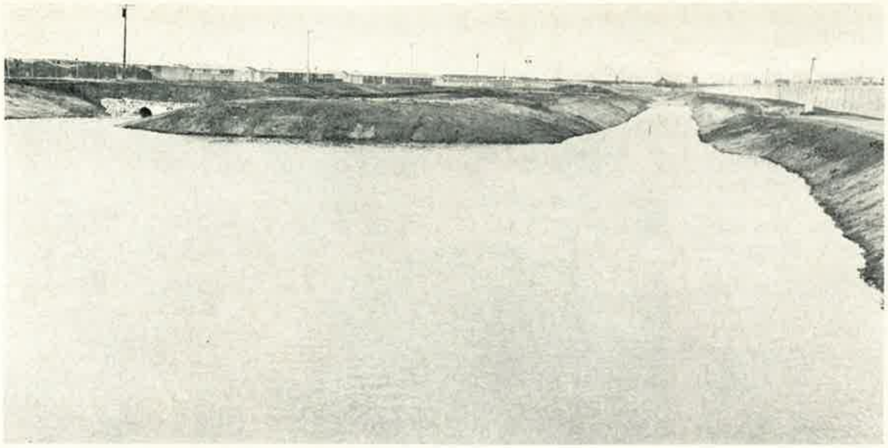
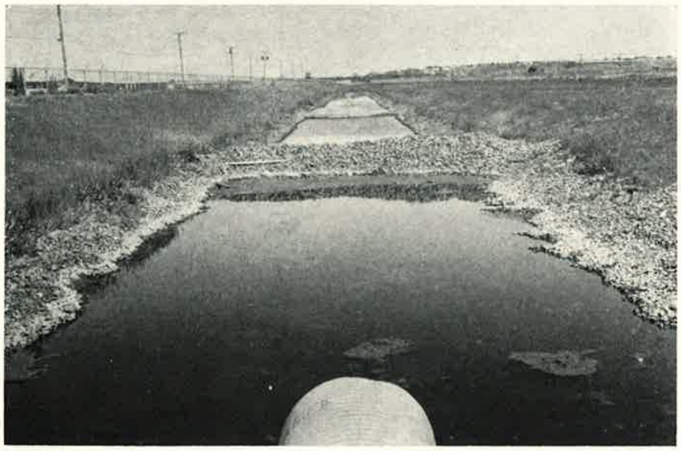


Photo courtesy Minot Daily News

■ **VIEW above shows recharge canals, partially filled, with the sediment basin in the foreground. Culvert at left runs under the access road. A more recent picture, below, was made after gravel dams were installed to reduce sediment load going into canals. The dams are also effective in removing floating masses of algae.**



be recharged through the 36 connectors.

Several months after the recharge system had been in operation, it was found that the connectors were becoming plugged with silt and clay. Moreover, the small diameter of the holes made it almost impossible to remove the gravel pack. Consequently, four holes, approximately 12 feet in diameter, were excavated in the canals to a depth of about 26 feet by a city-owned crane with a ¾-yard clam attachment. Thirty-four feet of 72-inch diameter corrugated culvert were permanently installed in each hole (the casing extended about 8 feet above the bottom of the canal). The upper 8 feet and the lower 4 feet of each culvert were perforated with an acetylene torch to facilitate water movement. To observe water levels, 36 feet of 2-inch diameter steel pipe were installed in each culvert prior to backfilling the excavation with washed ½-inch gravel both inside and outside of the culvert. The large diameter hydraulic connectors can provide a total of at least 1 mgd of recharge.

Site improvements. The alignment of the canals and settling basin with respect to the prevailing wind direction indicated a need for slope erosion control. Sod was used rather than seeding because of the steepness of the slopes and the immediate need for slope protection. All exposed slopes were sodded to operational water stage. This process provided excellent erosion protection on the canal margins; however, it became immediately evident that additional protection was needed on the pit slopes to reduce the erosive action of wind-driven waves.

The wave-erosion problem was eliminated by placing a heavy-duty plastic sheet, 12 feet wide, around the entire perimeter of the pit. It was positioned so that the mean water level in the pit would be at the approximate centerline of the plastic, thus providing 6 feet of lining above water level. Although ice in the pit exceeds 24 inches in thickness during the winter, the plastic liner has remained in place and undamaged. Installation involved the insertion of metal pins through wooden slats placed on the upper and lower edges of the liner.

Chain link security fencing with barbed wire climbing guards was placed around the entire recharge site. The fence is 6 feet high, including two gates, 12 feet wide.

Water-transmission system. The water supply for the artificial-recharge system is obtained from the Souris River at a point approximately 1,000 feet south of the recharge site. A deep well turbine pump was removed from an existing well adjacent to the river and two 25-horsepower horizontal pumps were installed in a pump house with intakes in the river. This installation is separate from the intakes and pumps for the surface water treatment plant, which are about a mile downstream from the recharge site. Because the abandoned deep well is connected to the city's system by a 10-inch cast iron main laid in the section line right-of-way, it was relatively easy to supply water to the recharge site. The main was cut and a plug was installed on the city side of the main. A 90 degree bend was placed in the pump line section and the main was extended into the recharge pit. A second 10-inch main was also laid. The double pump installation resulted in a pumping rate of approximately 4 mgd to the recharge site.

The water level in the artificial-recharge installation is monitored by electronic controls that automatically actuate the pumps from a control panel in the water-treatment plant.

Souris River Dam. A dam on the Souris River was constructed by the North Dakota State Water Commission several hundred yards downstream from the recharge site in order to deepen the water over the pump intakes, to augment the surface-water supply, and to increase natural ground-water recharge in the vicinity of the well field. The dam is a poured concrete structure with two gates capable of allowing 2,300 cfs to pass. The total cost of the dam was approximately $87,000, of which $30,000 was paid by the North Dakota State Water Commission. The remaining $57,000 was paid by the City of Minot.

Following construction of the dam, the city was able to pump 40 percent of 1.6 mgd of the municipal daily requirement directly from the river. During periods of drought, however, the quantity of water in surface storage will be depleted rapidly and the city will have to increase withdrawals from the ground-water reservoir accordingly.

The costs involved in the construction of Minot's dual-technique artificial-recharge facility were small in comparison to the benefits received, insignificant if compared to the estimated cost of $12 million for a pipeline from Minot to Garrison Reservoir, and infinitesimal if compared with the cost of a surface-water reservoir with a storage capacity equal to that of the Minot aquifer. The actual costs of constructing the entire recharge facility are summarized in Table 1.

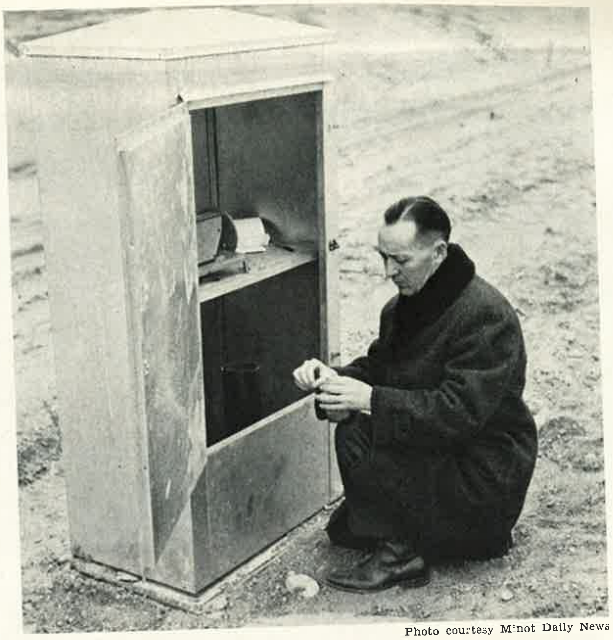


Photo courtesy Minot Daily News

■ **CITY MANAGER Vernon Fahy checks water level recorder during construction of the recharge facility. The observation well is 68 feet deep.**

Experience

During the last two years Minot has been able to take some portion of its supply from the river during all months except January and February. When there is ample flow, about 40 to 50 percent river water is used and the balance from wells. The amount available from the river decreases rapidly after October 1 when the upstream dam owned by the Bureau of Sports Fisheries and Wildlife is closed for the winter season.

The recharge system is operated whenever there is enough water in the river to do so. Last winter it was not possible to recharge because of lack of flow. Experience indicates that winter recharging is most efficient because of lack of algae and a lower sediment load.

The canals at the recharge site seem to offer conditions conducive to growth of algae. These growths can be killed by drying the canals for a few days. Coarse rock dams have been constructed at the point where the canals connect with the sedimentation pit thus requiring all water to flow through about a ten-foot width of coarse rock just as it enters the canals. This should filter out some of the coarser algae which have been pumped from the river as well as reduce the sediment load.

A definite time schedule for cleaning the recharge site has not been established but, based upon

(*Continued on page* 148)

Table 1—Costs and Estimates

Recharge site	
Purchase of land	$ 8,228.00
Excavation of basin and canal system (87¢ per cubic yard)	35,060.35
Boring of 36 30-inch diameter and 4 72-inch diameter hydraulic connectors, including culvert	12,347.50
Site improvements (sod, plastic liner, security fencing)	16,885.00
Water transmission system (1,000 feet of 10-inch cast iron main, installation of pumps)	33,653.00
Souris River dam (city cost $57,000)	87,000.00
Total cost	$193,173.85
Annual maintenance and cleaning costs of entire facility	$ 1,200.00
Estimate of costs for alternate method	
Pipeline to Garrison Reservoir (1959 estimate)	$12,000,000.00

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River Bank Debris Removal Program

A drive to remove debris now littering the banks of the Potomac and Anacostia Rivers and Rock Creek, in the District of Columbia area, was initiated in July. Approximately 100 youths between the ages of 16 and 21 are being employed by the District government for the remainder of the summer removing old tires, tin cans and other trash which otherwise would wash back into the waterways. The youths are Neighborhood Youth Corps enrollees who have been hired by the District Department of Licenses and Inspections for the clean-up work. They will be paid $1.60 per hour from funds provided by the Office of Economic Opportunity. Organizations will be into teams of ten, with each team directed by a college student supervisor. The supervisors have been employed by FWPCA and given special training for this assignment.

The trash will be placed in piles at designated riverbank sites where it will be put on barges by the Corps of Engineers and taken to landfill sites for burial.

Effects of Urban Renewal and Expressway Work

Due primarily to urban renewal and expressway construction, the Cincinnati Division of Water Pollution Control reports that it looses approximately one existing account for every three new accounts.

• • •

Artificial Recharge Facility

(*Continued from page 85*)

experience to date, it appears that an early spring cleaning and a late summer cleaning might be most effective. With an efficient filter at the river intake to remove sediment we might possibly get by with one cleaning per year. Cleaning of the sediment basin is accomplished by removing all accumulations from the pit with a track-mounted front end loader or dragline and by removing and washing all the rock in the larger connectors. The small hydraulic connectors are still functioning to a limited extent but no effort is being made to maintain them.

Several major benefits have occurred or can be anticipated through Minot's water-development program, and especially the artificial-recharge operation. Of prime importance is the rapid rise in water level throughout the entire

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aquifer. This rise, in places, exceeded 20 feet within 6 months of operation. Well-field pumping was shifted to the area of greatest water-level rise, thus reducing pumping costs and allowing recovery in the previous pumping centers. In addition, interference between pumping wells was reduced owing to the higher water level.

Future municipal withdrawals can be increased because of the large quantity of water added to underground storage. It has been estimated that during optimum operating conditions, at least 4 mgd are added to storage by artificial means, and at least 3 mgd by natural infiltration from the surface and from underflow from adjoining ground-water sources. The city, at present, withdraws an annual average of 1.6 mgd directly from the Souris River and 2.4 mgd from wells, thus the net quantity of water added to underground storage is about 4.6 mgd. Much of this water previously flowed unused down the Souris River.

The construction of the dam in the river stabilized the river stage and increased the depth of the water over the water-treatment plant intake. The added depth permitted a longer operating cycle of the plant's filter beds because of the decrease in the amount of sediment and algae in the raw water.

The ground water in the area of the recharge site is expensive to treat because of poor chemical quality. It is relatively high in sodium, bicarbonate, and total dissolved solids. Water from the Souris River, however, is considerably less mineralized. A mixture of 40 percent river water and 60 percent well water has been found the most economical to treat.

In addition, the higher levels enhanced the appearance of the river channel and increased the value of abutting properties.

The imaginative water-management program by the City of Minot, which effectively uses water resources locally available, has eliminated the necessity of importing water from the distant Garrison Reservoir. The $12 million saved is indicative of the tremendous economic potential of artificial recharge, in this instance employing hydraulic connection between the recharge source and the aquifer. □□□

Reference

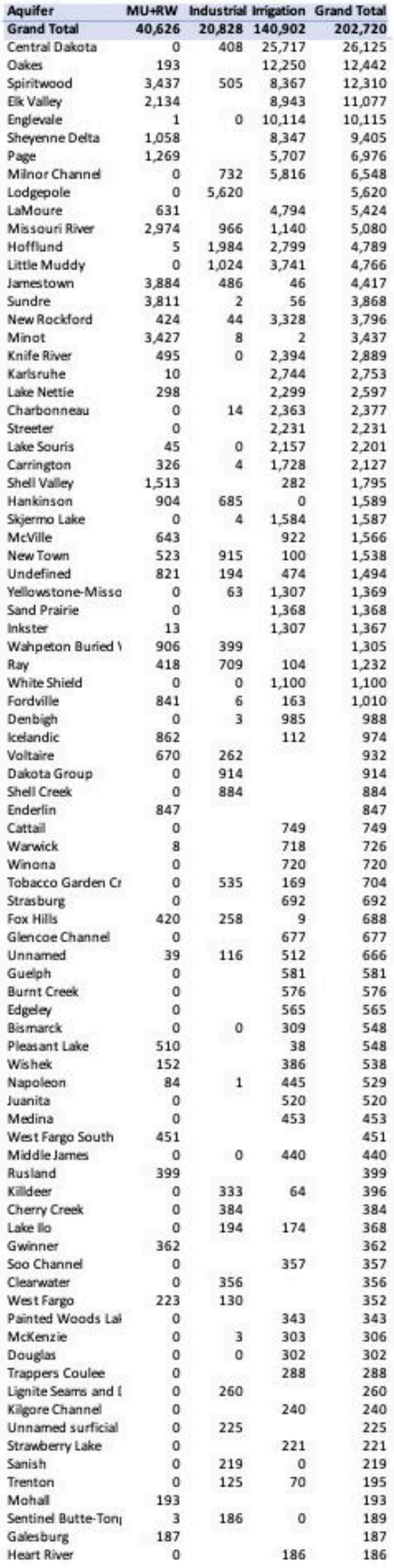
Pettyjohn, W. A., 1967, Geohydrology of the Souris River valley in the vicinity of Minot, North Dakota: U. S. Geol. Survey Water Supply Paper 1844, 53 p.

Appendix 3. All Named Aquifers In NDDWR Mapservice Database. Hyperlinks To County Studies Report Page Or Other Prominent Report Where They Are Described.

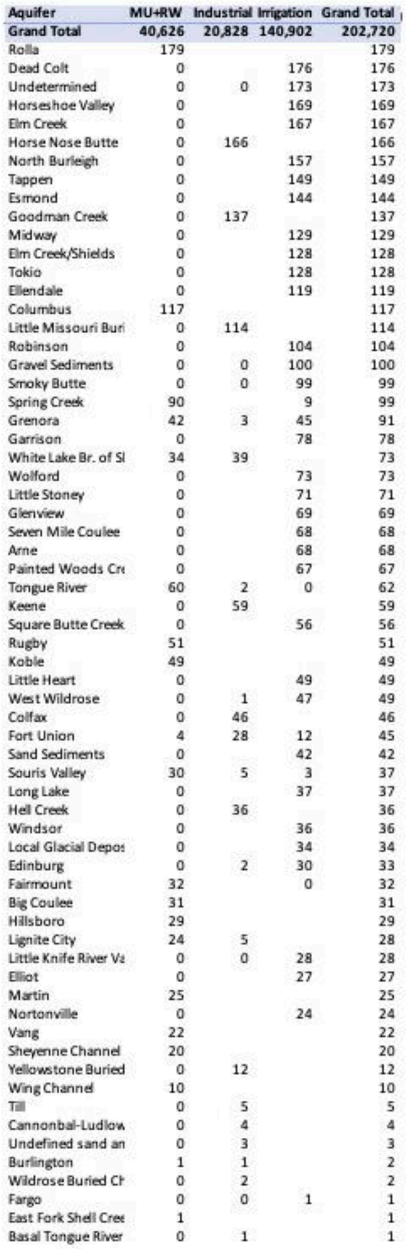
Adrian
Antelope Creek
Apple Creek
Austin
Bantel
Battle Creek
Beaver Creek
Beaver Creek2
Beaver Lake
Belmont
Bennie Peer
Bicker
Big Bend
Big Coulee
Bismarck
Braddock
Brampton
Brightwood
Buffalo Creek
Burnt Creek
Butte
Carrington
Cattail
Central Dakota
Charbonneau
Cherry Creek
Cherry Lake
Clayton
Clearwater
Cleary
Colfax
Columbus
Cottonwood Creek
Courtenay
Crane Creek
Crete
Crosby
Cut Bank Creek
Dead Colt
Deer Lake
Denbigh
Denbigh Buried Channel
Denbigh-Lake Souris
Des Lacs River
Douglas
Dry Fork Creek
Dry Lake
Dunseith
East Fork Shell Creek
Eastman
Edgeley
Edgemont
Edinburg
Elk Valley
Elk Valley middle
Elk Valley north
Elk Valley South
Ellendale
Elliot
Elm Creek
Emerado
Enderlin
Englevale
Englevale Lower
Englevale Middle
Englevale Upper
Eric Lake
Esmond
Estevan
Fairmount
Fillmore
Foothills
Foothills South
Fordville
Fort Mandan
Fox Haven
Galesburg
Garrison
Glenburn
Glencoe Channel
Glenview
Goldwin
Goodman Creek
Grand Forks
Grenora
Guelph
Gwinner
Hamilton
Hankinson
Heart River
Heimdal
Hiddenwood Lake
Hillsboro
Hillsburg
Hofflund
Homer
Horse Nose Butte
Horseshoe Valley
Icelandic
Inkster
James River
Jamestown
Juanita Lake
Karlsruhe
Karlsruhe Deep Channel
Keene
Kenmare
Kilgore
Killdeer
Klose
Knife River
Koble
Lake Ilo
Lake Nettie
Lake Souris
LaMoure
Landa
Leeds
Lignite City
Little Heart
Little Knife River Valley
Little Missouri River
Little Muddy
Little Stoney
Long Lake
Lost Lake
Lower Wishek
Lucy
Maddock
Manfred
Marstonmoor Plain
Martin
McClusky

McIntosh
McKenzie
McVille
Medford
Medina North
Medina South
Middle James
Midway
Milnor Channel
Minot
Missouri River
Missouri River - Lake Sak
Missouri River-Oahe
Mohall
Montpelier
Mount Moriah
Munich
Napoleon
New Rockford
New Town
North Burleigh
Northwest Buried Channel
Nortonville
Oakes
Oberon
Otter Creek
Page
Painted Woods Creek
Painted Woods Lake
Pembina Delta
Pembina River
Pipestem Creek
Plainview
Pleasant Lake
Pleasant Lake - Int. Chan.
Pleasant Lake - N Deep Chan
Pleasant Lake - S Deep Chan
Pony Gulch
Random Creek
Ray
Renner
Riverdale
Rocky Run
Rolla
Roosevelt
Rosefield
Rugby Aquifer
Rusland
Russell Lake
Ryder
Ryder Ridge
Sand Prairie
Sanish
Seven Mile Coulee
Shealy
Sheldon
Shell Creek
Shell Creek-Central
Shell Creek-East Branch
Shell Creek-White Lake
Shell Valley
Sheyenne Delta
Shields
Skjermo Lake
Smoky Butte
Snake Creek
Soo Channel
Souris River
Souris Valley
South Branch Beaver Creek
South Fessenden
Spiritwood
Spiritwood - Grand Rapids
Spiritwood near Jamestown
Spiritwood-Berlin
Spiritwood-Devils Lake
Spiritwood-Griggs
Spiritwood-LaMoure SE
Spiritwood-Oakes
Spiritwood-Rogers
Spiritwood-SE
Spiritwood-Sheyenne River
Spiritwood-Towner County
Spiritwood-Warwick
Spring Creek
Square Butte Creek
Squaw Creek
St. James
Starkweather
Stoneview
Stoney Creek
Strasburg
Strawberry Lake
Streeter
Sundre
Sydney
Thompson
Tiffany Flats
Tobacco Garden
Tokio
Tolgen
Tolgen North
Tower City
Trappers Coulee
Trenton
Turtle Lake
Upper Apple Creek
Upper Buffalo Creek
Vang
Voltaire
Wagonsport
Wahpeton Buried Valley
Wahpeton Complex
Wahpeton sand plain
Wahpeton shallow sand
Warwick Aquifer
Weller Slough
West Fargo
West Fargo North
West Fargo South
West Wildrose
White Earth
White Shield
Wildrose
Wimbledon
Windsor
Wing Channel
Winona
Wishek
Wolf Creek
Yellowstone
Yellowstone River Channel
Yellowstone-Missouri
Ypsilanti
Zap
Zeeland

Appendix 4. 2022 Reported Water Use From Aquifers (not including temp permits).



Aquifer	MU+RW	Industrial	Irrigation	Grand Total
Grand Total	**40,626**	**20,828**	**140,902**	**202,720**
Central Dakota	0	408	25,717	26,125
Oakes	193		12,250	12,442
Spiritwood	3,437	505	8,367	12,310
Elk Valley	2,134		8,943	11,077
Englevale	1	0	10,114	10,115
Sheyenne Delta	1,058		8,347	9,405
Page	1,269		5,707	6,976
Milnor Channel	0	732	5,816	6,548
Lodgepole	0	5,620		5,620
LaMoure	631		4,794	5,424
Missouri River	2,974	966	1,140	5,080
Hofflund	5	1,984	2,799	4,789
Little Muddy	0	1,024	3,741	4,766
Jamestown	3,884	486	46	4,417
Sundre	3,811	2	56	3,868
New Rockford	424	44	3,328	3,796
Minot	3,427	8	2	3,437
Knife River	495	0	2,394	2,889
Karlsruhe	10		2,744	2,753
Lake Nettie	298		2,299	2,597
Charbonneau	0	14	2,363	2,377
Streeter	0		2,231	2,231
Lake Souris	45	0	2,157	2,201
Carrington	326	4	1,728	2,127
Shell Valley	1,513		282	1,795
Hankinson	904	685	0	1,589
Skjermo Lake	0	4	1,584	1,587
McVille	643		922	1,566
New Town	523	915	100	1,538
Undefined	821	194	474	1,494
Yellowstone-Misso	0	63	1,307	1,369
Sand Prairie	0		1,368	1,368
Inkster	13		1,307	1,367
Wahpeton Buried	906	399		1,305
Ray	418	709	104	1,232
White Shield	0	0	1,100	1,100
Fordville	841	6	163	1,010
Denbigh	0	3	985	988
Icelandic	862		112	974
Voltaire	670	262		932
Dakota Group	0	914		914
Shell Creek	0	884		884
Enderlin	847			847
Cattail	0		749	749
Warwick	8		718	726
Winona	0		720	720
Tobacco Garden Cr	0	535	169	704
Strasburg	0		692	692
Fox Hills	420	258	9	688
Glencoe Channel	0		677	677
Unnamed	39	116	512	666
Guelph	0		581	581
Burnt Creek	0		576	576
Edgeley	0		565	565
Bismarck	0	0	309	548
Pleasant Lake	510		38	548
Wishek	152		386	538
Napoleon	84	1	445	529
Juanita	0		520	520
Medina	0		453	453
West Fargo South	451			451
Middle James	0	0	440	440
Rusland	399			399
Killdeer	0	333	64	396
Cherry Creek	0	384		384
Lake Ilo	0	194	174	368
Gwinner	362			362
Soo Channel	0		357	357
Clearwater	0	356		356
West Fargo	223	130		352
Painted Woods La	0		343	343
McKenzie	0	3	303	306
Douglas	0	0	302	302
Trappers Coulee	0		288	288
Lignite Seams and	0	260		260
Kilgore Channel	0		240	240
Unnamed surficial	0	225		225
Strawberry Lake	0		221	221
Sanish	0	219	0	219
Trenton	0	125	70	195
Mohall	193			193
Sentinel Butte-Ton	3	186	0	189
Galesburg	187			187
Heart River	0		186	186



Aquifer	MU+RW	Industrial	Irrigation	Grand Total
Grand Total	**40,626**	**20,828**	**140,902**	**202,720**
Rolla	179			179
Dead Colt	0		176	176
Undetermined	0	0	173	173
Horseshoe Valley	0		169	169
Elm Creek	0		167	167
Horse Nose Butte	0	166		166
North Burleigh	0		157	157
Tappen	0		149	149
Esmond	0		144	144
Goodman Creek	0	137		137
Midway	0		129	129
Elm Creek/Shields	0		128	128
Tokio	0		128	128
Ellendale	0		119	119
Columbus	117			117
Little Missouri Bur	0	114		114
Robinson	0		104	104
Gravel Sediments	0	0	100	100
Smoky Butte	0	0	99	99
Spring Creek	90		9	99
Grenora	42	3	45	91
Garrison	0		78	78
White Lake Br. of S	34	39		73
Wolford	0		73	73
Little Stoney	0		71	71
Glenview	0		69	69
Seven Mile Coulee	0		68	68
Arne	0		68	68
Painted Woods Cr	0		67	67
Tongue River	60	2	0	62
Keene	0	59		59
Square Butte Creek	0		56	56
Rugby	51			51
Koble	49			49
Little Heart	0		49	49
West Wildrose	0	1	47	49
Colfax	0	46		46
Fort Union	4	28	12	45
Sand Sediments	0		42	42
Souris Valley	30	5	3	37
Long Lake	0		37	37
Hell Creek	0	36		36
Windsor	0		36	36
Local Glacial Depos	0		34	34
Edinburg	0	2	30	33
Fairmount	32		0	32
Big Coulee	31			31
Hillsboro	29			29
Lignite City	24	5		28
Little Knife River Va	0	0	28	28
Elliot	0		27	27
Martin	25			25
Nortonville	0		24	24
Vang	22			22
Sheyenne Channel	20			20
Yellowstone Buried	0	12		12
Wing Channel	10			10
Till	0	5		5
Cannonball-Ludlow	0	4		4
Undefined sand an	0	3		3
Burlington	1	1		2
Wildrose Buried Ch	0	2		2
Fargo	0	0	1	1
East Fork Shell Cree	1			1
Basal Tongue River	0	1		1

Appendix 5.   Composite Hydrographs of Aquifers Using “Trends” Program

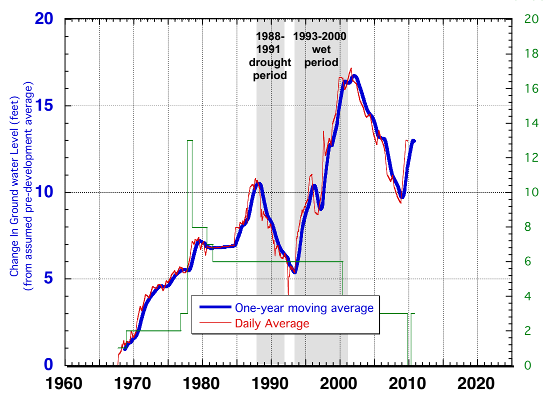
- Antelope Creek
- Apple Creek
- Bismarck
- Brampton
- Brightwood
- Carrington
- Cattail
- Central Dakota
- Charbonneau
- Cherry Creek
- Clearwater
- Columbus
- Crete
- Crosby
- Denbigh
- Denbigh Buried Channel
- Denbigh-Lake Souris
- Douglas
- East Fork Shell Creek
- Eastman
- Edgeley
- Elk Valley
- Elk Valley middle
- Elk Valley north
- Elk Valley South
- Ellendale
- Elliot
- Elm Creek
- Enderlin
- Englevale
- Englevale Lower
- Englevale Middle
- Englevale Upper
- Esmond
- Fairmount
- Fordville
- Garrison
- Glenburn
- Glencoe Channel
- Goodman Creek
- Grenora
- Guelph
- Gwinner
- Hankinson
- Heart River
- Heimdal
- Hofflund
- Horse Nose Butte
- Horseshoe Valley
- Icelandic
- Inkster
- James River
- Jamestown
- Juanita Lake
- Karlsruhe
- Karlsruhe Deep Channel
- Keene
- Kilgore
- Killdeer
- Knife River
- Lake Ilo
- Lake Nettie
- Lake Souris
- LaMoure
- Lignite City
- Little Heart
- Little Knife River Valley
- Little Missouri River
- Little Muddy
- Little Stoney
- Lost Lake
- Lower Wishek
- Maddock
- Manfred
- Martin
- McKenzie
- McVille
- Midway
- Milnor Channel
- Minot
- Missouri River
- Missouri River - Lake Sakakawea
- Missouri River-Oahe
- Mohall
- Munich
- Napoleon
- New Rockford
- New Town
- Northwest Buried Channel
- Oakes
- Page
- Painted Woods Lake
- Pembina River
- Pleasant Lake
- Pleasant Lake - Intermediate Channel
- Pleasant Lake - North Deep Channel
- Pleasant Lake - South Deep Channel
- Pony Gulch
- Ray
- Rugby Aquifer
- Rusland
- Ryder Ridge
- Sand Prairie
- Sanish
- Seven Mile Coulee
- Shell Creek
- Shell Creek-Central
- Shell Creek-East Branch
- Shell Creek-White Lake
- Shell Valley
- Sheyenne Delta
- Shields
- Skjermo Lake
- Smoky Butte
- Soo Channel
- Souris Valley
- Spiritwood
- Spiritwood - Grand Rapids
- Spiritwood near Jamestown
- Spiritwood-Devils Lake
- Spiritwood-Griggs
- Spiritwood-LaMoure SE
- Spiritwood-Oakes
- Spiritwood-Rogers
- Spiritwood-SE and Brampton
- Spiritwood-Sheyenne River
- Spiritwood-Towner County
- Spiritwood-Warwick
- Spring Creek
- Strasburg
- Strawberry Lake
- Streeter
- Sundre
- Tiffany Flats
- Tobacco Garden
- Trappers Coulee
- Trenton
- Turtle Lake
- Upper Apple Creek
- Voltaire
- Wahpeton Buried Valley
- Wahpeton Complex
- Wahpeton sand plain
- Wahpeton shallow sand
- Warwick Aquifer
- West Fargo
- West Fargo North
- West Fargo South
- West Wildrose
- White Shield
- Wildrose
- Wing Channel
- Winona
- Wishek
- Wolf Creek
- Yellowstone
- Yellowstone River Channel
- Yellowstone-Missouri

Source code for *Trends* algorithm

```
/*  ---------------------------------------------------          Date and time: 7/22/1993, 14:01:58
       User name (OS): Chris Bader : Christopher D. Bader         Last Modified: 11/21/2023
```

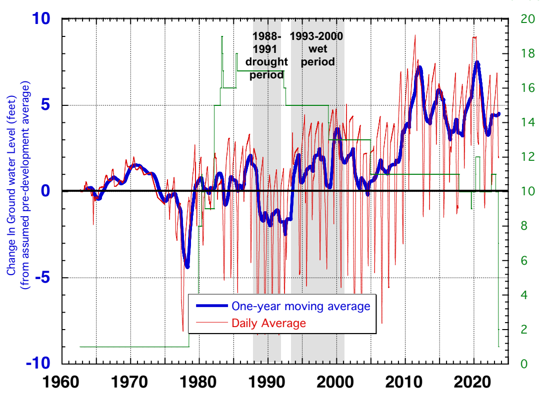
```
       ----------------------------------------------------
       Method: E_WatLev_Trends
       Description

         This procedure is called from the Export button
script from the
         WH Output Form layout.  The procedure is used to
generate
         Water Level trends for the individual
hydrologists.  In order to call
         this procedure the hydrologist must first pass the
wells to the export
         array within the layout and then select the
appropriate button setting
         to invoke the well run sheet selection from the
pop list for exporting
         water level information

       Parameters
       ----------------------------------------------------
*/

C_LONGINT($1; vParentProcess)
C_BLOB($2)

vParentProcess:=$1

ARRAY LONGINT(vWellIndexAr; 0)
BLOB TO VARIABLE($2; vWellIndexAr)

QUERY WITH ARRAY([Well_Header]Well_Index; vWellIndexAr)

C_BOOLEAN(terminateProcess; processCompleted)
terminateProcess:=False
//TRACE
C_BOOLEAN(vDone)
vDone:=False

C_LONGINT($i; $j)
C_LONGINT($Time; $vNum)
C_LONGINT($k)
C_REAL($Depth1; $Depth2; $Total)
C_DATE($BeginDate; $EndDate)
C_DATE($Date1; $Date2)
C_REAL($DiffDepth)
C_TEXT($LineRet)
C_TEXT(progressMessage)
C_REAL(progressStatus)

$vNum:=Records in selection([Well_Header])
If ($vNum#0)
       progressMessage:="Setting up Index Array"
       progressStatus:=0

       RELATE MANY SELECTION([Water_Levels]Well_Index)
       QUERY
SELECTION([Water_Levels]; [Water_Levels]Time_Meas=?00:00:00
?)
       QUERY
SELECTION([Water_Levels]; [Water_Levels]Depth_to_Water>-
9000; *)
       QUERY SELECTION([Water_Levels];  &
; [Water_Levels]Depth_to_Water<9000)
       ORDER BY([Water_Levels]; [Water_Levels]Date_Meas; >)
       // Establish the Begining and ending dates and
number of days between
       FIRST RECORD([Water_Levels])
       $BeginDate:=[Water_Levels]Date_Meas
       LAST RECORD([Water_Levels])
       $EndDate:=[Water_Levels]Date_Meas
       $Time:=$EndDate-$BeginDate
       ARRAY LONGINT(vWLTrendInd; $Time)
       ARRAY REAL(vWLYear; $Time)
       ARRAY REAL(vWLTrendSum; $Time)
       vWLYear{1}:=Year of($BeginDate)+(($BeginDate-
Date("01/01/"+String(Year of($BeginDate)))+1)/365.25)
       For ($i; 2; $Time)
              vWLYear{$i}:=vWLYear{$i-1}+0.002737851
       End for

       progressMessage:="Generating Array Data"
       progressStatus:=0

       FIRST RECORD([Well_Header])
       $i:=1
       While (($i<=$vNum) & (Not(terminateProcess)))
              progressStatus:=$i/$vNum
              progressMessage:="Processing Wells . . ."

              RELATE MANY([Well_Header]Well_Index)
              QUERY
SELECTION([Water_Levels]; [Water_Levels]Time_Meas=?00:00:00
?)
              QUERY
SELECTION([Water_Levels]; [Water_Levels]Depth_to_Water>-
9000; *)
              QUERY SELECTION([Water_Levels];  &
; [Water_Levels]Depth_to_Water<9000)
              ORDER
BY([Water_Levels]; [Water_Levels]Date_Meas; >)
              FIRST RECORD([Water_Levels])
              For ($j; 1; (Records in
selection([Water_Levels])-1))
                     $Depth1:=[Water_Levels]MP_Elevation-
[Water_Levels]Depth_to_Water
                     $Date1:=[Water_Levels]Date_Meas
                     NEXT RECORD([Water_Levels])
                     $Depth2:=[Water_Levels]MP_Elevation-
[Water_Levels]Depth_to_Water
                     $Date2:=[Water_Levels]Date_Meas
                     If ($Date2#$Date1)
                           $DiffDepth:=($Depth2-
$Depth1)/($Date2-$Date1)
                           For ($k; ($Date1-$BeginDate);
($Date2-$BeginDate-1))
                                  vWLTrendInd{$k}:=vWLTrend
Ind{$k}+1
                                  vWLTrendSum{$k}:=vWLTrend
Sum{$k}+$DiffDepth
                           End for
                     End if

              End for
              NEXT RECORD([Well_Header])
              $i:=$i+1
       End while

End if

processCompleted:=True

Repeat
       DELAY PROCESS(Current process; 120)
Until (terminateProcess)
ARRAY LONGINT(vWLTrendInd; 0)
ARRAY REAL(vWLYear; 0)
ARRAY REAL(vWLTrendSum; 0)
```

Composite Hydrograph of Observation Wells in the
Antelope Creek Aquifer



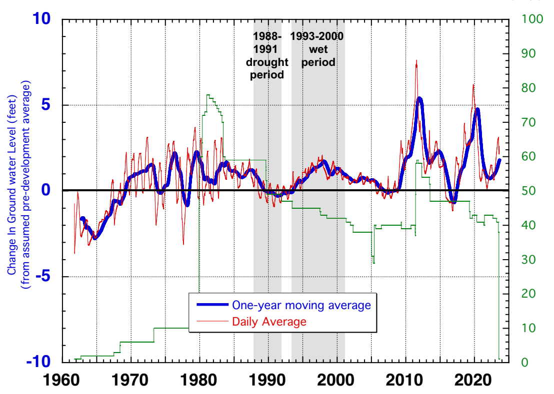
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Apple Creek Aquifer



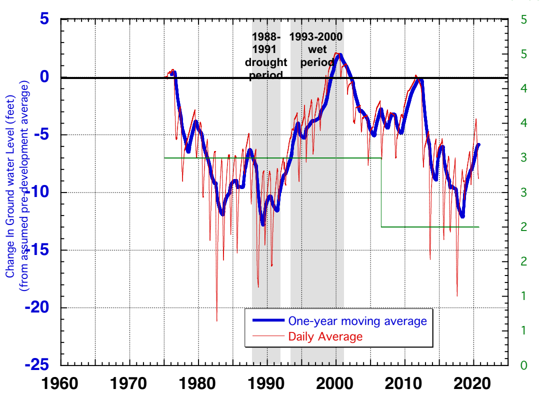
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Bismarck Aquifer



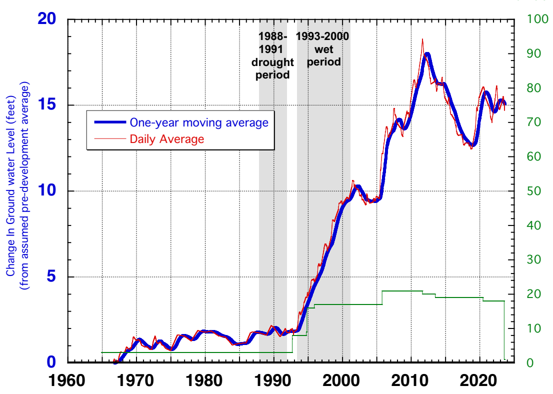
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Brampton Aquifer



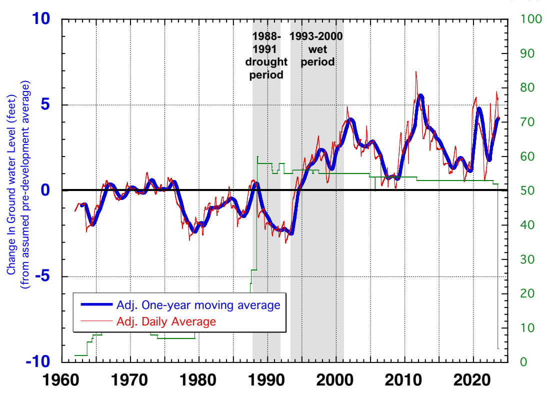
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Brightwood Aquifer



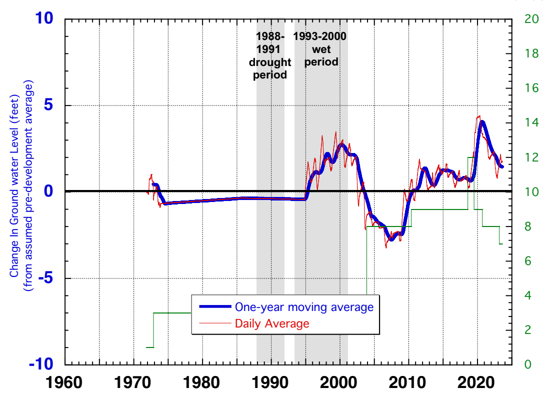
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Carrington Aquifer



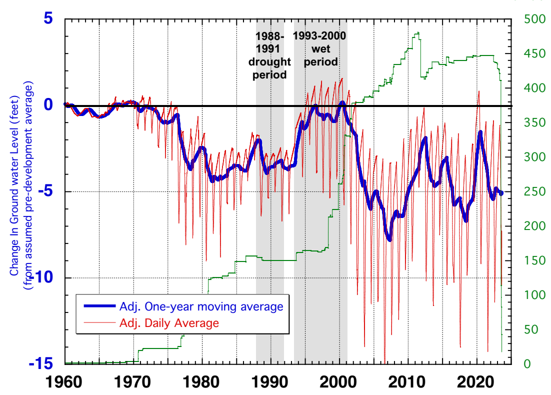
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Cattail Aquifer



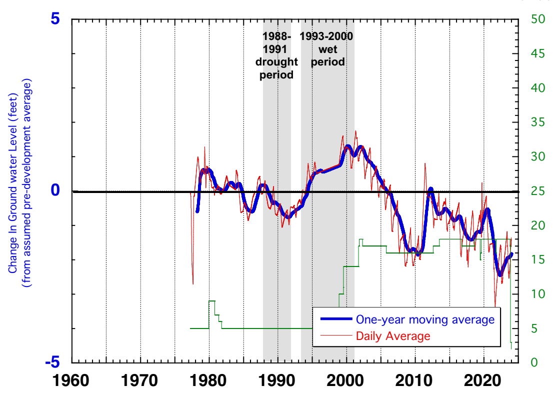
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Central Dakota Aquifer



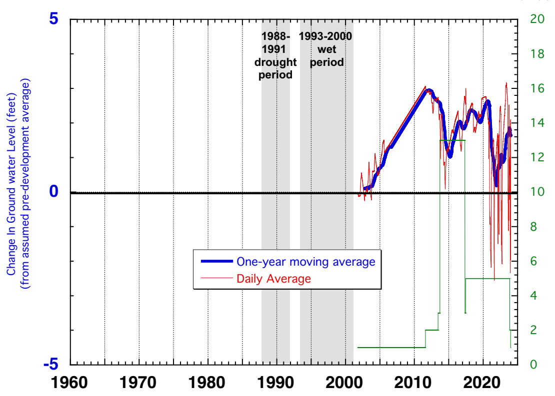
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Charbonneau Aquifer



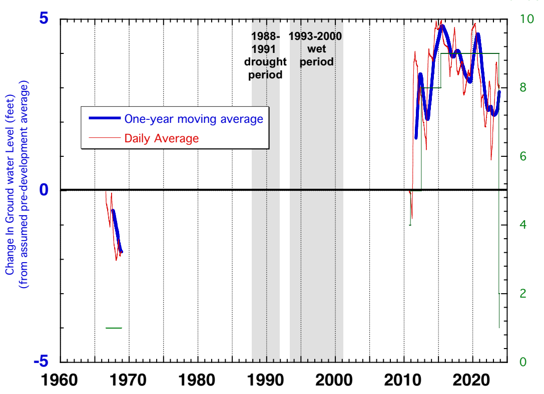
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Cherry Creek Aquifer



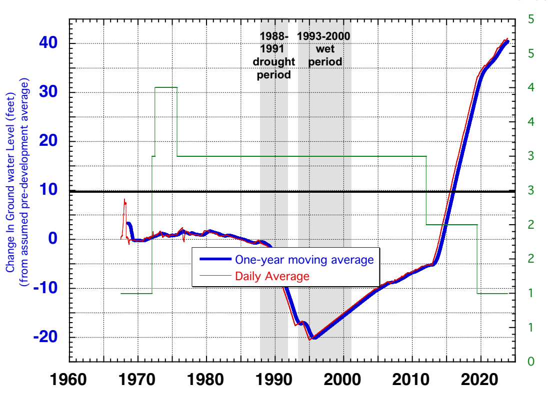
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Clearwater Aquifer



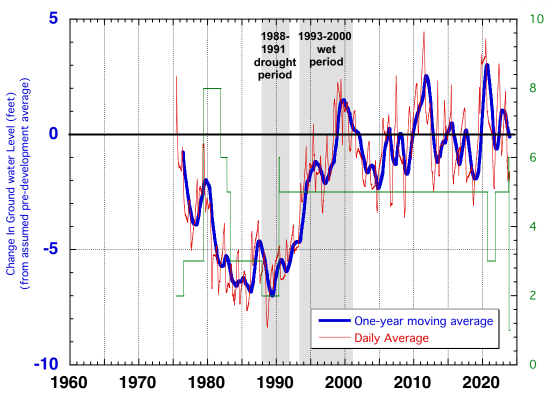
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Columbus Aquifer



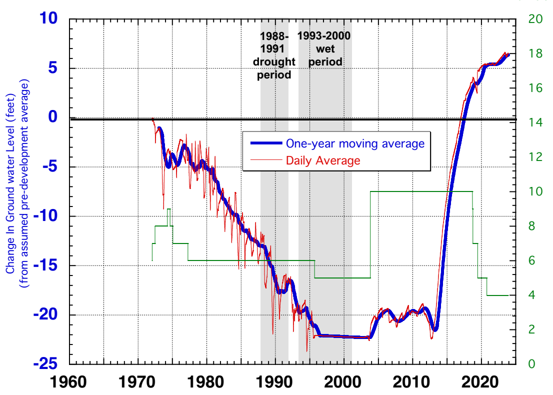
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Crete Aquifer



