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February 28, 2020

Ms. Karlene Fine
Executive Director
North Dakota Industrial Commission
600 East Boulevard Avenue
State Capitol, 14th Floor
Bismarck, ND 58505-0310

Dear Ms. Fine:

Subject: EERC Report for Deliverable D1 under the Project Entitled "Produced Water Management Through Geologic Homogenization, Conditioning, and Reuse" Contract No. G-051-101; EERC Fund 24576

Attached please find the subject report.

If you have any questions, please contact me by phone at (701) 777-5421, by fax at (701) 777-5181, or by e-mail at kglazewski@undeerc.org.

Sincerely,

Kyle A. Glazewski
Senior Analyst

KAG/kal

Attachment

c: Brent Brannan, North Dakota Industrial Commission

BAKKEN WATER MANAGEMENT PRACTICES AND POTENTIAL OUTLOOK (UPDATE FEBRUARY 2020)

Project Title:
Produced Water Management Through Geologic Homogenization, Conditioning, and Reuse

Deliverable D1

Prepared for:

Karlene Fine

North Dakota Industrial Commission
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600 East Boulevard Avenue, Department 405
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Contract No. G-051-101

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EXECUTIVE SUMMARY

This report provides a snapshot of water management practices and trends associated with oil production in the North Dakota portion of the Bakken Petroleum System (Bakken). The report provides an interim update to the Energy and Environmental Research Center's (EERC) Bakken Water Management Practices and Potential Outlook[1] by summarizing changes that have occurred across the Bakken region since ~2015. The EERC has been awarded funding through the North Dakota Industrial Commission Oil and Gas Research Program and the U.S. Department of Energy's National Energy Technology Laboratory to assess the techno-economic viability of using geologic homogenization, conditioning, and reuse (GHCR) as a means of addressing the challenges associated with produced water management in the Williston Basin. This report updates water management practices, identifies changes in water management trends since the prior report, and identifies information gaps as a starting point in evaluating the current oil and gas industry water management practices associated with Bakken oil production as part of the project's techno-economic assessment.

From 2008 to 2020, North Dakota oil production has risen from ~35,000 barrels (bbl)/day to over 1.5 million bbl/day,[2] and continues to rise. With that increased oil production, there has been a commensurate increase in freshwater demand, Bakken produced water generation, and subsequent disposal. This update presents data through 2018, the most recent year of record with a complete data set available. Freshwater demand for oil and gas activity has increased from approximately 13.5 million bbl/yr in 2008 to 314 million bbl/yr in 2018.[3] Over the same time, in North Dakota produced water volumes from the Bakken have increased from 6.4 million bbl/yr to 485.6 million bbl/yr and saltwater disposal (SWD) related to conventional and unconventional oil and gas production has increased from 106.8 million bbl/yr to 601.9 million bbl/yr.[2] Despite increases, current state resources and infrastructure have adapted to manage the increased injection volumes. However, SWD injection has resulted in localized areas of high pressure in the Inyan Kara Formation, the primary geologic formation used for SWD,[4] which increases the economics and risk associated with drilling new Bakken production wells. As a result, alternative methods for managing produced water could improve long-term techno-economic sustainability of oil and gas production in North Dakota.

If viable, using a geologic formation as a natural medium for managing produced water recycling and reuse would represent a significant breakthrough in produced water management. A

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[1] Kurz, B.A., Stepan, D.J., Glazewski, K.A., Stevens, B.G., Doll, T.E., Kovacevich, J.T., and Wocken, C.A., 2016, A review of Bakken water management practices and potential outlook: Final report prepared for members of the Bakken Production Optimization Program, EERC Publication 2016-EERC-03-11, Grand Forks, North Dakota, Energy & Environmental Research Center, March.

[2] North Dakota Mineral Resources, 2020, Director's cut, December 2019 production, www.dmr.nd.gov/oilgas/directorscut/directorscut-2020-02-14.pdf (accessed February 2020).

[3] North Dakota State Water Commission, 2019, www.swc.nd.gov/info_edu/state_water_plan/archives/pdfs/2019_Water_Development_Plan.pdf (accessed February 2020).

[4] Schmidt, D.D., Mackay, B.A., Williams, B.L., Beck, F.E., Bell, A.B., Mcmahon, B.W., Bradley, H., Lian, E.G.W., 2015, Overcoming obstacles for produced water in Bakken well stimulations: Society of Petroleum Engineers, Presented at the SPE Hydraulic Fracturing Technology Conference, The Woodlands, Texas, February 3–5, 2015, SPE Paper: 173372-MS.

comprehensive produced water assessment will build upon the information contained in this report to provide an understanding of water management challenges and opportunities facing the Bakken region in western North Dakota. The water assessment will delve deeper into produced water chemistries, volumes, management practices, costs, and forecasts and will be reported in October 2020 via a produced water quality assessment report. This information will provide the metrics to evaluate the techno-economic viability of the GHCR concept, and inform key conditions that will limit or drive the commercial adoption of GHCR.

BAKKEN WATER MANAGEMENT PRACTICES AND POTENTIAL OUTLOOK (UPDATE FEBRUARY 2020)

INTRODUCTION

Water management in the North Dakota portion of the Bakken Petroleum System (Bakken) represents a significant economic and technical challenge for sustainable oil and gas production in western North Dakota. As the No. 2 oil-producing state in the United States, North Dakota has surpassed 1.5 million barrels/day of oil production (Department of Mineral Resources, 2020).With that level of production comes significant demand for freshwater use and produced water management (i.e., formation water and hydraulic fracture fluid flowback water), and subsequent disposal. Freshwater demand for oil and gas industry applications has increased from approximately 13.5 million barrels per year (bbl/yr) in 2008 to 314 million bbl/yr in 2018 (North Dakota State Water Commission, 2019). Similarly, reported produced water volumes from the Bakken Formation in North Dakota have increased from 6.4 million bbl/yr in 2008 to 485.6 million bbl/yr in 2018, while saltwater disposal (SWD) related to conventional and unconventional oil and gas production, which does not include enhanced oil recovery, in the state has increased from 106.8 million bbl/yr in 2008 to 601.9 million bbl/yr in 2018 (North Dakota Mineral Resources, 2020). To date, there have been over 14,000 producing Bakken wells in the state, and most recent projections estimate an additional 25,000 to 65,000 wells will be required to fully develop the play, resulting in sustained production growth for decades to come (Department of Mineral Resources, 2020).With the projected growth of oil and gas production, state and industry leaders will continue to adapt and seek solutions for the growing need for increased water supply and produced water management and disposal options.

The Energy & Environmental Research Center (EERC) has been awarded a project to assess the techno-economic viability of using geologic homogenization, conditioning, and reuse (GHCR) as a solution for produced water recycling and reuse. In order to perform a techno-economic evaluation of potential recycling and reuse options, an understanding of the current North Dakota produced water landscape is necessary including management practices, water volumes, water composition, and disposal practices. The EERC's Bakken Water Management Practices and Potential Outlook (Kurz and others, 2016) investigates the pertinent issues surrounding produced water management and serves as a useful starting point for a techno-economic analysis of produced water recycling and reuse. This report provides an update to the Bakken Water Management Practices and Potential Outlook (Kurz and others, 2016) report and will:

- Provide a snapshot of current water management practices and trends in the Bakken.
- Summarize changes in water use practices that have occurred since ~2015.
- Evaluate water supply capacity and produced water disposal facilities.
- Identify information gaps to be addressed through project efforts.

While this report will provide updates to produced water practices and trends, this is intended to serve as an interim report. As the aforementioned produced water recycling and reuse project continues, a produced water assessment will build on this report's findings. The EERC will engage with project partners, including Nuverra Environmental Solutions (Nuverra), the North Dakota

Industrial Commission (NDIC) Oil and Gas Research Program (OGRP), the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL), and select members of the EERC-led Bakken Production and Optimization Program (BPOP), to conduct an assessment characterizing the variability and distribution of Inyan Kara Formation and Bakken produced water quality in North Dakota. The assessment will incorporate available water composition data provided by project partners and be supplemented by the collection and analysis of water samples from partner well locations. A full water quality assessment report detailing the results of the produced water assessment will be completed by October 2020.