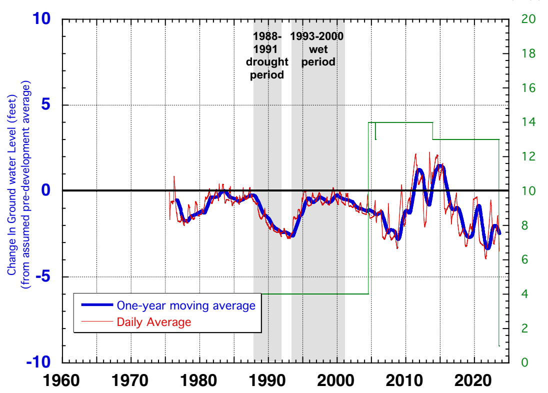
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Crosby Aquifer



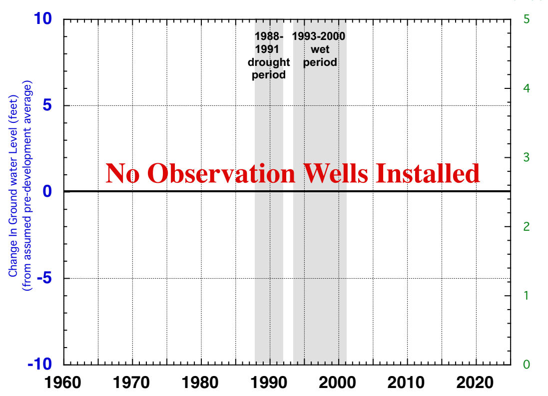
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Denbigh Aquifer



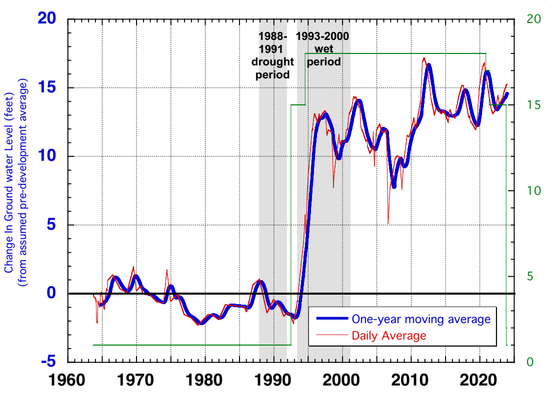
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Douglas Aquifer



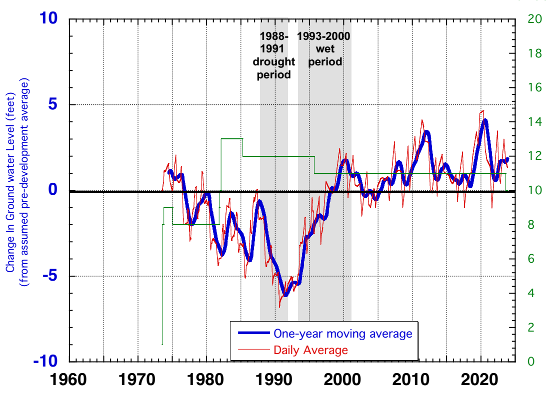
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Eastman Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

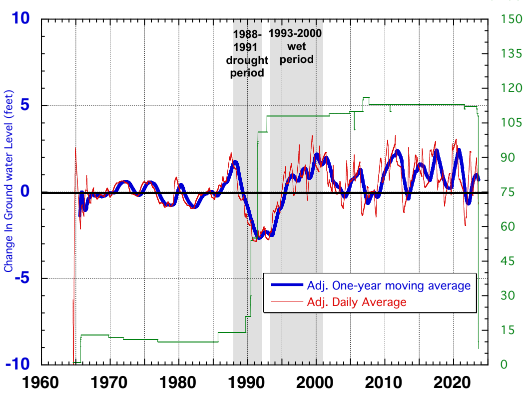
Composite Hydrograph of Observation Wells in the
Edgeley Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

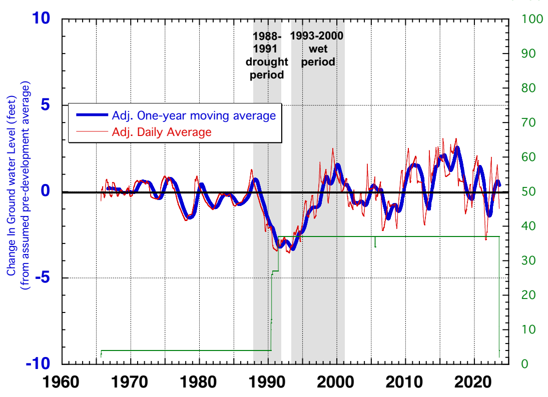
Elk Valley Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

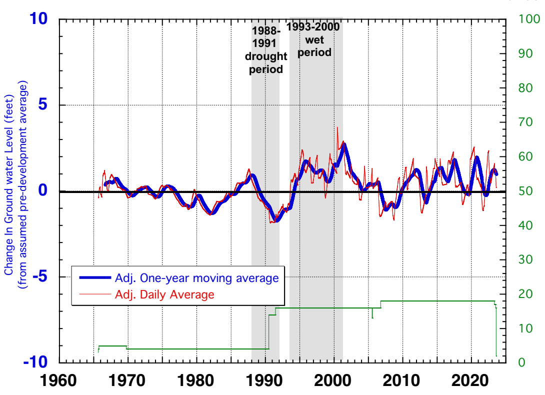
Elk Valley Aquifer north unit



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

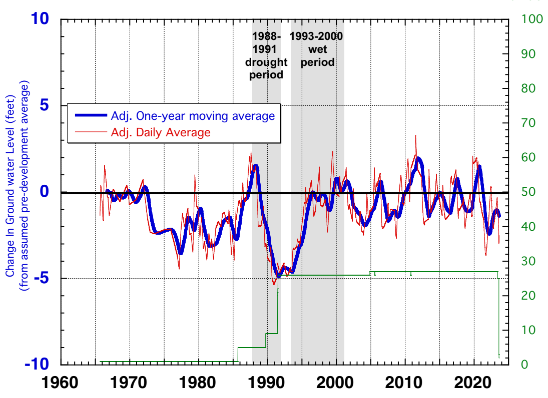
Elk Valley Aquifer middle unit



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

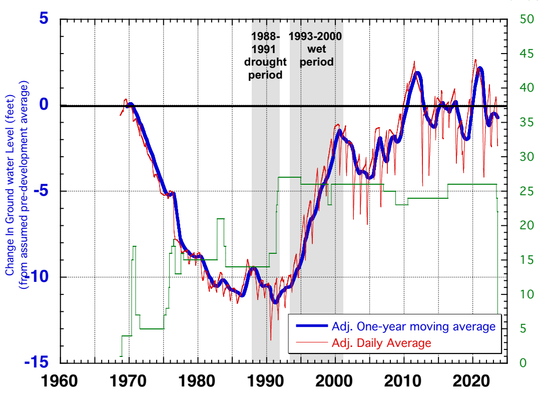
Elk Valley Aquifer near GF-Traill WU



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

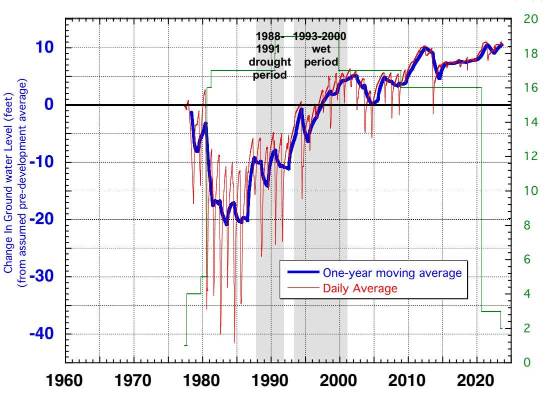
Ellendale Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

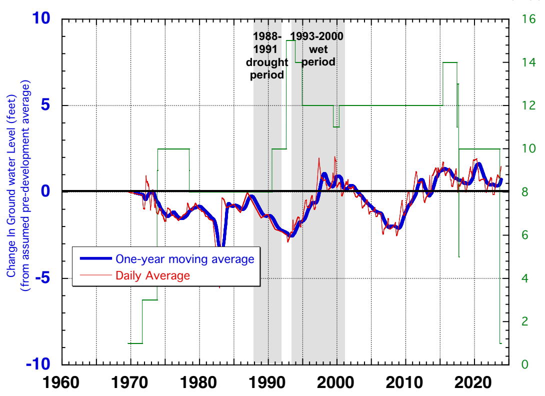
Composite Hydrograph of Observation Wells in the

Elliot Aquifer



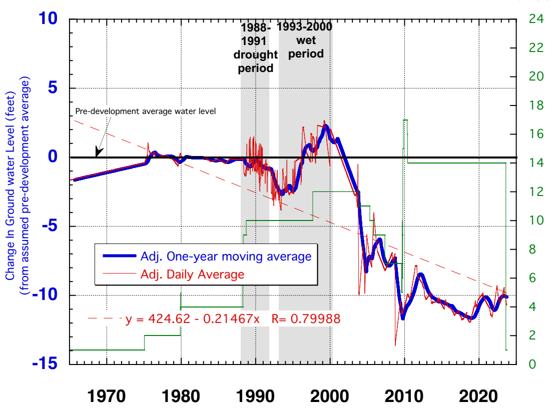
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Elm Creek Aquifer



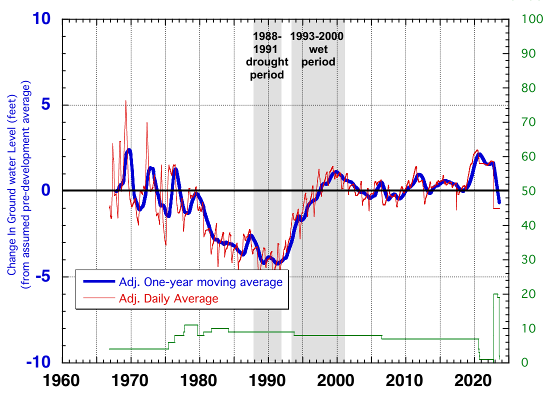
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Enderlin Aquifer



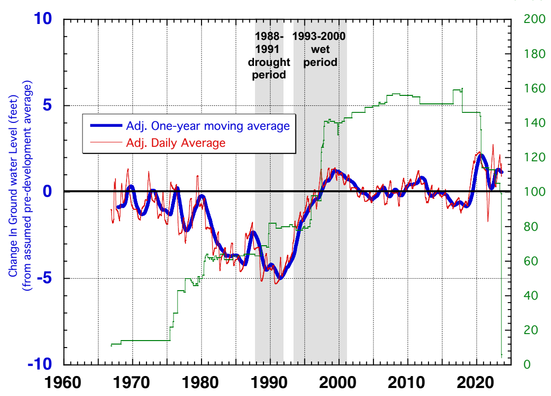
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Englevale Aquifer



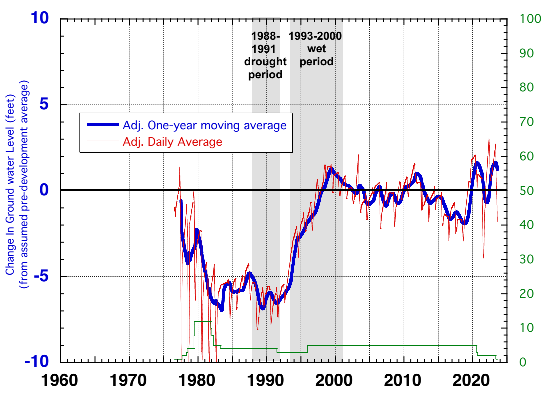
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Englevale-upper Aquifer



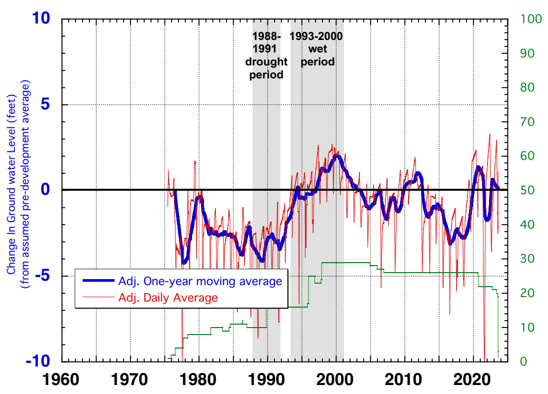
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Englevale-middle Aquifer



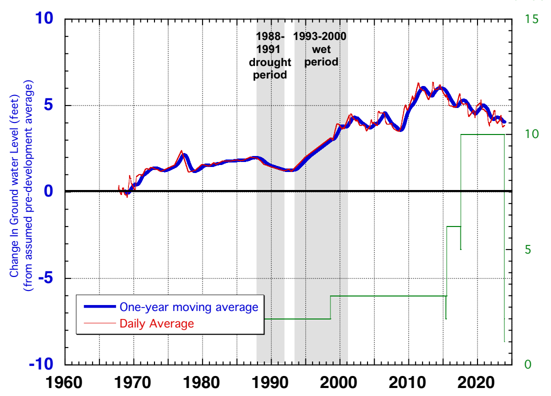
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Englevale-lower Aquifer



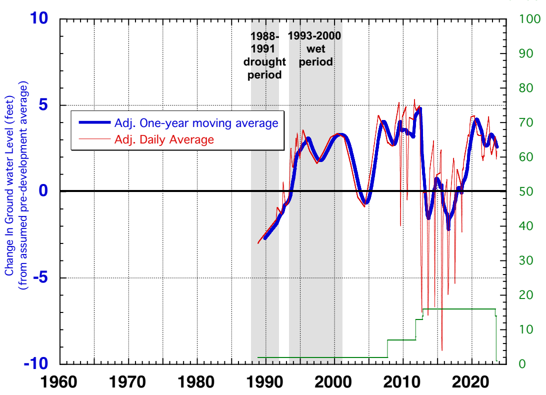
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Esmond Aquifer



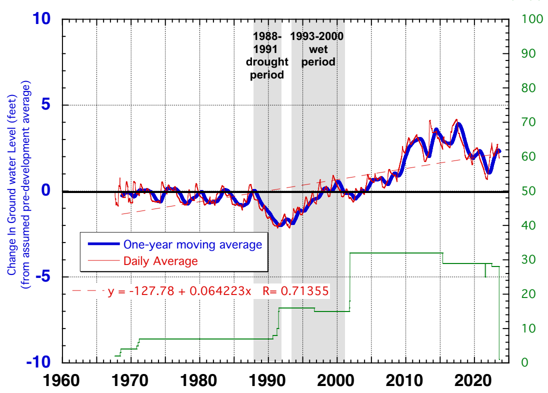
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Fairmount Aquifer



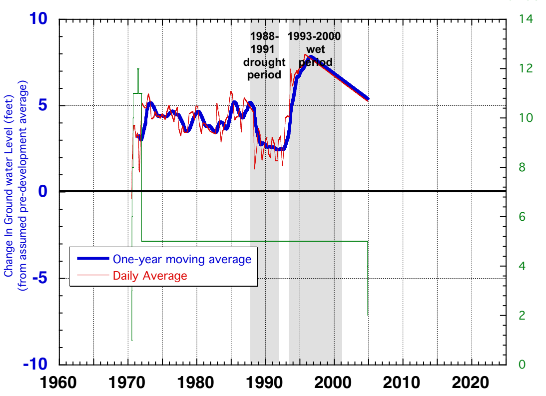
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Fordville Aquifer



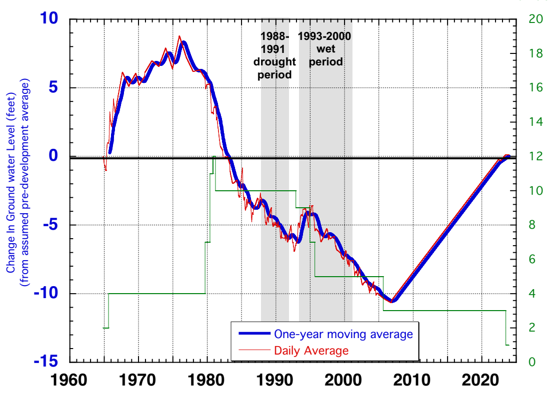
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Garrison Aquifer



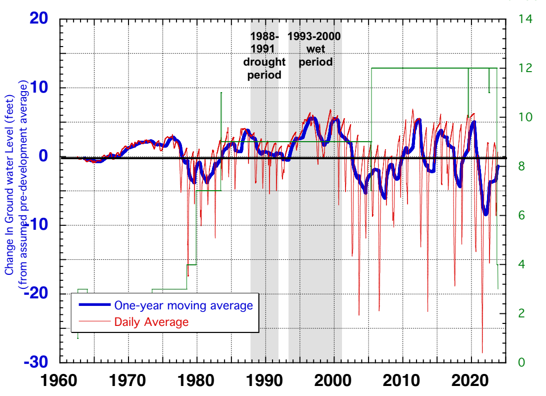
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Glenburn Aquifer



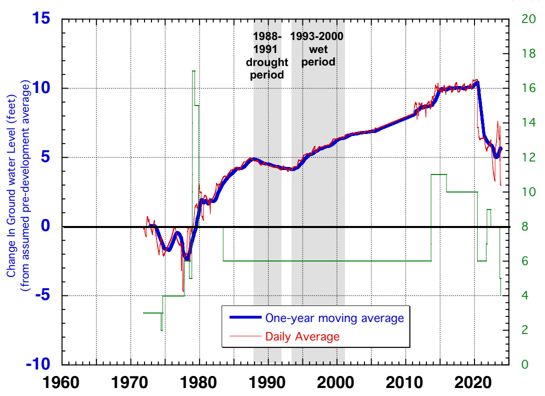
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Glencoe Channel Aquifer



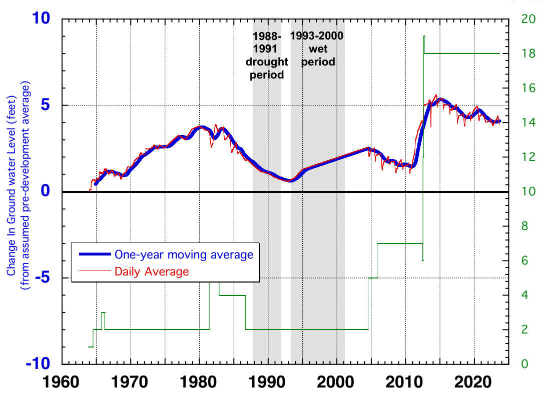
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Goodman Creek Aquifer



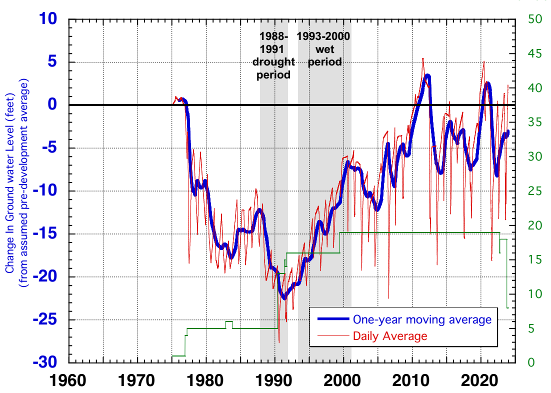
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Grenora Aquifer



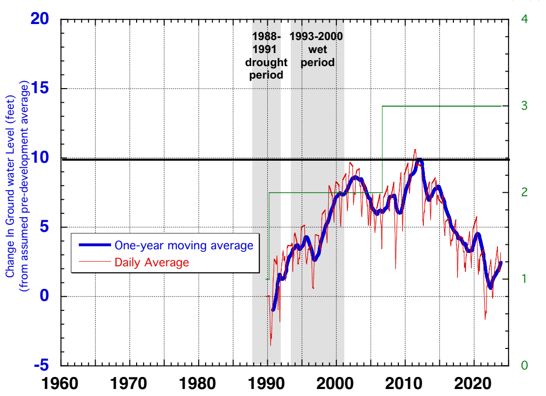
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Guelph Aquifer



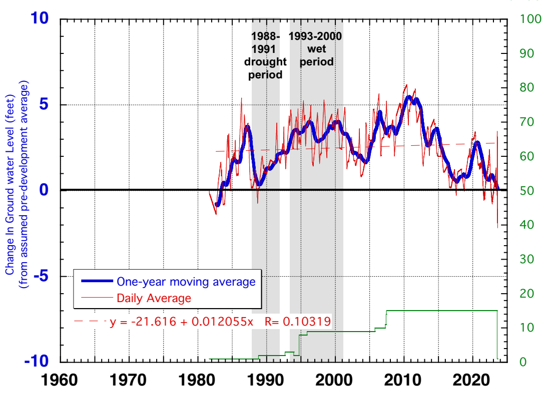
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Gwinner Aquifer



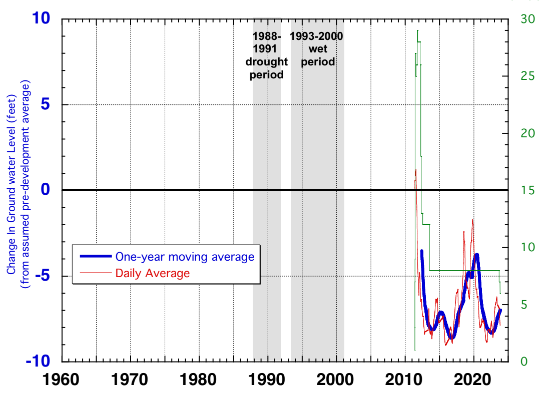
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Hankinson Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Heart River Aquifer



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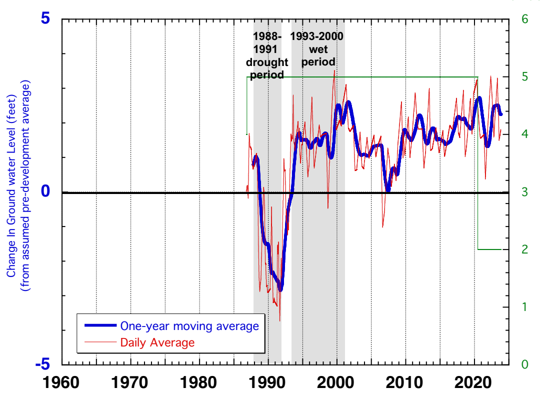
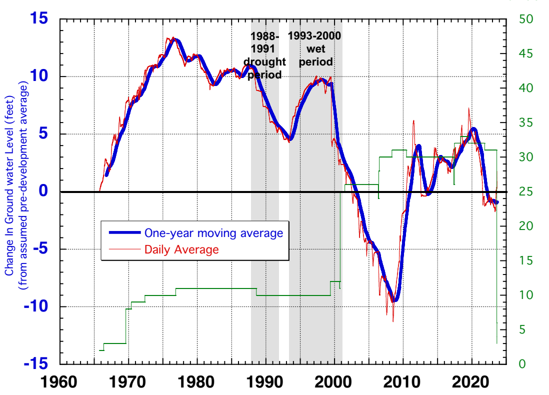
Composite Hydrograph of Observation Wells in the
Heimdal Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
HofflundAquifer



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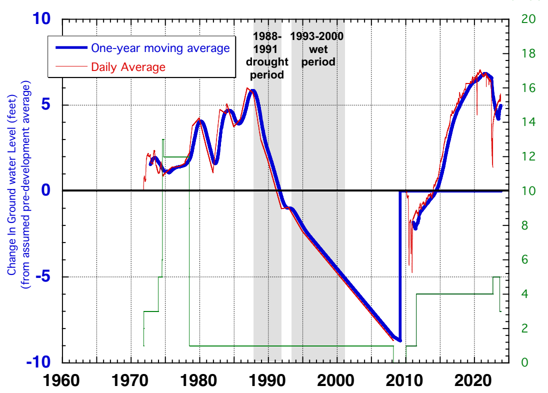
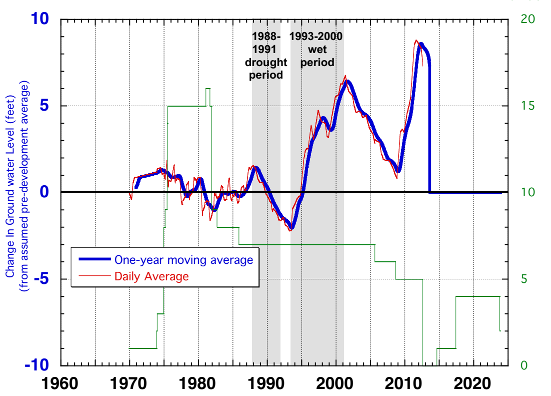
Composite Hydrograph of Observation Wells in the
Horse Nose Butte Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Horseshoe Valley Aquifer



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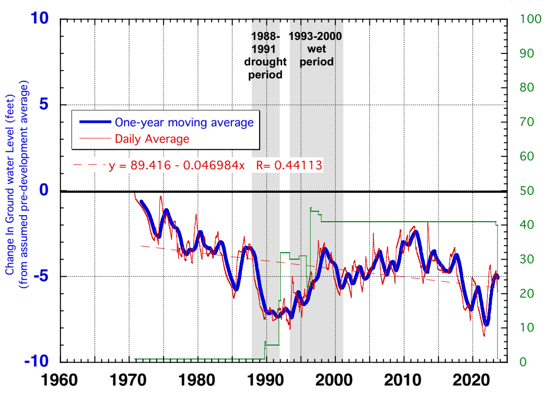
Composite Hydrograph of Observation Wells in the
Icelandic Aquifer



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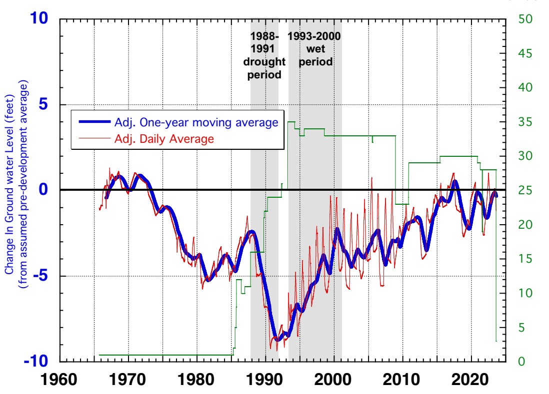
Composite Hydrograph of Observation Wells in the
Inkster Aquifer



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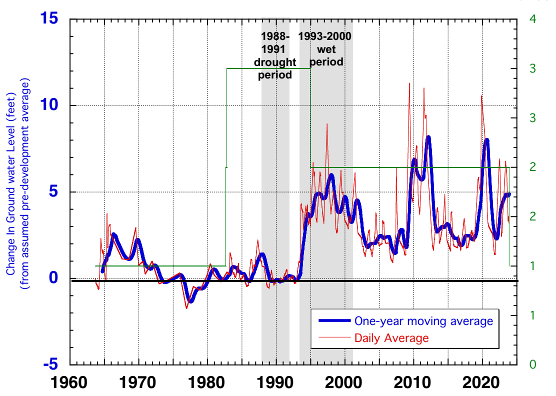
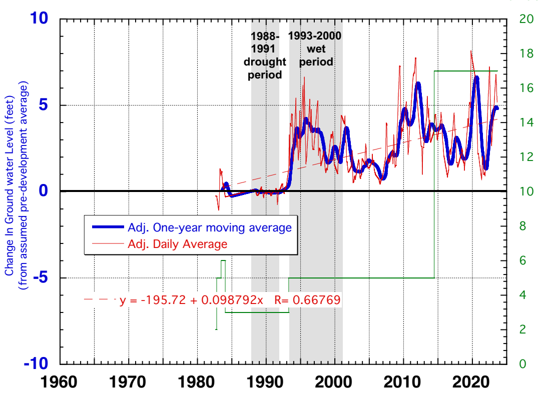
Composite Hydrograph of Observation Wells in the
James River Aquifer



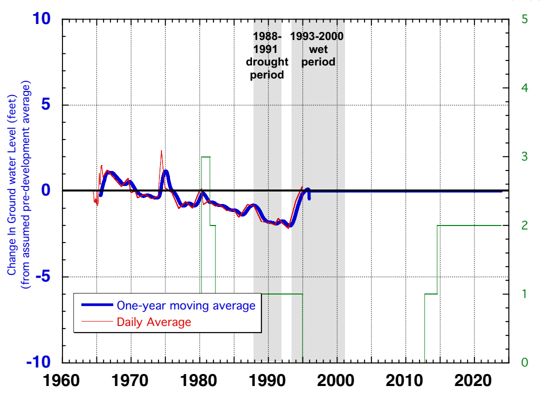
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Jamestown Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Juanita Aquifer



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Composite Hydrograph of Observation Wells in the
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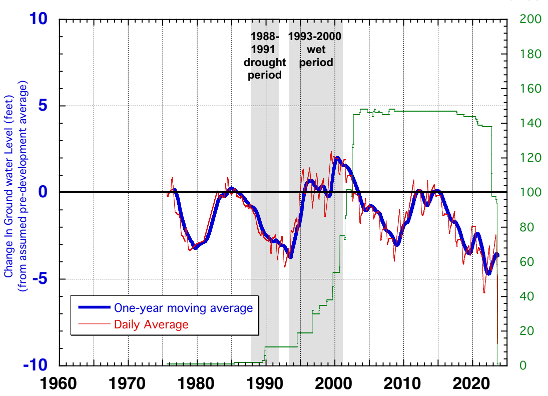

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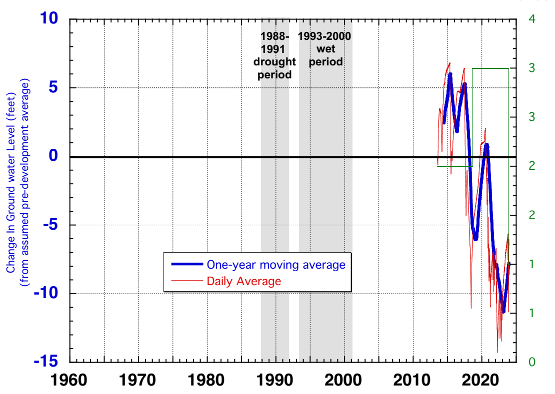
Composite Hydrograph of Observation Wells in the
Keene Aquifer



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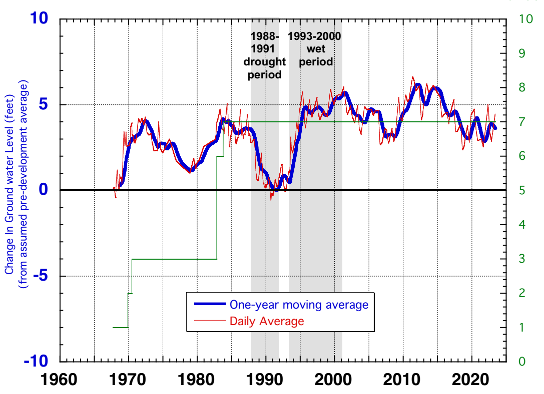
Composite Hydrograph of Observation Wells in the
Kilgore Aquifer



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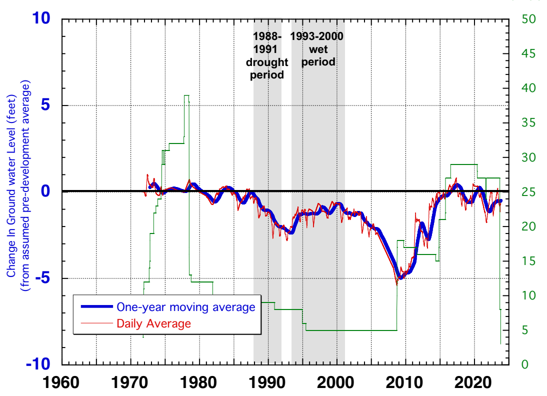
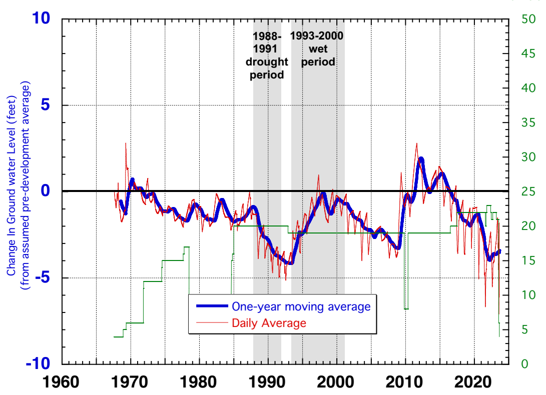
Composite Hydrograph of Observation Wells in the Killdeer Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the Knife River Aquifer



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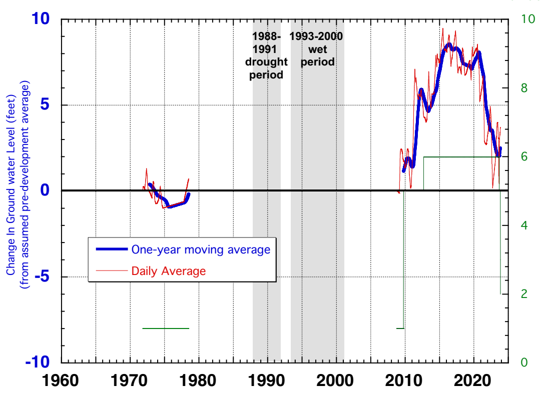
Composite Hydrograph of Observation Wells in the Lake Ilo Aquifer



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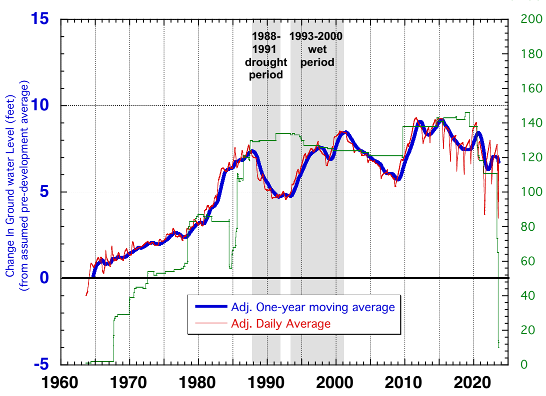
Composite Hydrograph of Observation Wells in the Lake Nettie Aquifer



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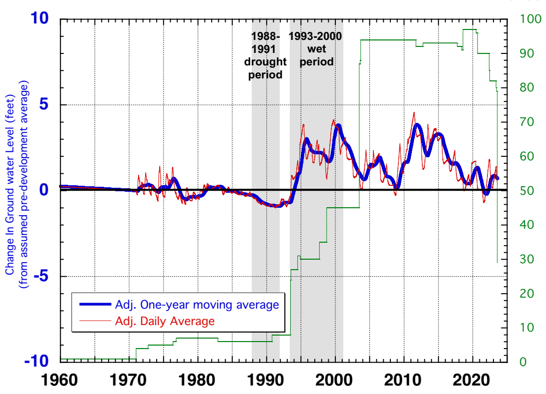
Composite Hydrograph of Observation Wells in the Lake Souris Aquifer



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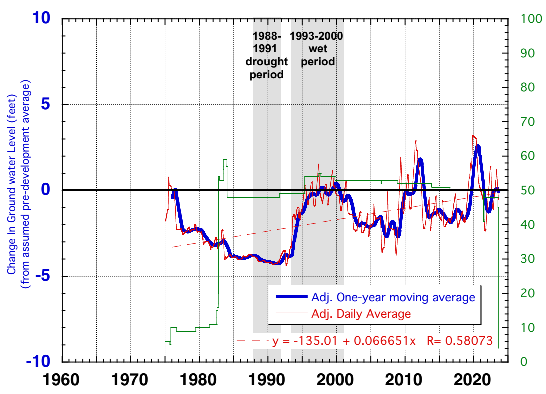
Composite Hydrograph of Observation Wells in the LaMoure Aquifer



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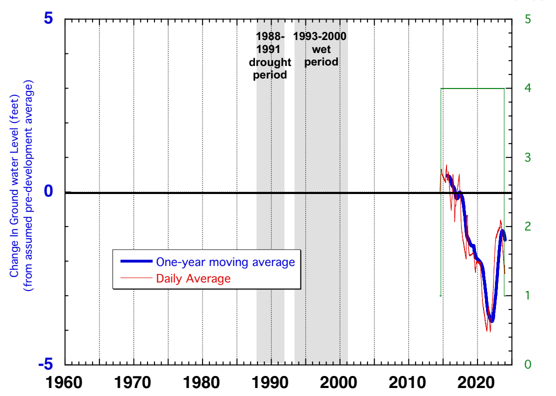
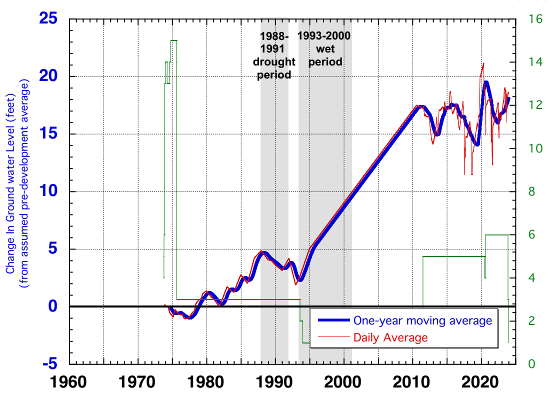
Composite Hydrograph of Observation Wells in the
Lignite City Aquifer



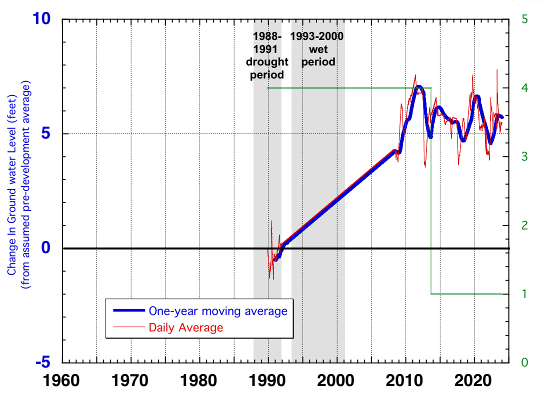
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Little Heart Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Little Knife River Valley Aquifer



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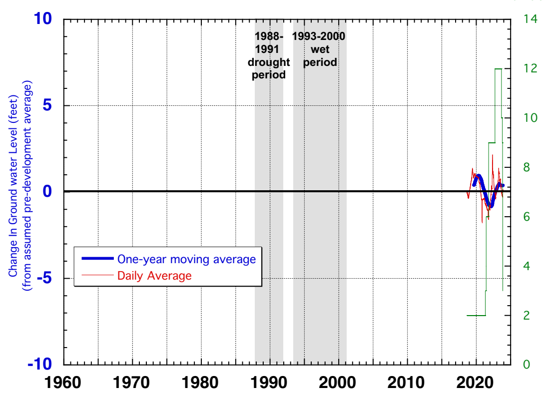
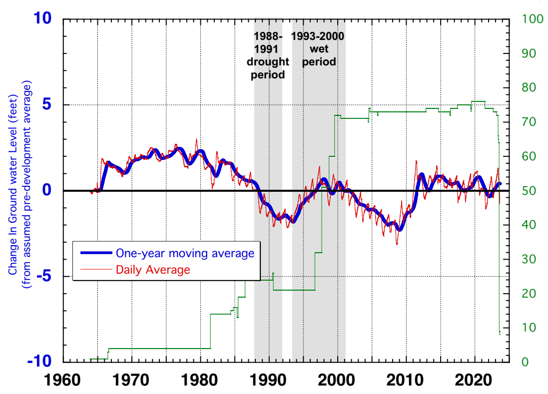
Composite Hydrograph of Observation Wells in the
Little Missouri Buried Channel Aquifer



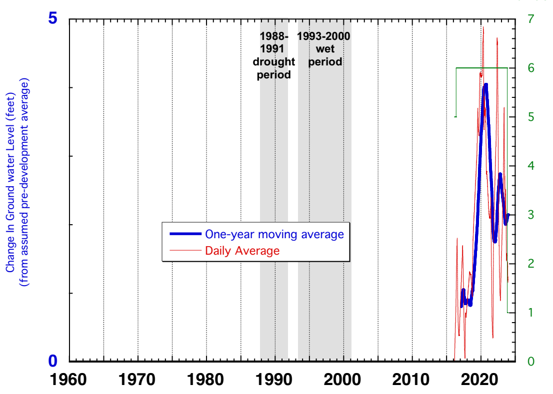
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Little Muddy Aquifer



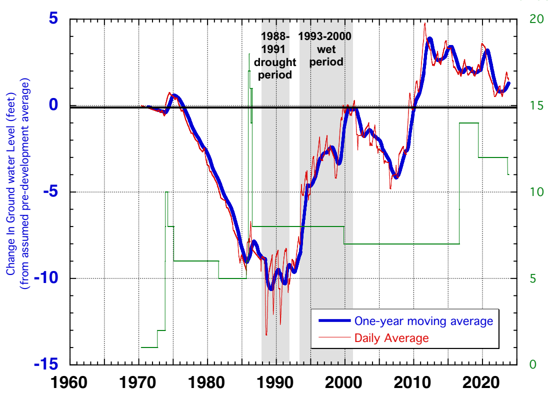
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Little Stoney Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Lost Lake Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
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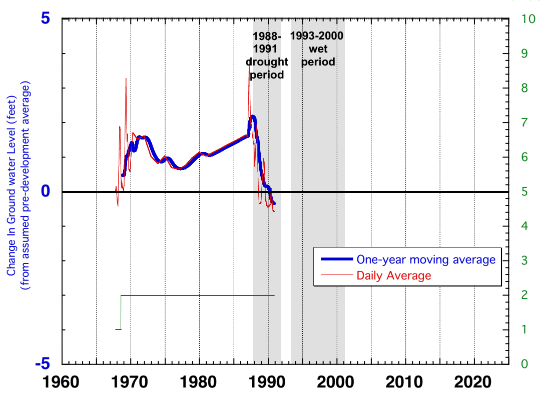
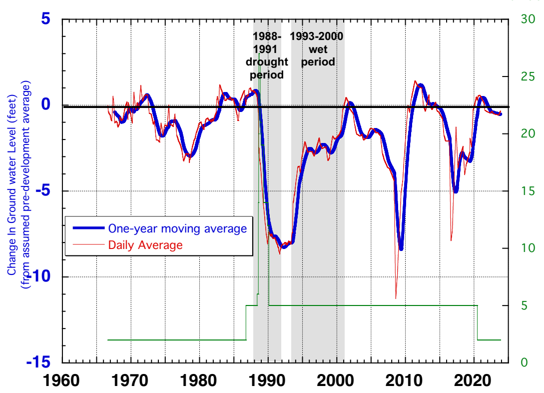


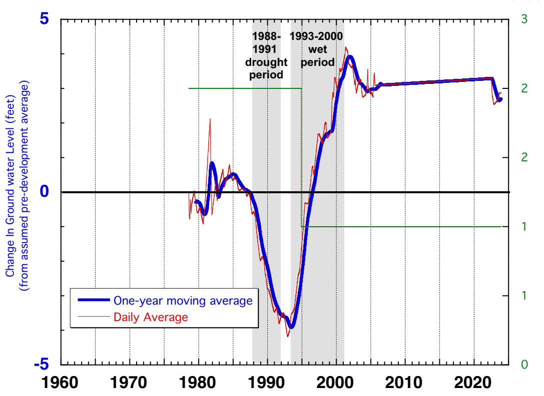
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Manfred Aquifer



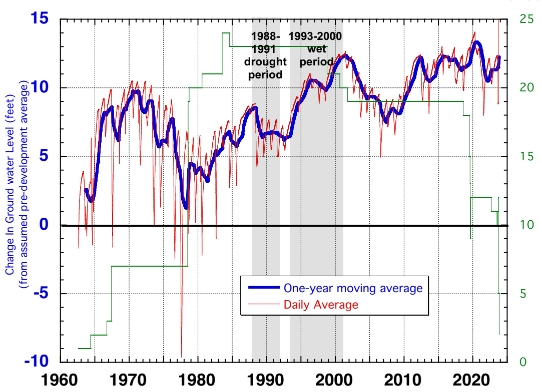
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Martin Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Mckenzie Aquifer



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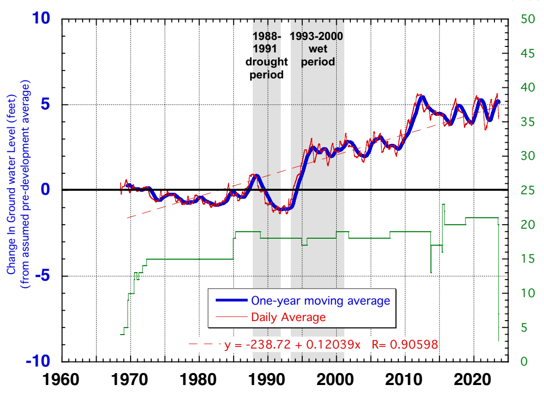
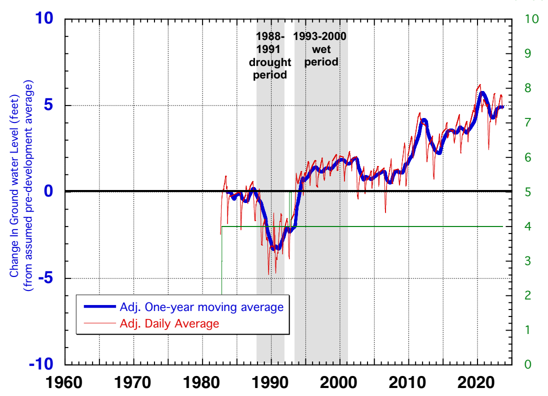
Composite Hydrograph of Observation Wells in the
McVille Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Midway Aquifer



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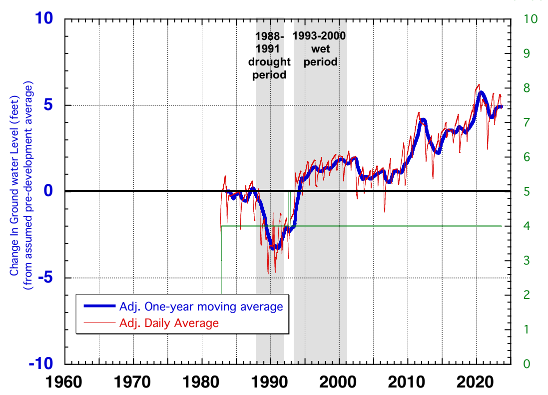
Composite Hydrograph of Observation Wells in the
Midway Aquifer



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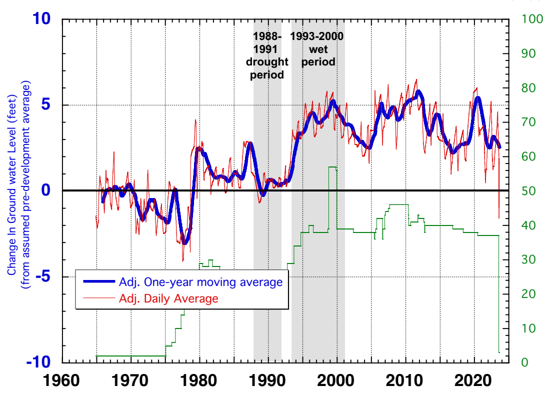
Composite Hydrograph of Observation Wells in the
Milnor Channel Aquifer



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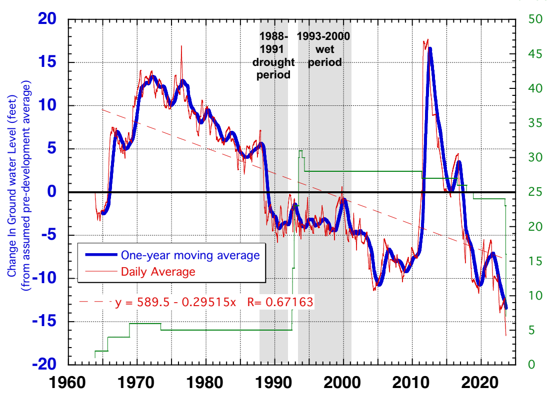
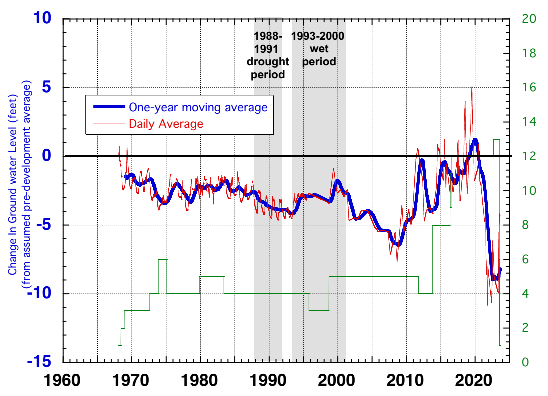
Composite Hydrograph of Observation Wells in the
Minot Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Missouri River Aquifer



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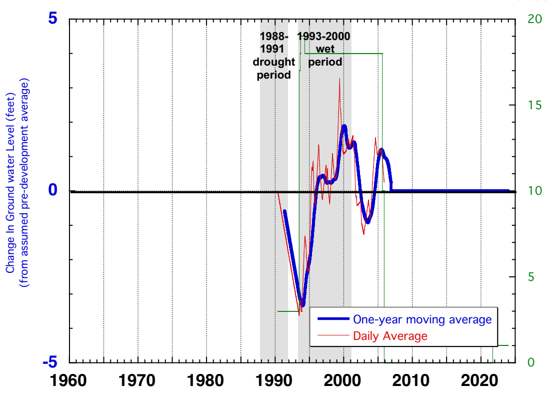
Composite Hydrograph of Observation Wells in the
Mohall Aquifer



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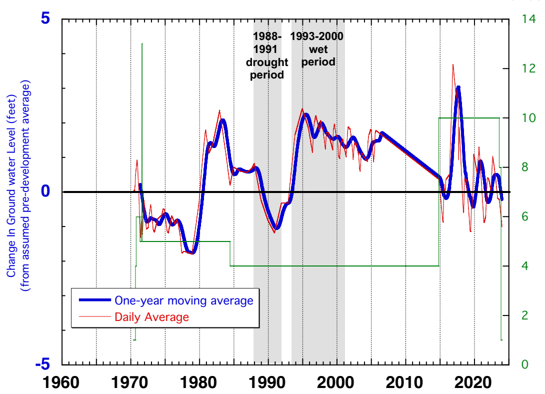
Composite Hydrograph of Observation Wells in the

Munich Aquifer



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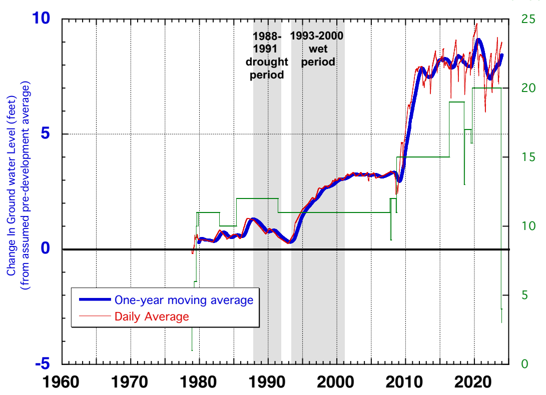
Composite Hydrograph of Observation Wells in the

Napoleon Aquifer



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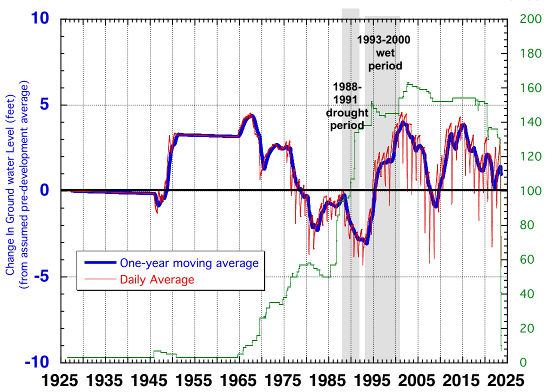
Composite Hydrograph of Observation Wells in the

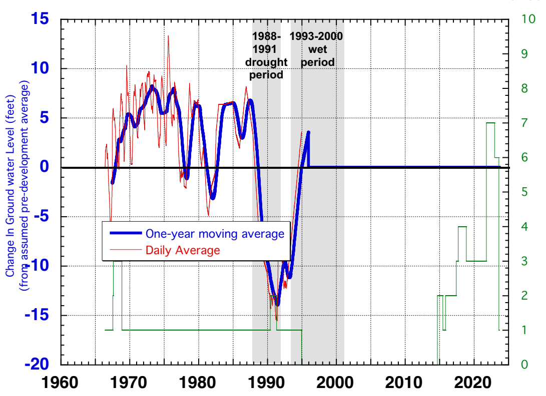
New Rockford Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

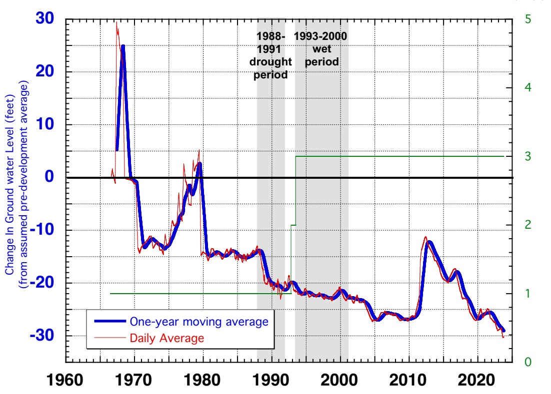
New Town Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

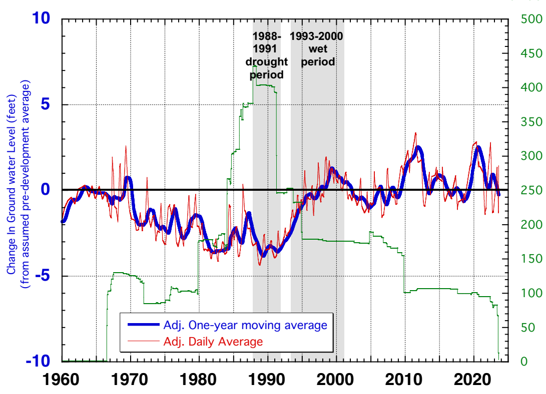
Northwest Buried Channel Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

Oakes Aquifer



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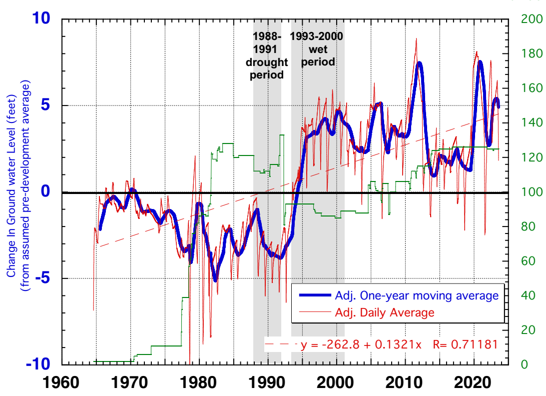
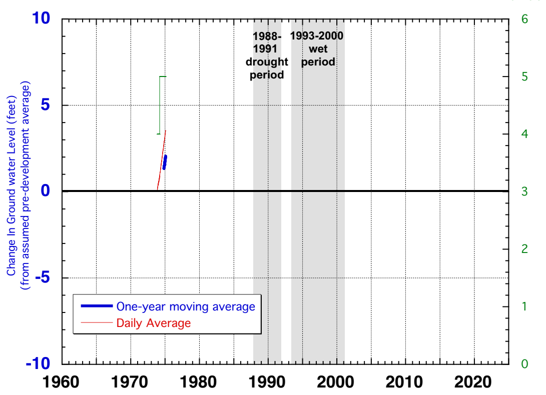


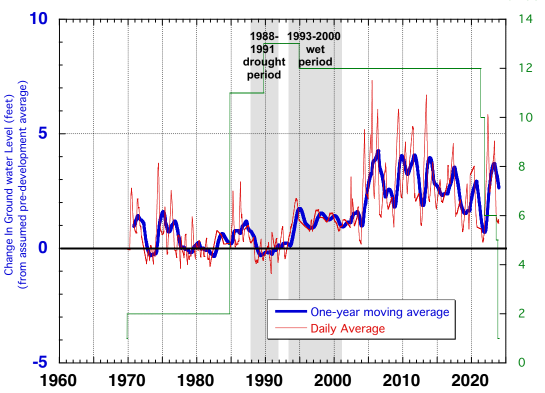
Composite Hydrograph of Observation Wells in the
Page Aquifer

Date Source: ND Dept. of Water Resources Site inventory Database



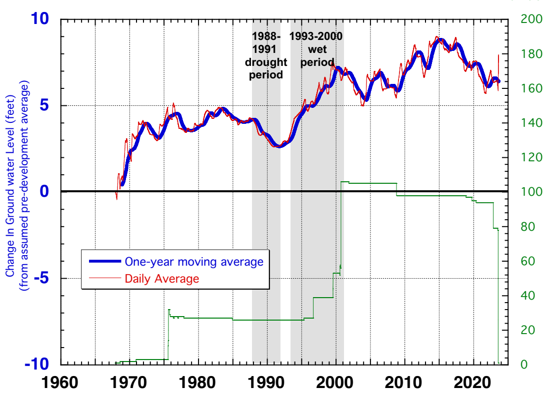
Composite Hydrograph of Observation Wells in the
Painted Woods Lake Aquifer

Date Source: ND Dept. of Water Resources Site inventory Database



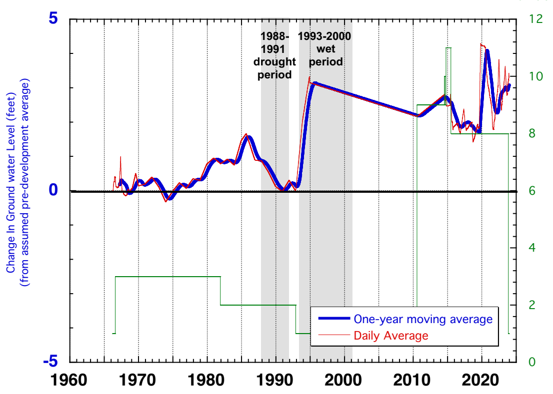
Composite Hydrograph of Observation Wells in the
Pembina River Aquifer

Date Source: ND Dept. of Water Resources Site inventory Database



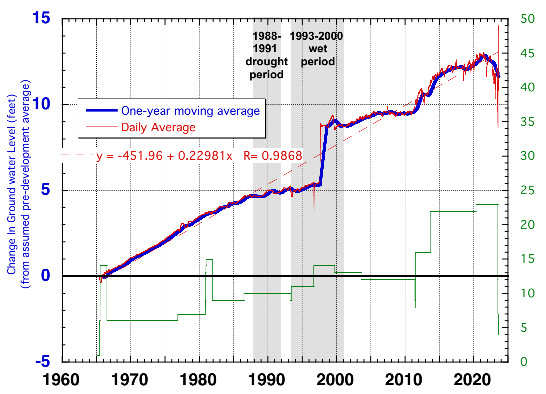
Composite Hydrograph of Observation Wells in the
Pleasant Lake Aquifer

Date Source: ND Dept. of Water Resources Site inventory Database



Composite Hydrograph of Observation Wells in the
Pony Gulch Aquifer

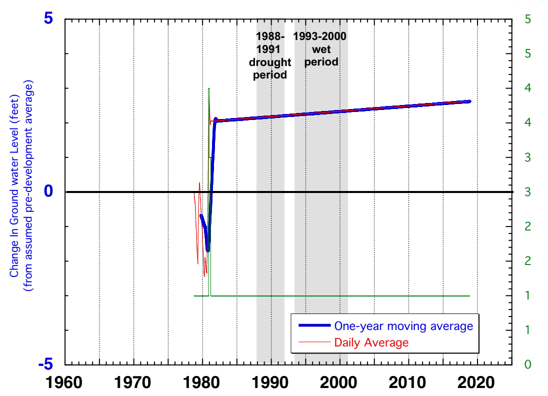
Date Source: ND Dept. of Water Resources Site inventory Database



Composite Hydrograph of Observation Wells in the
Ray Aquifer

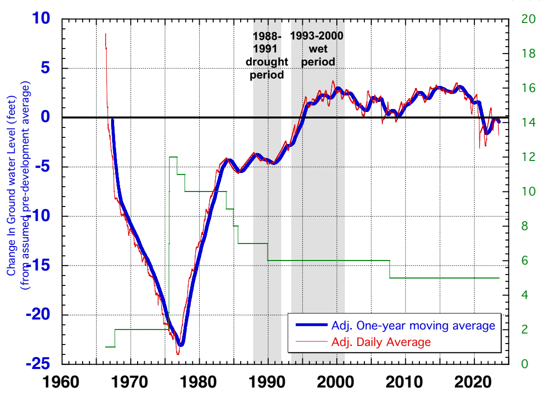
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Rolla Aquifer



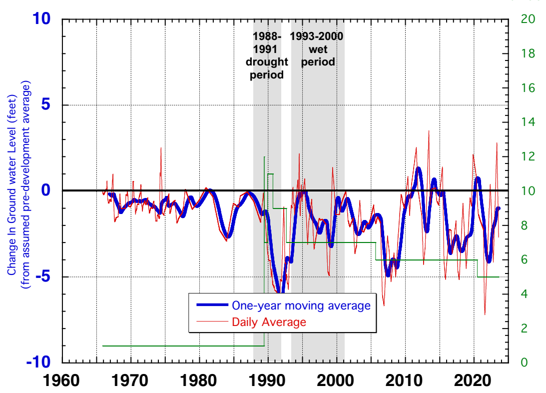
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Rugby Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Rusland Aquifer



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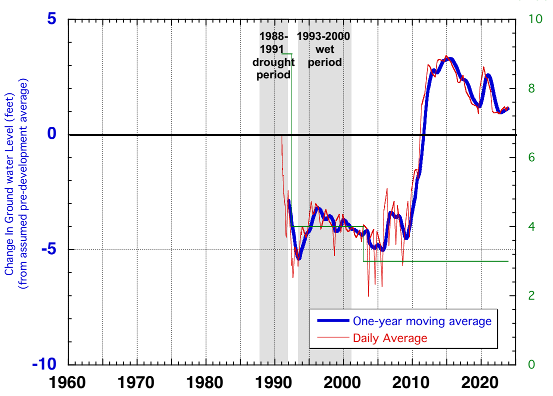
Composite Hydrograph of Observation Wells in the
Ryder Ridge Aquifer



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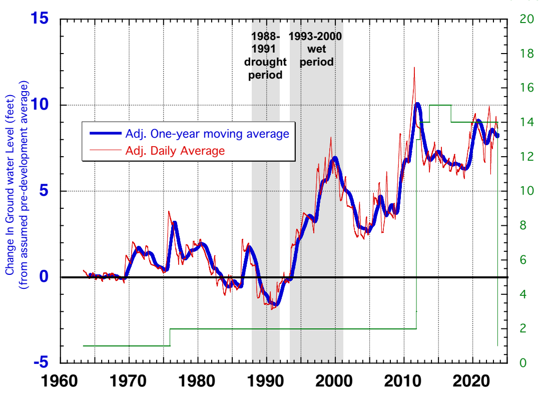
Composite Hydrograph of Observation Wells in the
Sand Prairie Aquifer



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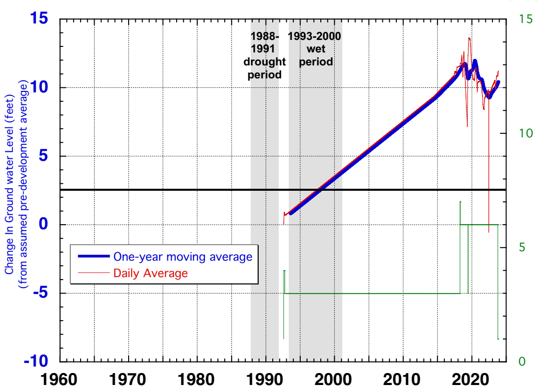
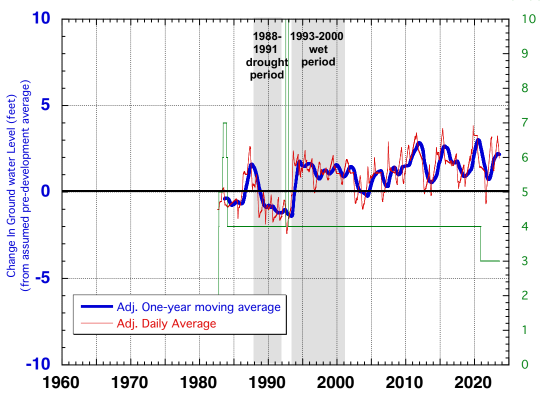
Composite Hydrograph of Observation Wells in the
Sanish Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

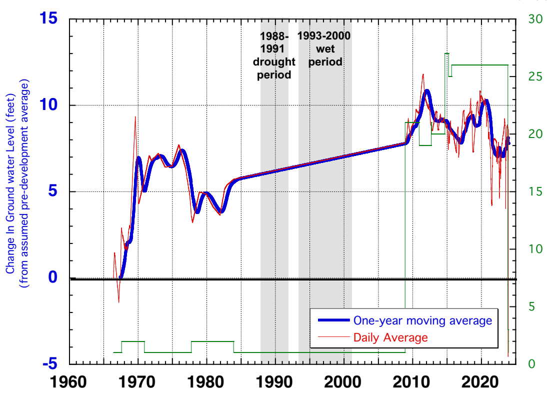
Seven Mile Coulee Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

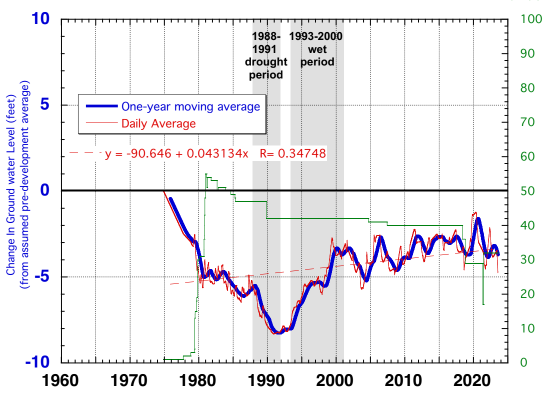
Shell Creek Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

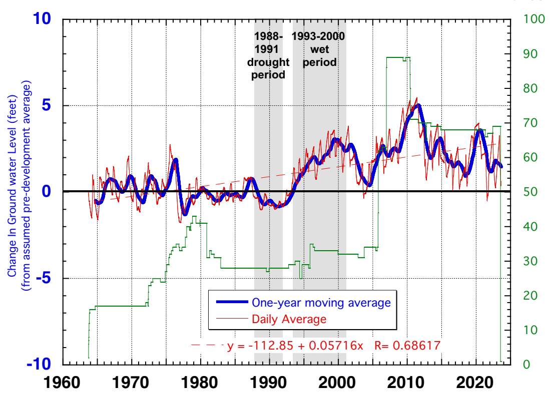
Shell Valley Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

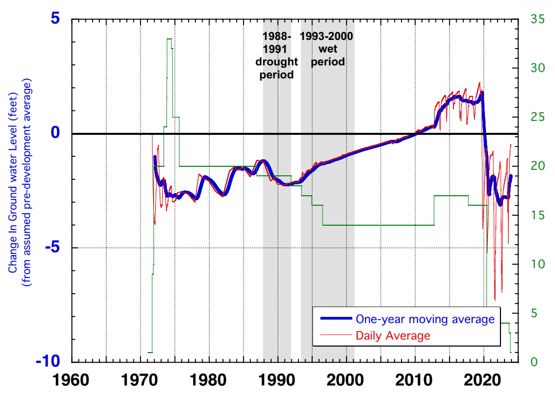
Sheyenne Delta Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

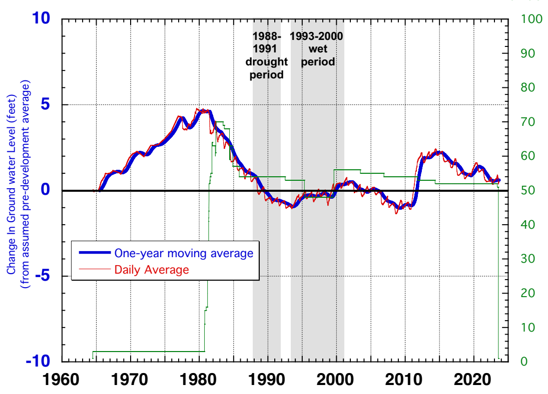
Shields Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

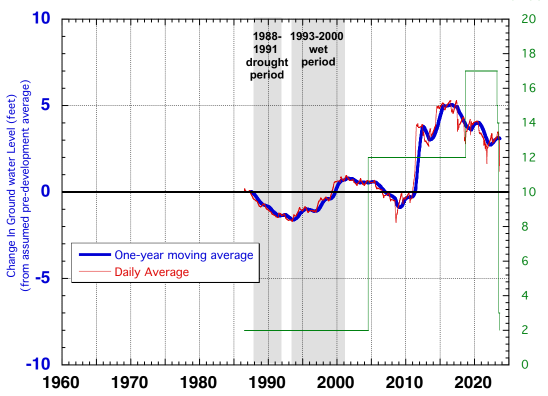
Composite Hydrograph of Observation Wells in the

Skjermo Lake Aquifer



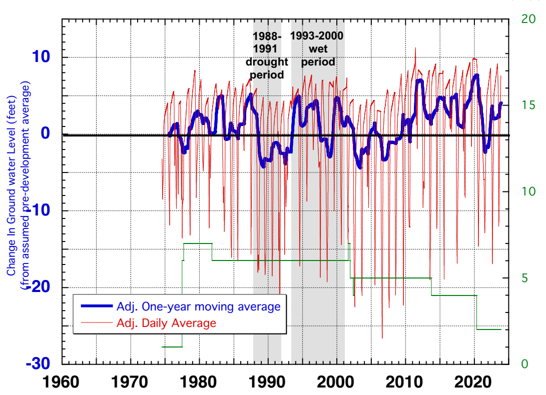
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Smoky Butte Aquifer



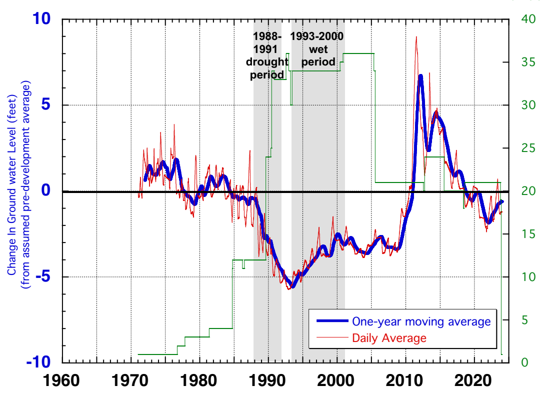
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Soo Channel Aquifer



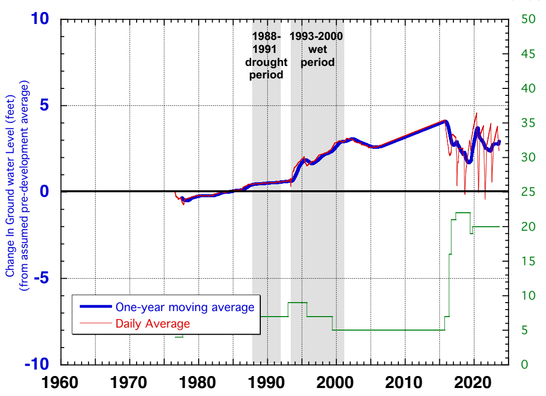
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Souris Valley Aquifer



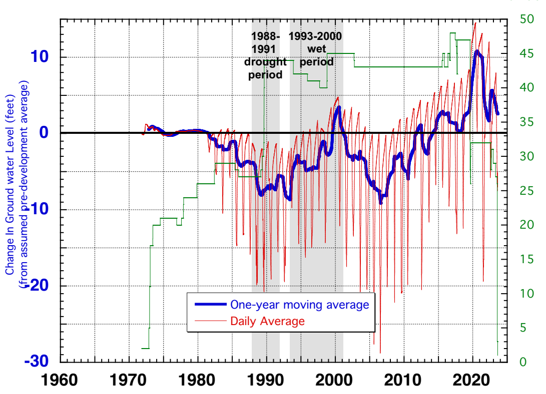
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Spring Creek Aquifer



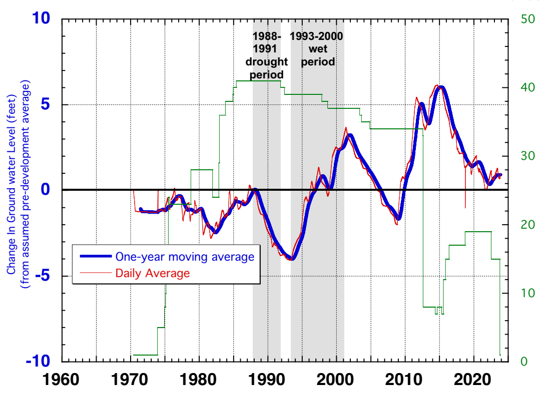
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Strausburg Aquifer



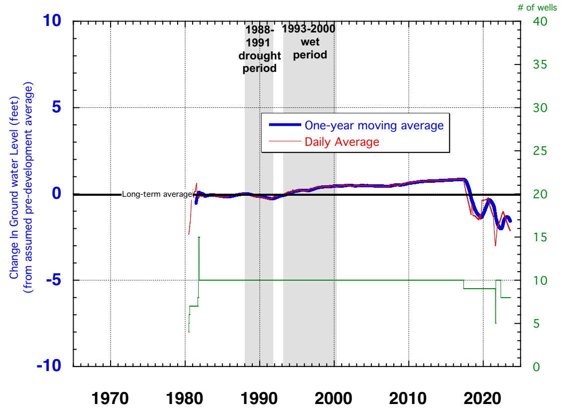
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Strawberry Lake Aquifer



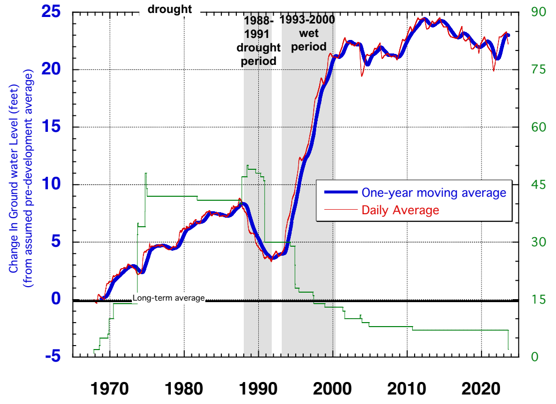
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the Spiritwood Aquifer in Towner County



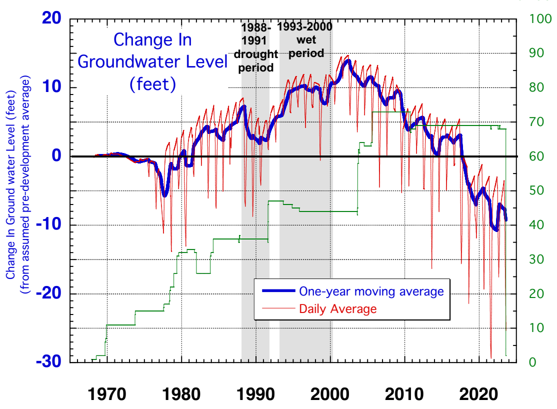
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the Spiritwood (near Devils Lake) Aquifer



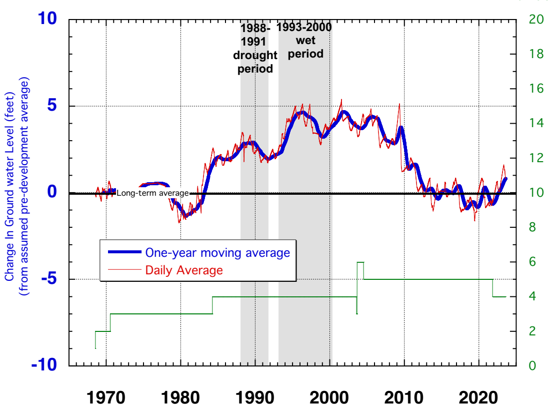
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the Spiritwood Aquifer (Near Warwick aquifer)



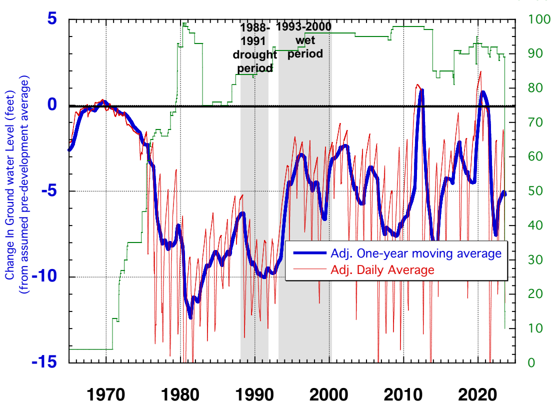
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the Spiritwood Aquifer near Sheyenne River



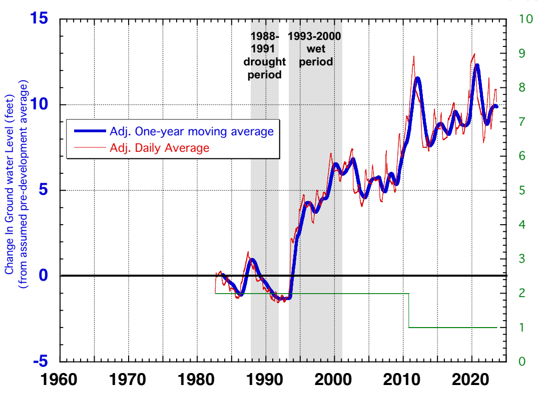
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the Spiritwood Aquifer in Griggs County



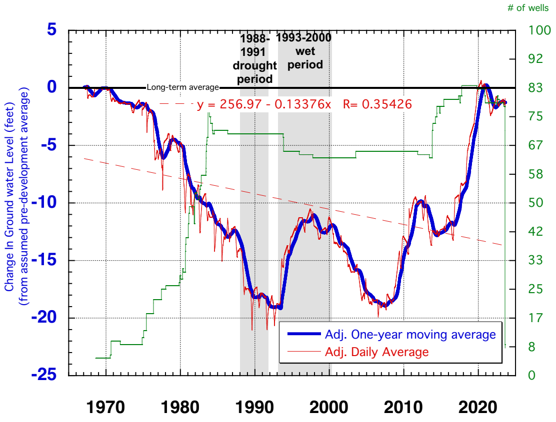
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the Spiritwood-Rogers Aquifer



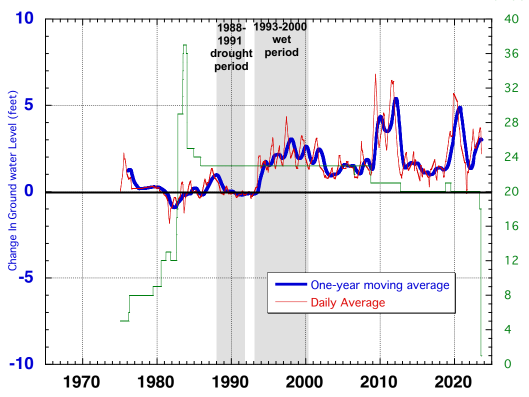
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Spiritwood Aquifer Segment near Jamestown



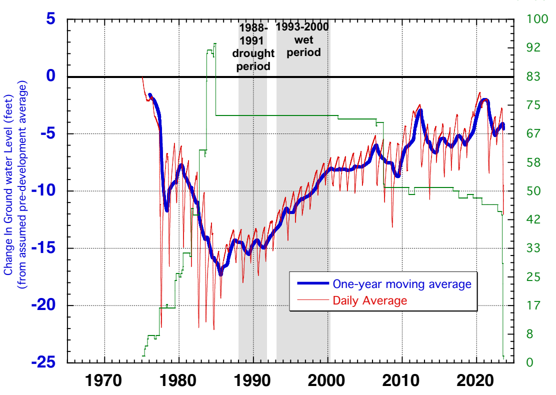
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Spiritwood Aquifer near Grand Rapids



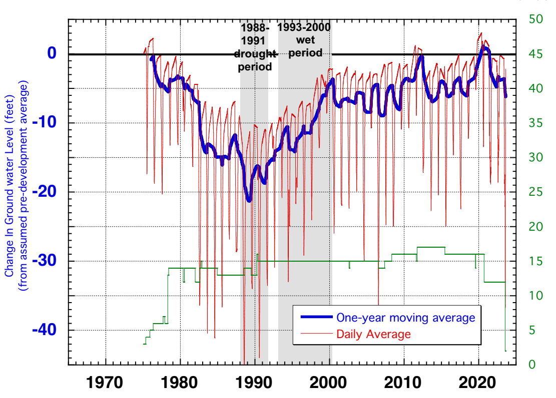
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Spiritwood Aquifer LaMoure SE



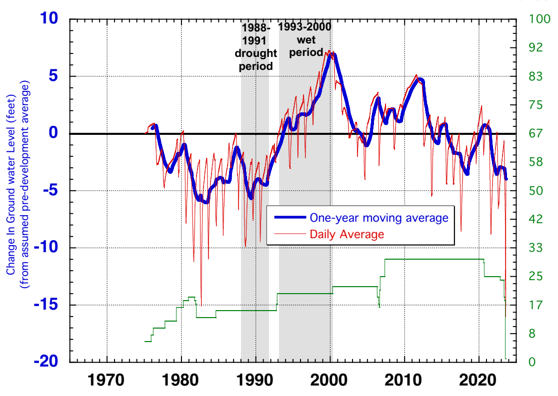
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Spiritwood Aquifer near Oakes



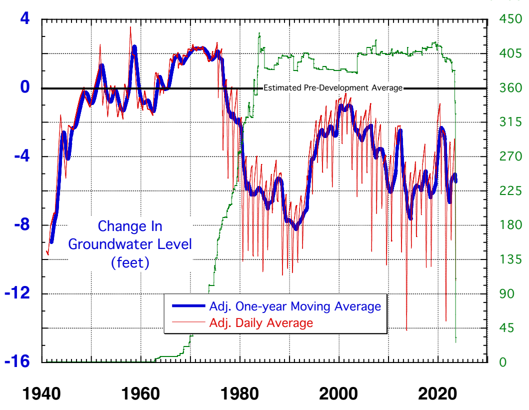
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Spiritwood SE and Brampton Aquifers



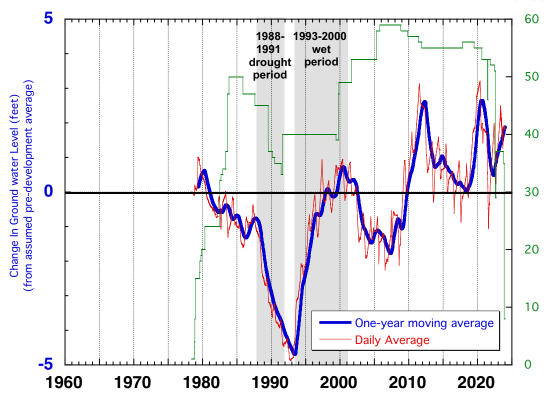
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of All Observation Wells in the
Spiritwood Aquifer



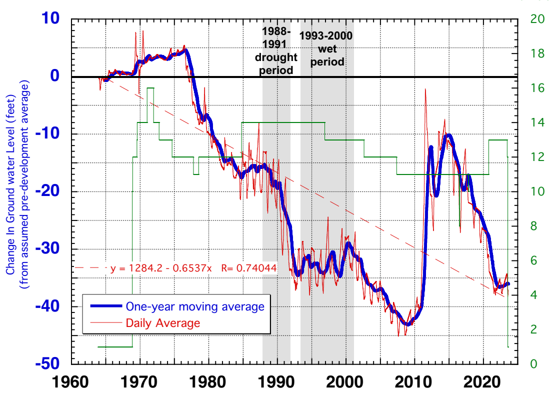
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Streeter Aquifer



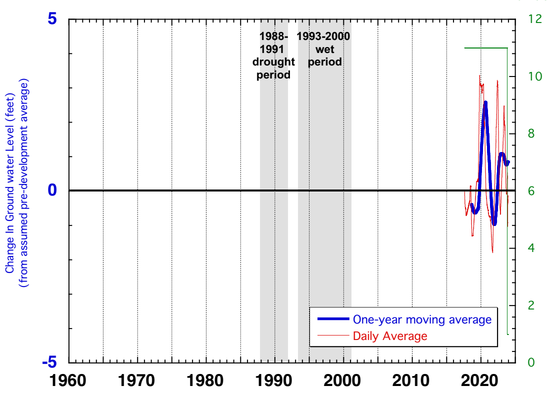
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Sundre Aquifer



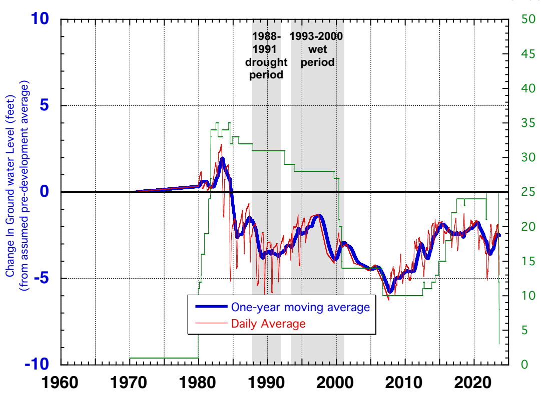
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Tiffany Flats Aquifer



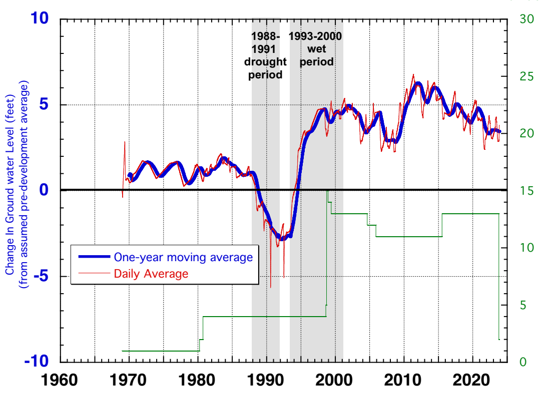
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Tobacco Garden Creek Aquifer



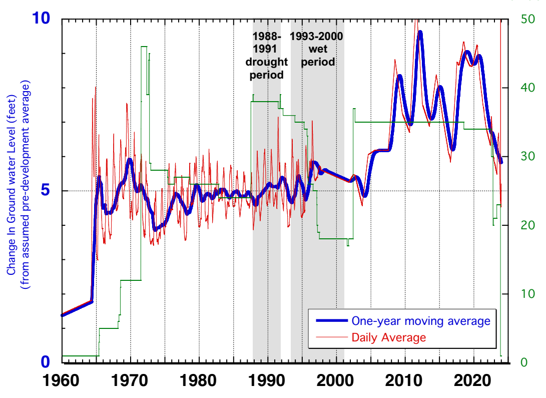
Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Trappers Coulee Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

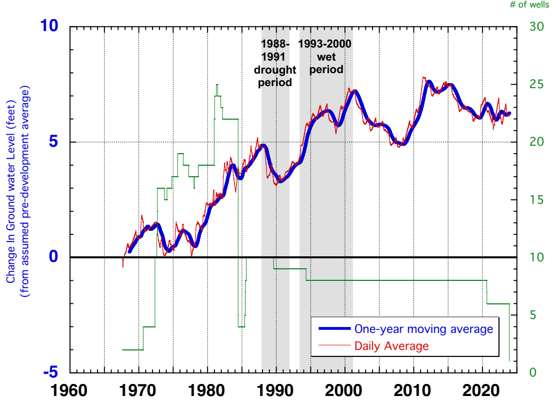
Composite Hydrograph of Observation Wells in the
Trenton Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

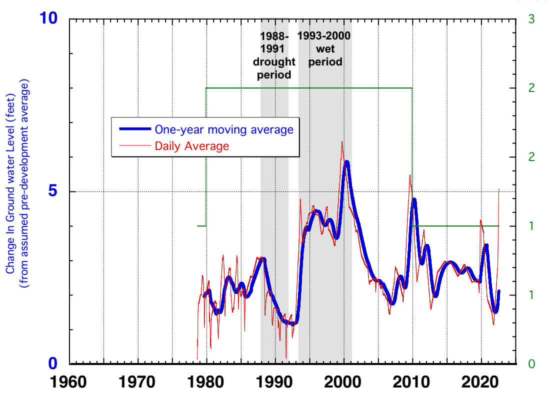
Turtle Lake Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

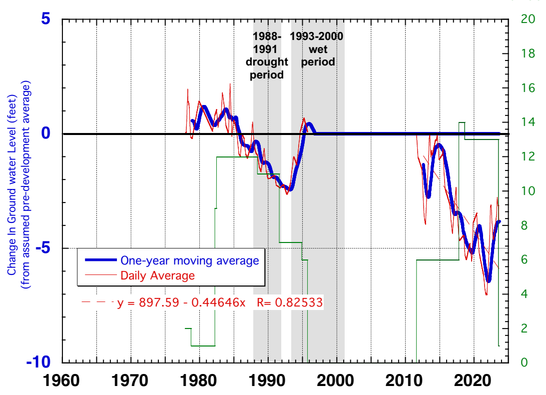
Upper Apple Creek Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

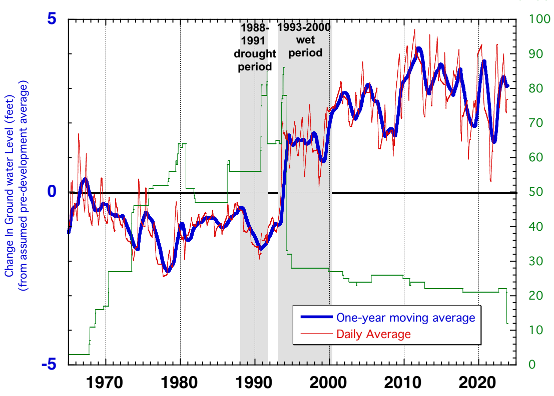
Voltaire Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

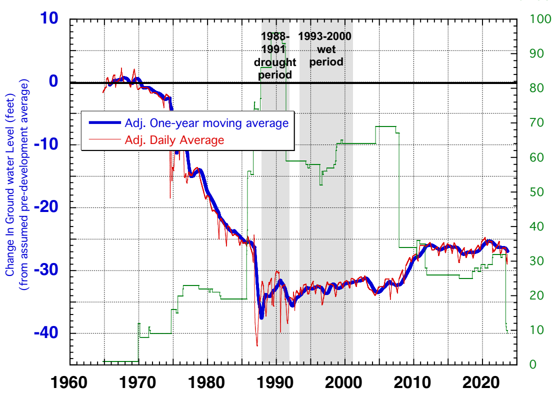
Warwick Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

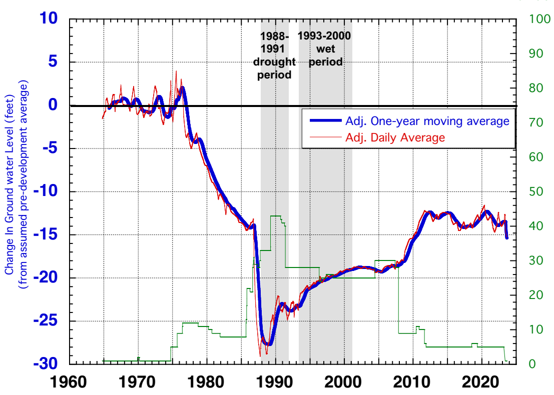
Wapheton Aquifer Complex



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

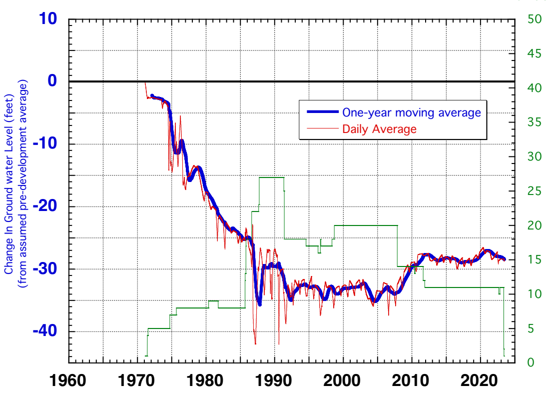
Wapheton Shallow Sand Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