Throughout this document, reference will be made to data collected from "Bakken" wells. This is intended to indicate wells within the North Dakota portion of the Bakken petroleum system, which includes wells completed in the Three Forks Formation and the Bakken Formation. For consistency, data shown throughout the report will primarily focus on the 2008–2018 timeframe. While 2019 data are available, the nature of oil and gas data provides confidential status for new wells that can limit the completeness of the data set. Further, wells that came online in 2019 have limited production history to analyze, thus limiting the utility of analyzing produced oil or water trends (e.g., the first 18 months of oil production) for that year's wells. North Dakota State Water Commission (ND SWC) water use reporting for 2019 is not complete as final water volumes continue to get reported into early 2020 and have not been compiled at the time of writing this report. Therefore, information presented in this report is based on data sets through 2018, the most recent year of record that includes a complete, or near complete, data set. In the subsequent produced water quality assessment report, additional data will be incorporated as appropriate.

PREVIOUS WORK

As oil and gas development in the Bakken began to increase in the mid- to late 2000s, there was uncertainty in the region over the availability of freshwater resources needed to meet the increasing demands for hydraulic fracturing in North Dakota. There were a limited number of water depots, a relatively long and often contested permitting process for new water depots, concerns about depletion of fresh groundwater resources, and significant barriers from federal agencies regarding withdrawals from Lake Sakakawea. To help address that uncertainty, the EERC conducted two projects: a Phase 1 effort that investigated the potential to reuse flowback water from hydraulic fracturing operations (Stepan and others, 2010) and a Phase 2 effort that investigated the treatment of nonportable groundwater for use in hydraulic fracturing (Kurz and others, 2011). Subsequently, the EERC revisited Bakken-region water management practices in 2015 to evaluate the changes that had impacted industry's water management (Kurz and others, 2016).

The Phase 1 project investigated treatment and recycling of Bakken fracturing flowback water as a means to reduce the demand for freshwater and provide a supplemental supply near drilling and fracturing activities. The character of the fracturing flowback water with respect to both quantity and quality presented significant challenges for widespread water-recycling opportunities. A relatively small percentage (17% to 47%; 23% on average) of the water used for hydraulic fracturing was recovered in a 2- to 10-day time frame. Further, the dissolved solids levels in the flowback increased rapidly to observed levels as high as 220,000 mg/L. These factors presented significant challenges for developing cost-effective treatment strategies with the goal of producing freshwater, even with the most robust technologies available at the time, and widespread recycling was deemed unlikely to be economically viable.

The Phase 2 project, which was conducted from 2010 to 2011, in conjunction with Hess Corporation, successfully demonstrated the technical and economic feasibility of using reverse osmosis (RO) treatment of brackish groundwater from the Inyan Kara formation to produce freshwater for use in hydraulic fracturing. GE Water Process and Technologies (GE) was contracted to provide a mobile pretreatment and RO system. The project demonstrated greater than 70% treated water recovery and greater than 90% removal of major ions. Over 25 million gallons (595,000 bbl) of brackish groundwater was treated during the demonstration, producing over 17.8 million gallons (424,000 bbl) of high-quality freshwater for use in hydraulic fracturing. The brine concentrate generated from the process was reinjected into the subsurface.

In 2015, the EERC, through efforts conducted through BPOP, revisited the changes that occurred in the Bakken region that had impacted water use, handling, and the feasibility of recycling and reuse. These changes included:

- Hydraulic fracturing technology developments.
- Substantial improvements to the water supply and disposal infrastructure.
- Modifications to the water appropriations hierarchy.
- Changes in federal agency restrictions to waters of Lake Sakakawea.
- Increased produced water generation.
- Increased awareness of well maintenance water/brine dilution demands.
- Technological advancements that enable saline water use in fracturing fluids.
- Increased concern and public pressure over brine transport, storage, and spills.

HYDRAULIC FRACTURING DEVELOPMENTS AND IMPACTS ON FRESHWATER USE

Initial oil production from the Bakken Formation occurred through traditional vertical wells dating back to 1953 through 1985 (Pearson and others, 2013; Nordeng and LeFevre, 2011). In 1986, the first horizontal wells were drilled into the formation and generally consisted of upper Bakken shale horizontal wellbores producing from natural fractures with preperforated liners. In 2000, Bakken development began using stimulation practices for horizontal wells that were typically openhole, single-stage completions, which resulted in significant productivity gains when coupled with the use of uncemented liners.

By 2006, well stimulation practices entailed low-viscosity, high-rate injection of fracturing fluids that included freshwater with sand, friction reducers, antiscalants, surfactants, biocides, and oxidizing breakers. Single-stage fracture stimulations were the standard practice; fracturing fluid volumes averaged about 23,000 barrels (1 million gallons) of freshwater coupled with up to 2 million pounds of proppant (Nordeng and LeFevre, 2011); and pumping rates were typically on the order of 110 barrels per minute (bpm).

In 2007, the first multistage fracture was completed in the Parshall Field and was rapidly duplicated in other areas of the Bakken. By 2008, the average stage count per well was about ten (Nordeng and LeFever, 2011); this count steadily increased to an average of 32 stages per well by the end of 2014. As shown in Figure 1, average lateral lengths of wells have increased from about 7300 feet in 2008 to 9800 feet in 2018. The shift in average lateral lengths of ~7300 feet in 2008 to ~9500 feet in mid-2012 was a result of NDIC shifting the standard spacing units within the Bakken from 640 acres to 1280 acres, which enabled operators to drill 9500-foot laterals within the spacing unit (Pearson and others, 2013).

As a result, multiple factors, including improved stimulation techniques, increase in lateral lengths, and the number of fracture stages, the volumes of fluid (freshwater mixed with fracturing chemicals) injected per well have increased from about 20,000 barrels per well in 2008 to about 217,000 barrels per well in 2018 (Figure 1), based on over 13,000 wells completed over that time period. Part of this increase in water use is a result of the expanding use of slickwater stimulations, which, because of the low viscosity of the fracturing fluid system, require pumping 3 to 4 times the volume of water at a higher injection rate than gel-based stimulations. Injection rates for slickwater stimulations are typically in excess of 70 bpm, whereas gel-based stimulations range from 30 to 40 bpm (Pearson and others, 2013).

Figure 2 is a scatter plot showing the volume of fracturing fluid used for each Bakken well completed from 2008 through 2018. This chart, updated and modified from Pearson and others (2013), reflects the continued increase in slickwater-based stimulations that started to gain popularity ~2012, and fluid volumes exceeding 500,000 bbl/well are becoming increasingly common.