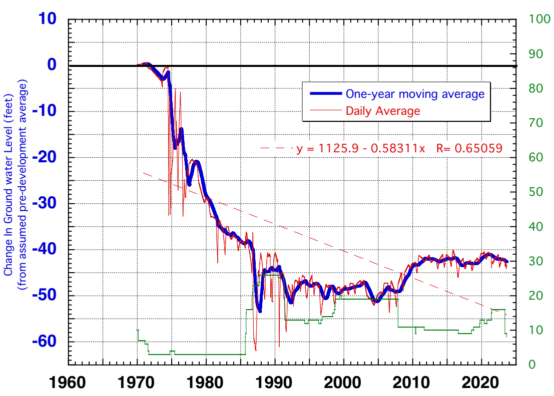
Wapheton Sand Plain Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

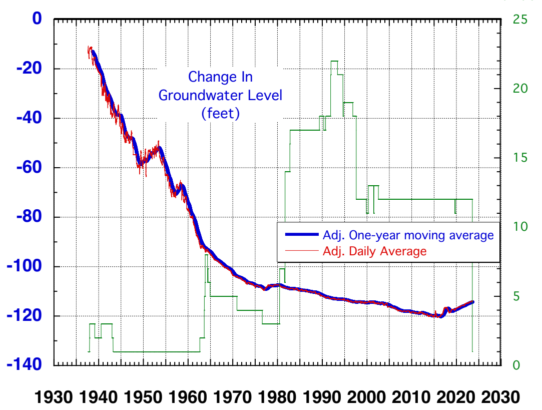
Wapheton Buried Valley Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of All Observation Wells in the

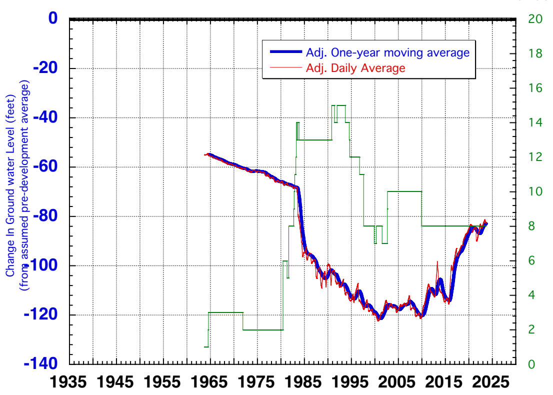
West Fargo North Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

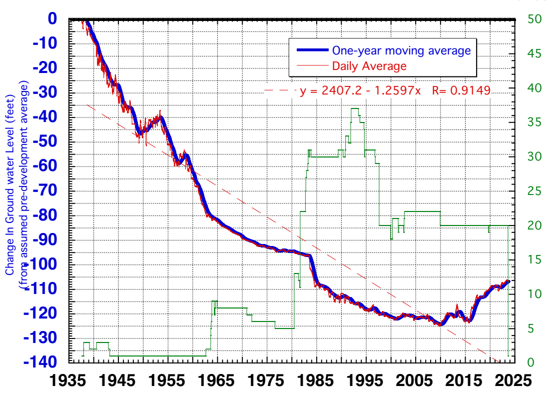
West Fargo South Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

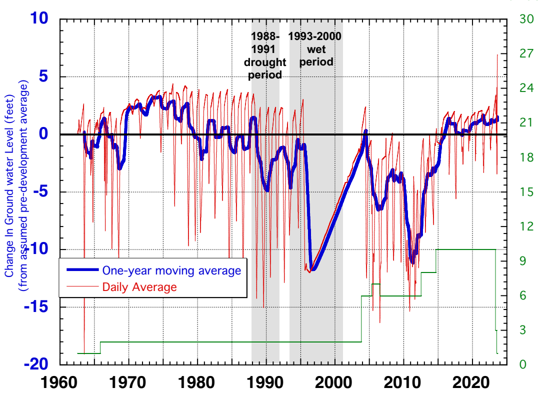
West Fargo Aquifer System



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

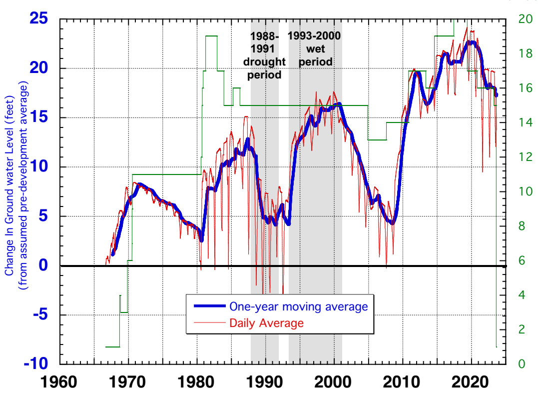
West Wildrose Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

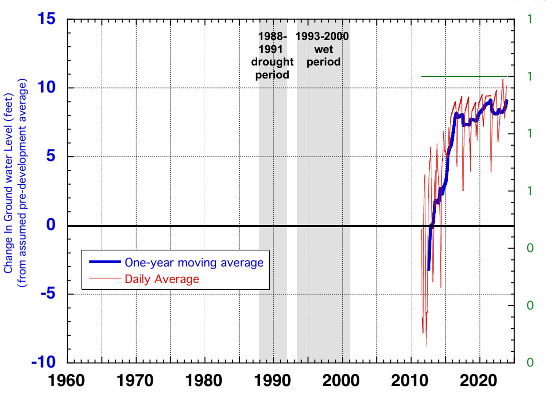
White Shield Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

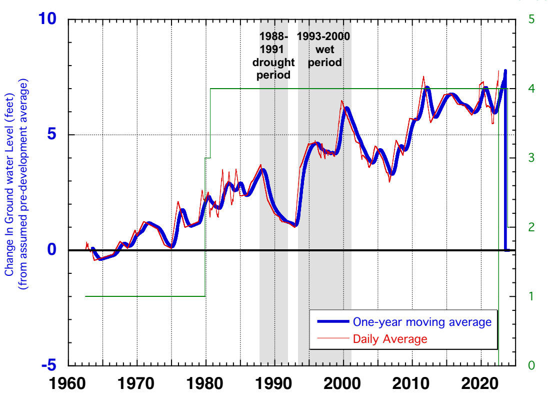
Wildrose Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

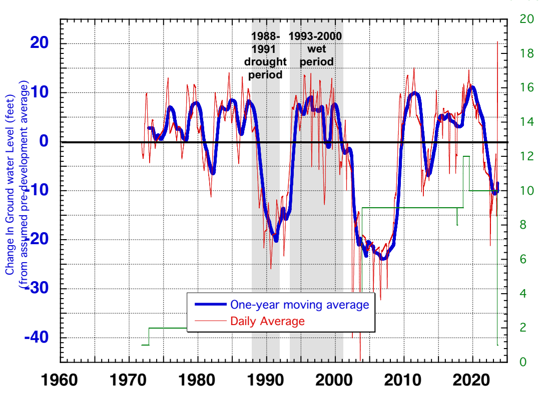
Wing Channel Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

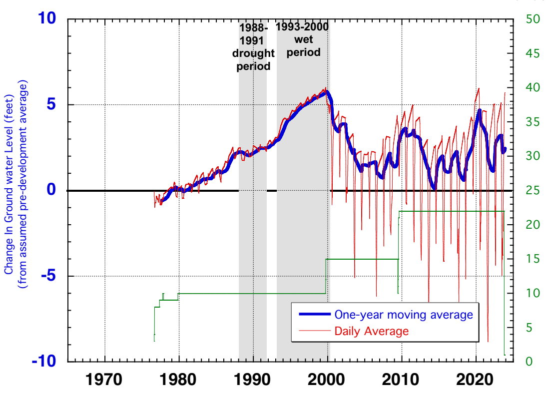
Winona Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

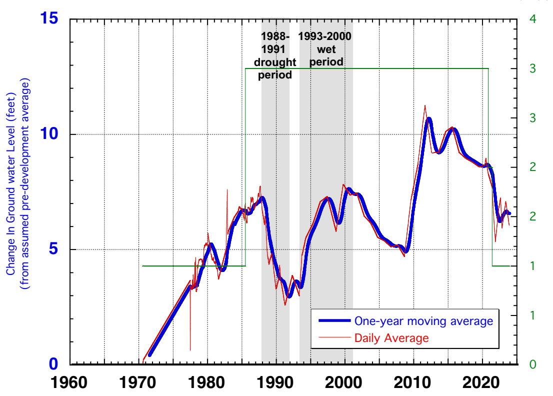
Wishek Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

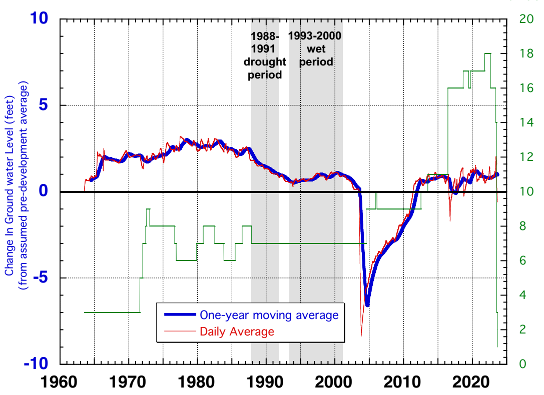
Wolf Creek Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the

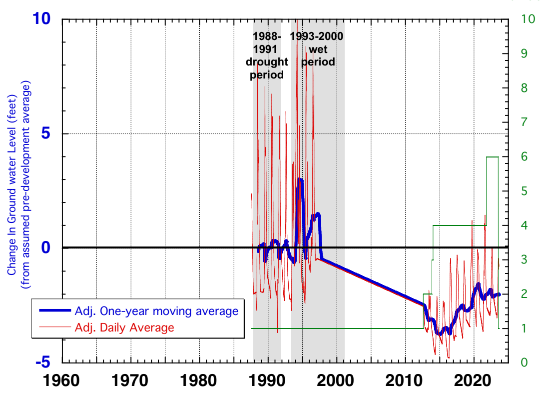
Yellowstone Buried Channel Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

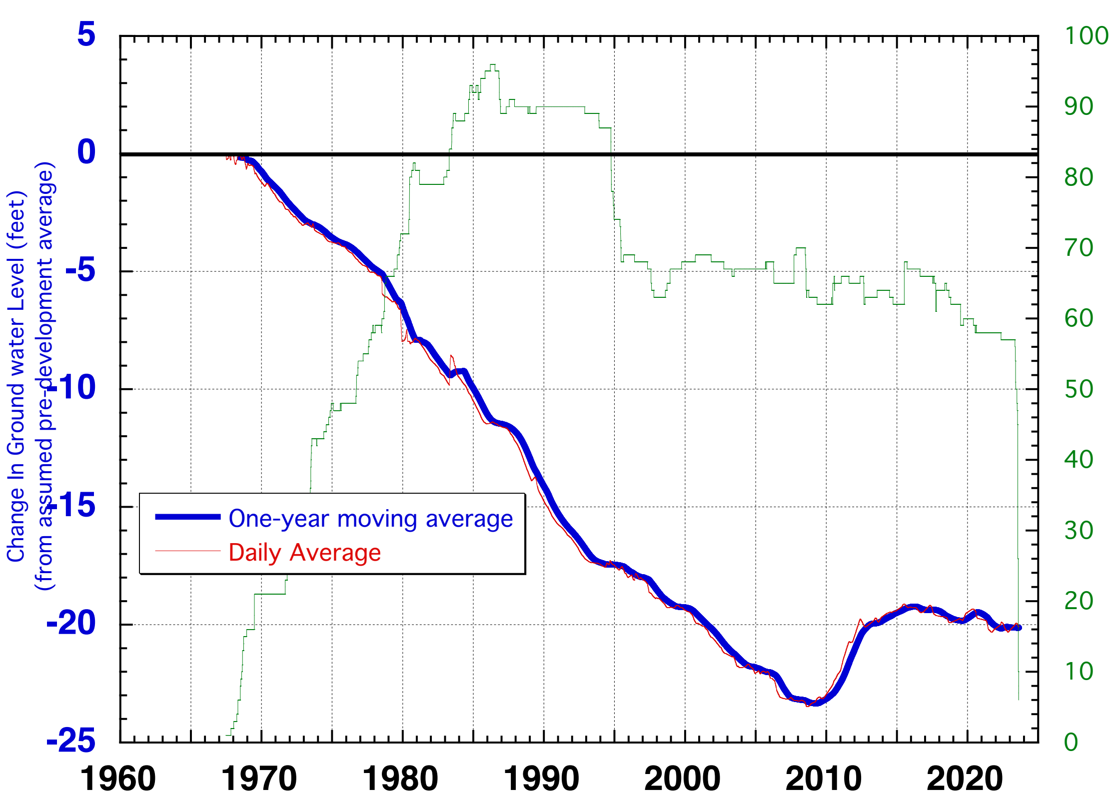
Composite Hydrograph of Observation Wells in the

Yellowstone-Missouri Aquifer

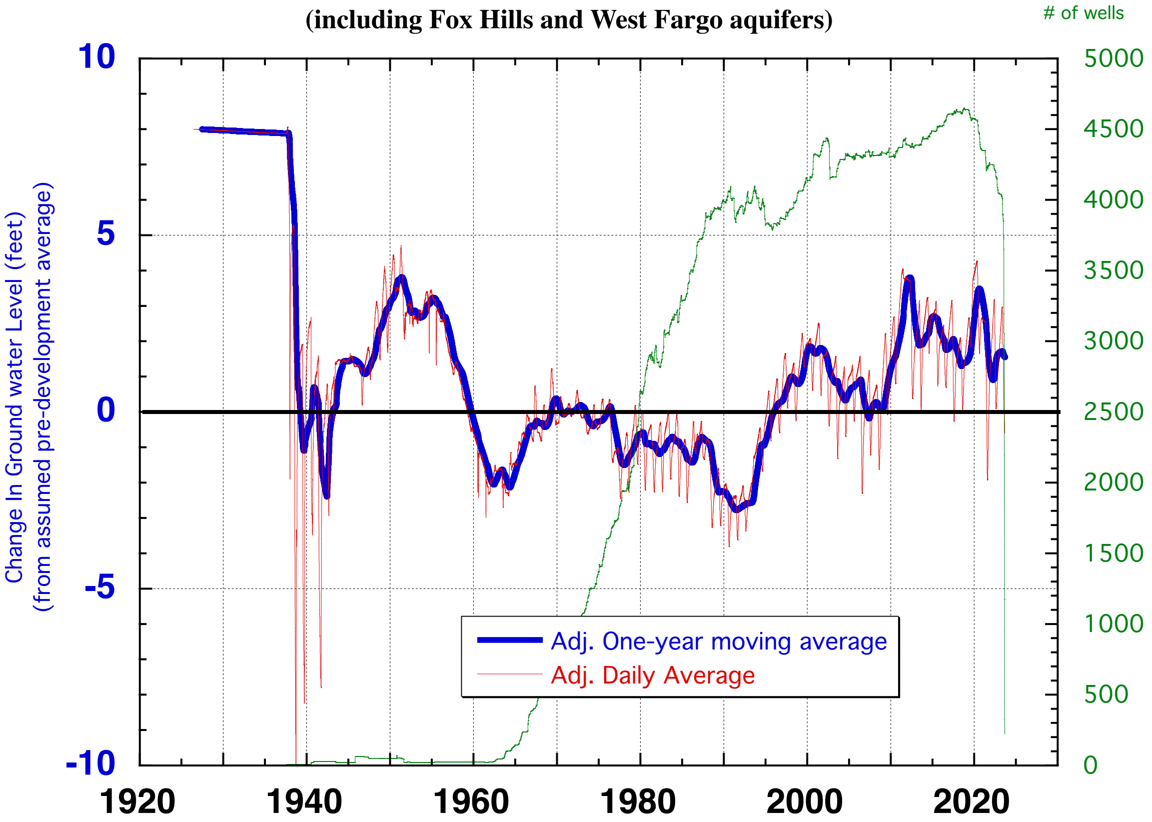


Date Source: ND Dept. of Water Resources Site inventory Database

Composite Hydrograph of Observation Wells in the
Fox Hills Aquifer



Date Source: ND Dept. of Water Resources Site inventory Database

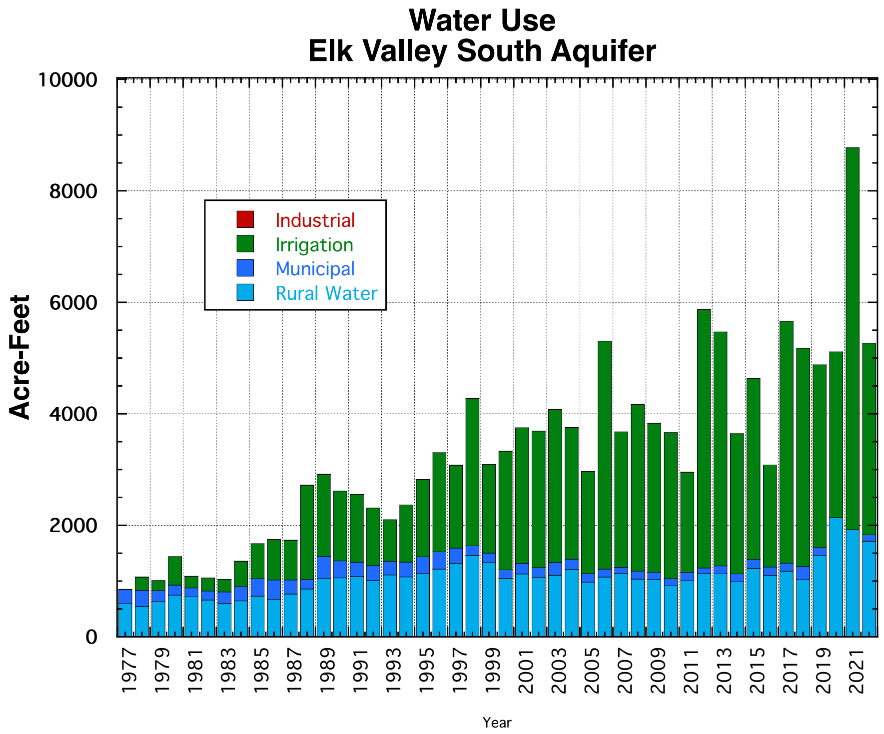


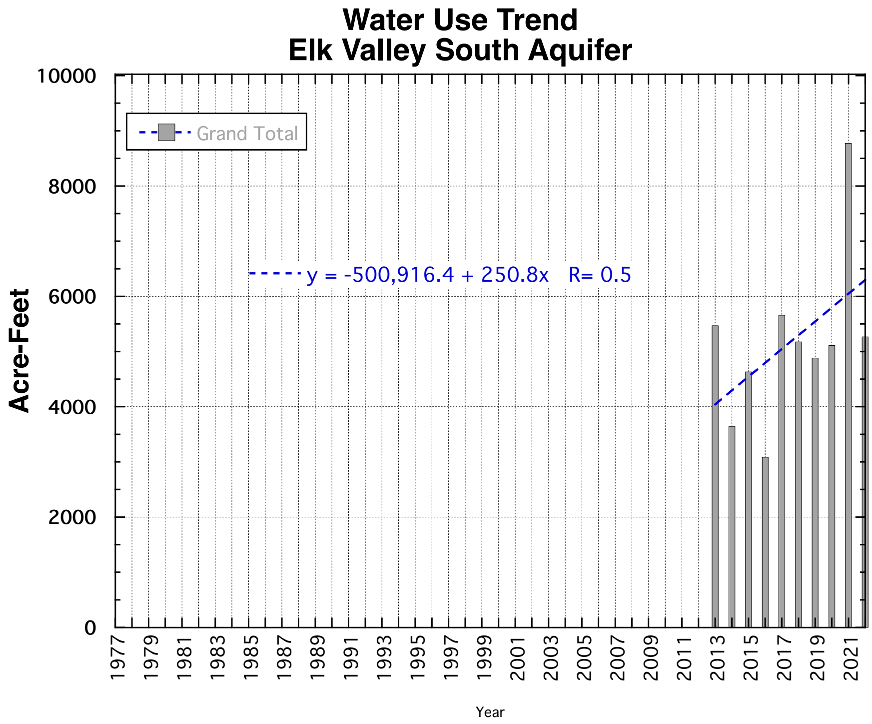
Composite Hydrograph of Observation Wells

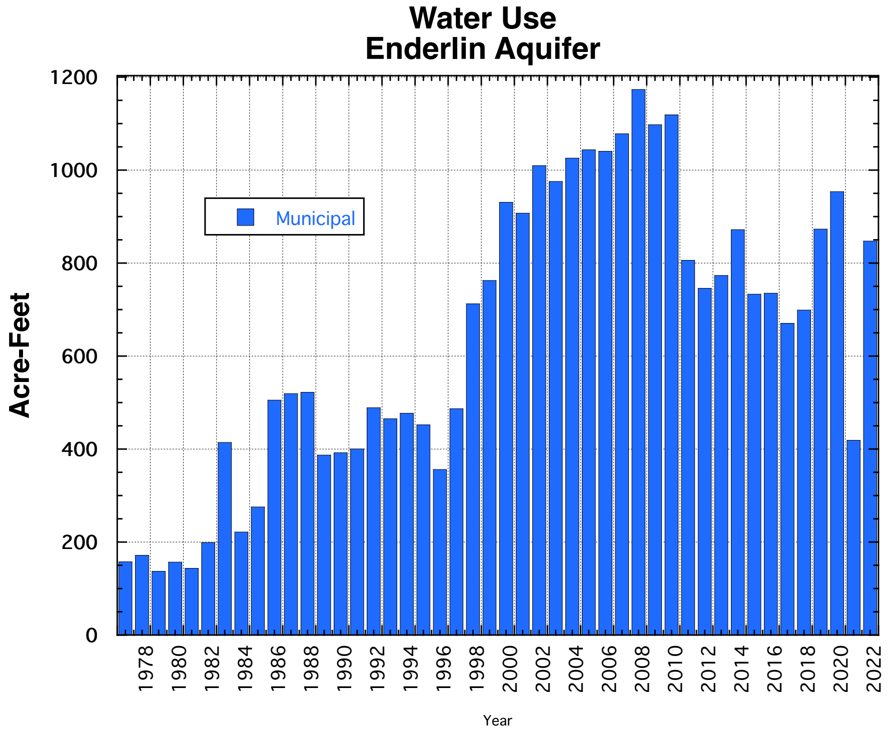
All Wells Statewide

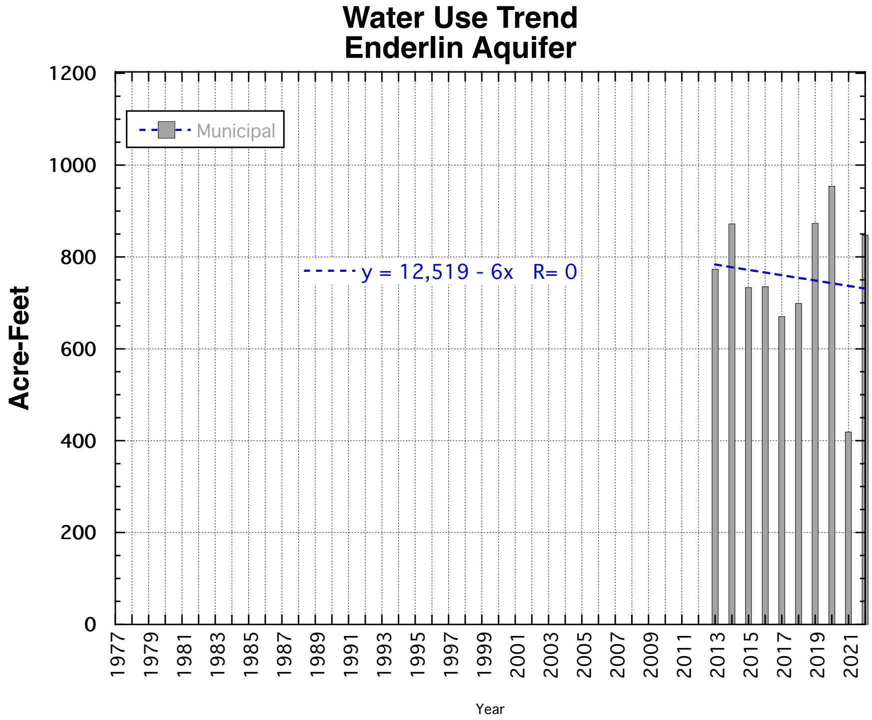
(including Fox Hills and West Fargo aquifers)

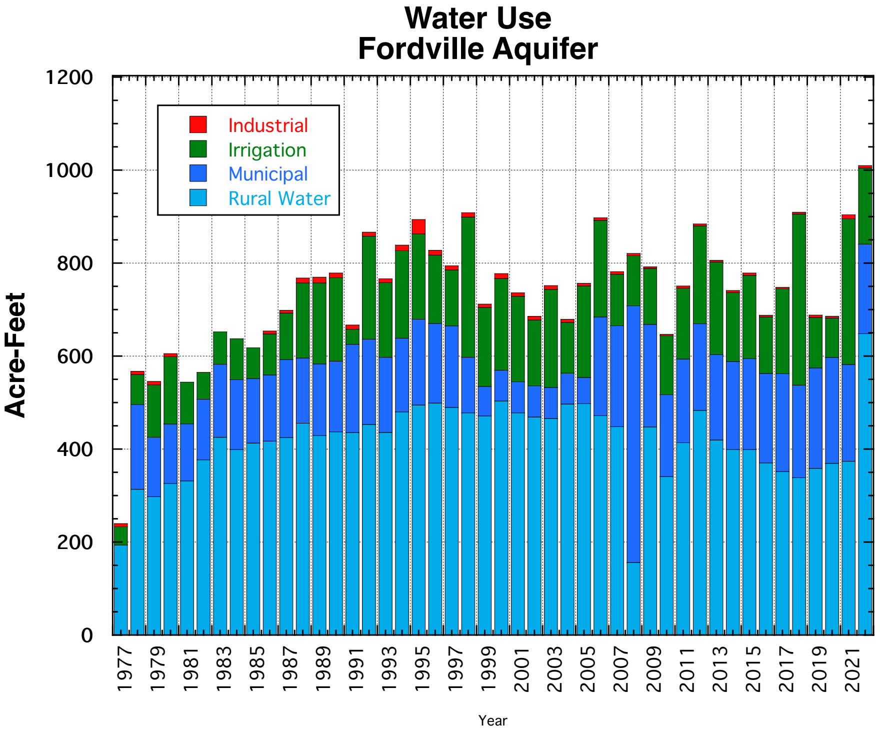
Date Source: ND Dept. of Water Resources Site inventory Database

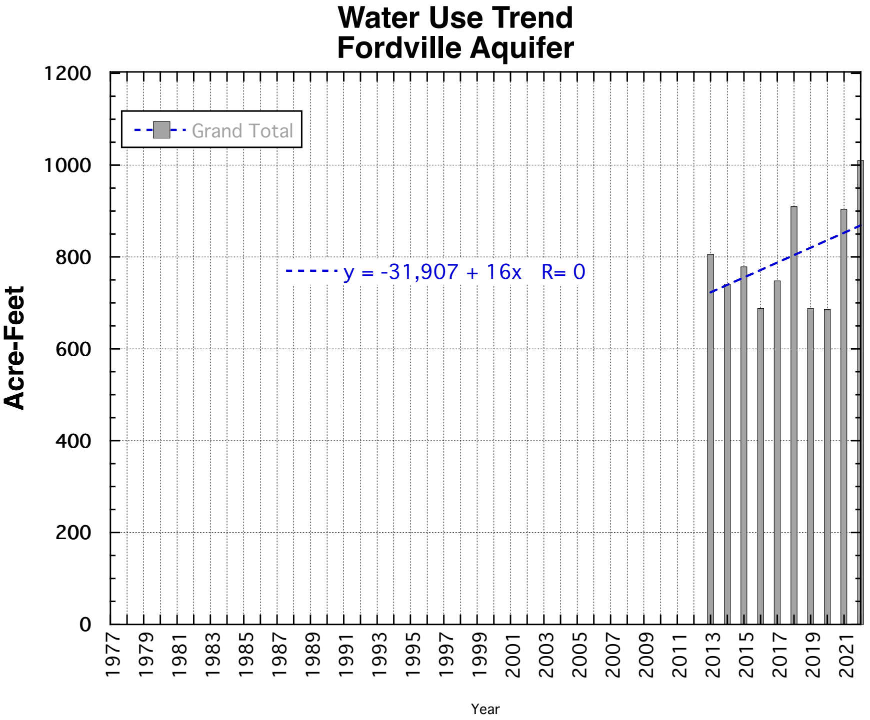

Water Use
Elk Valley South Aquifer
10000
8000
6000
4000
2000
0
Acre-Feet
Industrial
Irrigation
Municipal
Rural Water
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

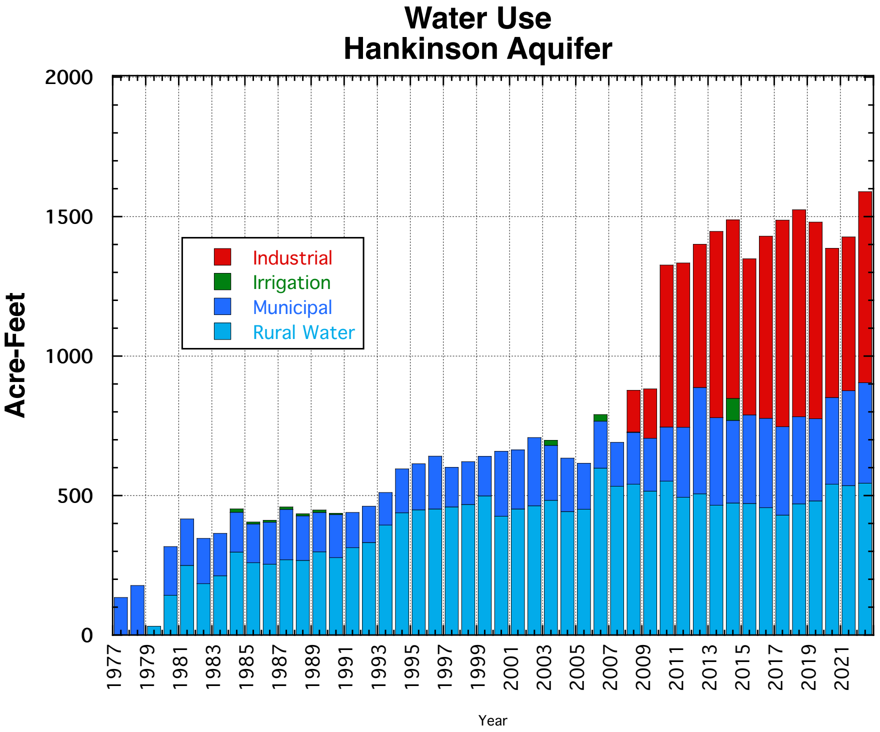

Water Use Trend
Elk Valley South Aquifer
10000
8000
6000
4000
2000
0
Acre-Feet
Grand Total
y = -500,916.4 + 250.8x R= 0.5
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

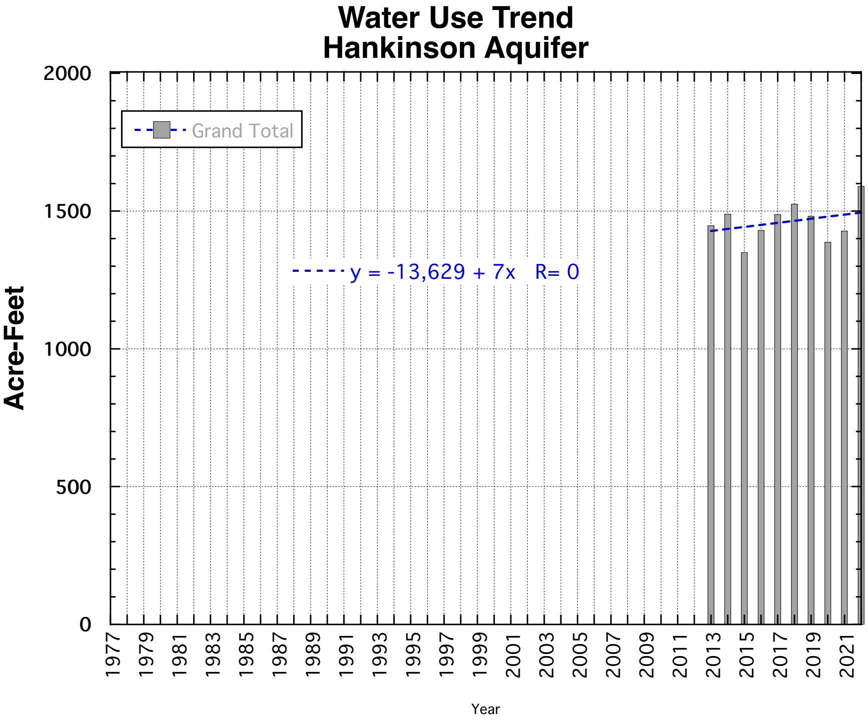

Water Use
Enderlin Aquifer
Municipal
Acre-Feet
0
200
400
600
800
1000
1200
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
2022
Year

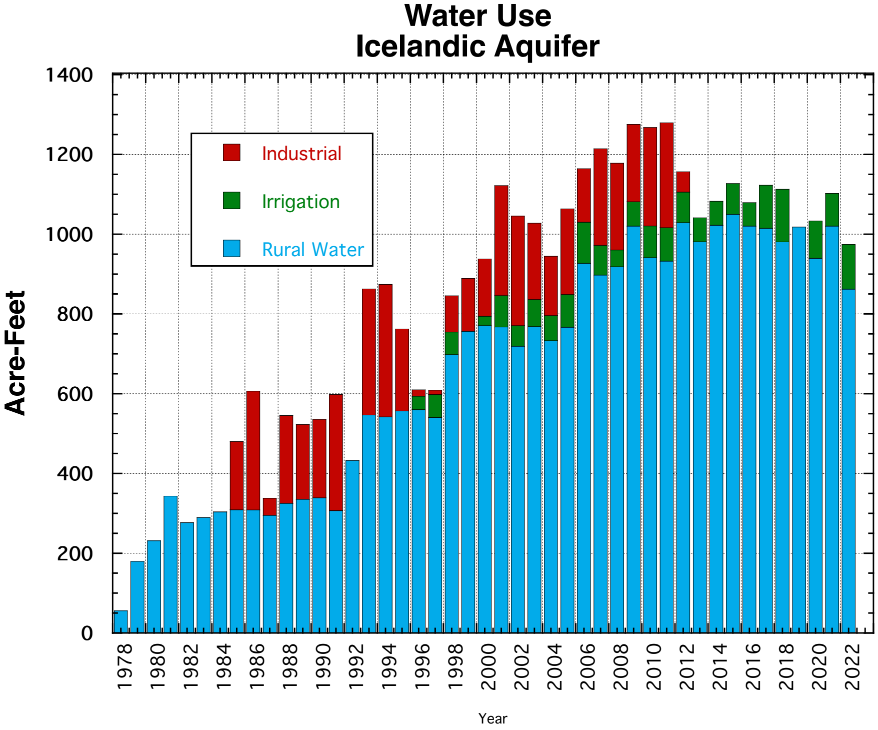

Water Use Trend
Enderlin Aquifer
Municipal
y = 12,519 - 6x R= 0
Acre-Feet
0
200
400
600
800
1000
1200
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

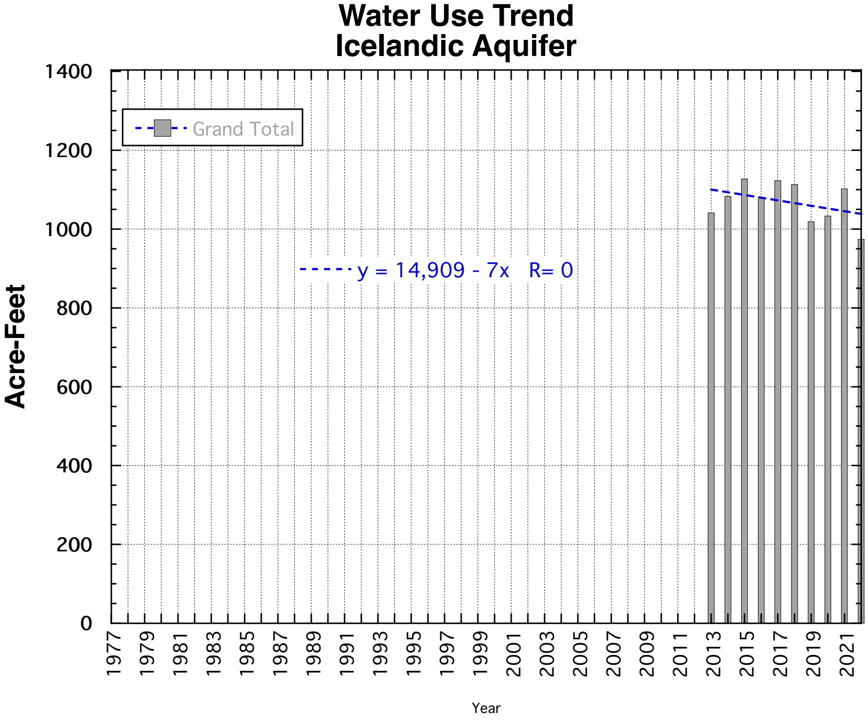

Water Use
Fordville Aquifer

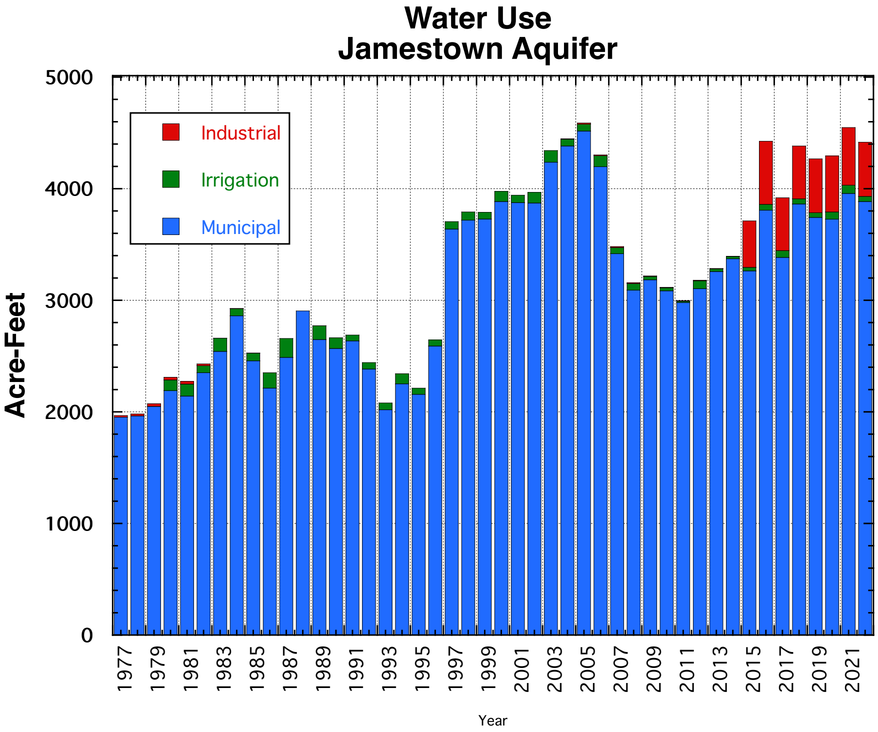

Water Use Trend
Fordville Aquifer

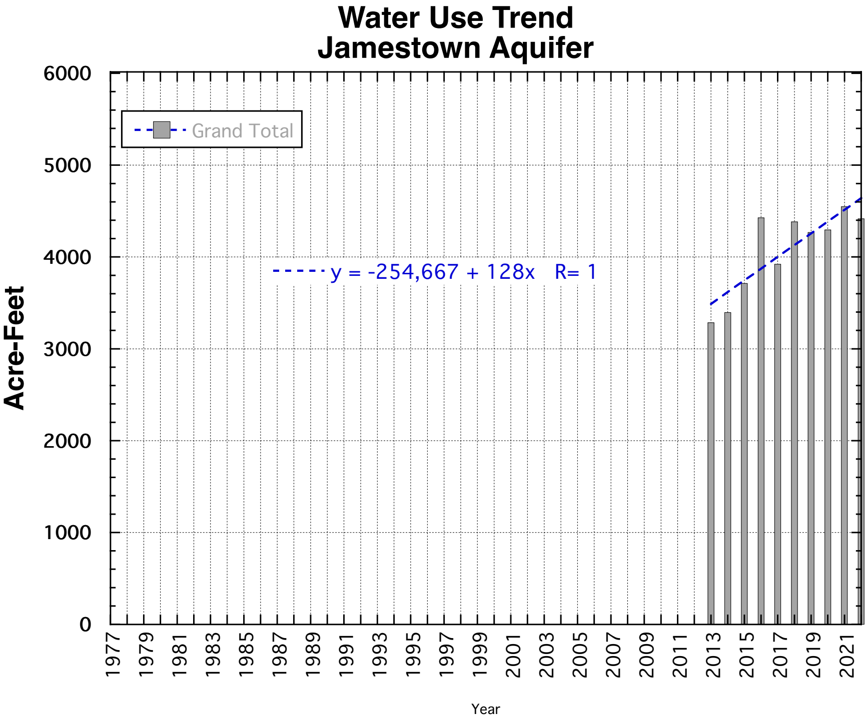

Water Use
Hankinson Aquifer
Acre-Feet
2000
1500
1000
500
0
Industrial
Irrigation
Municipal
Rural Water
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

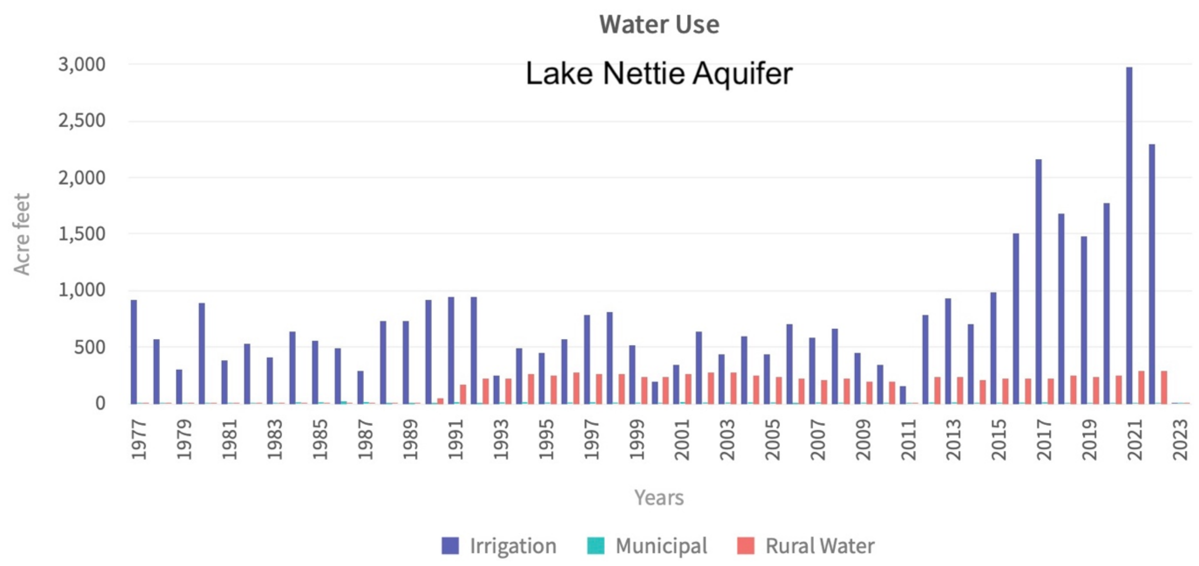

Water Use Trend
Hankinson Aquifer
Acre-Feet
2000
1500
1000
500
0
Grand Total
y = -13,629 + 7x R= 0
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

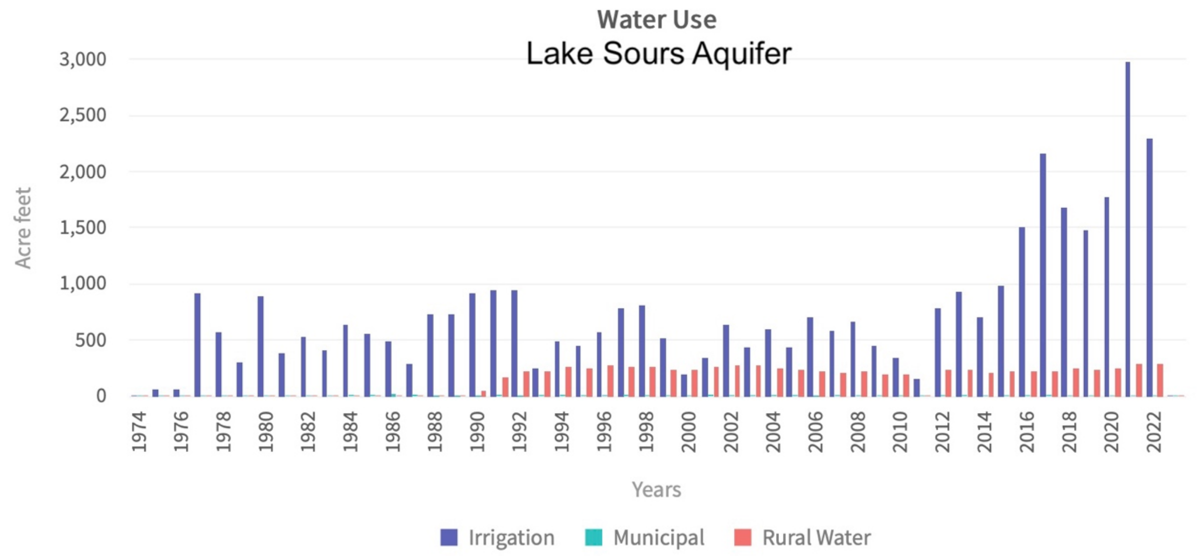

Water Use
Icelandic Aquifer
Industrial
Irrigation
Rural Water
Acre-Feet
0
200
400
600
800
1000
1200
1400
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
2022
Year


Water Use Trend
Icelandic Aquifer
Grand Total
y = 14,909 - 7x R= 0
Acre-Feet
0
200
400
600
800
1000
1200
1400
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

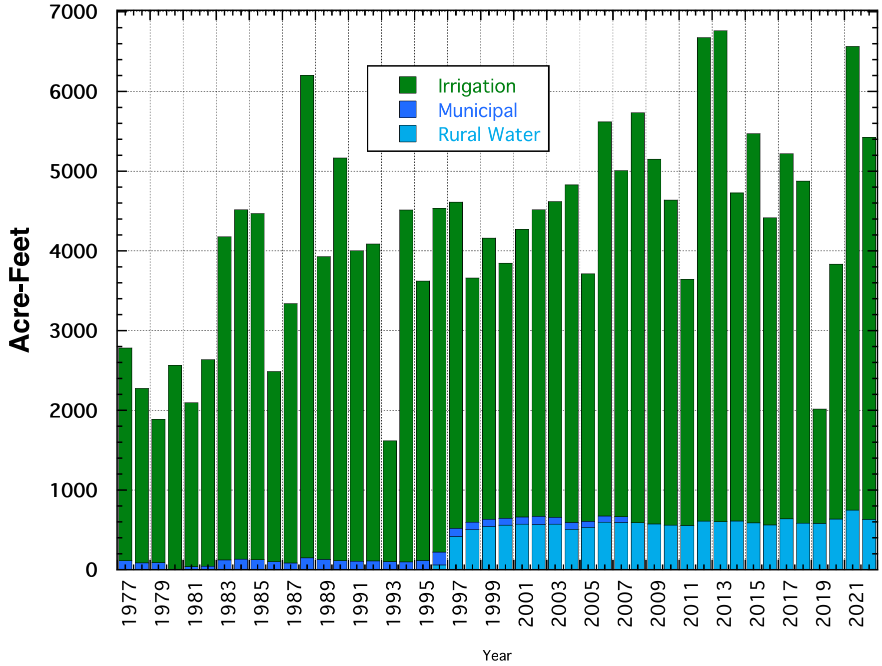

Water Use
Jamestown Aquifer
Industrial
Irrigation
Municipal
Acre-Feet
5000
4000
3000
2000
1000
0
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year


Water Use Trend
Jamestown Aquifer
Grand Total
y = -254,667 + 128x R= 1
Acre-Feet
6000
5000
4000
3000
2000
1000
0
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

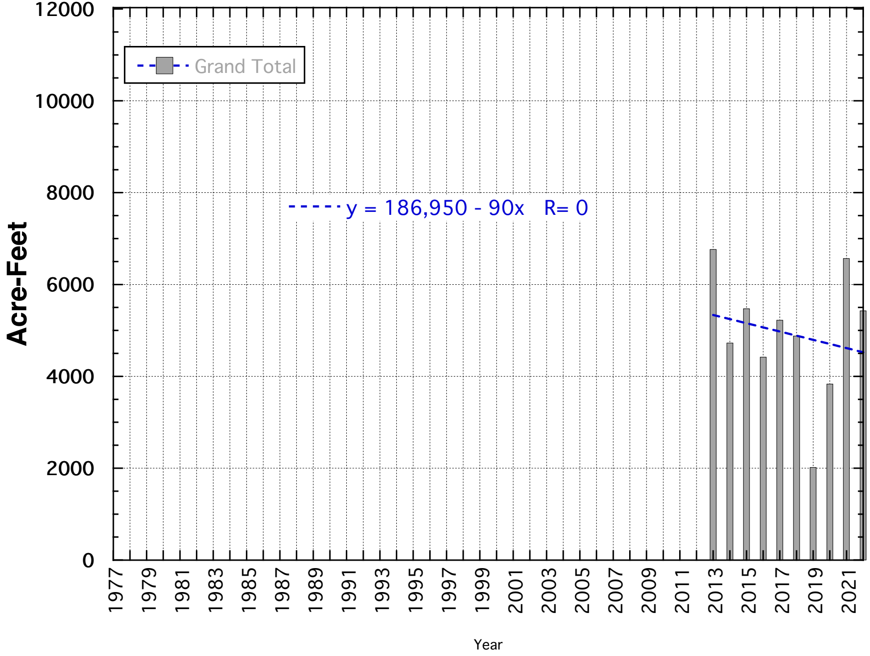

Water Use
Lake Nettie Aquifer
Acre feet
3,000
2,500
2,000
1,500
1,000
500
0
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
2023
Years
Irrigation
Municipal
Rural Water

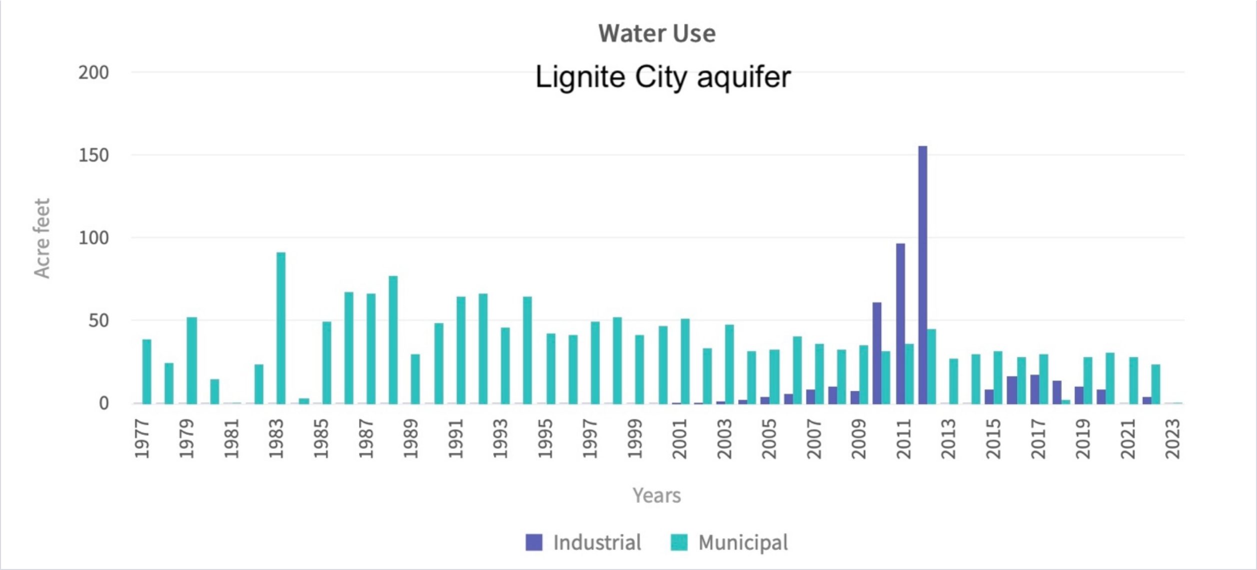

Water Use
Lake Sours Aquifer
Acre feet
3,000
2,500
2,000
1,500
1,000
500
0
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
2022
Years
Irrigation
Municipal
Rural Water

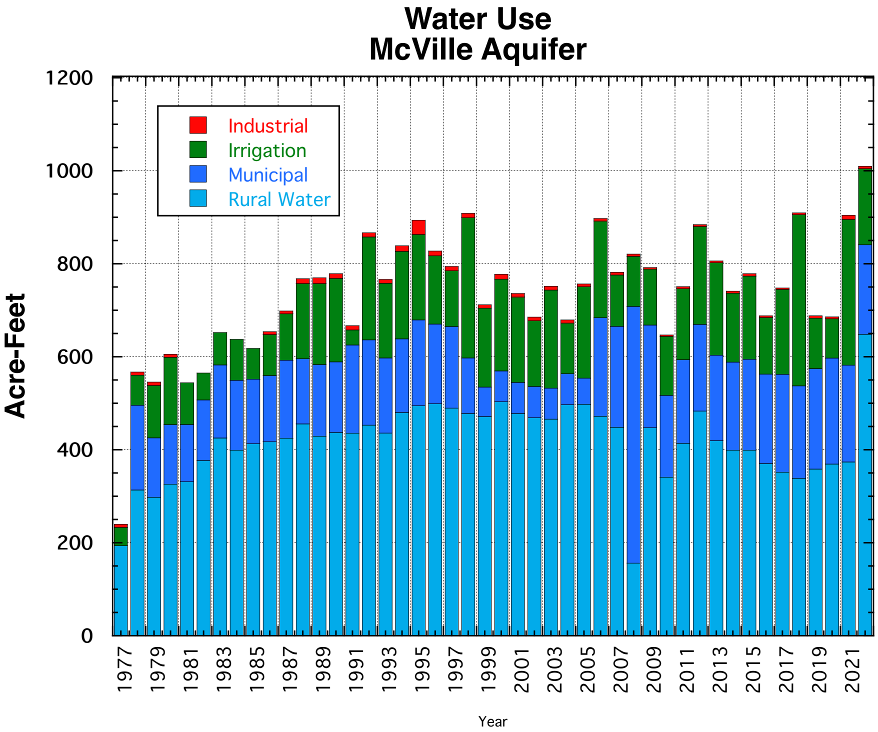
Water Use
LaMoure Aquifer

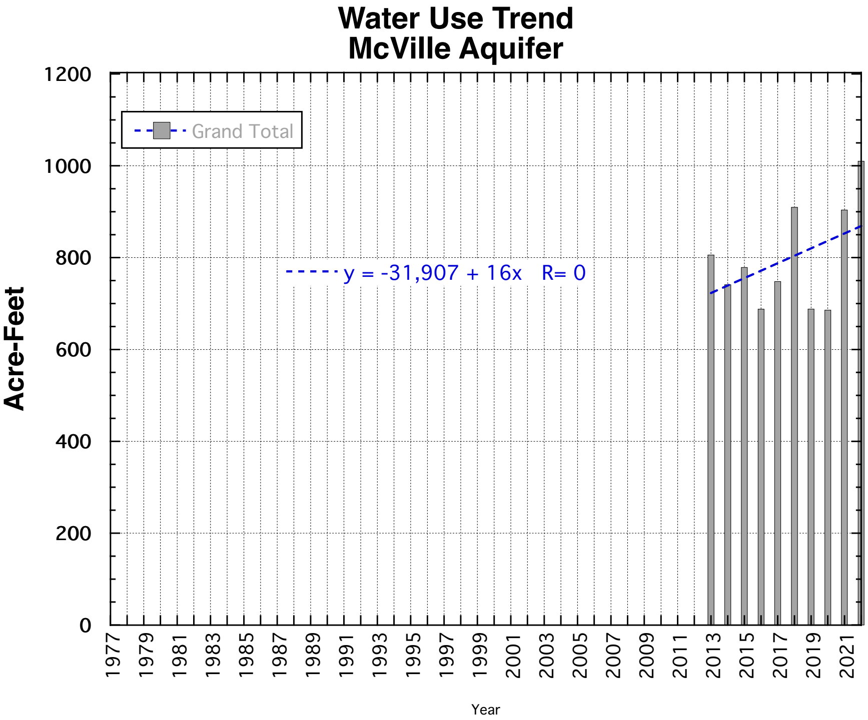


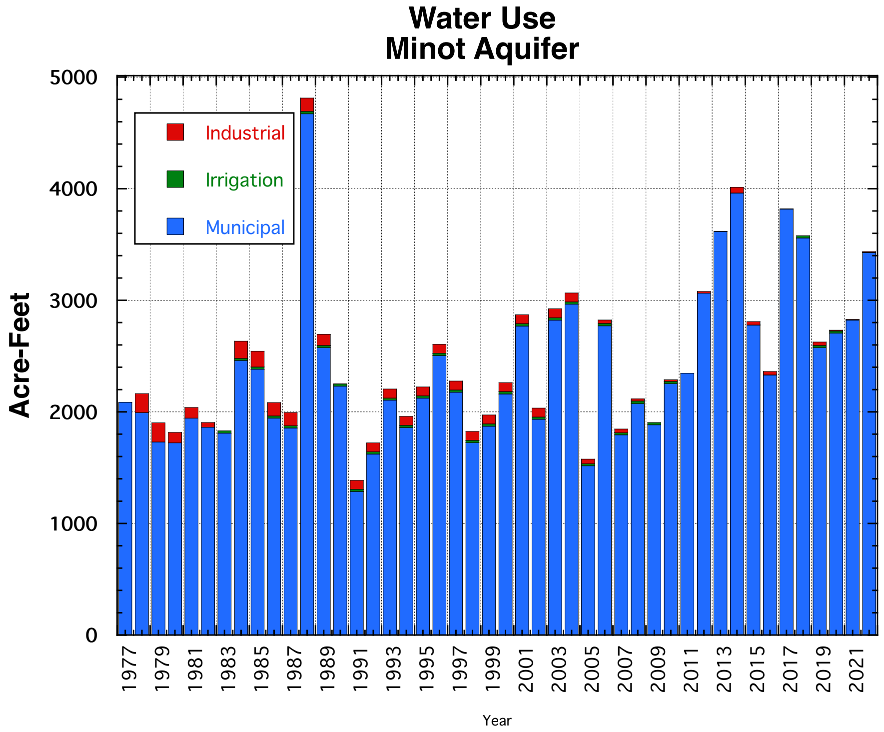
Water Use Trend
LaMoure Aquifer

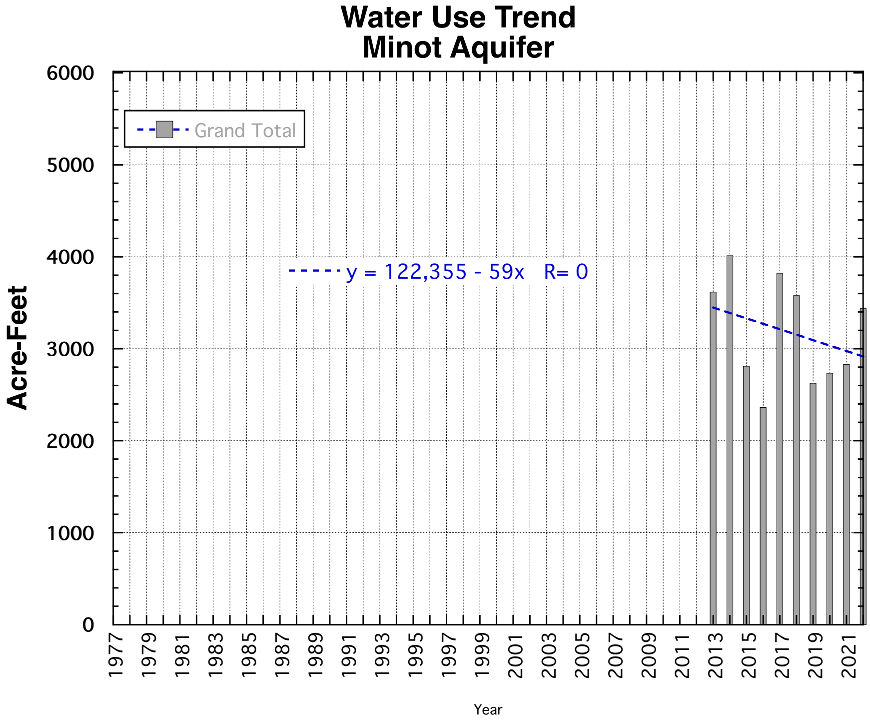


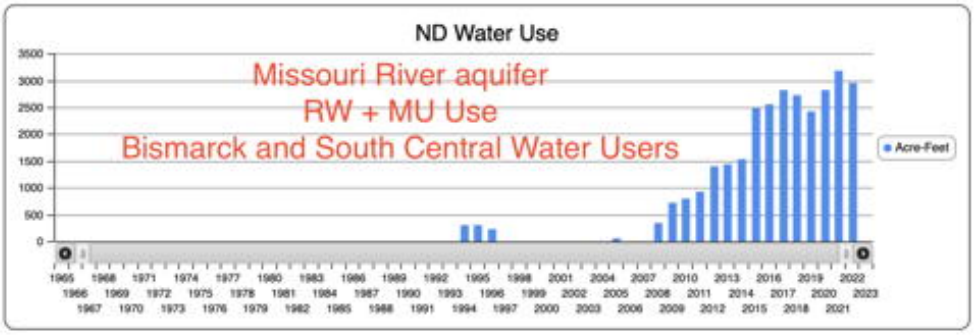

Water Use
Lignite City aquifer
Acre feet
200
150
100
50
0
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
2023
Years
Industrial
Municipal

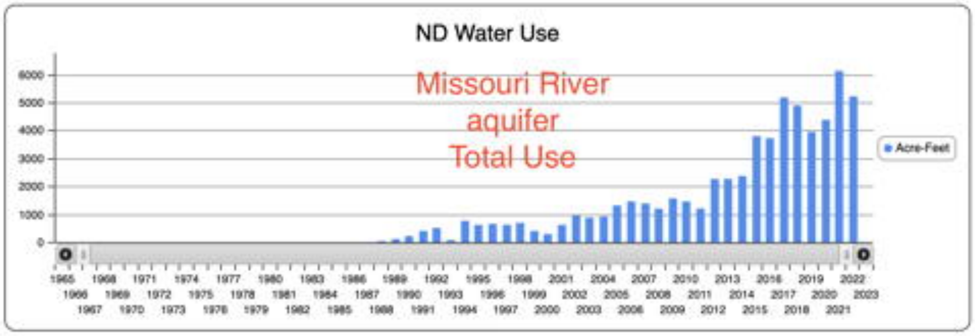

Water Use
McVille Aquifer
Acre-Feet
1200
1000
800
600
400
200
0
Industrial
Irrigation
Municipal
Rural Water
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

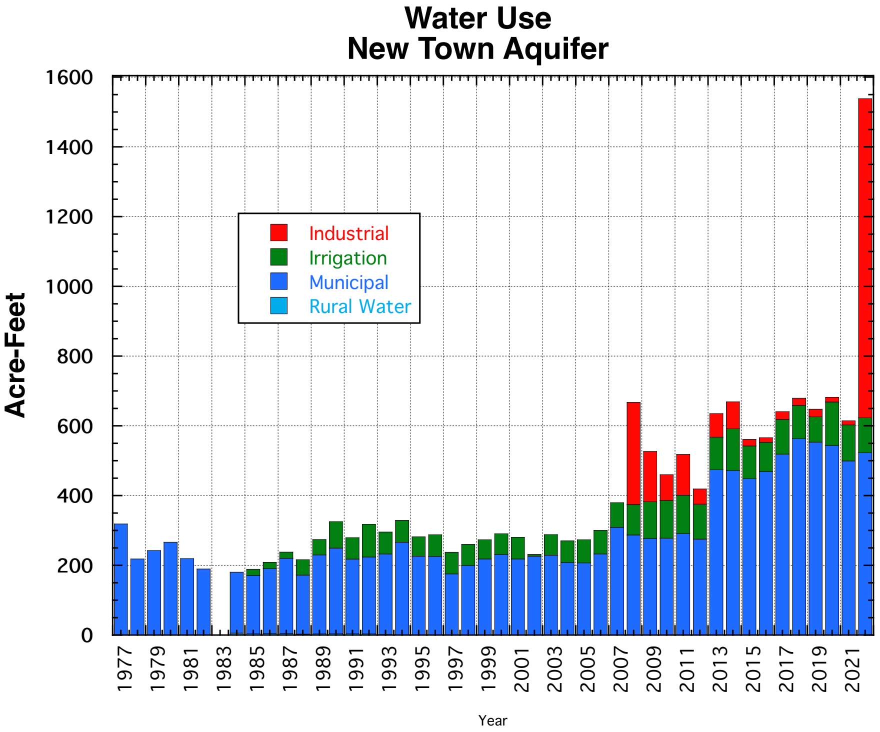

Water Use Trend
McVille Aquifer
Acre-Feet
1200
1000
800
600
400
200
0
Grand Total
y = -31,907 + 16x R= 0
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

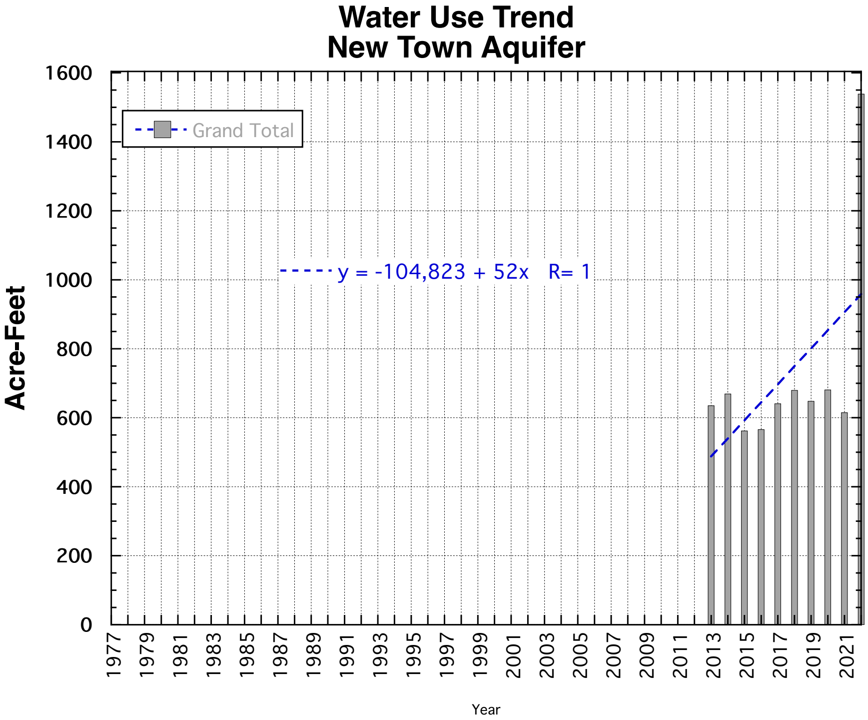

Water Use
Minot Aquifer
Industrial
Irrigation
Municipal
Acre-Feet
0
1000
2000
3000
4000
5000
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

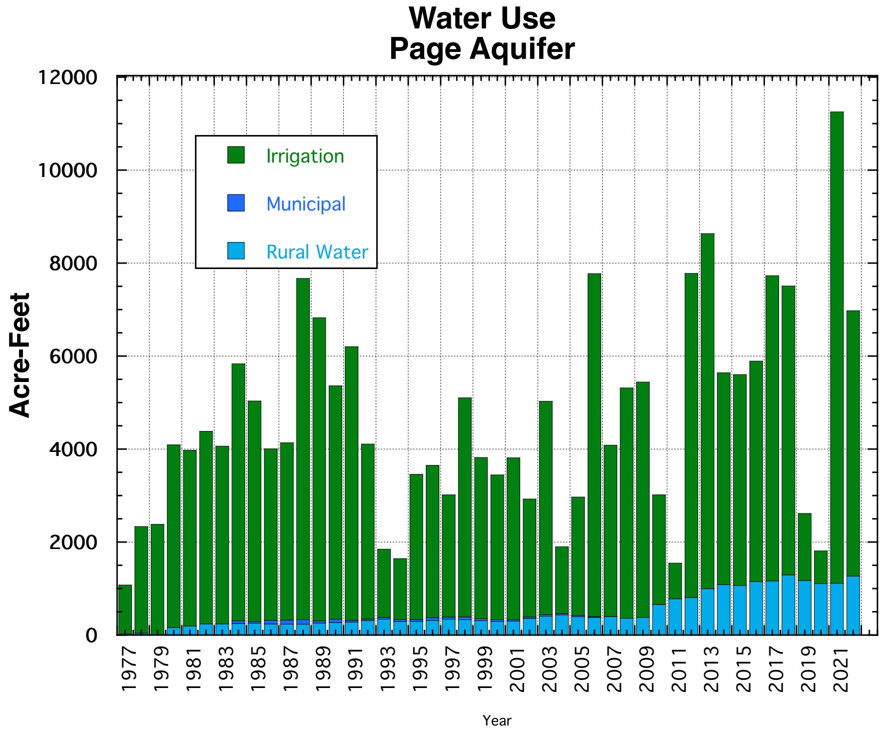

Water Use Trend
Minot Aquifer
Grand Total
y = 122,355 - 59x R= 0
Acre-Feet
0
1000
2000
3000
4000
5000
6000
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

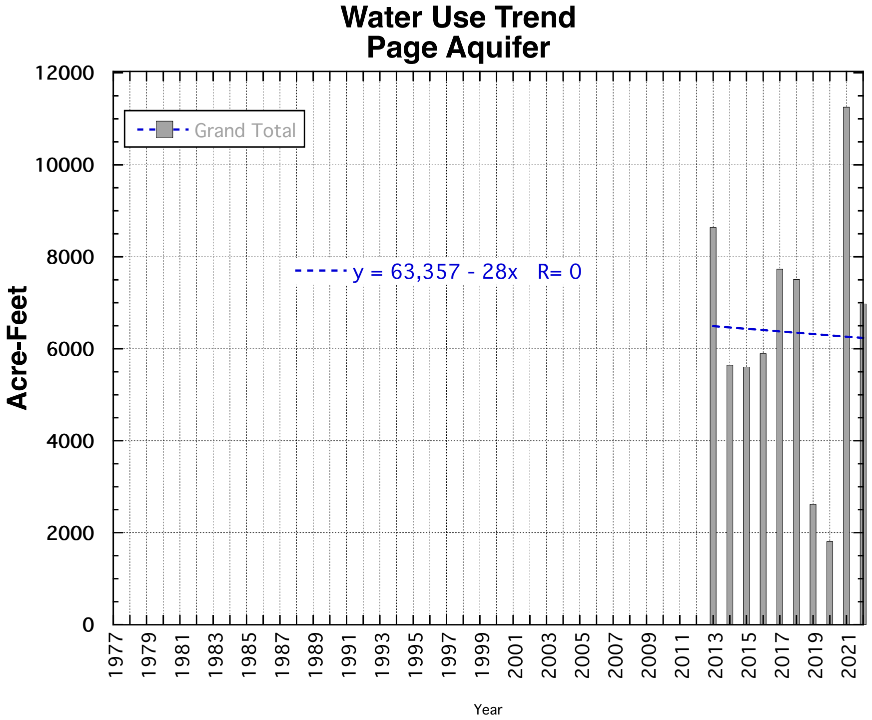

ND Water Use
Missouri River aquifer
RW + MU Use
Bismarck and South Central Water Users
3500
3000
2500
2000
1500
1000
500
0
Acre-Feet
1965 1968 1971 1974 1977 1980 1983 1986 1989 1992 1995 1998 2001 2004 2007 2010 2013 2016 2019 2022
1966 1969 1972 1975 1978 1981 1984 1987 1990 1993 1996 1999 2002 2005 2008 2011 2014 2017 2020 2023
1967 1970 1973 1976 1979 1982 1985 1988 1991 1994 1997 2000 2003 2006 2009 2012 2015 2018 2021

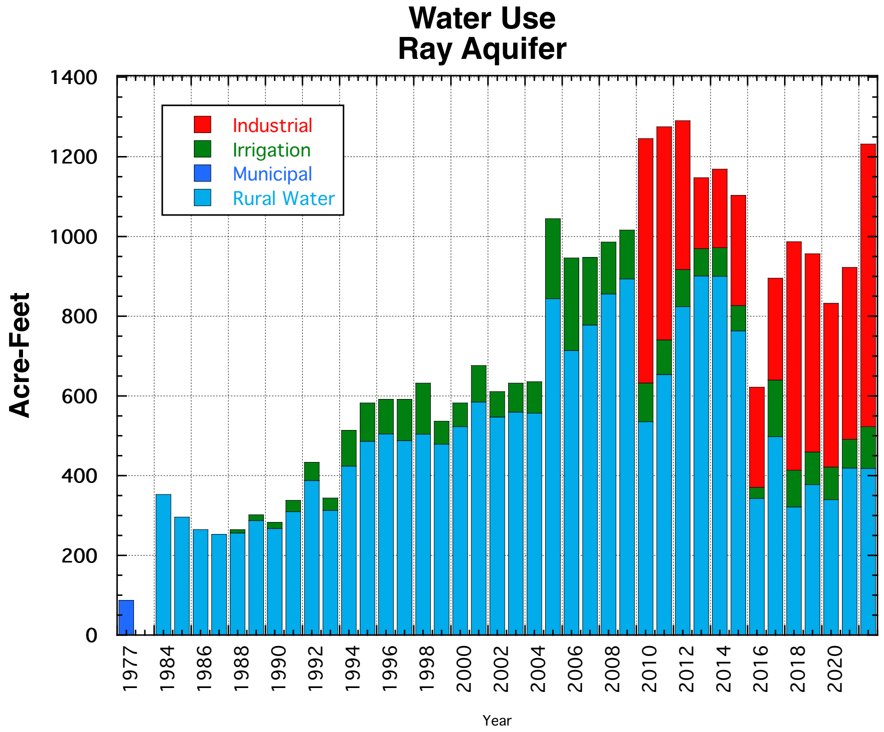

ND Water Use
Missouri River
aquifer
Total Use
6000
5000
4000
3000
2000
1000
0
Acre-Feet
1965 1968 1971 1974 1977 1980 1983 1986 1989 1992 1995 1998 2001 2004 2007 2010 2013 2016 2019 2022
1966 1969 1972 1975 1978 1981 1984 1987 1990 1993 1996 1999 2002 2005 2008 2011 2014 2017 2020 2023
1967 1970 1973 1976 1979 1982 1985 1988 1991 1994 1997 2000 2003 2006 2009 2012 2015 2018 2021

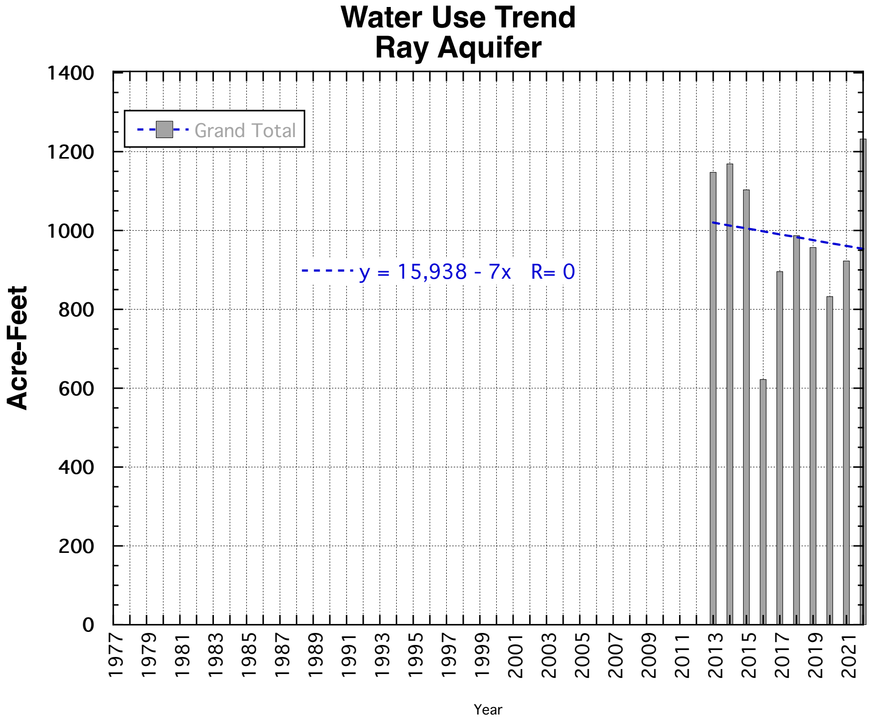

Water Use
New Town Aquifer
Acre-Feet
0
200
400
600
800
1000
1200
1400
1600
Industrial
Irrigation
Municipal
Rural Water
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

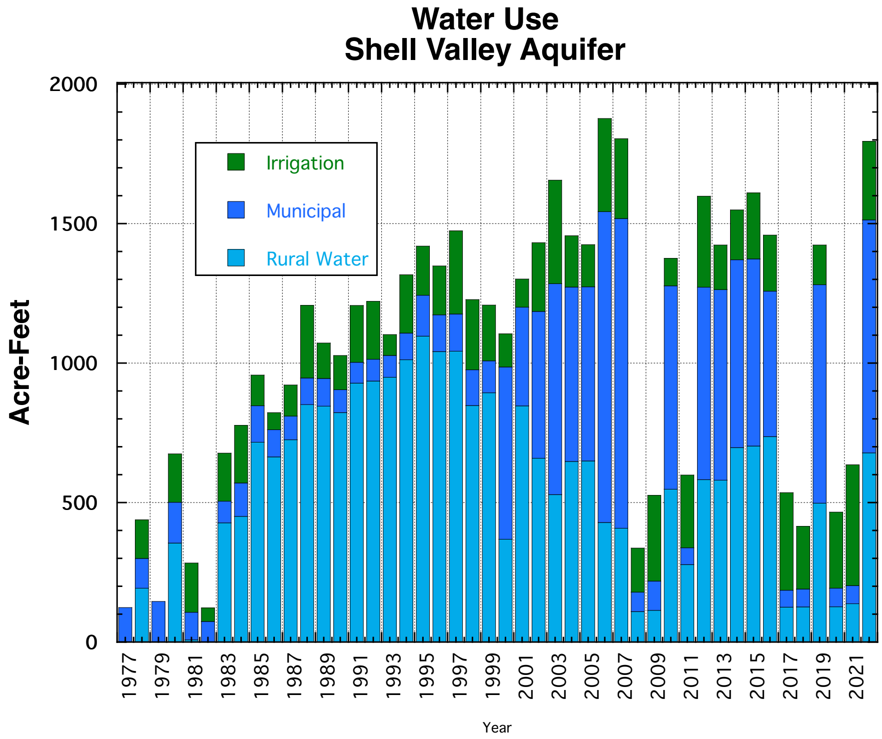

Water Use Trend
New Town Aquifer
Acre-Feet
0
200
400
600
800
1000
1200
1400
1600
Grand Total
y = -104,823 + 52x R= 1
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

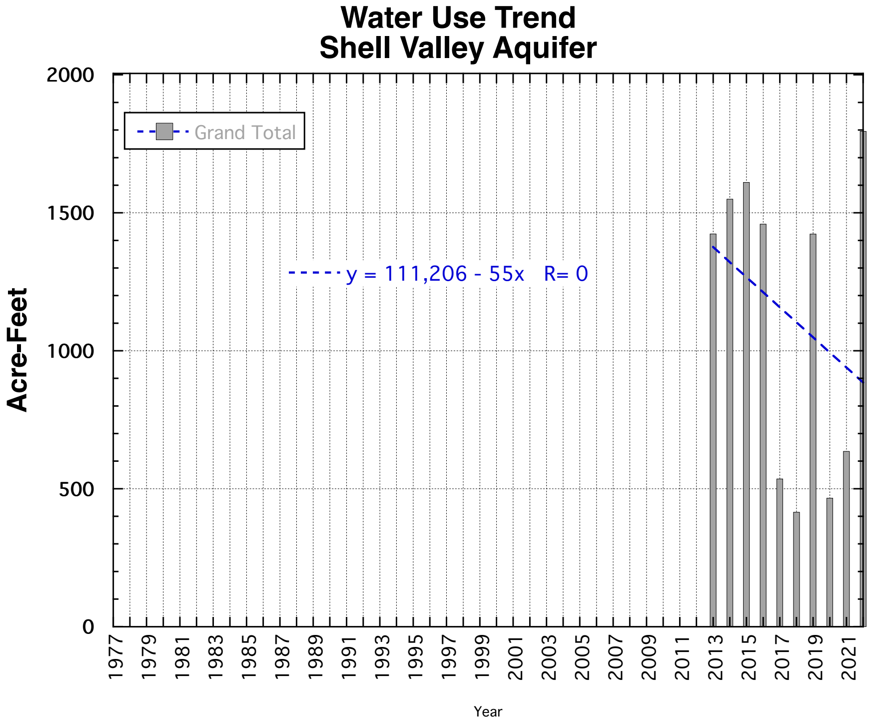

Water Use
Page Aquifer
Irrigation
Municipal
Rural Water
Acre-Feet
0
2000
4000
6000
8000
10000
12000
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

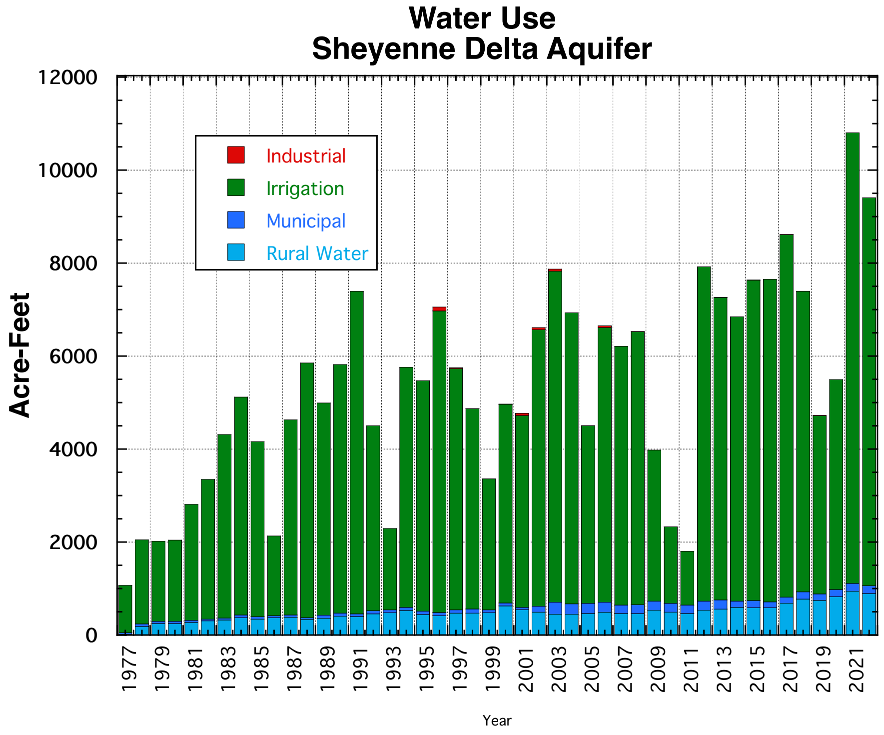

Water Use Trend
Page Aquifer
Grand Total
y = 63,357 - 28x   R= 0
Acre-Feet
0
2000
4000
6000
8000
10000
12000
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

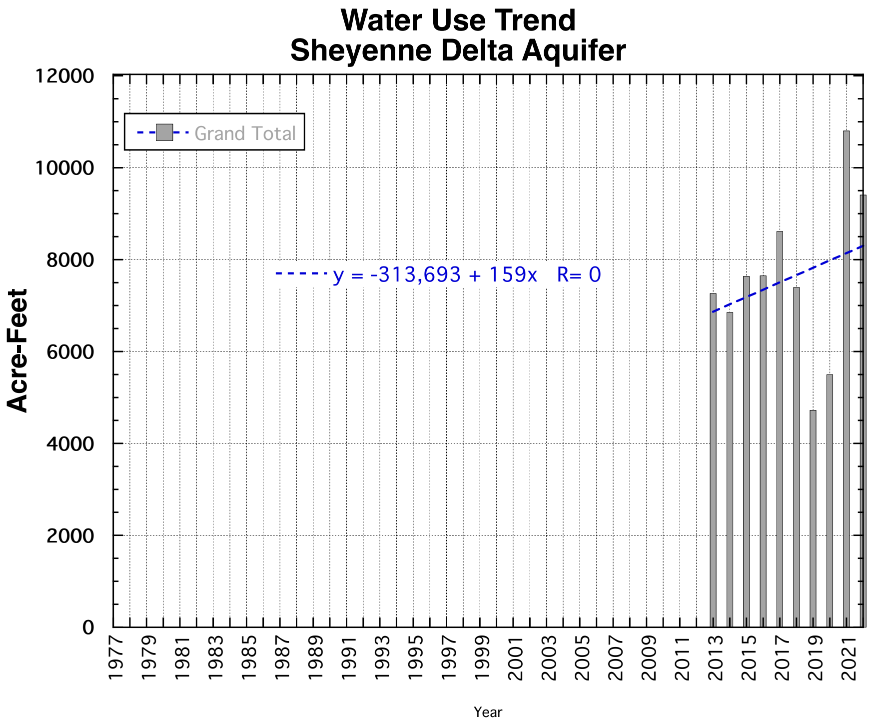

Water Use
Ray Aquifer
Industrial
Irrigation
Municipal
Rural Water
Acre-Feet
0
200
400
600
800
1000
1200
1400
1977
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
Year

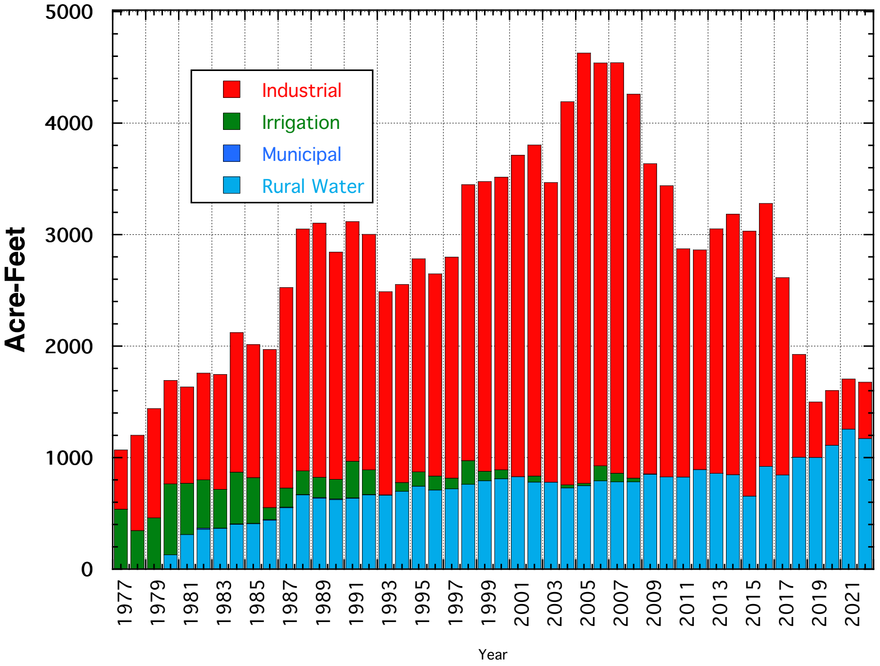

Water Use Trend
Ray Aquifer
Grand Total
y = 15,938 - 7x R= 0
Acre-Feet
0
200
400
600
800
1000
1200
1400
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year


Water Use
Shell Valley Aquifer
Acre-Feet
2000
1500
1000
500
0
Irrigation
Municipal
Rural Water
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

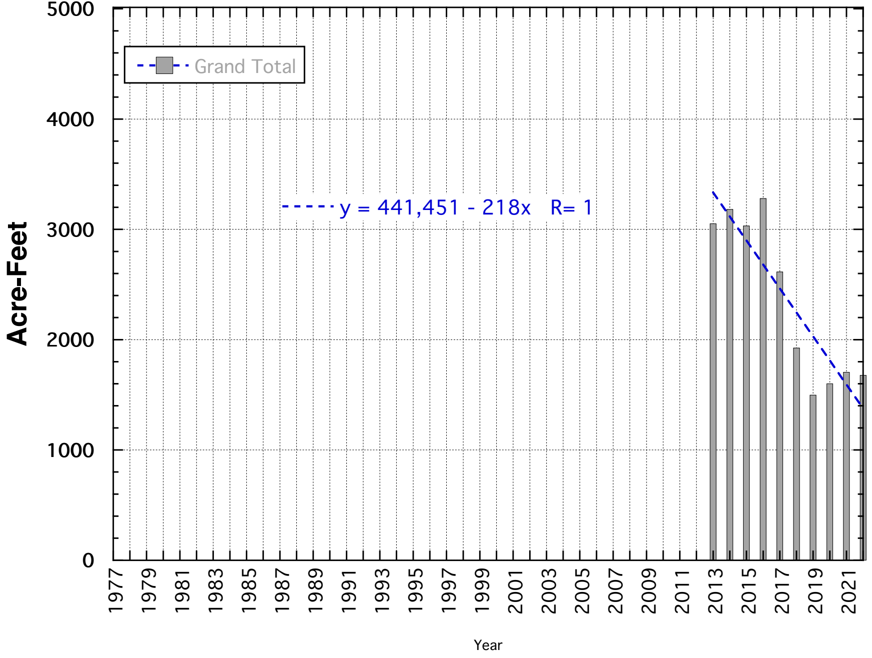

Water Use Trend
Shell Valley Aquifer
Acre-Feet
2000
1500
1000
500
0
Grand Total
y = 111,206 - 55x R= 0
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year