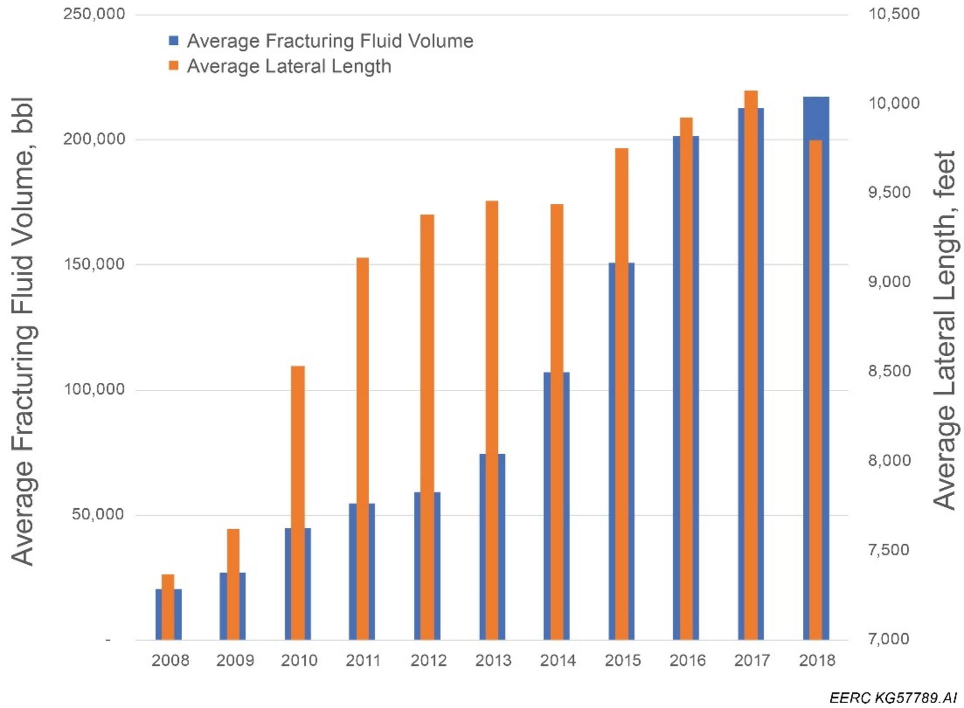

Figure 1. The average lateral lengths and fracturing fluid volume per well between 2008 and 2018 (data source: Enverus, 2019).

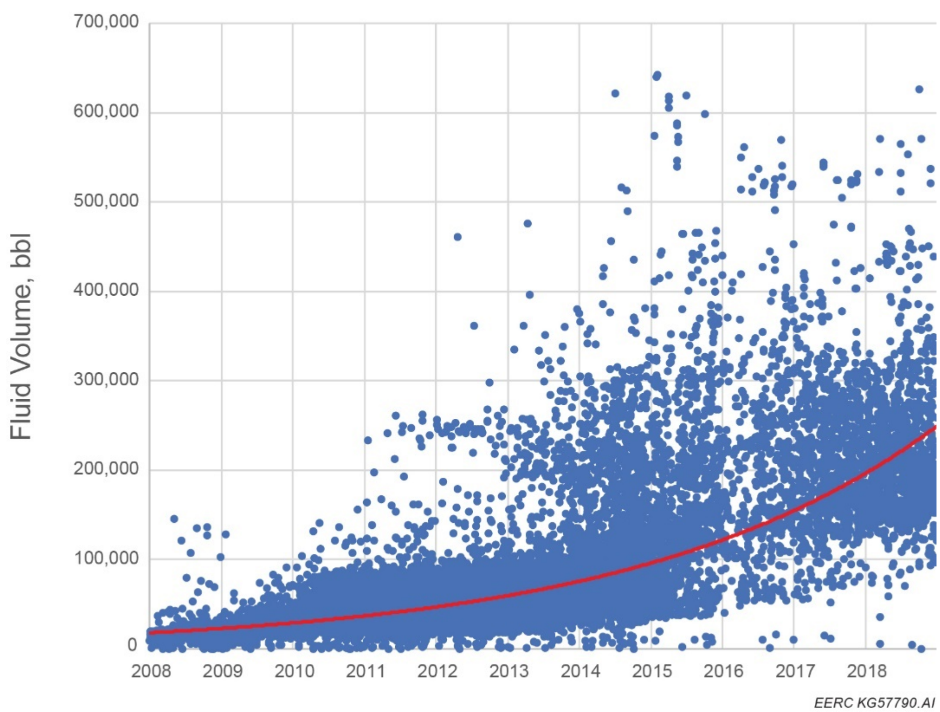

Figure 2. A plot of the fracturing fluid volume used for each Bakken well completed between 2008 and 2018 (data source: Enverus, 2019).

BAKKEN FRESHWATER DEMAND AND SUPPLY

The availability of freshwater was a key concern during the early stage of Bakken development. Over the 2006 to 2010 time frame, the rate of drilling and completion operations rapidly increased, and the development of water supply infrastructure was unable to keep up with the fast pace of development. While there were abundant supplies of freshwater available in Lake Sakakawea and the Missouri River system, there were a limited number of water depots, and they could supply only a fraction of the anticipated freshwater demands. Having water available in a timely manner was a critical element to completing operations and establishing mineral leases. As a result, water haulers would spend hours waiting in line to fill up at the available water supply locations and then transport that water over long haul distances.

The early concerns related to water availability have been tempered by infrastructure development and increased access to water supplies (i.e., Lake Sakakawea). Developments since 2016 to municipal water treatment plants, water supply pipelines, and industrial water use are described briefly in the following subsections.

Expansion of Municipal Water Treatment Plant Capacities

Water treatment plant upgrades and expansion of treatment capacity are critical in meeting increasing water demands for municipal, rural, and industrial uses. Construction continues across western North Dakota. A few examples of completed upgrades are given below.

- The city of Williston expanded the water treatment plant capacity to 21 million gallons per day (MGD) in 2017 (Williston Economic Development, 2020). Excess capacity from the treatment plant expansion supplies potable water to the Western Area Water Supply Project (WAWSP) (described below).

- As part of the Northwest Area Water Supply Project (NAWSP), the city of Minot Water Treatment Plant upgraded filtration, backwash, and controls systems (NAWSP handout, 2019).

- A supplemental water treatment plant in Dickinson came online in February 2018 as part of the Southwest Pipeline Project (SWPP) (Southwest Water Authority, 2020).

Water Supply Pipelines

The continued development and/or expansion of water supply pipelines are important for water supply in western North Dakota. The three major pipeline projects include WAWSP, the SWPP, and the NAWSP. While these pipelines were generally built to provide water for municipal and domestic use, the extra pipeline capacity has provided a valuable water supply resource for the oil and gas industry.

WAWSP is a domestic water supply project to meet the growing municipal, rural, and industrial water needs of northwestern North Dakota and supplies drinking water to over 70,000 people in Williston, Watford City, Ray, Tioga, Stanley, Wildrose, and Crosby and is estimated to provide water to 160,000 people by 2038 (Western Area Water Supply Authority, 2020). A key attribute of WAWSP is the ability to provide unused pipeline capacity during population growth to the oil and gas industry to pay for a majority of the project. Upgrades to and expansion of the Williston Water Treatment Plant allow the opportunity to provide potable water to WAWSP, along with groundwater supplied by the water treatment plant in Ray, North Dakota. Figure 3 is a map showing the infrastructure of the WAWSP (Western Area Water Supply Authority, 2020), and current interactive maps are available through the Western Area Water Supply Authority website (wawsp.com).

SWPP is a regional water supply system that draws water from Lake Sakakawea and serves more than 58,000 people through more than 5000 miles of pipeline in southwest North Dakota (Southwest Water Authority, 2020). The SWPP continues to expand through multiple construction projects as the Southwest Water Authority brings water to more people across southwestern North Dakota in need of freshwater (Southwest Water Authority, 2020). A map of SWPP is provided in Figure 4.

NAWSP is a water supply project to supply water to the people of northwestern North Dakota. Project construction began in 2002 but has been contested through a lawsuit brought both by Manitoba (biota transfer concerns) and the state of Missouri (negative depletion of water in the Missouri River). After court rulings and appeals, Manitoba ultimately settled with the Department of Interior and dropped its appeal. In May 2019, the District of Columbia Circuit Court of Appeals affirmed previous rulings in favor of the project, which allows the project to move forward (North Dakota’s Northwest Area Water Supply Project, 2019). Despite the legal challenges and delays, approximately 230 miles of pipeline are in place, along with pump stations and storage reservoirs, and an upgrade of Minot’s Water Treatment Plant has also been completed. When the project is ultimately completed, NAWSP is designed to supply 27 MGD to 81,000 people. Figure 5 is a map that shows the components of NAWSP.