Water Use
Sheyenne Delta Aquifer
Acre-Feet
12000
10000
8000
6000
4000
2000
0
Industrial
Irrigation
Municipal
Rural Water
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

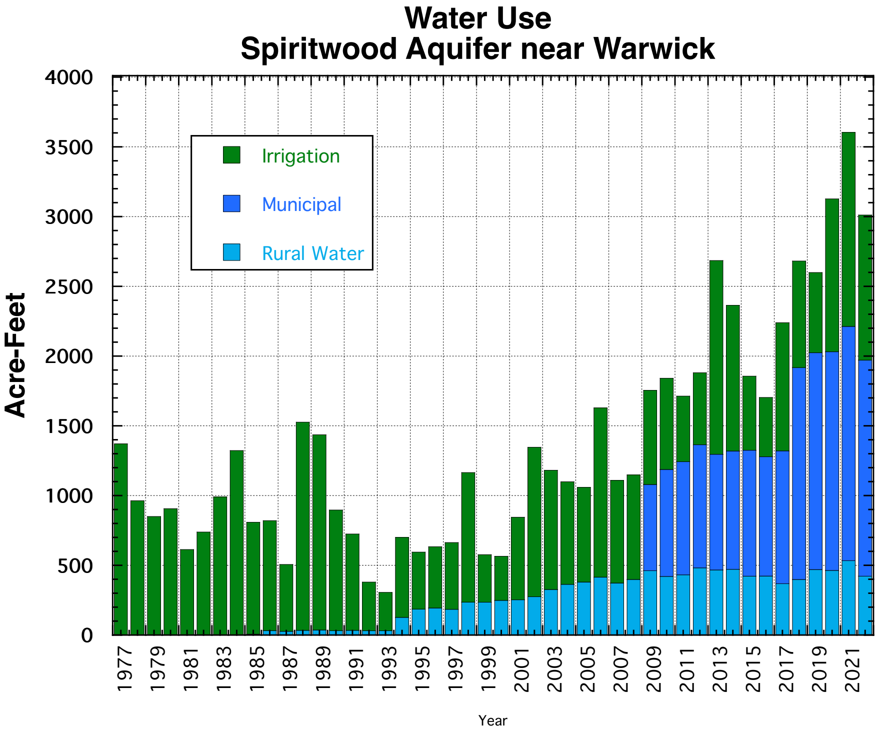

Water Use Trend
Sheyenne Delta Aquifer
Acre-Feet
12000
10000
8000
6000
4000
2000
0
Grand Total
y = -313,693 + 159x R= 0
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

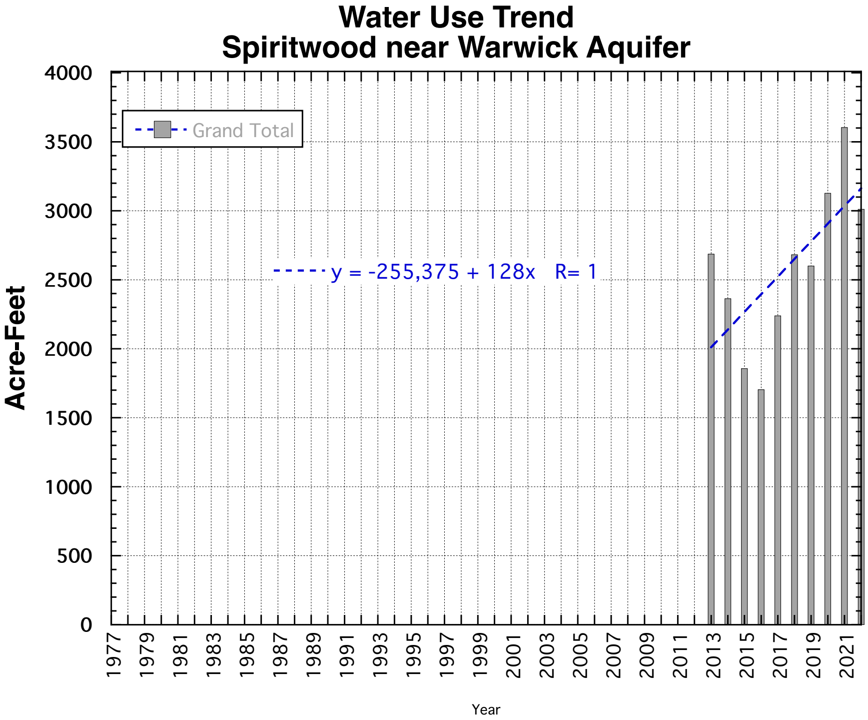


Water Use
Spiritwood Aquifer Segment near Jamestown

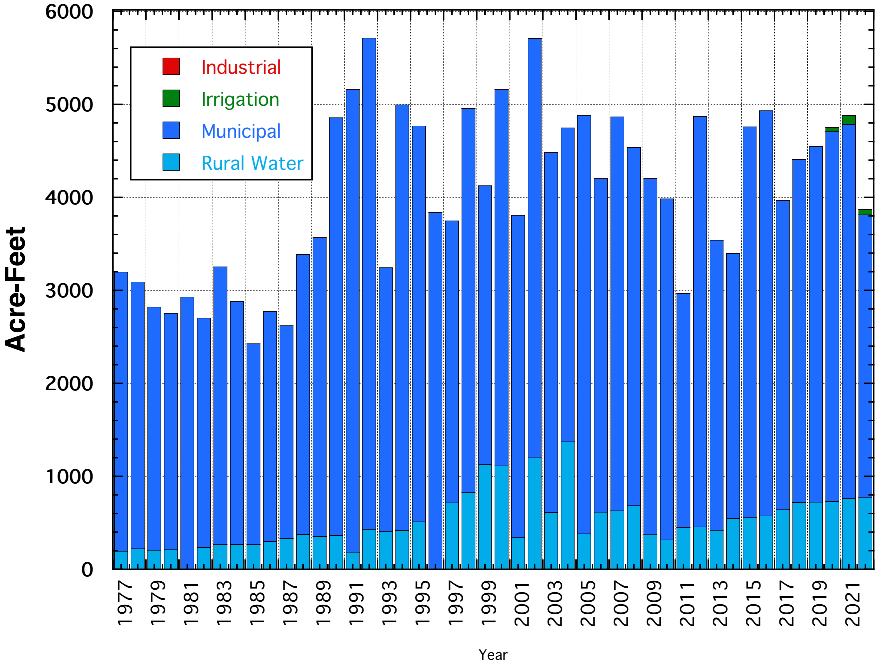


Water Use Trend
Spiritwood Aquifer Segment near Jamestown

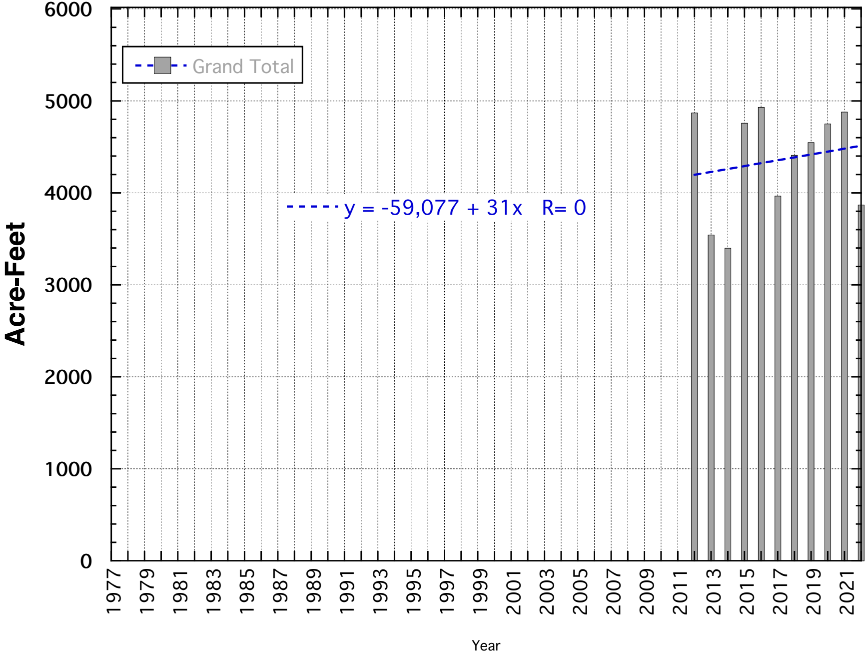

Water Use
Spiritwood Aquifer near Warwick
Acre-Feet
0
500
1000
1500
2000
2500
3000
3500
4000
🟩 Irrigation
🟦 Municipal
🟦 Rural Water
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

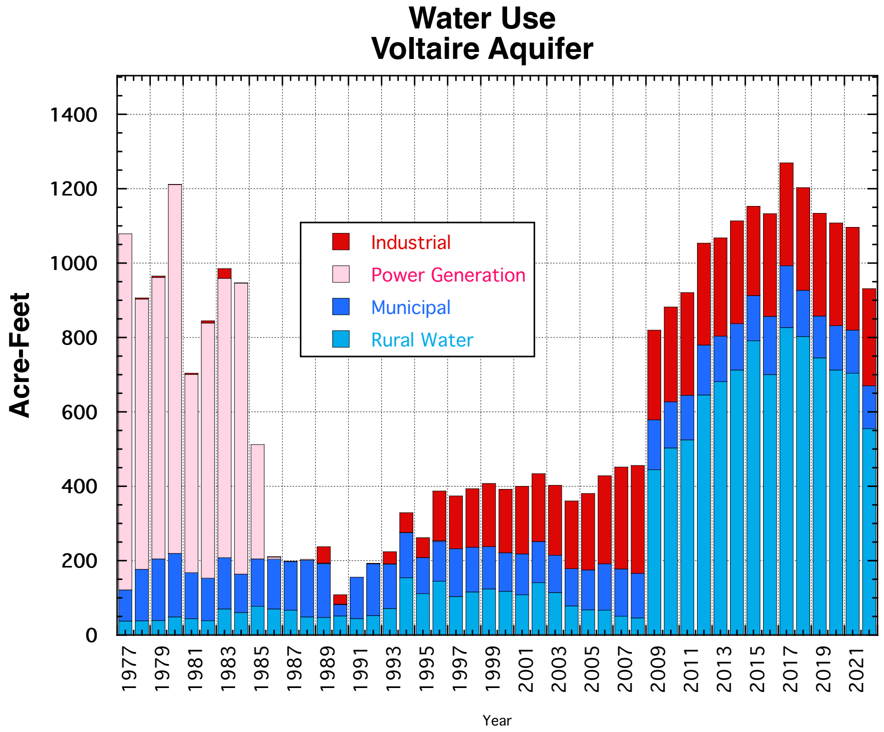

Water Use Trend
Spiritwood near Warwick Aquifer
Acre-Feet
0
500
1000
1500
2000
2500
3000
3500
4000
Grand Total
y = -255,375 + 128x R= 1
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

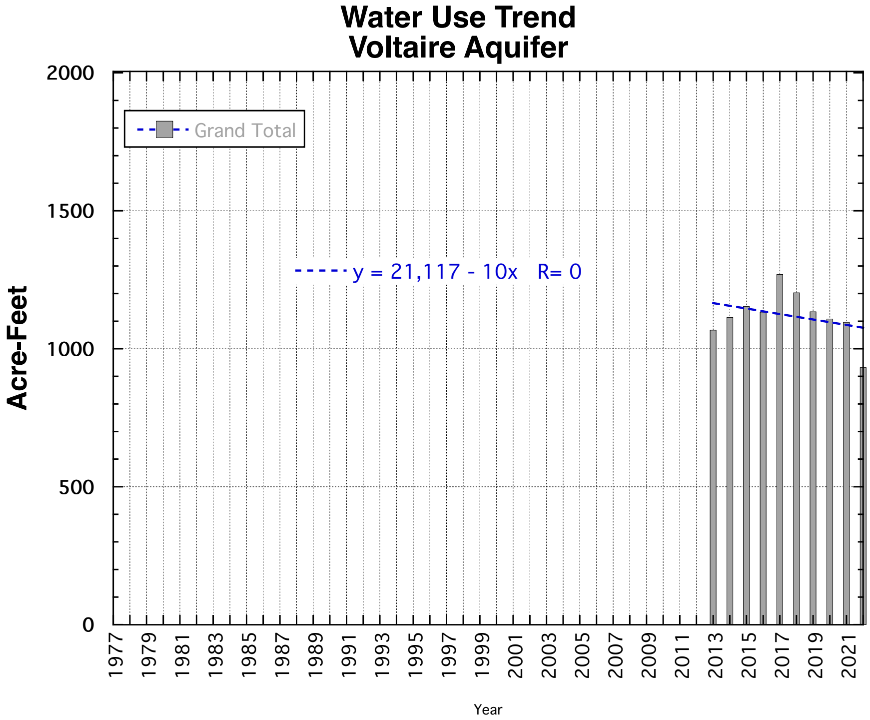
Water Use
Sundre Aquifer

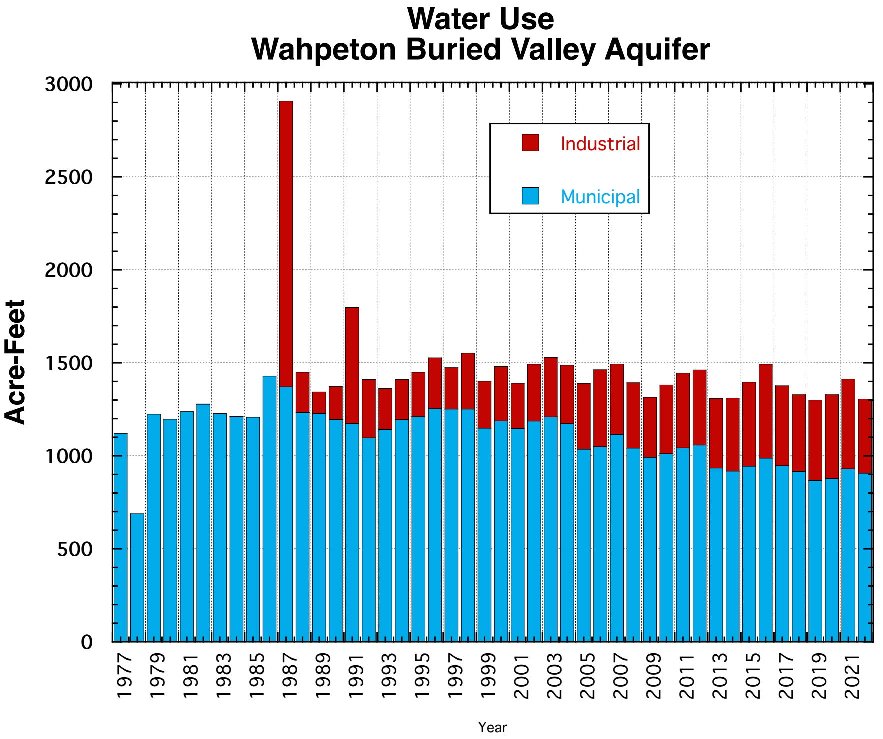


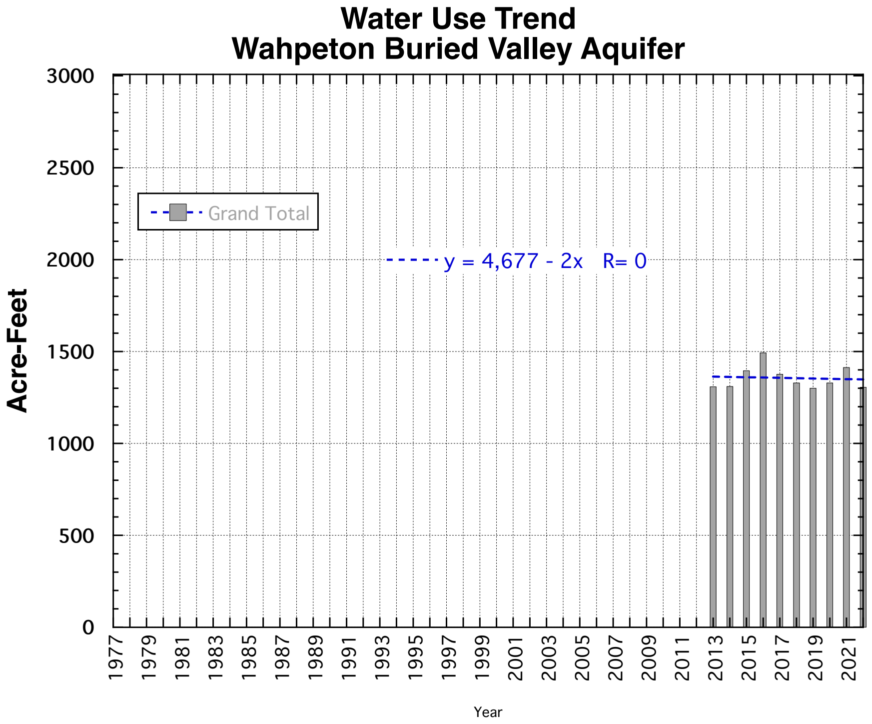
Water Use Trend
Sundre Aquifer

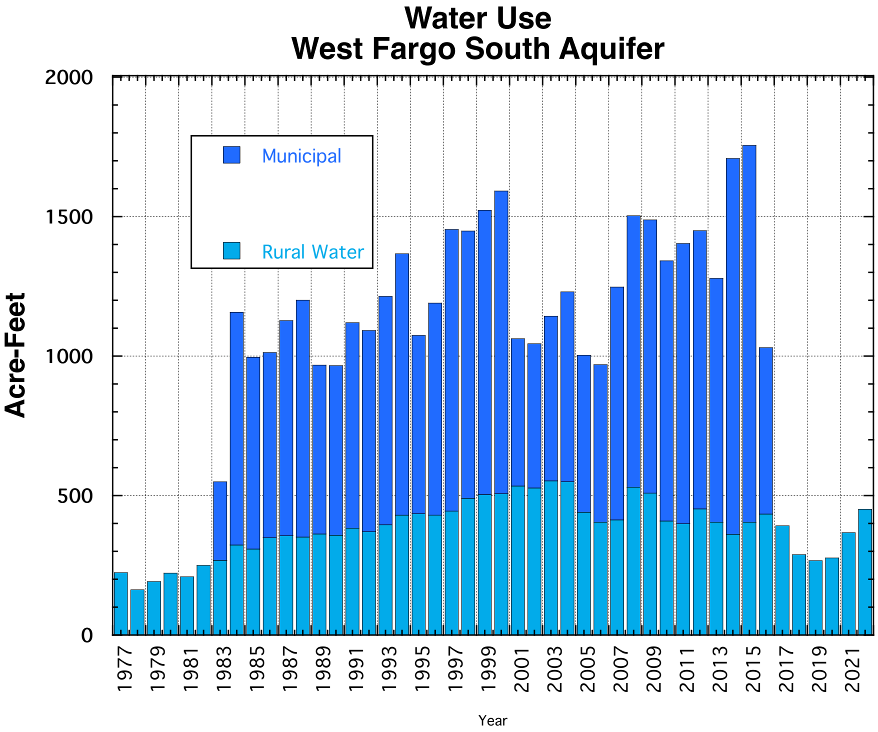



Water Use
Voltaire Aquifer
Acre-Feet
0
200
400
600
800
1000
1200
1400
Industrial
Power Generation
Municipal
Rural Water
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year

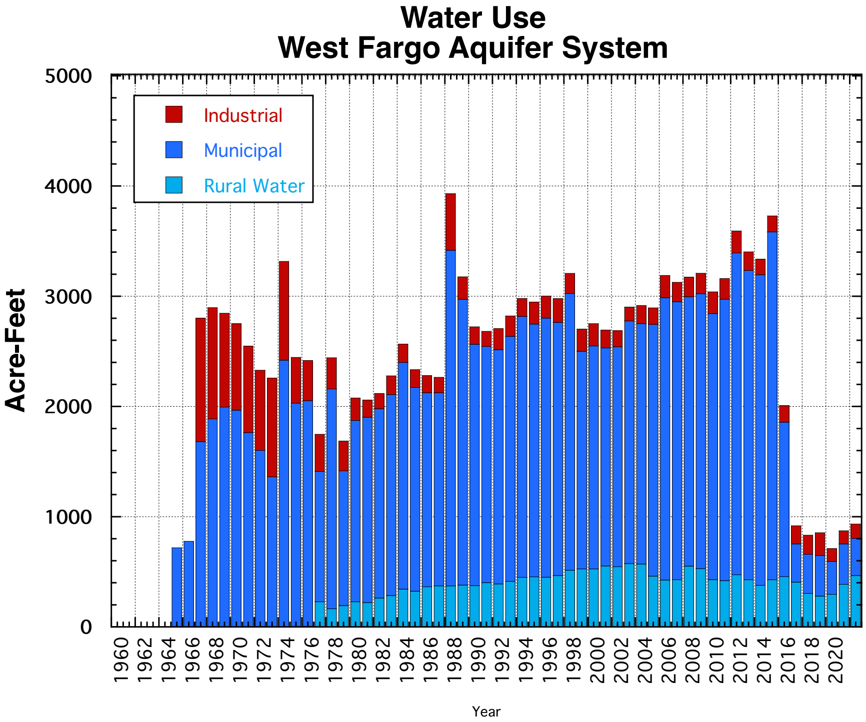

Water Use Trend
Voltaire Aquifer
Acre-Feet
0
500
1000
1500
2000
Grand Total
y = 21,117 - 10x   R= 0
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
Year


Water Use
Wahpeton Buried Valley Aquifer

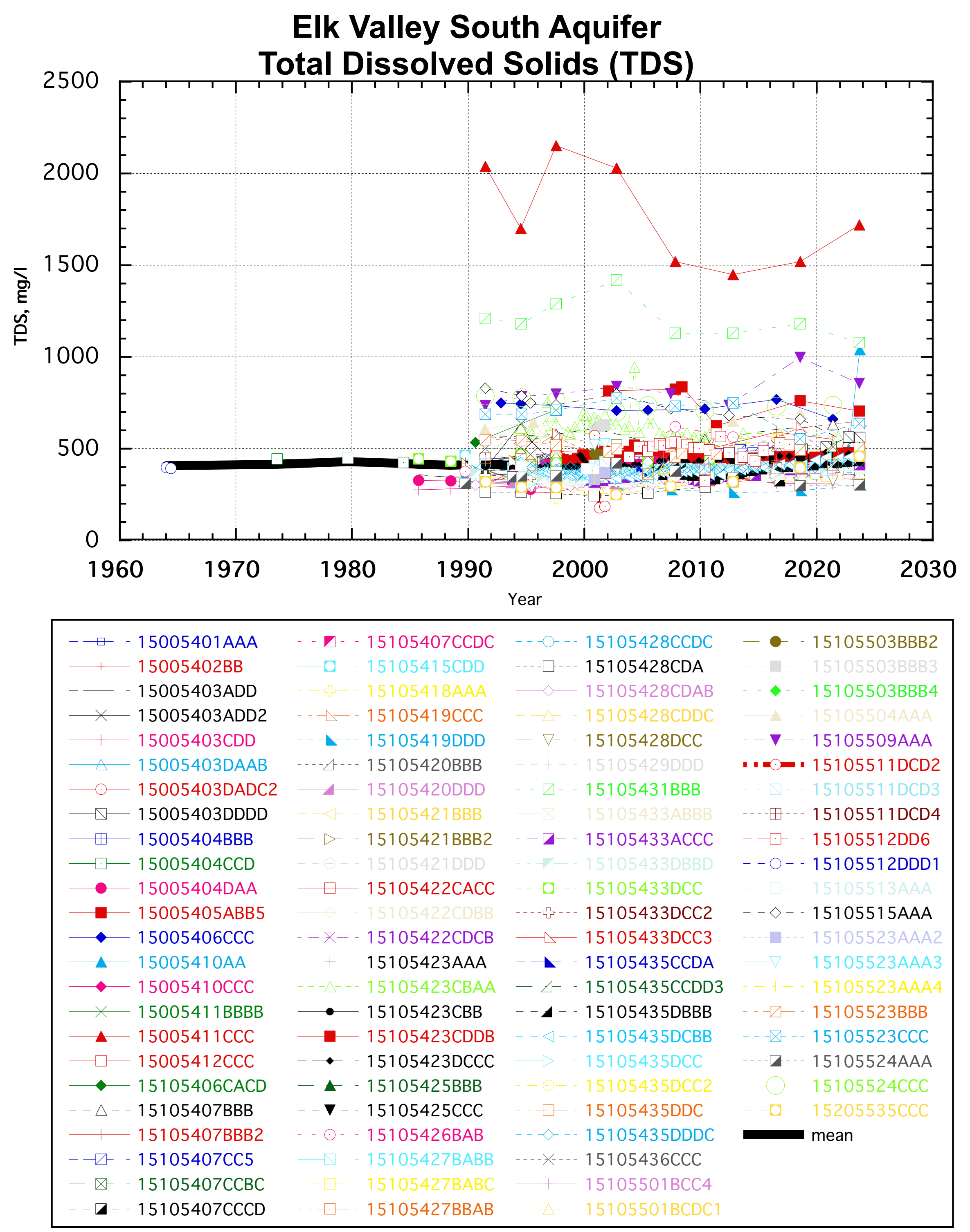

Water Use Trend
Wahpeton Buried Valley Aquifer

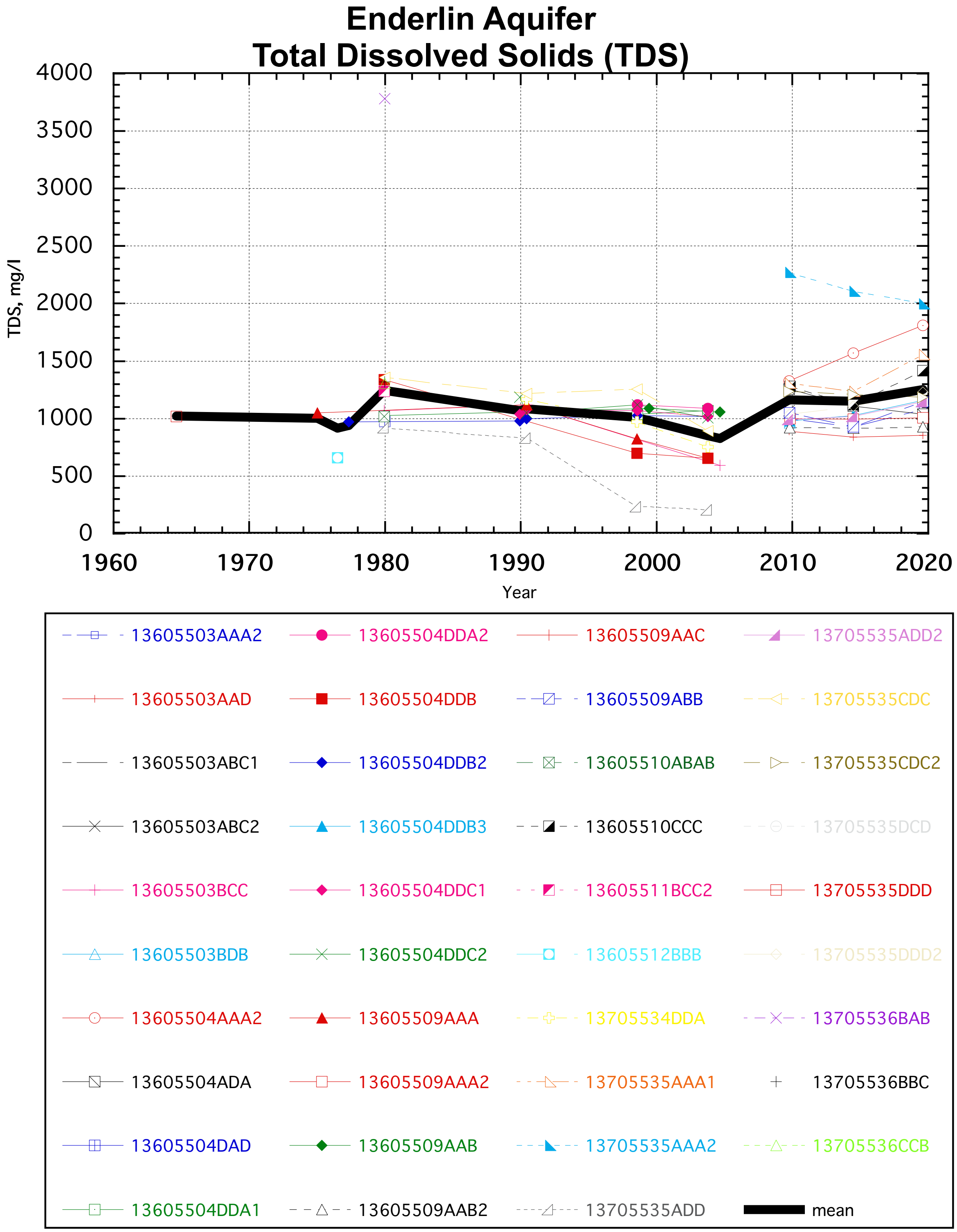


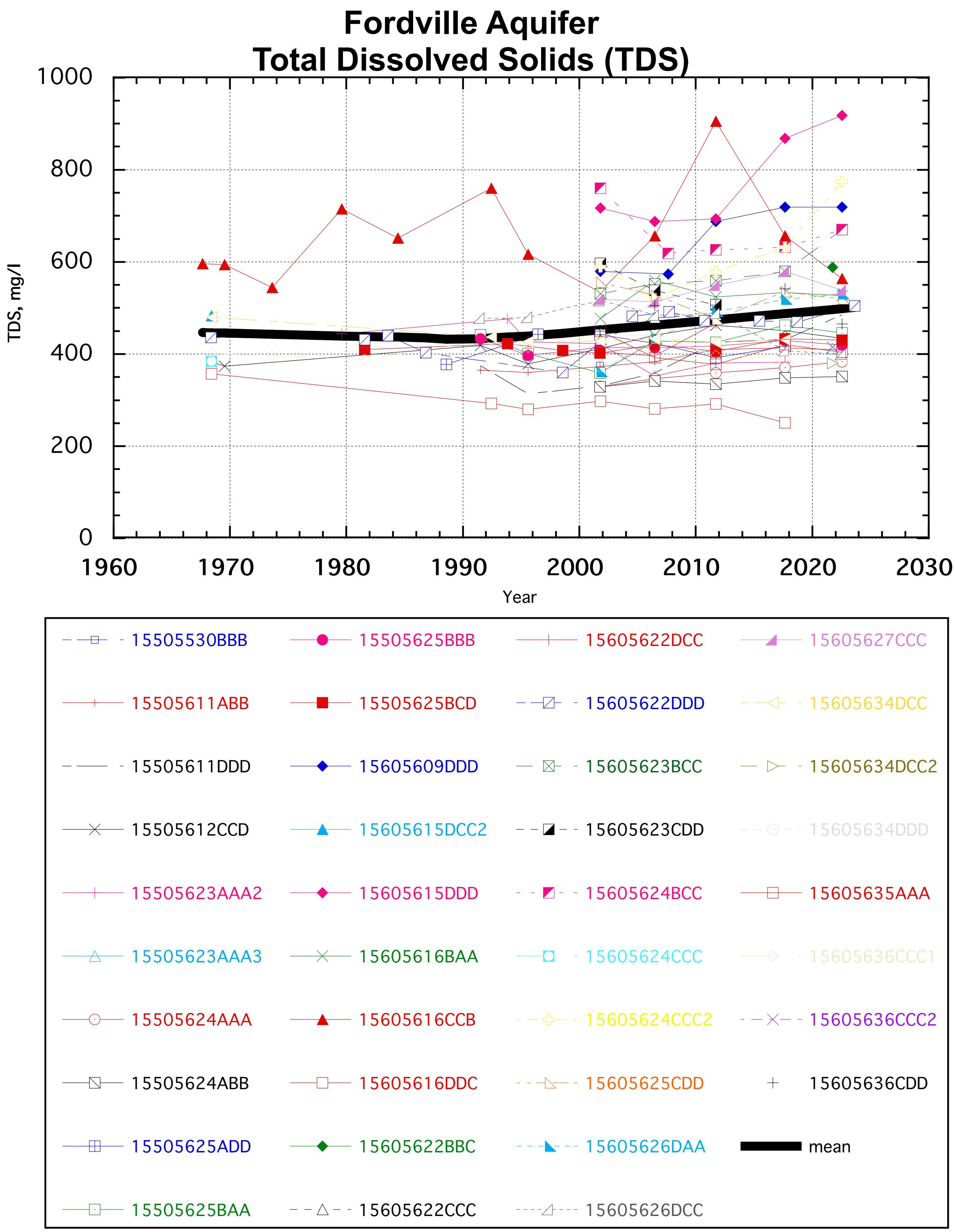
Water Use
West Fargo South Aquifer
Municipal
Rural Water
Acre-Feet
Year
0
500
1000
1500
2000
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021

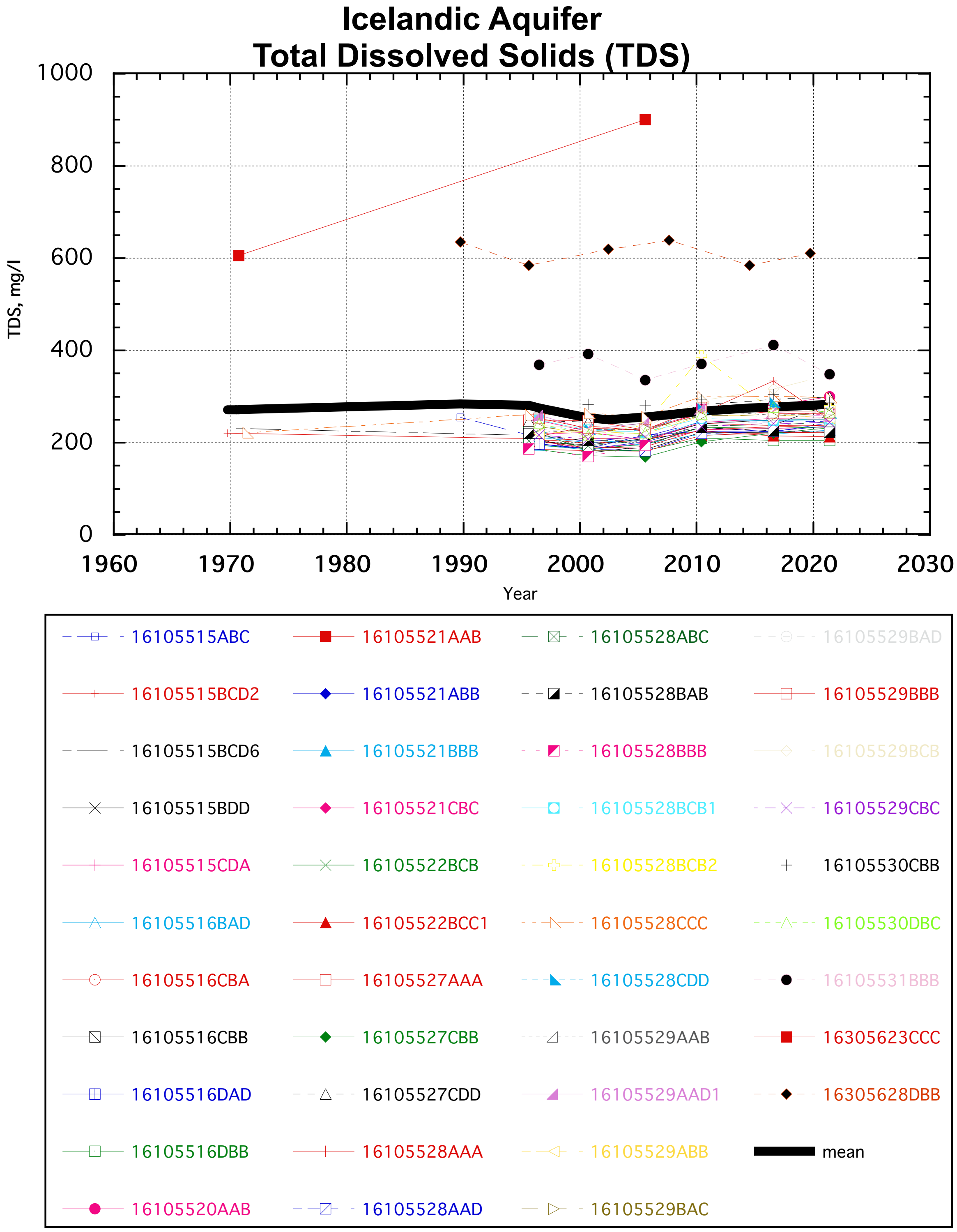


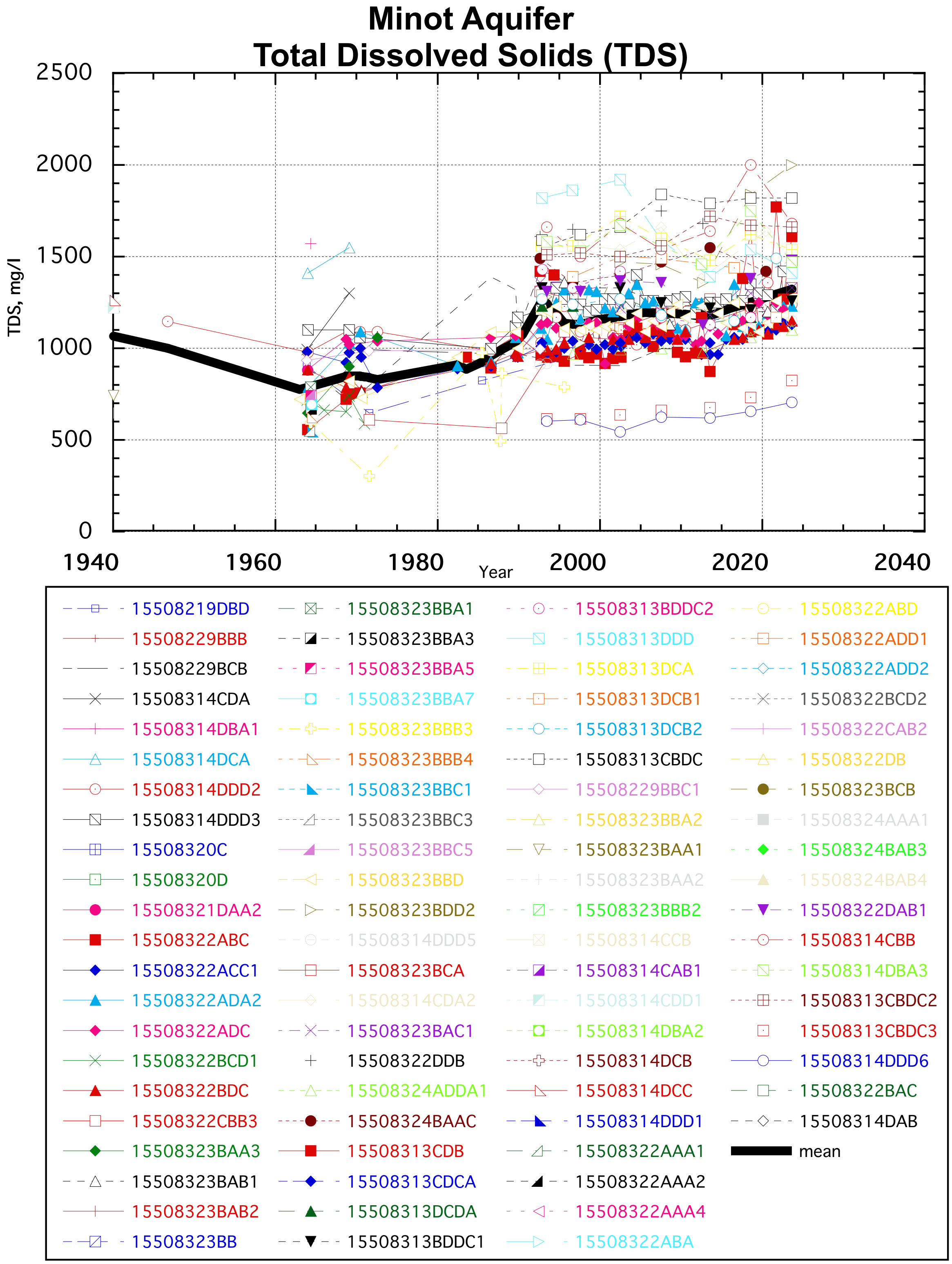
Water Use
West Fargo Aquifer System
Industrial
Municipal
Rural Water
Acre-Feet
Year
0
1000
2000
3000
4000
5000
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020

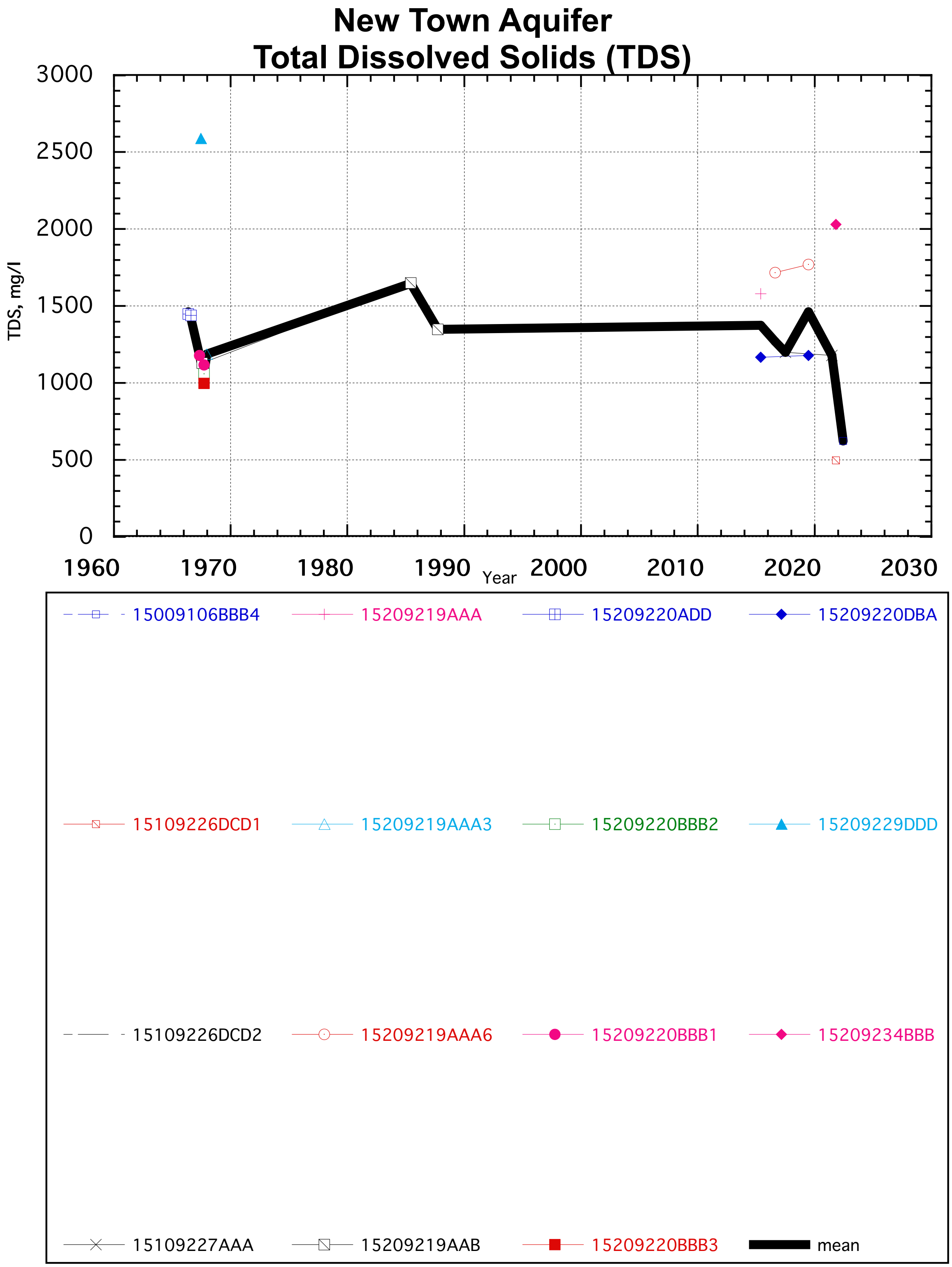

Elk Valley South Aquifer
Total Dissolved Solids (TDS)
TDS, mg/l
2500
2000
1500
1000
500
0
1960
1970
1980
1990
2000
2010
2020
2030
Year
15005401AAA
15005402BB
15005403ADD
15005403ADD2
15005403CDD
15005403DAAB
15005403DADC2
15005403DDDD
15005404BBB
15005404CCD
15005404DAA
15005405ABB5
15005406CCC
15005410AA
15005410CCC
15005411BBBB
15005411CCC
15005412CCC
15105406CACD
15105407BBB
15105407BBB2
15105407CC5
15105407CCBC
15105407CCCD
15105407CCDC
15105415CDD
15105418AAA
15105419CCC
15105419DDD
15105420BBB
15105420DDD
15105421BBB
15105421BBB2
15105421DDD
15105422CACC
15105422CDBB
15105422CDCB
15105423AAA
15105423CBAA
15105423CBB
15105423CDDB
15105423DCCC
15105425BBB
15105425CCC
15105426BAB
15105427BABB
15105427BABC
15105427BBAB
15105428CCDC
15105428CDA
15105428CDAB
15105428CDDC
15105428DCC
15105429DDD
15105431BBB
15105433ABBB
15105433ACCC
15105433DBBD
15105433DCC
15105433DCC2
15105433DCC3
15105435CCDA
15105435CCDD3
15105435DBBB
15105435DCBB
15105435DCC
15105435DCC2
15105435DDC
15105435DDDC
15105436CCC
15105501BCC4
15105501BCDC1
15105503BBB2
15105503BBB3
15105503BBB4
15105504AAA
15105509AAA
15105511DCD2
15105511DCD3
15105511DCD4
15105512DD6
15105512DDD1
15105513AAA
15105515AAA
15105523AAA2
15105523AAA3
15105523AAA4
15105523BBB
15105523CCC
15105524AAA
15105524CCC
15205535CCC
mean