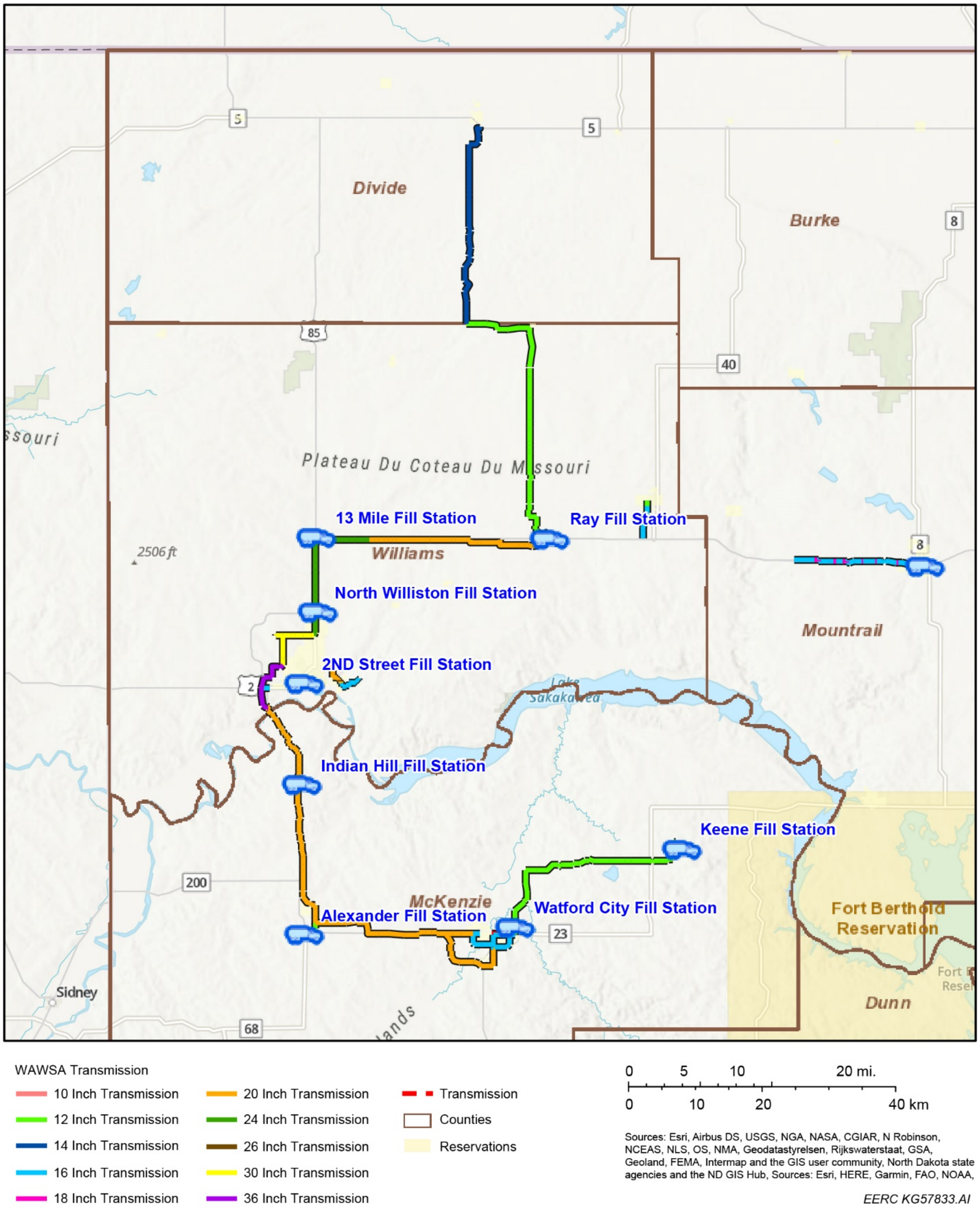

Figure 3. Major infrastructure components of WAWSP (image taken from Western Area Water Supply Authority website, 2020).

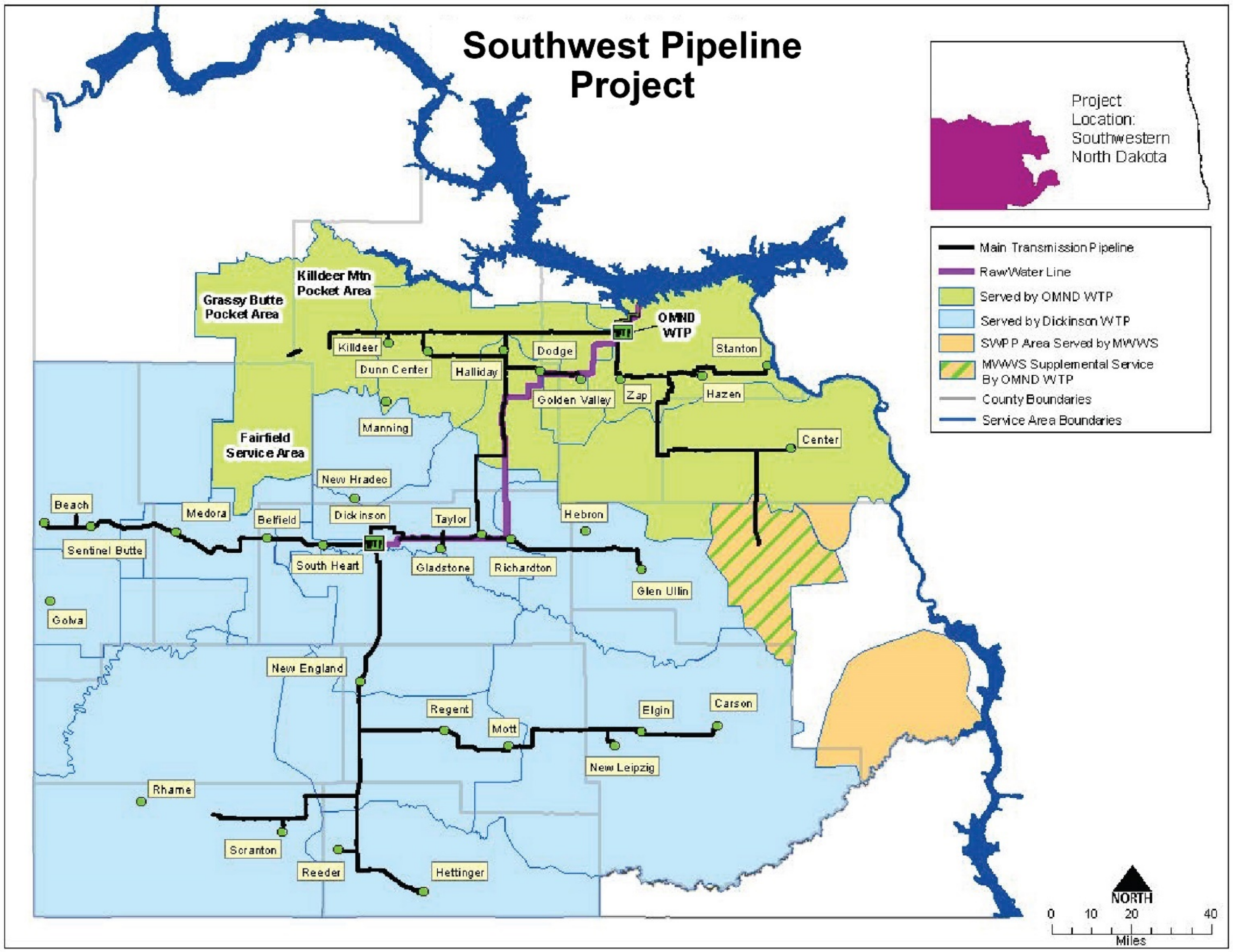

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Figure 4. The major infrastructure components of SWPP (image taken from Southwest Water Authority, 2020).

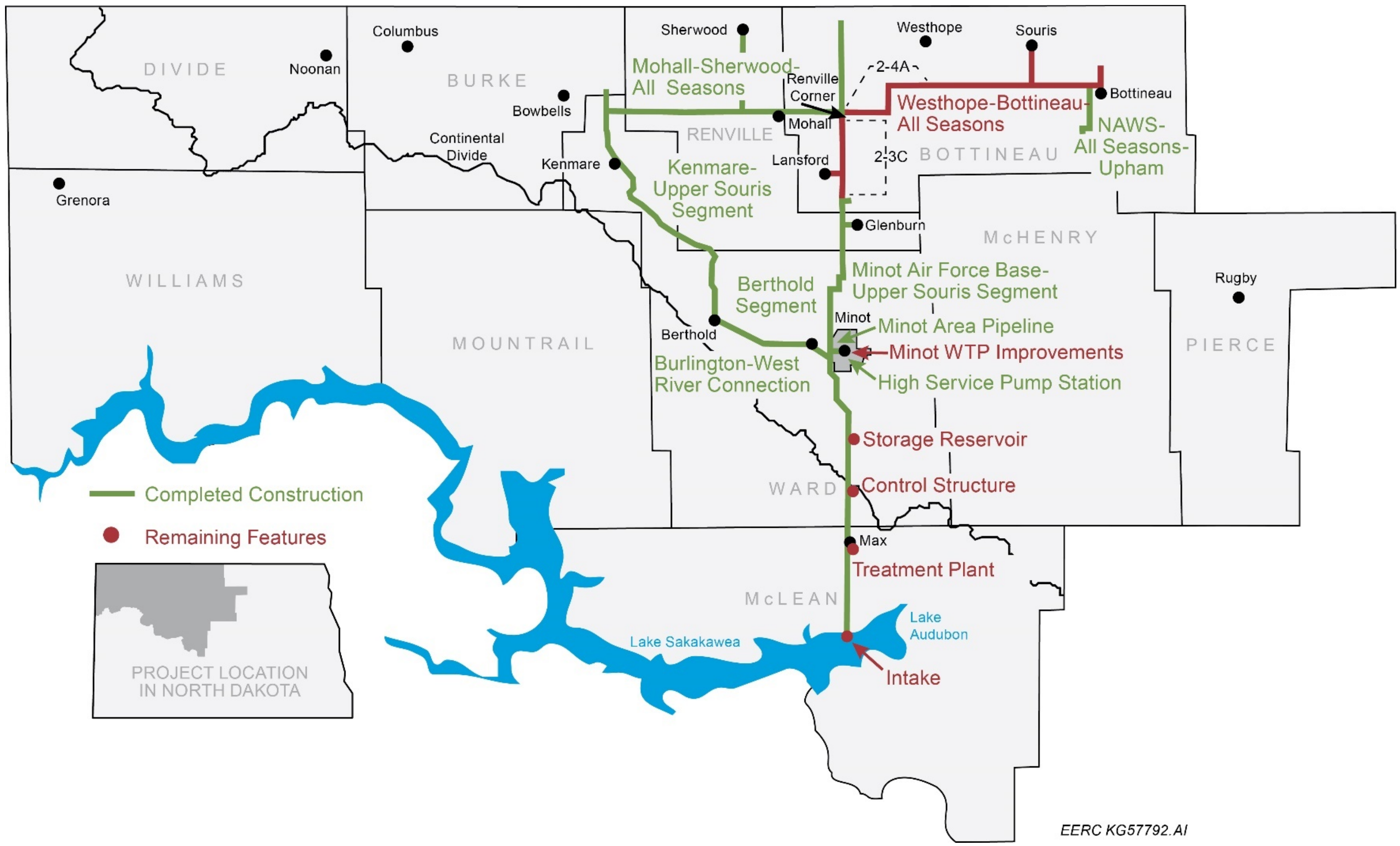

Figure 5. The major infrastructure components of NAWSP (North Dakota State Water Commission, 2019).

Changes in Industrial Water Use

The vast improvements that have been made to the water supply infrastructure in the Bakken region have helped industry meet water demand for oil and gas development. To assess the changes that have occurred in water use as a result of oil and gas development in the Bakken, one can review reported industrial water use from the North Dakota State Water Commission and reported water use for hydraulic fracturing activities from Enverus (Drilling Info) or FracFocus. Since 2008, oil and gas-related industry water use in the Bakken region has increased from just over 13.5 million barrels (~567 million gallons) in 2008 to 314 million barrels (~13.2 billion gallons) in 2018 (Figure 6) (North Dakota State Water Commission, 2019). Similarly, water use in hydraulic fracturing has increased from an average of 20,000 barrels per well (~840,000 gallons per well) in 2008 to 217,000 barrels per well (~9.1 million gallons per well) in 2018 (Figure 6).

Water permit location information was used to map the expansion of industrial water use permits over time. To better understand the difference in the various types of water permits issued by ND SWC (2019), a brief description is warranted. Permits for water use are broken into two types: water permits and temporary permits. Water permits are issued for more than one calendar year, whereas temporary permits are issued for only one calendar year. Temporary water permits are normally active as they are issued on a year-to- year basis. Temporary permits may also be

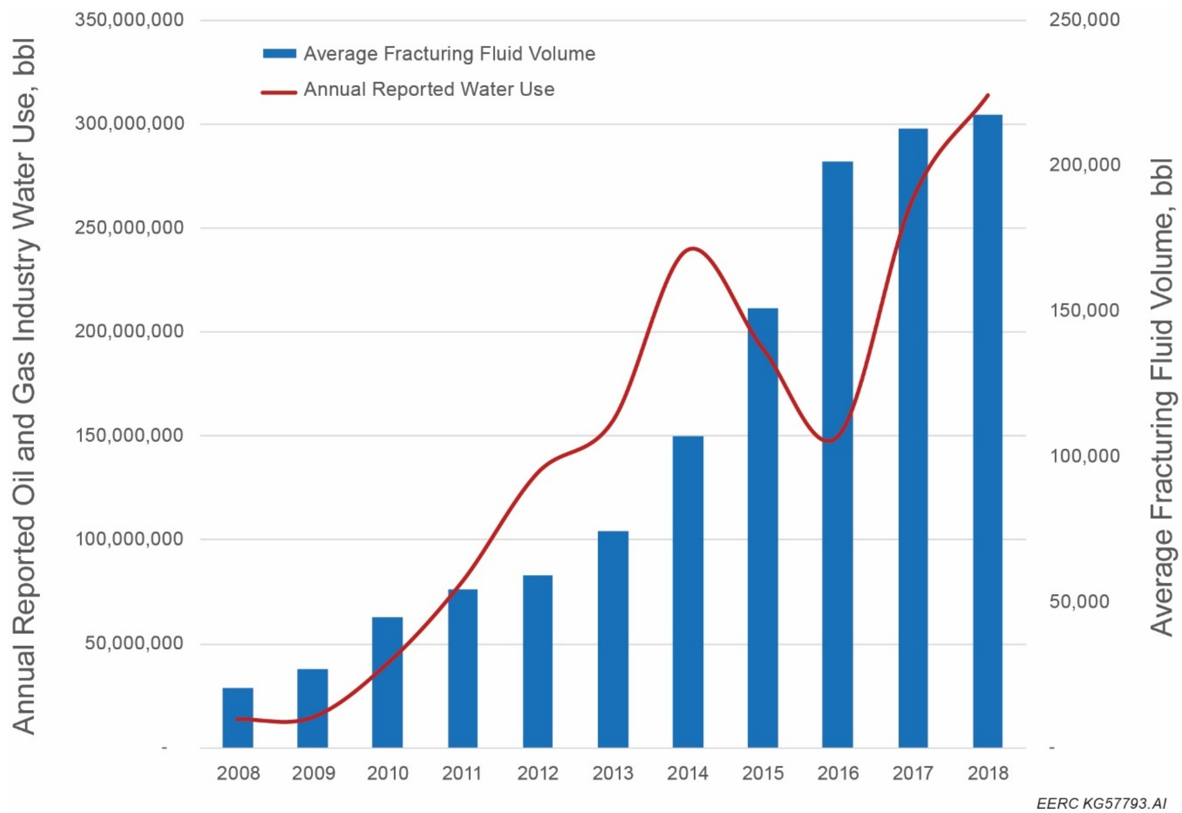

Figure 6. Plot of industrial water use from permitted sites for oil-related activities for 2008 through 2018 (data source: North Dakota State Water Commission, 2019, Enverus).

issued in cases where water is transferred from one designated use to another (i.e., irrigation to industrial), a practice that has become very common as the oil and gas industry's demand for water has increased.