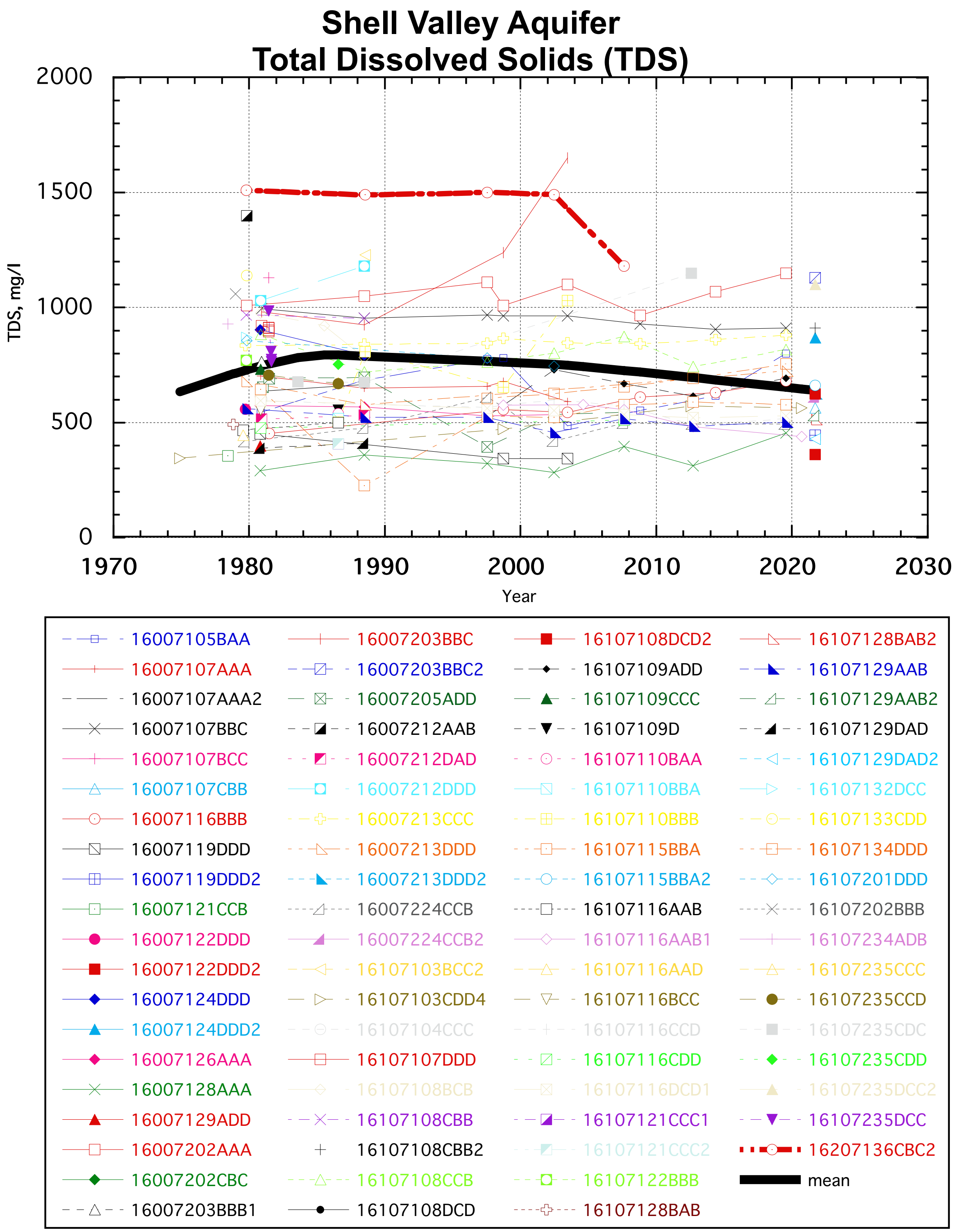

Enderlin Aquifer
Total Dissolved Solids (TDS)
TDS, mg/l
4000
3500
3000
2500
2000
1500
1000
500
0
1960
1970
1980
1990
2000
2010
2020
Year
13605503AAA2
13605504DDA2
13605509AAC
13705535ADD2
13605503AAD
13605504DDB
13605509ABB
13705535CDC
13605503ABC1
13605504DDB2
13605510ABAB
13705535CDC2
13605503ABC2
13605504DDB3
13605510CCC
13705535DCD
13605503BCC
13605504DDC1
13605511BCC2
13705535DDD
13605503BDB
13605504DDC2
13605512BBB
13705535DDD2
13605504AAA2
13605509AAA
13705534DDA
13705536BAB
13605504ADA
13605509AAA2
13705535AAA1
13705536BBC
13605504DAD
13605509AAB
13705535AAA2
13705536CCB
13605504DDA1
13605509AAB2
13705535ADD
mean

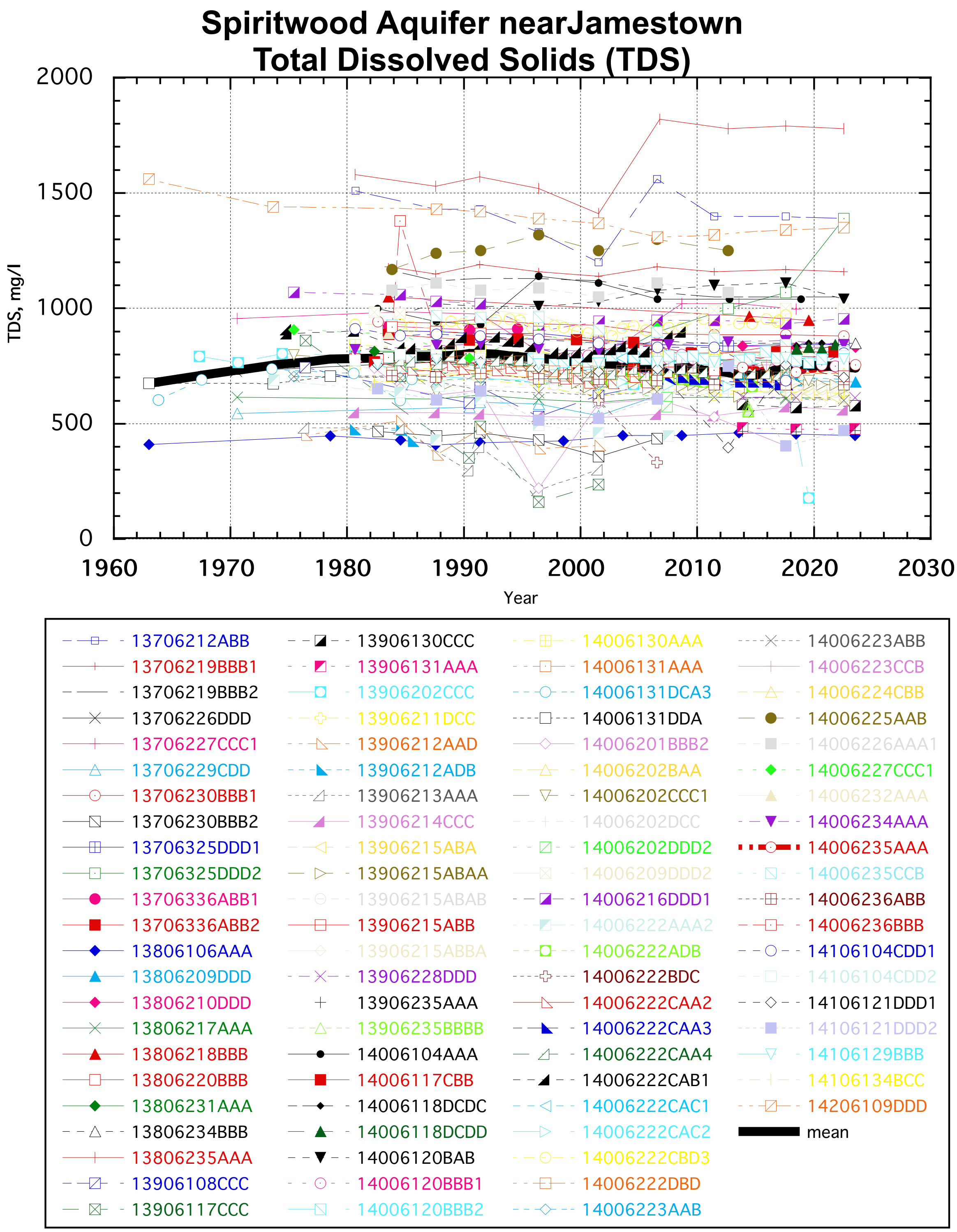

Fordville Aquifer
Total Dissolved Solids (TDS)
TDS, mg/l
1000
800
600
400
200
0
1960
1970
1980
1990
2000
2010
2020
2030
Year
15505530BBB
15505625BBB
15605622DCC
15605627CCC
15505611ABB
15505625BCD
15605622DDD
15605634DCC
15505611DDD
15605609DDD
15605623BCC
15605634DCC2
15505612CCD
15605615DCC2
15605623CDD
15605634DDD
15505623AAA2
15605615DDD
15605624BCC
15605635AAA
15505623AAA3
15605616BAA
15605624CCC
15605636CCC1
15505624AAA
15605616CCB
15605624CCC2
15605636CCC2
15505624ABB
15605616DDC
15605625CDD
15605636CDD
15505625ADD
15605622BBC
15605626DAA
mean
15505625BAA
15605622CCC
15605626DCC

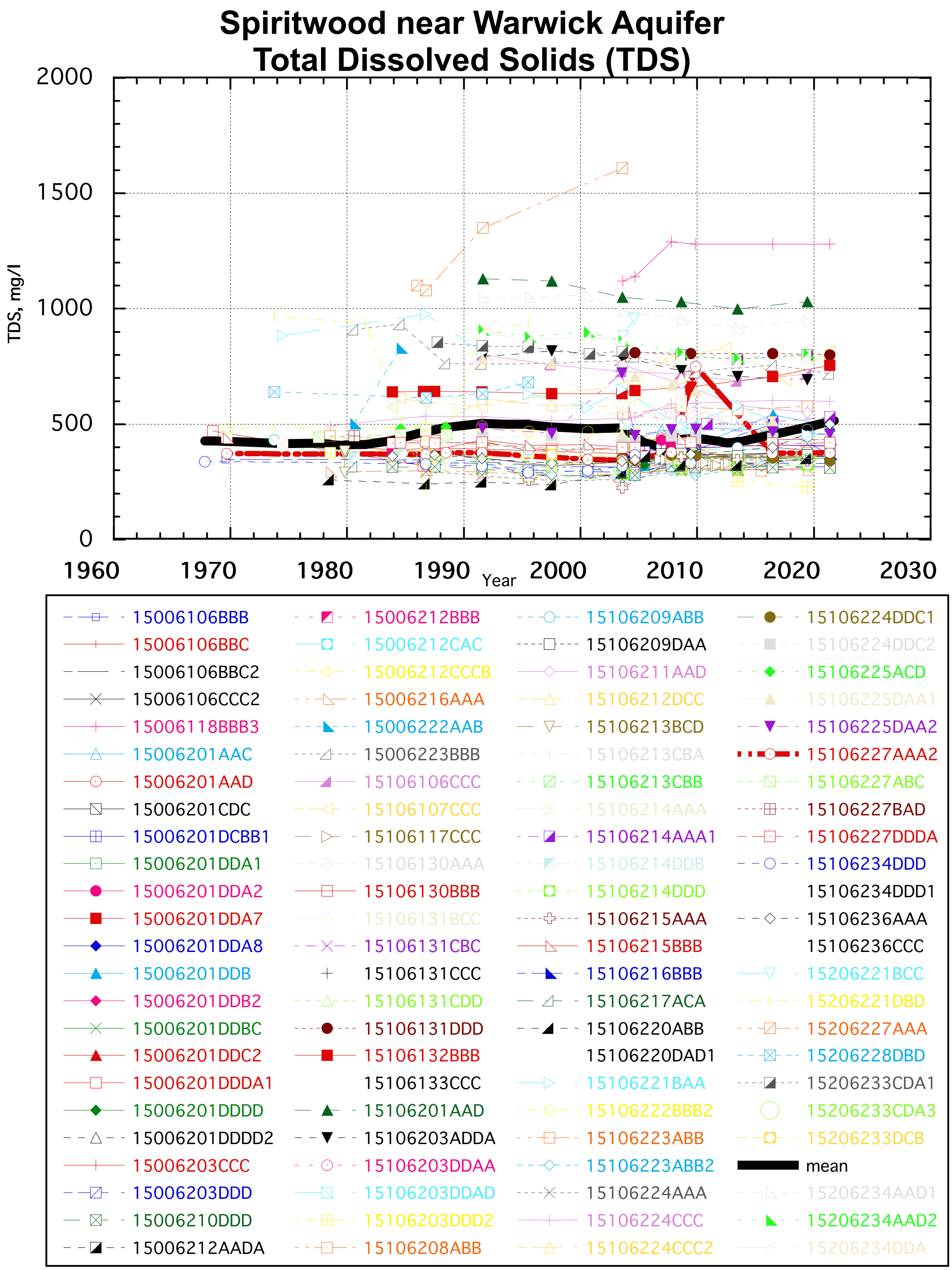

Icelandic Aquifer
Total Dissolved Solids (TDS)
TDS, mg/l
1000
800
600
400
200
0
1960
1970
1980
1990
2000
2010
2020
2030
Year
16105515ABC
16105521AAB
16105528ABC
16105529BAD
16105515BCD2
16105521ABB
16105528BAB
16105529BBB
16105515BCD6
16105521BBB
16105528BBB
16105529BCB
16105515BDD
16105521CBC
16105528BCB1
16105529CBC
16105515CDA
16105522BCB
16105528BCB2
16105530CBB
16105516BAD
16105522BCC1
16105528CCC
16105530DBC
16105516CBA
16105527AAA
16105528CDD
16105531BBB
16105516CBB
16105527CBB
16105529AAB
16305623CCC
16105516DAD
16105527CDD
16105529AAD1
16305628DBB
16105516DBB
16105528AAA
16105529ABB
mean
16105520AAB
16105528AAD
16105529BAC


Minot Aquifer
Total Dissolved Solids (TDS)
TDS, mg/l
2500
2000
1500
1000
500
0
1940
1960
1980
Year
2000
2020
2040
15508219DBD
15508229BBB
15508229BCB
15508314CDA
15508314DBA1
15508314DCA
15508314DDD2
15508314DDD3
15508320C
15508320D
15508321DAA2
15508322ABC
15508322ACC1
15508322ADA2
15508322ADC
15508322BCD1
15508322BDC
15508322CBB3
15508323BAA3
15508323BAB1
15508323BAB2
15508323BB
15508323BBA1
15508323BBA3
15508323BBA5
15508323BBA7
15508323BBB3
15508323BBB4
15508323BBC1
15508323BBC3
15508323BBC5
15508323BBD
15508323BDD2
15508314DDD5
15508323BCA
15508314CDA2
15508323BAC1
15508322DDB
15508324ADDA1
15508324BAAC
15508313CDB
15508313CDCA
15508313DCDA
15508313BDDC1
15508313BDDC2
15508313DDD
15508313DCA
15508313DCB1
15508313DCB2
15508313CBDC
15508229BBC1
15508323BBA2
15508323BAA1
15508323BAA2
15508323BBB2
15508314CCB
15508314CAB1
15508314CDD1
15508314DBA2
15508314DCB
15508314DCC
15508314DDD1
15508322AAA1
15508322AAA2
15508322AAA4
15508322ABA
15508322ABD
15508322ADD1
15508322ADD2
15508322BCD2
15508322CAB2
15508322DB
15508323BCB
15508324AAA1
15508324BAB3
15508324BAB4
15508322DAB1
15508314CBB
15508314DBA3
15508313CBDC2
15508313CBDC3
15508314DDD6
15508322BAC
15508314DAB
mean

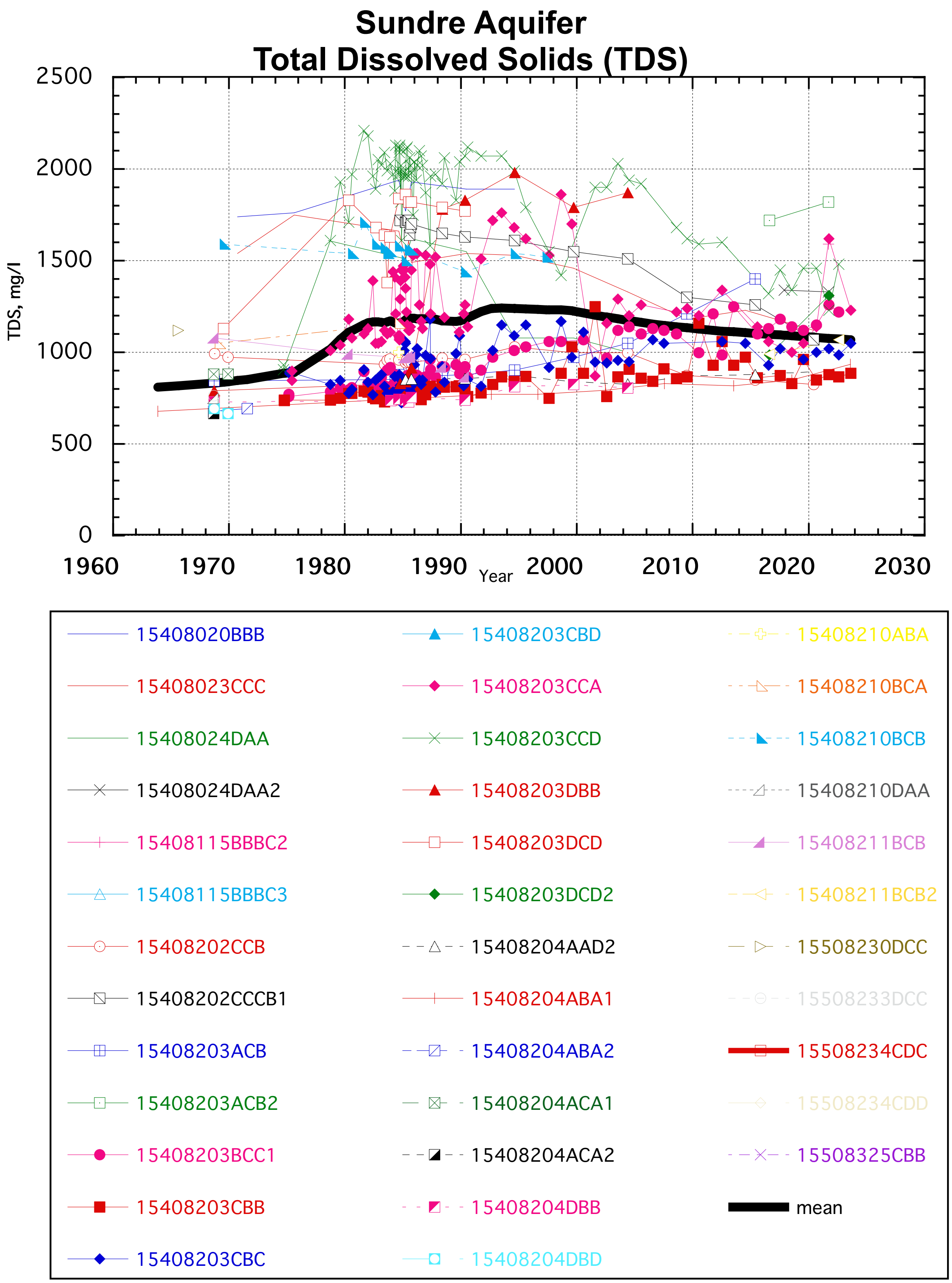

New Town Aquifer
Total Dissolved Solids (TDS)
TDS, mg/l
3000
2500
2000
1500
1000
500
0
1960
1970
1980
1990
Year
2000
2010
2020
2030
15009106BBB4
15209219AAA
15209220ADD
15209220DBA
15109226DCD1
15209219AAA3
15209220BBB2
15209229DDD
15109226DCD2
15209219AAA6
15209220BBB1
15209234BBB
15109227AAA
15209219AAB
15209220BBB3
mean

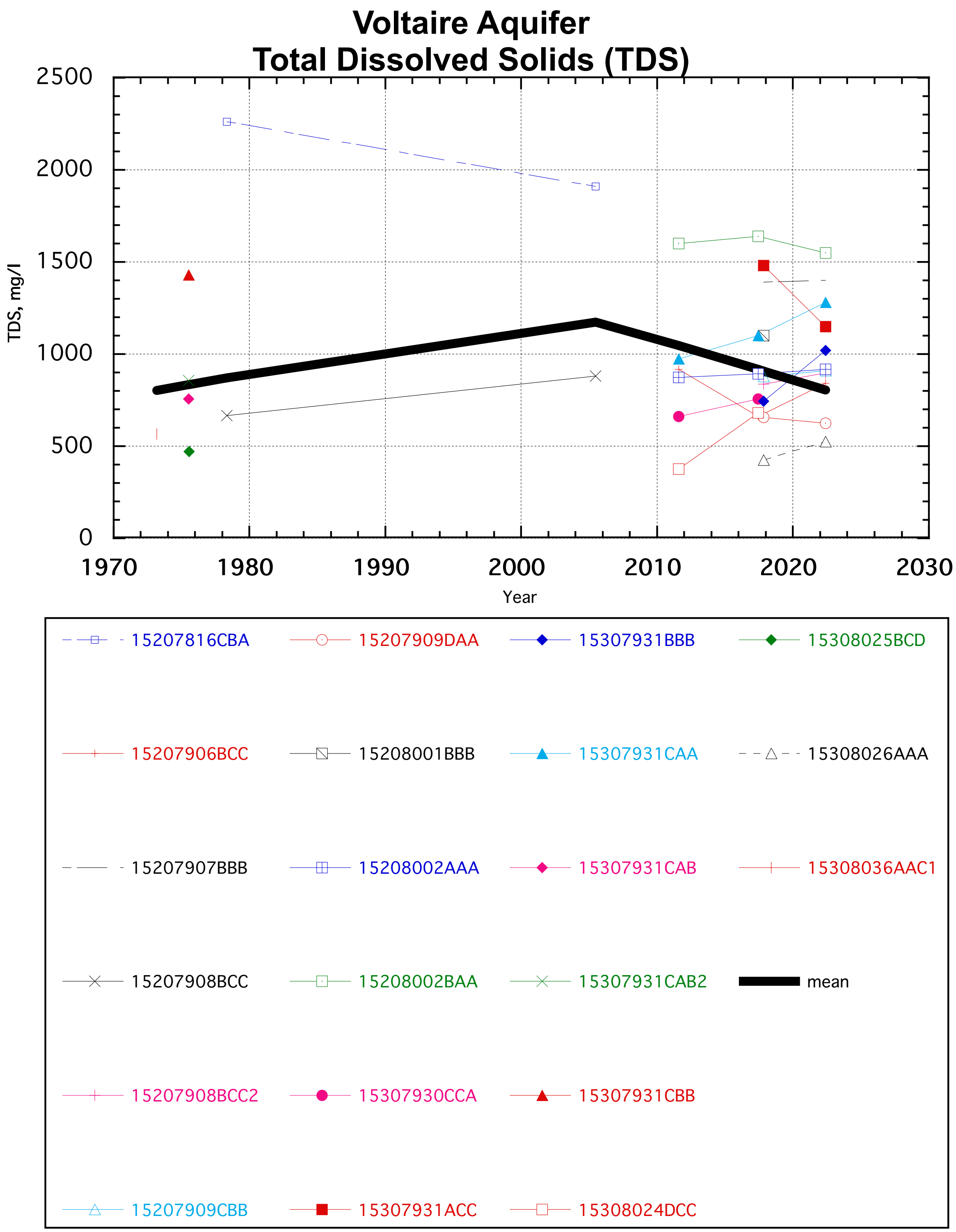

Shell Valley Aquifer
Total Dissolved Solids (TDS)
TDS, mg/l
2000
1500
1000
500
0
1970
1980
1990
2000
2010
2020
2030
Year
16007105BAA
16007107AAA
16007107AAA2
16007107BBC
16007107BCC
16007107CBB
16007116BBB
16007119DDD
16007119DDD2
16007121CCB
16007122DDD
16007122DDD2
16007124DDD
16007124DDD2
16007126AAA
16007128AAA
16007129ADD
16007202AAA
16007202CBC
16007203BBB1
16007203BBC
16007203BBC2
16007205ADD
16007212AAB
16007212DAD
16007212DDD
16007213CCC
16007213DDD
16007213DDD2
16007224CCB
16007224CCB2
16107103BCC2
16107103CDD4
16107104CCC
16107107DDD
16107108BCB
16107108CBB
16107108CBB2
16107108CCB
16107108DCD
16107108DCD2
16107109ADD
16107109CCC
16107109D
16107110BAA
16107110BBA
16107110BBB
16107115BBA
16107115BBA2
16107116AAB
16107116AAB1
16107116AAD
16107116BCC
16107116CCD
16107116CDD
16107116DCD1
16107121CCC1
16107121CCC2
16107122BBB
16107128BAB
16107128BAB2
16107129AAB
16107129AAB2
16107129DAD
16107129DAD2
16107132DCC
16107133CDD
16107134DDD
16107201DDD
16107202BBB
16107234ADB
16107235CCC
16107235CCD
16107235CDC
16107235CDD
16107235DCC2
16107235DCC
16207136CBC2
mean

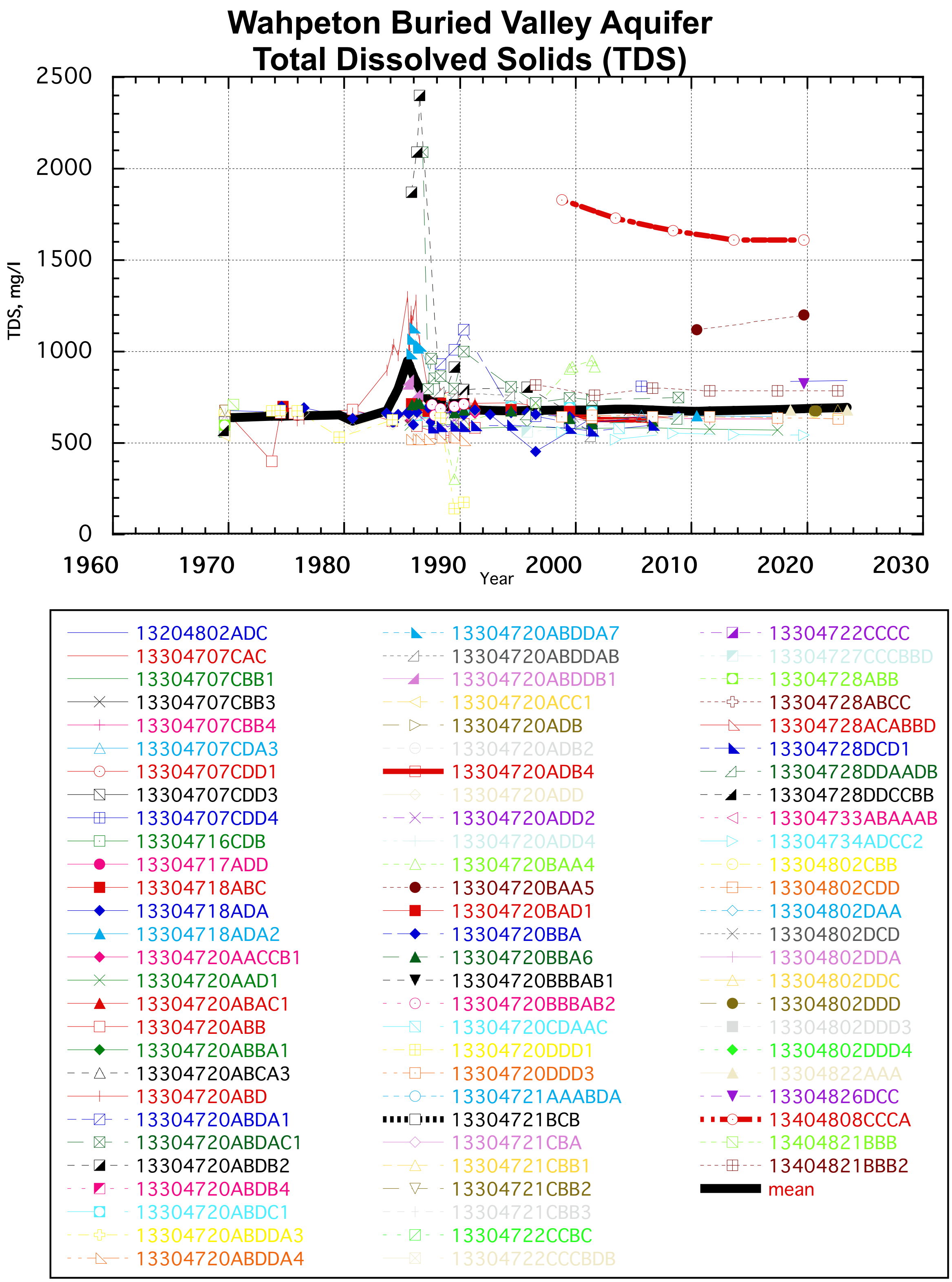

Spiritwood Aquifer nearJamestown
Total Dissolved Solids (TDS)
TDS, mg/l
2000
1500
1000
500
0
1960
1970
1980
1990
2000
2010
2020
2030
Year
13706212ABB
13706219BBB1
13706219BBB2
13706226DDD
13706227CCC1
13706229CDD
13706230BBB1
13706230BBB2
13706325DDD1
13706325DDD2
13706336ABB1
13706336ABB2
13806106AAA
13806209DDD
13806210DDD
13806217AAA
13806218BBB
13806220BBB
13806231AAA
13806234BBB
13806235AAA
13906108CCC
13906117CCC
13906130CCC
13906131AAA
13906202CCC
13906211DCC
13906212AAD
13906212ADB
13906213AAA
13906214CCC
13906215ABA
13906215ABAA
13906215ABAB
13906215ABB
13906215ABBA
13906228DDD
13906235AAA
13906235BBBB
14006104AAA
14006117CBB
14006118DCDC
14006118DCDD
14006120BAB
14006120BBB1
14006120BBB2
14006130AAA
14006131AAA
14006131DCA3
14006131DDA
14006201BBB2
14006202BAA
14006202CCC1
14006202DCC
14006202DDD2
14006209DDD2
14006216DDD1
14006222AAA2
14006222ADB
14006222BDC
14006222CAA2
14006222CAA3
14006222CAA4
14006222CAB1
14006222CAC1
14006222CAC2
14006222CBD3
14006222DBD
14006223AAB
14006223ABB
14006223CCB
14006224CBB
14006225AAB
14006226AAA1
14006227CCC1
14006232AAA
14006234AAA
14006235AAA
14006235CCB
14006236ABB
14006236BBB
14106104CDD1
14106104CDD2
14106121DDD1
14106121DDD2
14106129BBB
14106134BCC
14206109DDD
mean

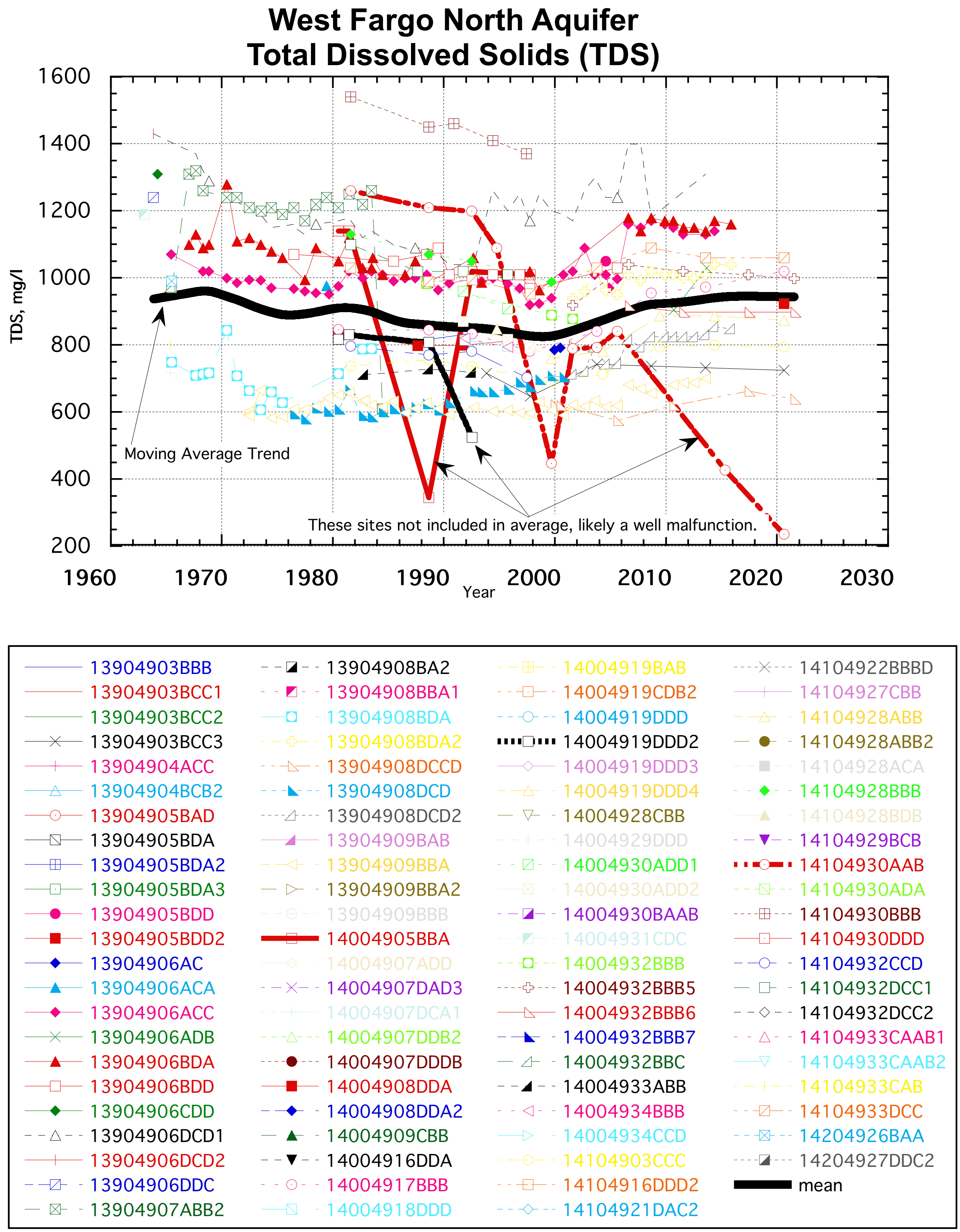


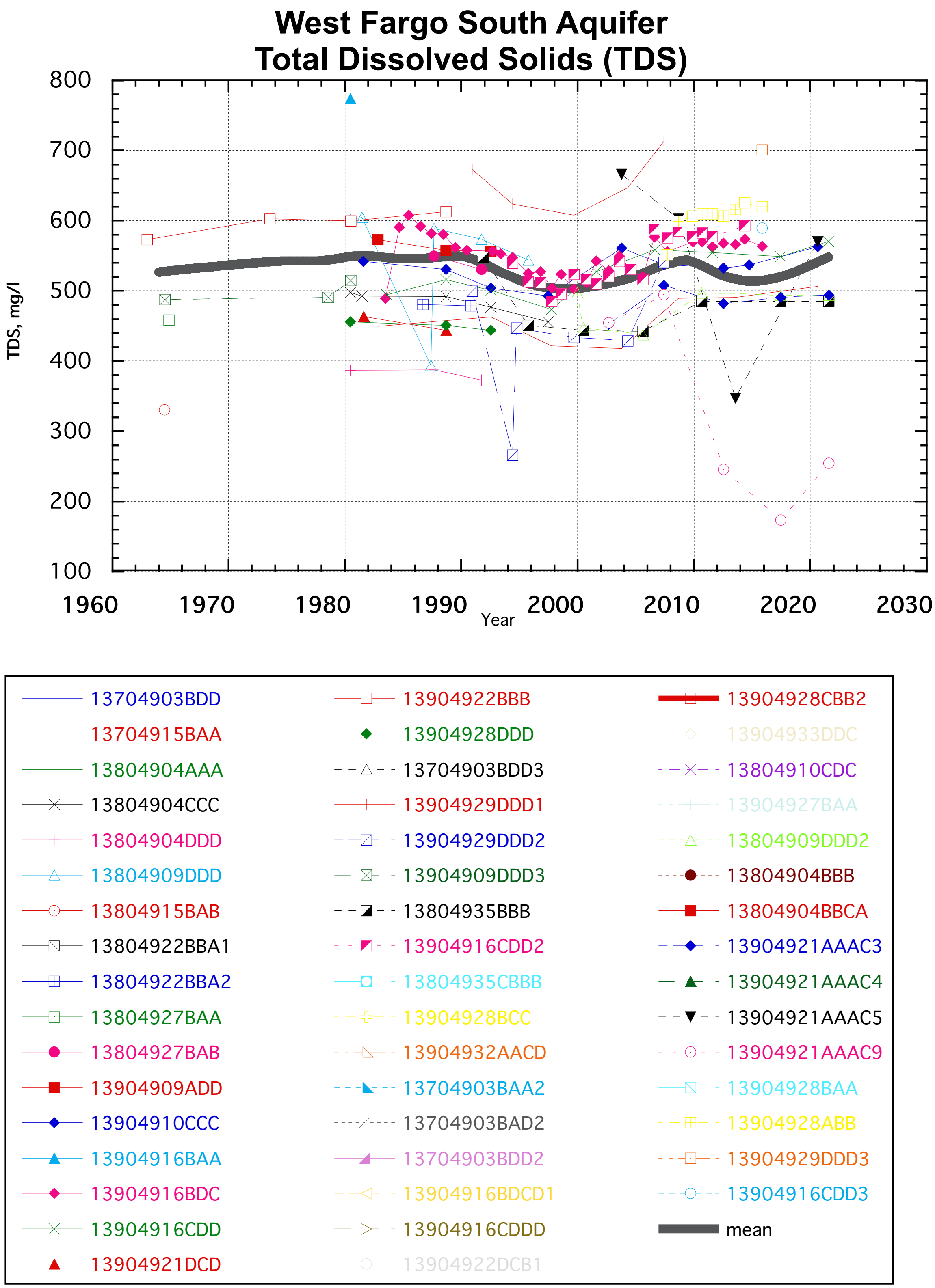
Spiritwood near Warwick Aquifer
Total Dissolved Solids (TDS)

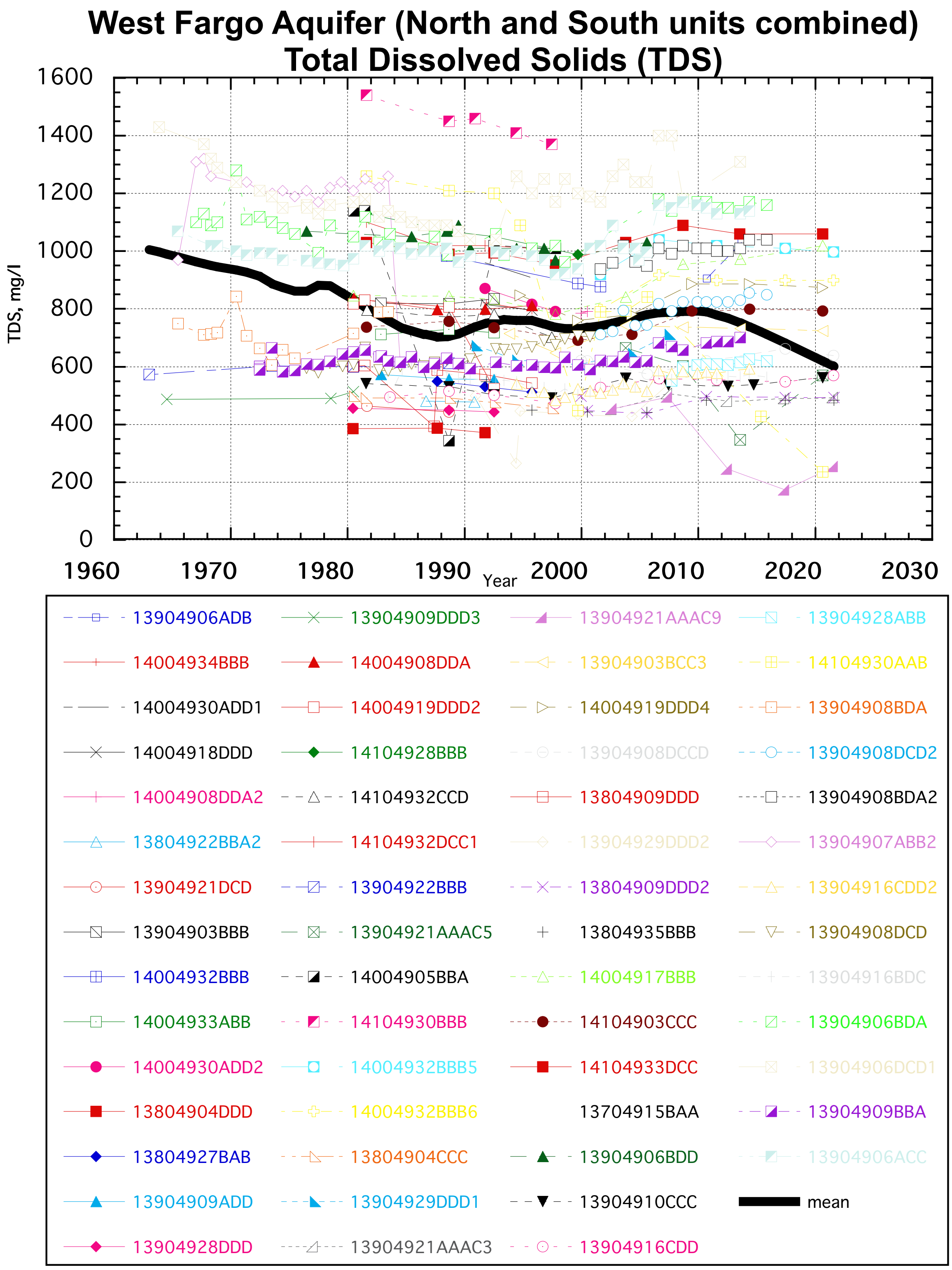

Sundre Aquifer
Total Dissolved Solids (TDS)
TDS, mg/l
2500
2000
1500
1000
500
0
1960
1970
1980
1990
Year
2000
2010
2020
2030
15408020BBB
15408023CCC
15408024DAA
15408024DAA2
15408115BBBC2
15408115BBBC3
15408202CCB
15408202CCCB1
15408203ACB
15408203ACB2
15408203BCC1
15408203CBB
15408203CBC
15408203CBD
15408203CCA
15408203CCD
15408203DBB
15408203DCD
15408203DCD2
15408204AAD2
15408204ABA1
15408204ABA2
15408204ACA1
15408204ACA2
15408204DBB
15408204DBD
15408210ABA
15408210BCA
15408210BCB
15408210DAA
15408211BCB
15408211BCB2
15508230DCC
15508233DCC
15508234CDC
15508234CDD
15508325CBB
mean


Voltaire Aquifer
Total Dissolved Solids (TDS)
TDS, mg/l
2500
2000
1500
1000
500
0
1970
1980
1990
2000
2010
2020
2030
Year
15207816CBA
15207909DAA
15307931BBB
15308025BCD
15207906BCC
15208001BBB
15307931CAA
15308026AAA
15207907BBB
15208002AAA
15307931CAB
15308036AAC1
15207908BCC
15208002BAA
15307931CAB2
mean
15207908BCC2
15307930CCA
15307931CBB
15207909CBB
15307931ACC
15308024DCC