As shown in Figure 7, the number of active industrial temporary water use permits increased from 17 permits in 2008 to 396 permits in 2018. These temporary permits show locations that are designated in the permit to the ND SWC as water depot locations or as permits specifically targeting oil development. Another way of tracking water distribution and changes to the water supply infrastructure is to look at only the water depot locations by current status such as existing, pending, and expired (Figure 8, data courtesy of ND SWC). The 565 undeveloped and application-pending water depots as of January 2020, as well as the number of temporary water permits, provide an indication that the freshwater supply infrastructure continues to expand to support Bakken development.

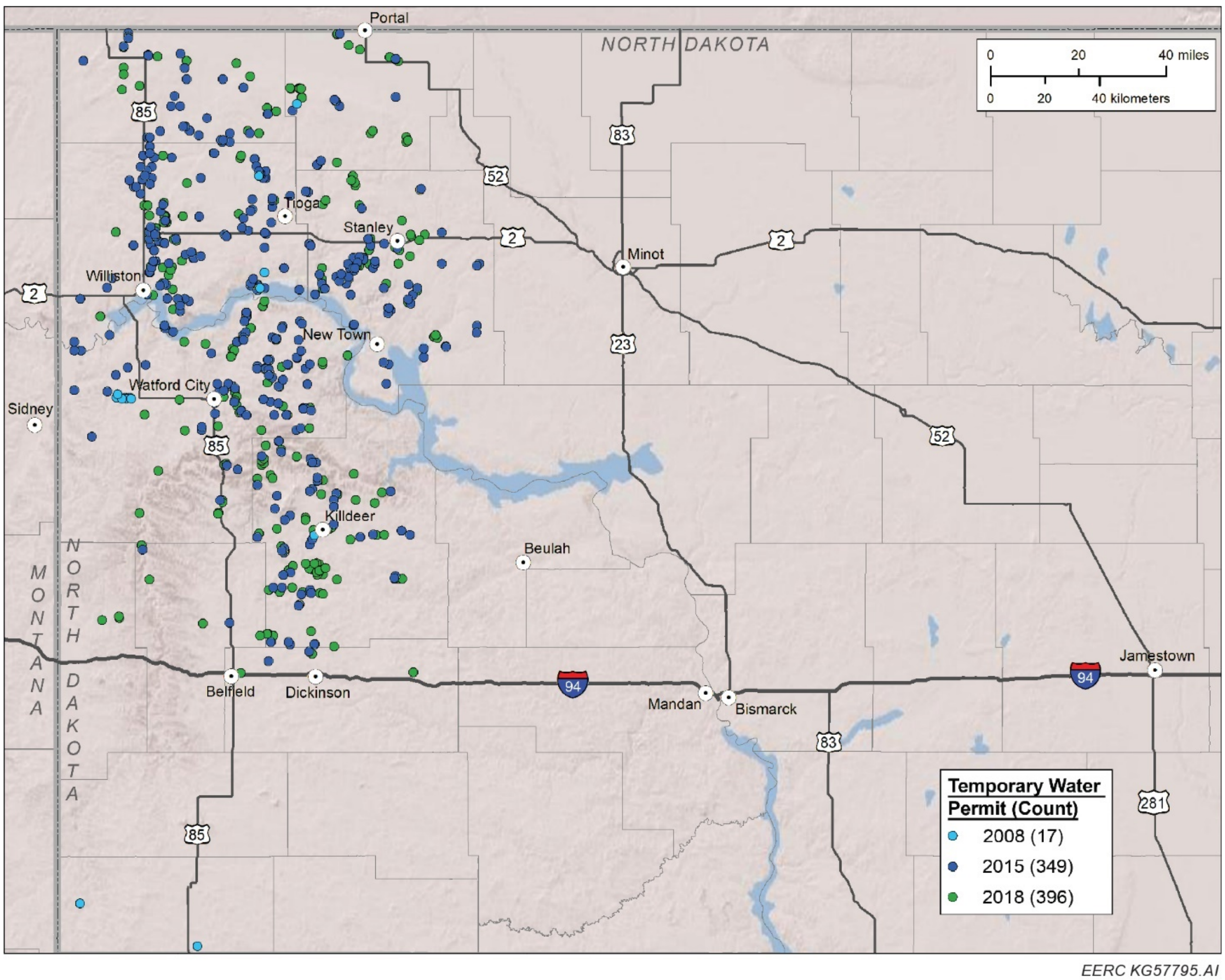

Figure 7. Temporary industrial water permit locations in 2008, 2015, and 2018 (data source: North Dakota State Water Commission, 2019).

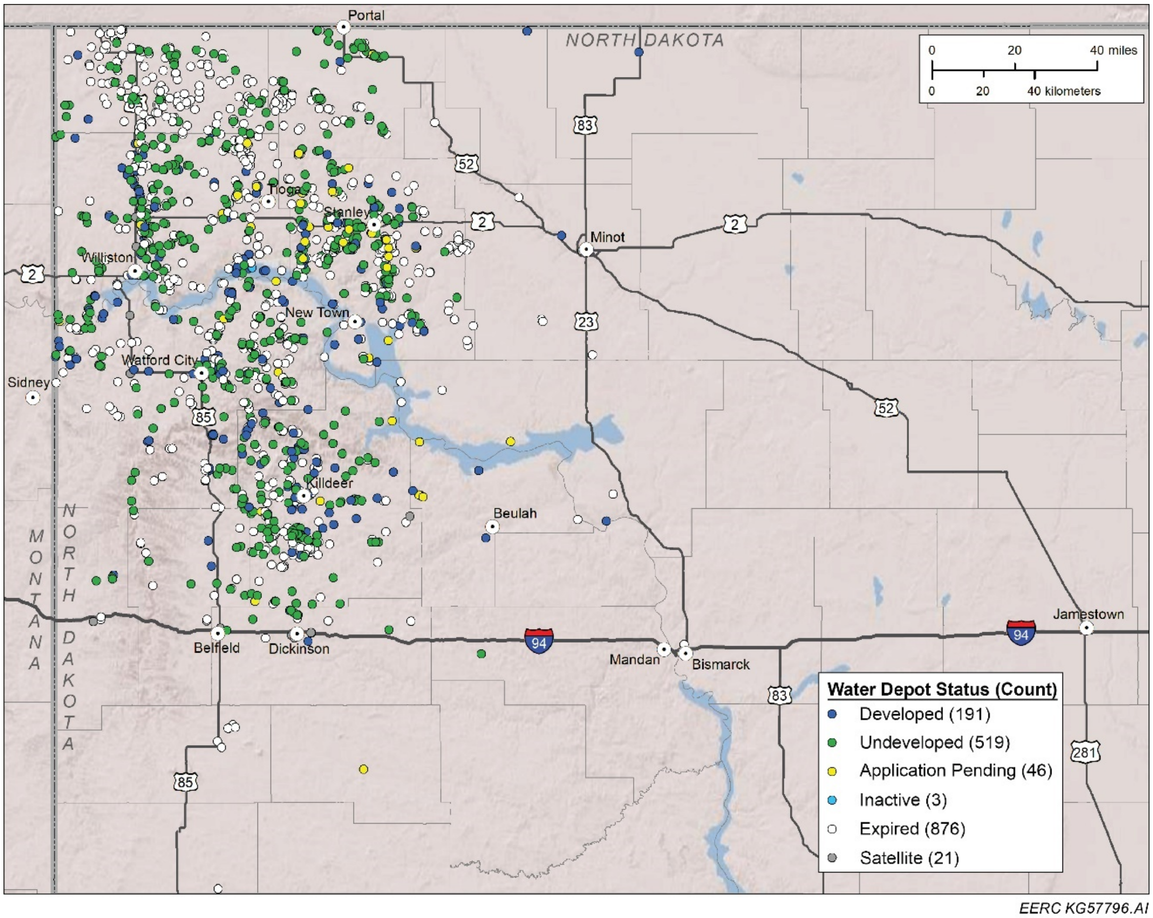

Figure 8. Water depot status across western North Dakota as of 2020 (data source: North Dakota State Water Commission, 2019).