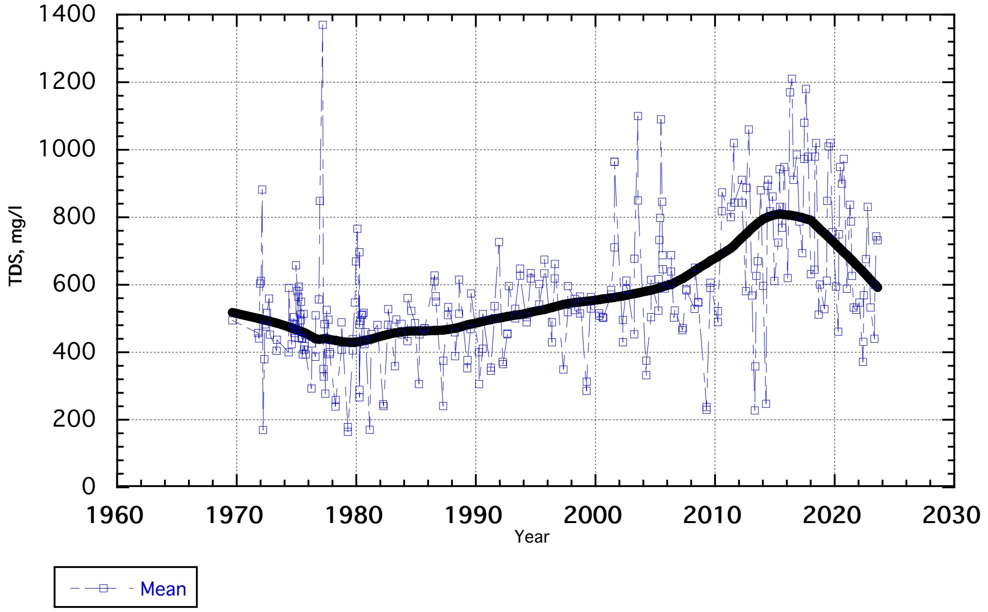

Wahpeton Buried Valley Aquifer
Total Dissolved Solids (TDS)
TDS, mg/l
2500
2000
1500
1000
500
0
1960
1970
1980
1990
2000
2010
2020
2030
Year
13204802ADC
13304707CAC
13304707CBB1
13304707CBB3
13304707CBB4
13304707CDA3
13304707CDD1
13304707CDD3
13304707CDD4
13304716CDB
13304717ADD
13304718ABC
13304718ADA
13304718ADA2
13304720AACCB1
13304720AAD1
13304720ABAC1
13304720ABB
13304720ABBA1
13304720ABCA3
13304720ABD
13304720ABDA1
13304720ABDAC1
13304720ABDB2
13304720ABDB4
13304720ABDC1
13304720ABDDA3
13304720ABDDA4
13304720ABDDA7
13304720ABDDAB
13304720ABDDB1
13304720ACC1
13304720ADB
13304720ADB2
13304720ADB4
13304720ADD
13304720ADD2
13304720ADD4
13304720BAA4
13304720BAA5
13304720BAD1
13304720BBA
13304720BBA6
13304720BBBAB1
13304720BBBAB2
13304720CDAAC
13304720DDD1
13304720DDD3
13304721AAABDA
13304721BCB
13304721CBA
13304721CBB1
13304721CBB2
13304721CBB3
13304722CCBC
13304722CCCBDB
13304722CCCC
13304727CCCBBD
13304728ABB
13304728ABCC
13304728ACABBD
13304728DCD1
13304728DDAADB
13304728DDCCBB
13304733ABAAAB
13304734ADCC2
13304802CBB
13304802CDD
13304802DAA
13304802DCD
13304802DDA
13304802DDC
13304802DDD
13304802DDD3
13304802DDD4
13304822AAA
13304826DCC
13404808CCCA
13404821BBB
13404821BBB2
mean

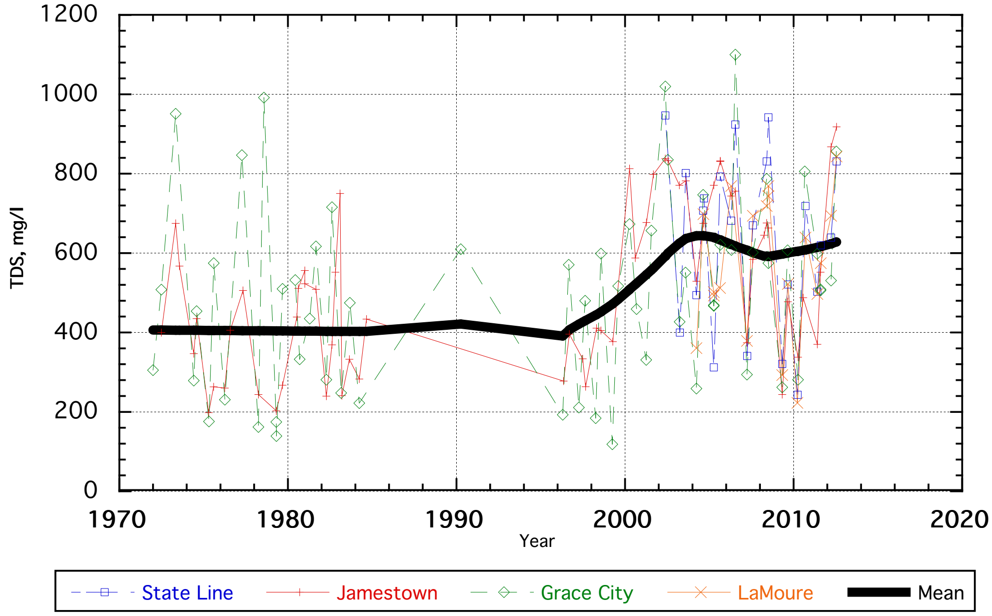

West Fargo North Aquifer
Total Dissolved Solids (TDS)
1600
1400
1200
1000
800
600
400
200
TDS, mg/l
1960
1970
1980
1990
2000
2010
2020
2030
Year
Moving Average Trend
These sites not included in average, likely a well malfunction.
13904903BBB
13904903BCC1
13904903BCC2
13904903BCC3
13904904ACC
13904904BCB2
13904905BAD
13904905BDA
13904905BDA2
13904905BDA3
13904905BDD
13904905BDD2
13904906AC
13904906ACA
13904906ACC
13904906ADB
13904906BDA
13904906BDD
13904906CDD
13904906DCD1
13904906DCD2
13904906DDC
13904907ABB2
13904908BA2
13904908BBA1
13904908BDA
13904908BDA2
13904908DCCD
13904908DCD
13904908DCD2
13904909BAB
13904909BBA
13904909BBA2
13904909BBB
14004905BBA
14004907ADD
14004907DAD3
14004907DCA1
14004907DDB2
14004907DDDB
14004908DDA
14004908DDA2
14004909CBB
14004916DDA
14004917BBB
14004918DDD
14004919BAB
14004919CDB2
14004919DDD
14004919DDD2
14004919DDD3
14004919DDD4
14004928CBB
14004929DDD
14004930ADD1
14004930ADD2
14004930BAAB
14004931CDC
14004932BBB
14004932BBB5
14004932BBB6
14004932BBB7
14004932BBC
14004933ABB
14004934BBB
14004934CCD
14104903CCC
14104916DDD2
14104921DAC2
14104922BBBD
14104927CBB
14104928ABB
14104928ABB2
14104928ACA
14104928BBB
14104928BDB
14104929BCB
14104930AAB
14104930ADA
14104930BBB
14104930DDD
14104932CCD
14104932DCC1
14104932DCC2
14104933CAAB1
14104933CAAB2
14104933CAB
14104933DCC
14204926BAA
14204927DDC2
mean

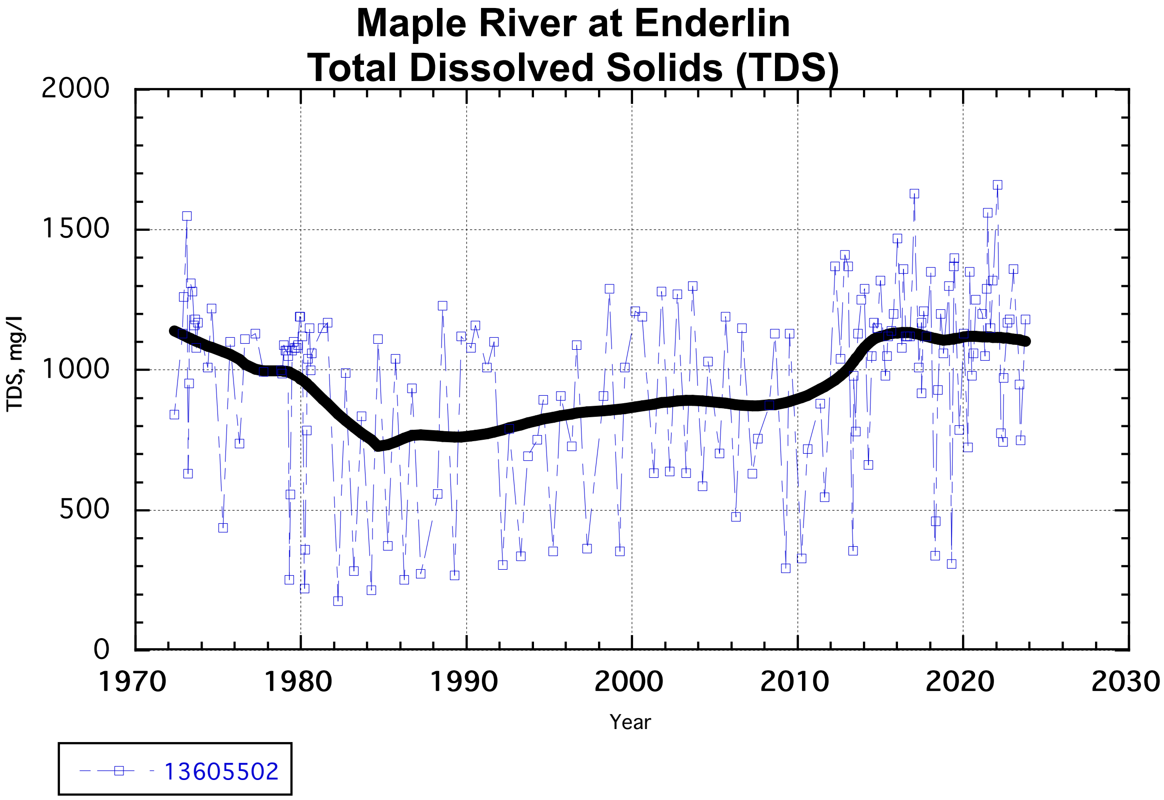

West Fargo South Aquifer
Total Dissolved Solids (TDS)
TDS, mg/l
800
700
600
500
400
300
200
100
1960
1970
1980
1990
2000
2010
2020
2030
Year
13704903BDD
13704915BAA
13804904AAA
13804904CCC
13804904DDD
13804909DDD
13804915BAB
13804922BBA1
13804922BBA2
13804927BAA
13804927BAB
13904909ADD
13904910CCC
13904916BAA
13904916BDC
13904916CDD
13904921DCD
13904922BBB
13904928DDD
13704903BDD3
13904929DDD1
13904929DDD2
13904909DDD3
13804935BBB
13904916CDD2
13804935CBBB
13904928BCC
13904932AACD
13704903BAA2
13704903BAD2
13704903BDD2
13904916BDCD1
13904916CDDD
13904922DCB1
13904928CBB2
13904933DDC
13804910CDC
13904927BAA
13804909DDD2
13804904BBB
13804904BBCA
13904921AAAC3
13904921AAAC4
13904921AAAC5
13904921AAAC9
13904928BAA
13904928ABB
13904929DDD3
13904916CDD3
mean

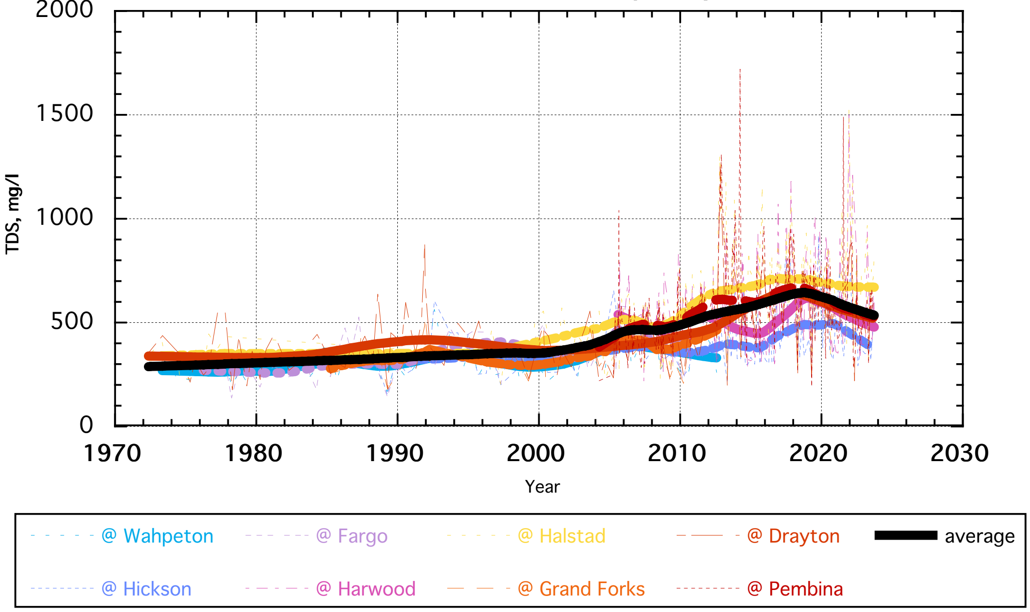

West Fargo Aquifer (North and South units combined)
Total Dissolved Solids (TDS)
TDS, mg/l
0
200
400
600
800
1000
1200
1400
1600
1960
1970
1980
1990
Year
2000
2010
2020
2030
13904906ADB
13904909DDD3
13904921AAAC9
13904928ABB
14004934BBB
14004908DDA
13904903BCC3
14104930AAB
14004930ADD1
14004919DDD2
14004919DDD4
13904908BDA
14004918DDD
14104928BBB
13904908DCCD
13904908DCD2
14004908DDA2
14104932CCD
13804909DDD
13904908BDA2
13804922BBA2
14104932DCC1
13904929DDD2
13904907ABB2
13904921DCD
13904922BBB
13804909DDD2
13904916CDD2
13904903BBB
13904921AAAC5
13804935BBB
13904908DCD
14004932BBB
14004905BBA
14004917BBB
13904916BDC
14004933ABB
14104930BBB
14104903CCC
13904906BDA
14004930ADD2
14004932BBB5
14104933DCC
13904906DCD1
13804904DDD
14004932BBB6
13704915BAA
13904909BBA
13804927BAB
13804904CCC
13904906BDD
13904906ACC
13904909ADD
13904929DDD1
13904910CCC
mean
13904928DDD
13904921AAAC3
13904916CDD

Appendix 8. Plots of TDS Trends from Selected Rivers.

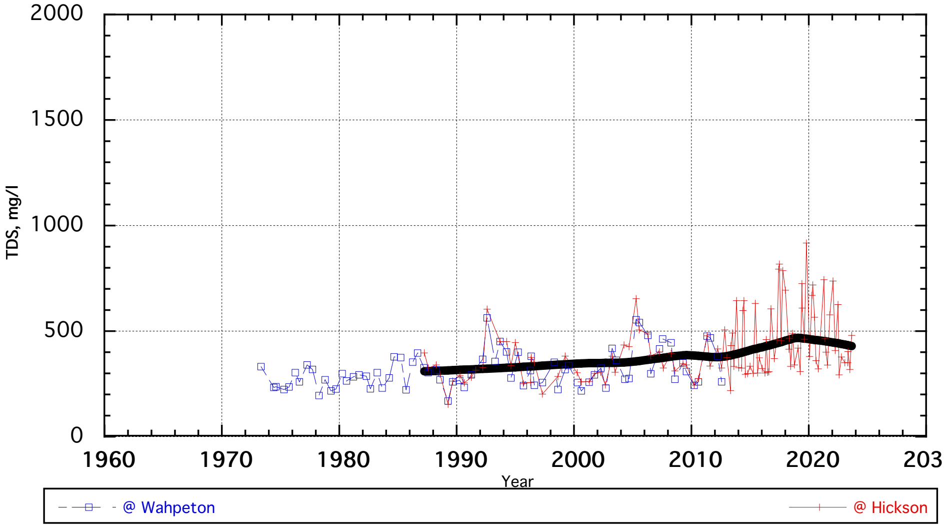

Forest River at Fordville
Total Dissolved Solids (TDS)


James River (all Stations)
Total Dissolved Solids (TDS)


Maple River at Enderlin
Total Dissolved Solids (TDS)
2000
1500
1000
500
0
TDS, mg/l
1970
1980
1990
2000
2010
2020
2030
Year
13605502

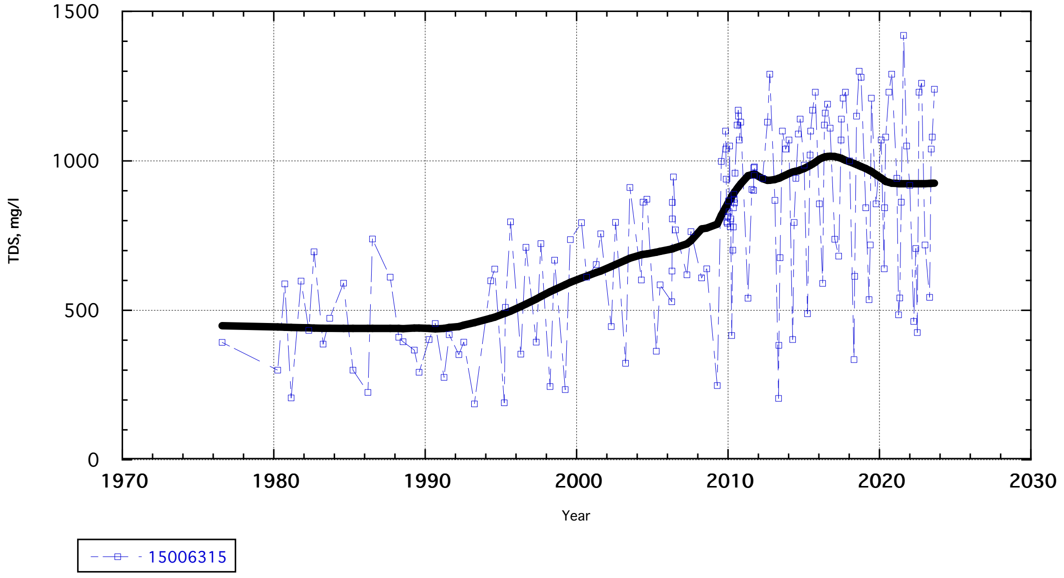


Red River Array and Trend
Total Dissolved Solids (TDS)

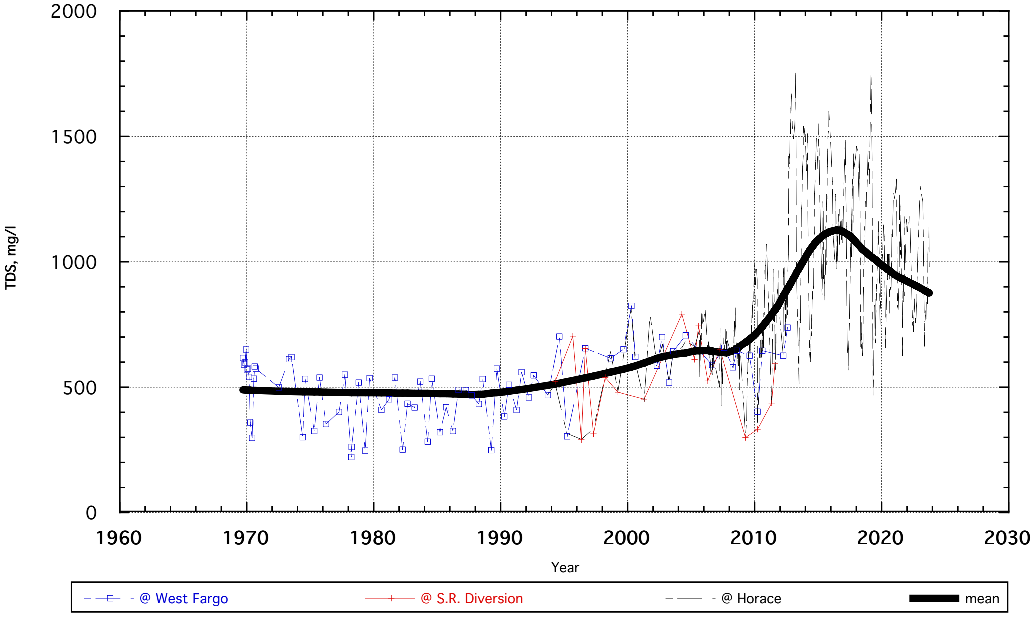


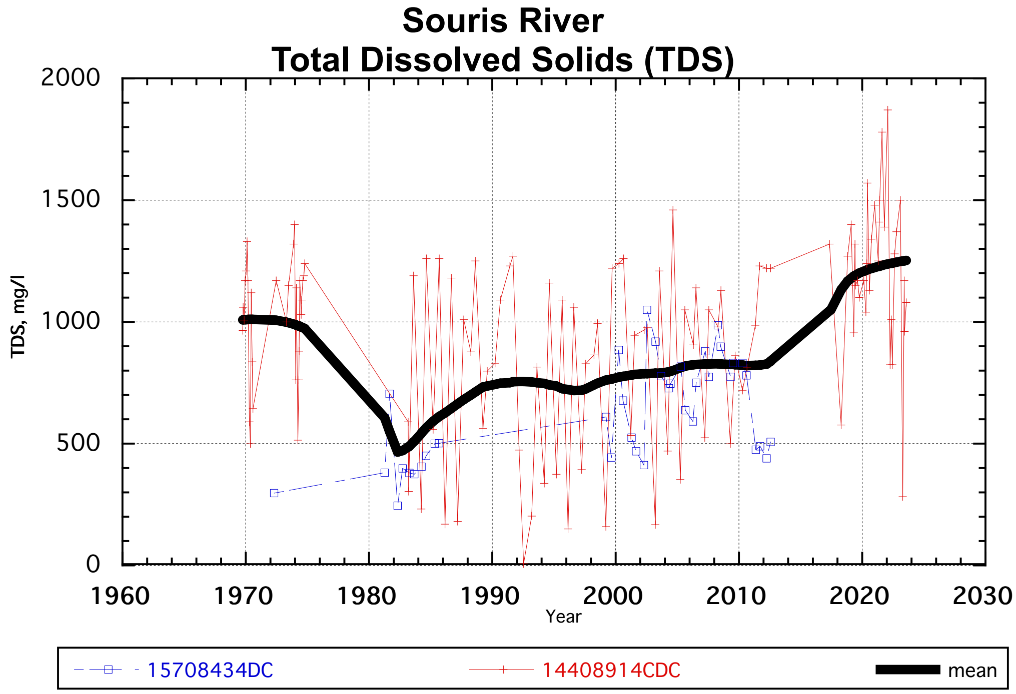
Red River near Wahpeton and Hickson
Total Dissolved Solids (TDS)

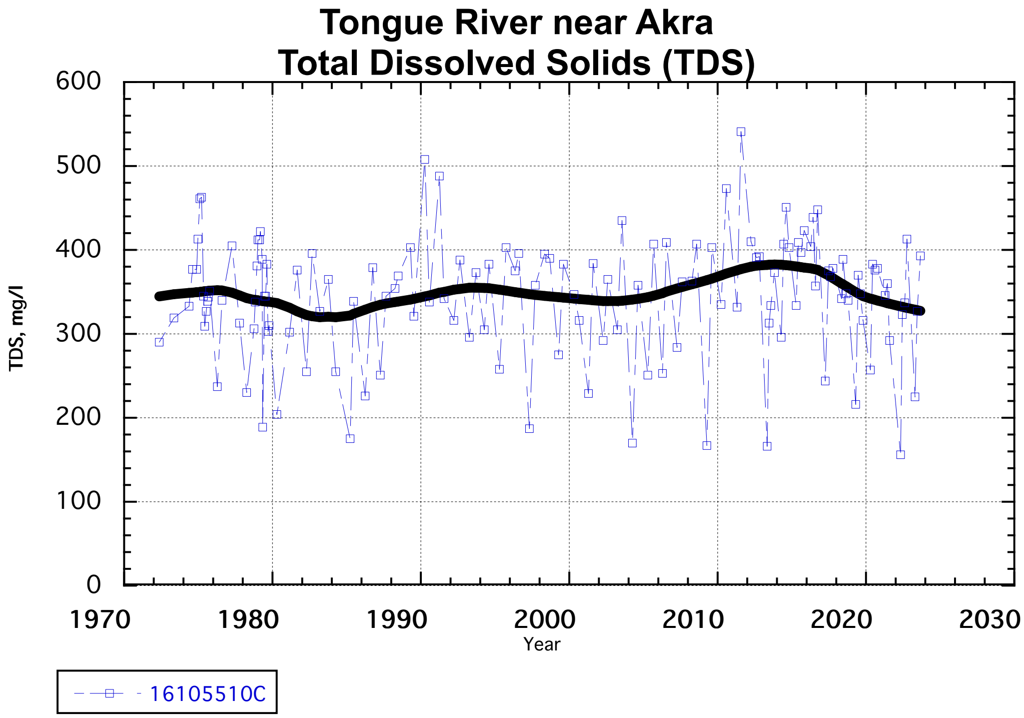
Sheyenne River at Warwick
Total Dissolved Solids (TDS)

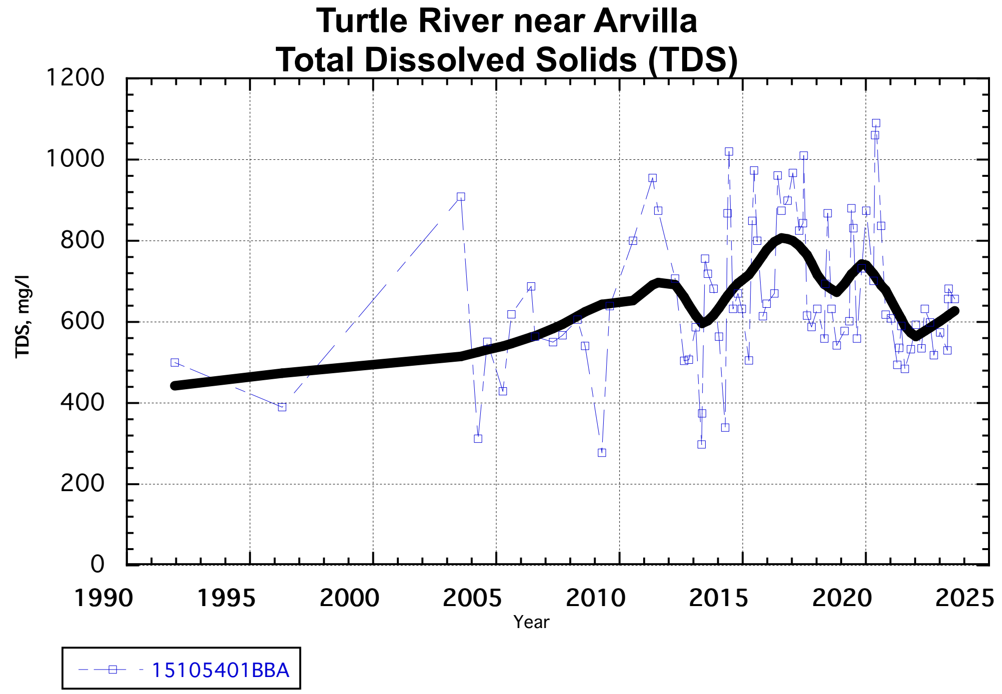


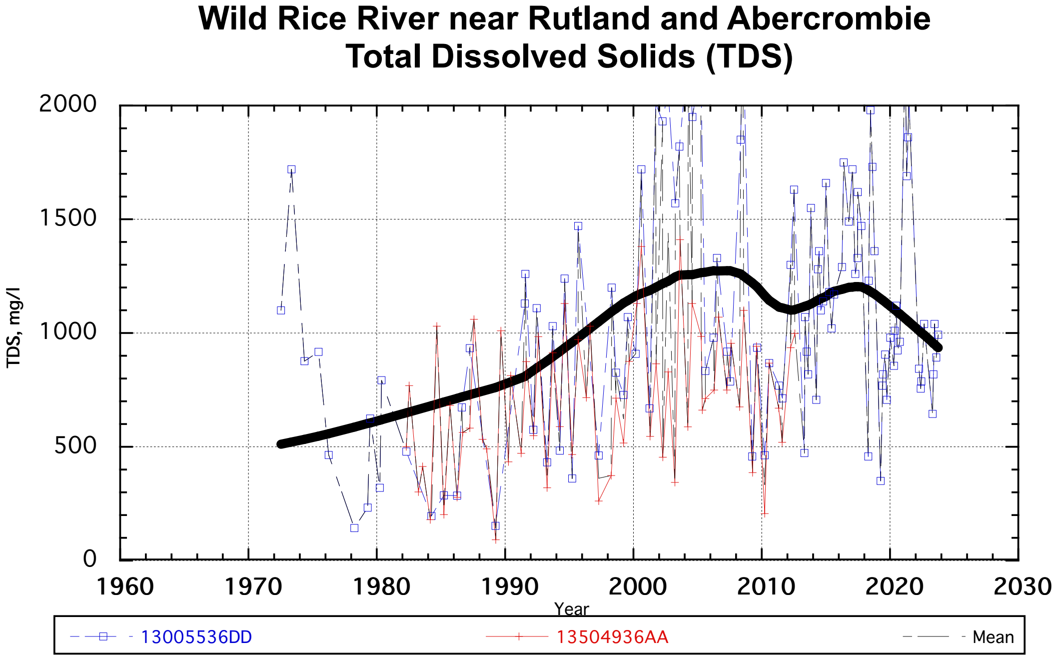
Sheyenne River near West Fargo
Total Dissolved Solids (TDS)

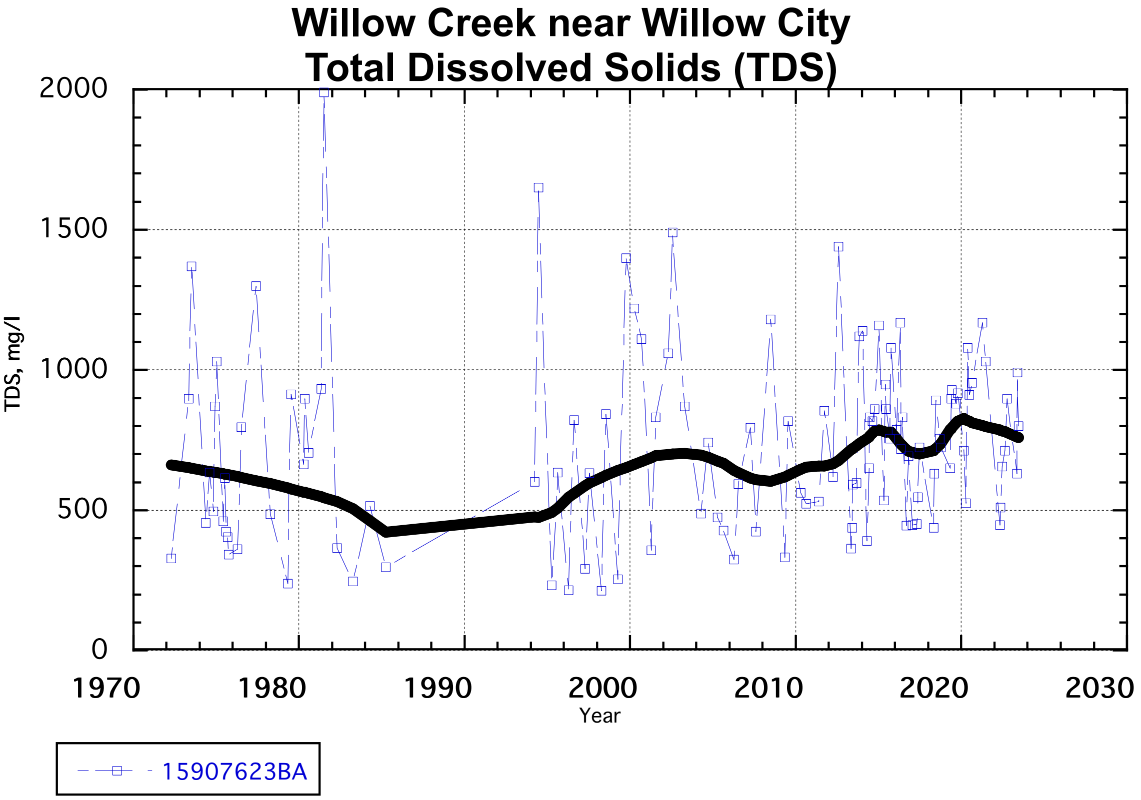



Souris River
Total Dissolved Solids (TDS)
TDS, mg/l
2000
1500
1000
500
0
1960
1970
1980
1990
2000
2010
2020
2030
Year
15708434DC
14408914CDC
mean

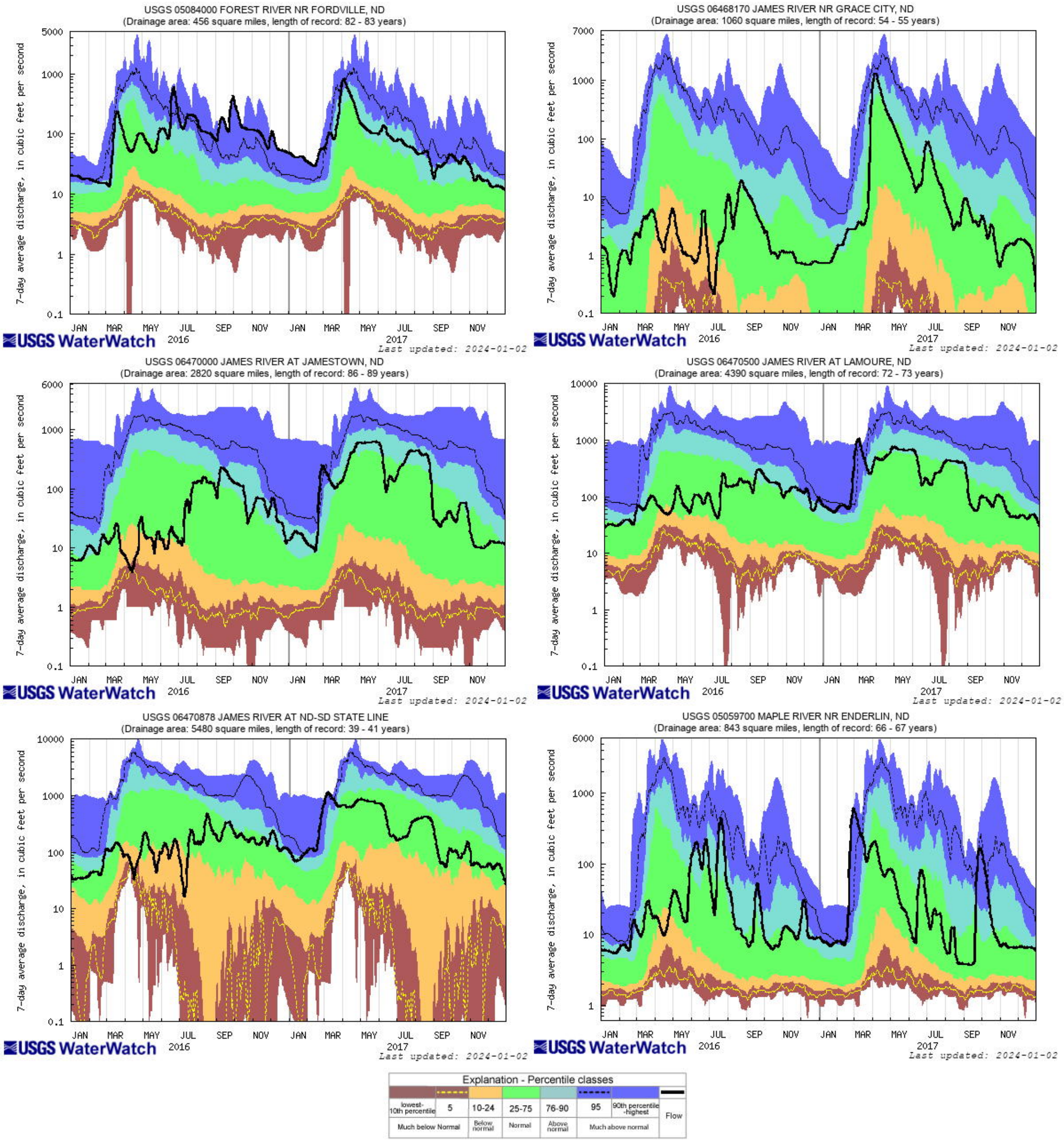

Tongue River near Akra
Total Dissolved Solids (TDS)
TDS, mg/l
600
500
400
300
200
100
0
1970
1980
1990
2000
2010
2020
2030
Year
16105510C

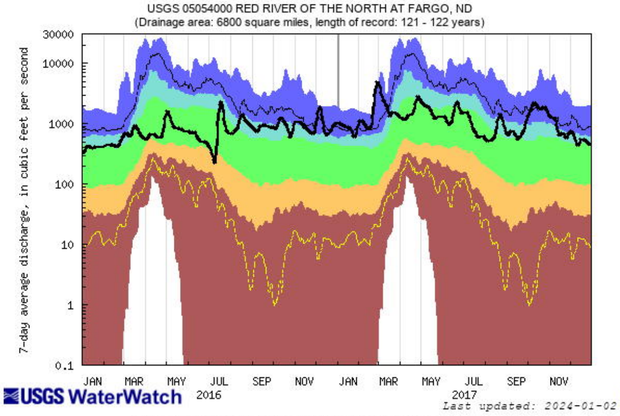

Turtle River near Arvilla
Total Dissolved Solids (TDS)
TDS, mg/l
0
200
400
600
800
1000
1200
1990
1995
2000
2005
2010
2015
2020
2025
Year
15105401BBA

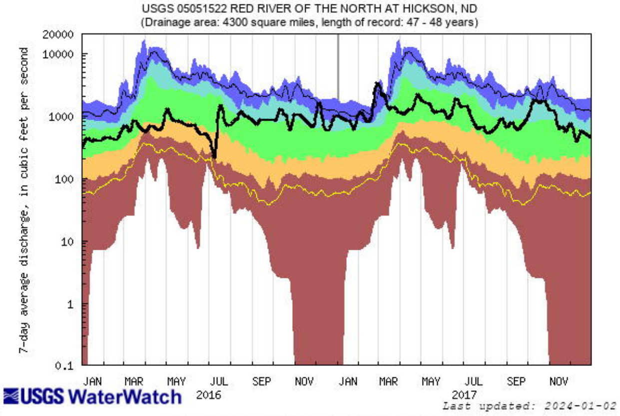

Wild Rice River near Rutland and Abercrombie
Total Dissolved Solids (TDS)
TDS, mg/l
0
500
1000
1500
2000
1960
1970
1980
1990
2000
2010
2020
2030
Year
13005536DD
13504936AA
Mean

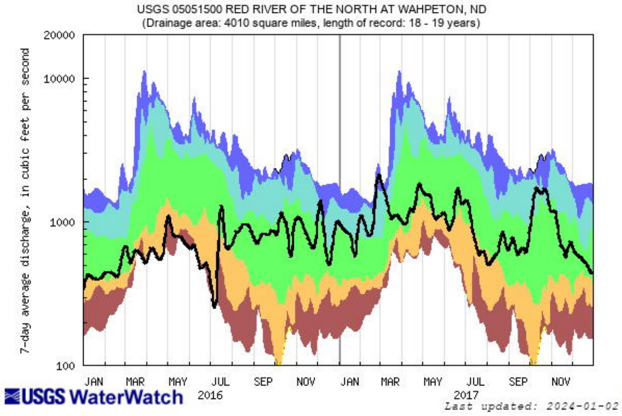

Willow Creek near Willow City
Total Dissolved Solids (TDS)
TDS, mg/l
2000
1500
1000
500
0
1970
1980
1990
2000
2010
2020
2030
Year
15907623BA

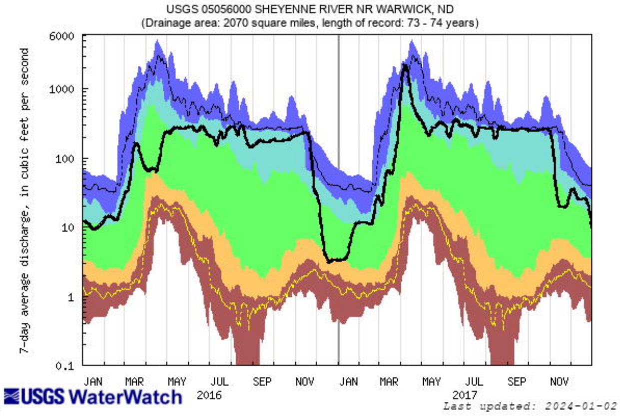
Appendix 9. Plots of Streamflow Duration Hydrographs from Selected Streamgage Sites (from waterwatch.usgs.gov).

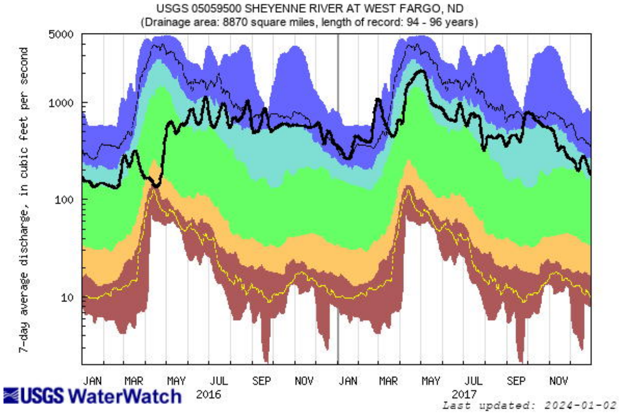




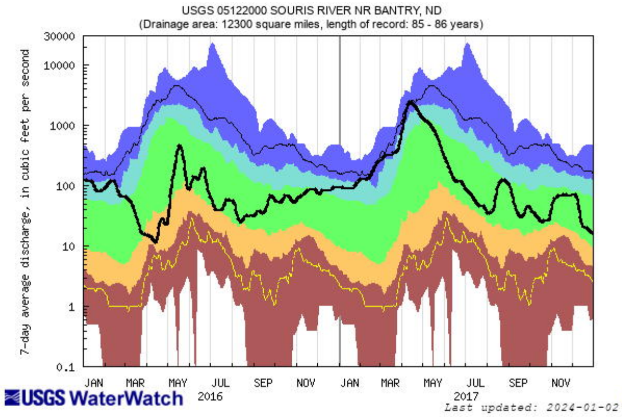


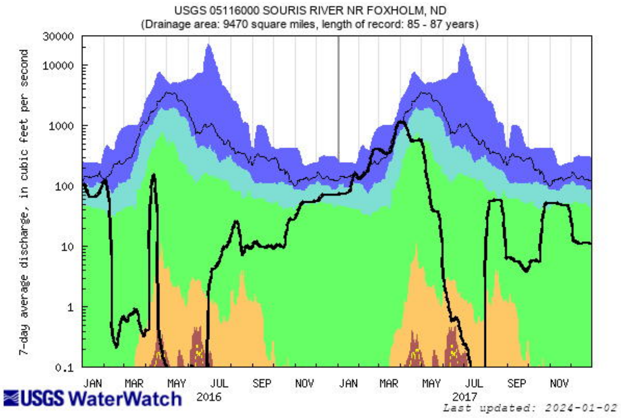


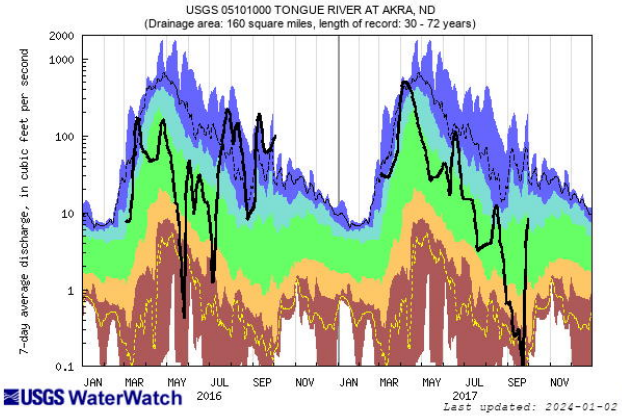


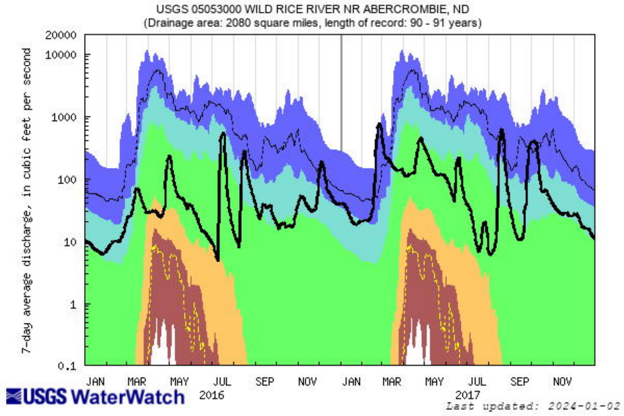


Explanation - Percentile classes							
🟫	- - -	🟧	🟩	🟦	- - -	🟦	▬
lowest-10th percentile	5	10-24	25-75	76-90	95	90th percentile -highest	Flow
Much below Normal		Below normal	Normal	Above normal	Much above normal		


USGS 05122000 SOURIS RIVER NR BANTRY, ND
(Drainage area: 12300 square miles, length of record: 85 - 86 years)


USGS 05116000 SOURIS RIVER NR FOXHOLM, ND
(Drainage area: 9470 square miles, length of record: 85 - 87 years)


USGS 05101000 TONGUE RIVER AT AKRA, ND
(Drainage area: 160 square miles, length of record: 30 - 72 years)


USGS 05053000 WILD RICE RIVER NR ABERCROMBIE, ND
(Drainage area: 2080 square miles, length of record: 90 - 91 years)

Explanation - Percentile classes

🟫	- - -	🟧	🟩	🟦	- - -	🟪	━
lowest-10th percentile	5	10-24	25-75	76-90	95	90th percentile -highest	Flow
Much below Normal		Below normal	Normal	Above normal	Much above normal		

ABOUT THE AUTHOR

Jon C. Patch is a Consulting Hydrogeologist. He formerly served as the Director of Water Appropriations at the North Dakota State Water Commission, a position he attained after over 30 years of service in the agency. He has been lead or co-lead investigator in numerous water resource investigations and groundwater studies, most notably as it relates to this investigation, an aquifer recharge and recovery project in a shallow unconfined aquifer in Grand Forks County, North Dakota.

- **Qualifications:**
    - M.Sc. in Environmental Engineering, North Dakota State University
    - B.Sc. in Geological Engineering, University of North Dakota
- **Professional Experience:**
    - Over 40 years of professional experience in the fields of engineering, hydrology and hydrogeology, 38 of which were at the North Dakota State Water Commission
    - Former Director of Water Appropriations
- **Expertise:**
    - Water resource management
    - Groundwater modeling
    - Water rights adjudication
- **Contributions:**
    - Established methodologies and technology in aquifer testing, water resource investigations, and monitoring
- **Certifications:**
    - Registered Professional Engineer, North Dakota