TRENDS IN BAKKEN PRODUCED WATER GENERATION

Produced water volumes from the Bakken have increased from 6.4 million bbl/yr in 2008 to 485.6 million bbl/yr in 2018 (Table 1). While the increase is partially attributable to a greater number of wells, the average volume of water per well is also increasing (Table 1, Figure 9). Figure 10 illustrates the spatial and temporal changes in produced water generation. Wells in 2008 had relatively lower volumes of produced water, and a majority of the wells had a lower water cut[1] (Figure 11). In 2015, the number of wells and total water volumes per well increased (Table 1, Figure 10). There is also a greater geographic distribution of wells, revealing a "core area" with lower water cut compared to the surrounding area (Figure 11). In 2018, total water produced and average water volumes increased (Table 1, Figure 10), the "core area" of lower water cut is reduced in size (Figure 11), and the geographic distribution of wells has decreased as demonstrated by

[1] Water cut is calculated for each well and is the volume of water produced divided by the total volume of fluids (water + oil) produced.

Table 1. Trend in Produced Water Generation in the Bakken Since 2008*

Year	Total Producing Bakken Wells	Total Produced Water, million bbl	Average Annual Produced Water per Well, bbl
2008	893	6.4	7,167
2009	1,362	12.2	8,957
2010	2,141	32.6	15,227
2011	3,391	64.1	18,903
2012	5,189	135.3	26,074
2013	7,160	194.1	27,109
2014	9,339	283.9	30,399
2015	10,787	337.4	31,278
2016	11,444	313.3	27,377
2017	12,390	367.9	29,693
2018	13,595	485.6	35,719

* Data source: North Dakota Industrial Commission, 2019.

fewer wells to the north and south portions of the 2018 maps. The average water cut in 2018 across the basin is just under 50%, or about one barrel of water per barrel of oil. In Figure 12, the average water cut continues to increase each year, and the drop in water cut observed from the first quarter to the second quarter show the influence of flowback water over the first quarter of well production. Despite the increase in produced water, average cumulative oil production per well has continued to increase (Figure 13).

The trends in water production and water cut illustrated in the last five figures (Figures 9–13) and Table 1 can be attributed to several factors:

- Improved well stimulation techniques result in larger stimulated reservoir volumes and an improved ability to contact the pore fluids within the reservoir.

- A decrease in reservoir pressure over time may allow for increased migration of water from within the reservoir (Cenegy and others, 2011) or into the reservoir from the overlying Lodgepole Formation or the underlying Birdbear Formation, especially if fractures were generated during well stimulation that extend beyond the target reservoir.

- Changes in produced water volumes and water cut trends are illustrated in Figures 9 through 13 and Table 1. These trends are attributed to evolving operational practices and influenced by geologic properties that vary with well location. Factors influencing these trends will be investigated through the produced water quality assessment.

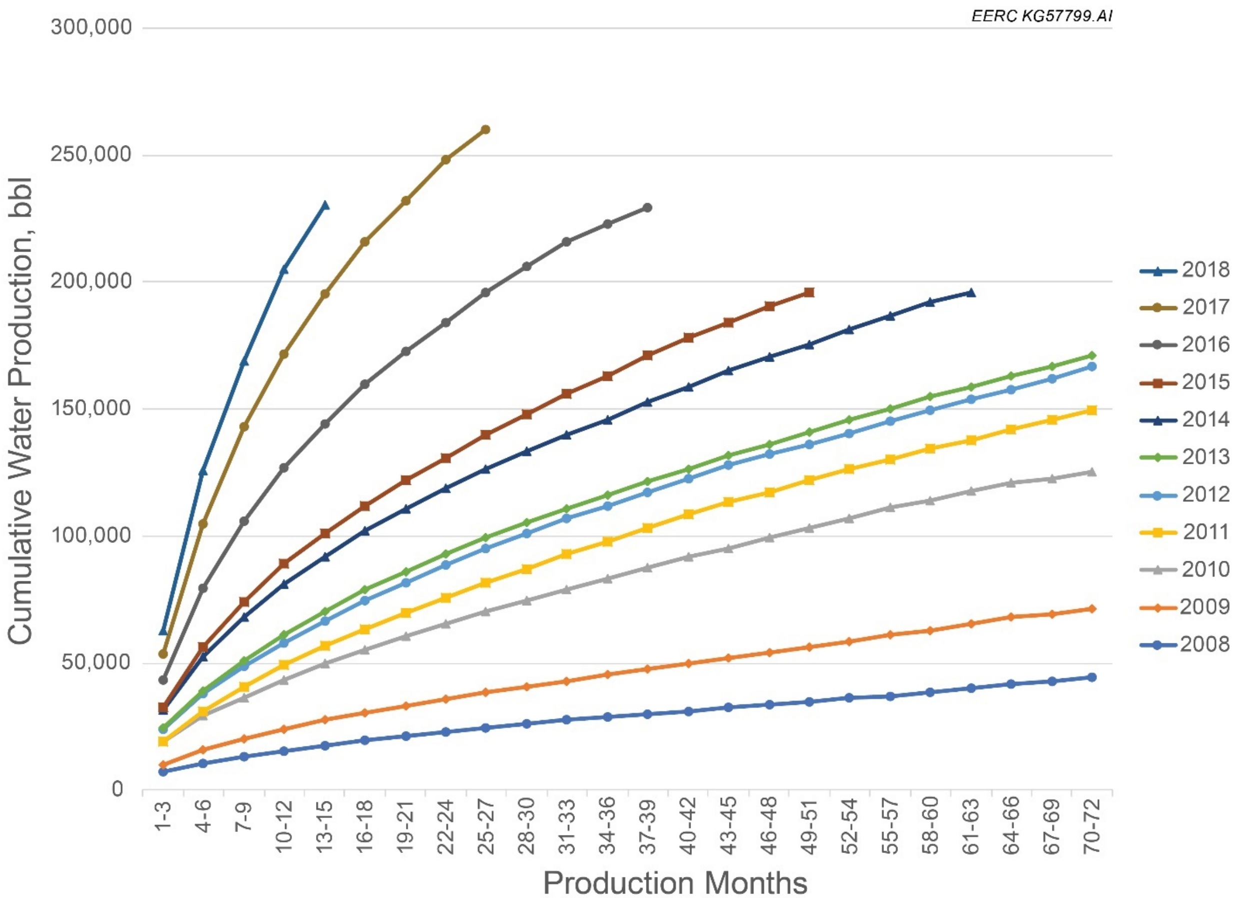

Figure 9. Average cumulative water production by quarter for wells completed between 2008 and 2018 (data source: North Dakota Industrial Commission, 2019).

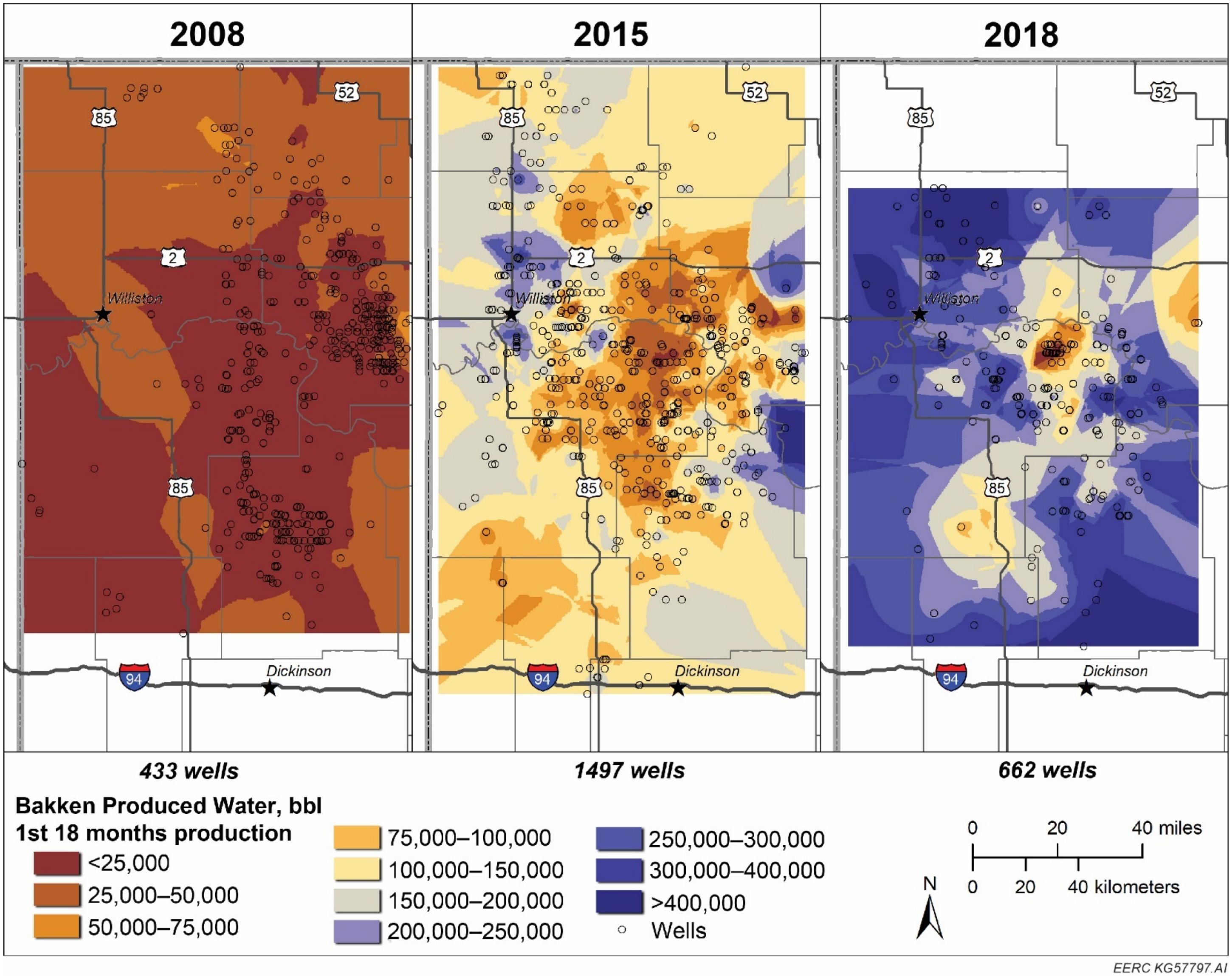

Figure 10. Average produced water generated from Bakken wells during the first 18 months of production (data source: North Dakota Industrial Commission, 2019).

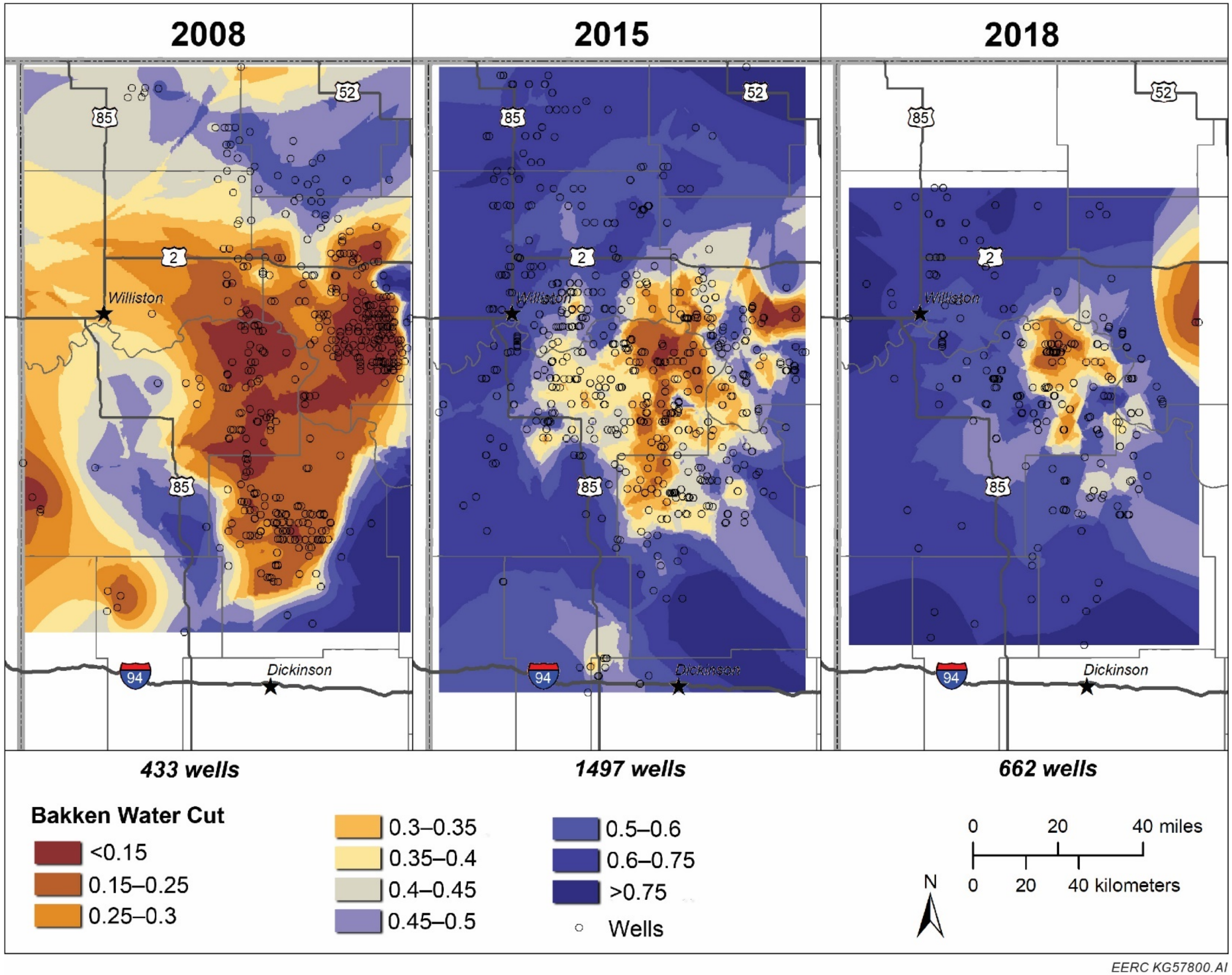

Figure 11. Average water cut of Bakken and Three Forks wells during Months 2 through 19 of production (data source: North Dakota Industrial Commission, 2019).

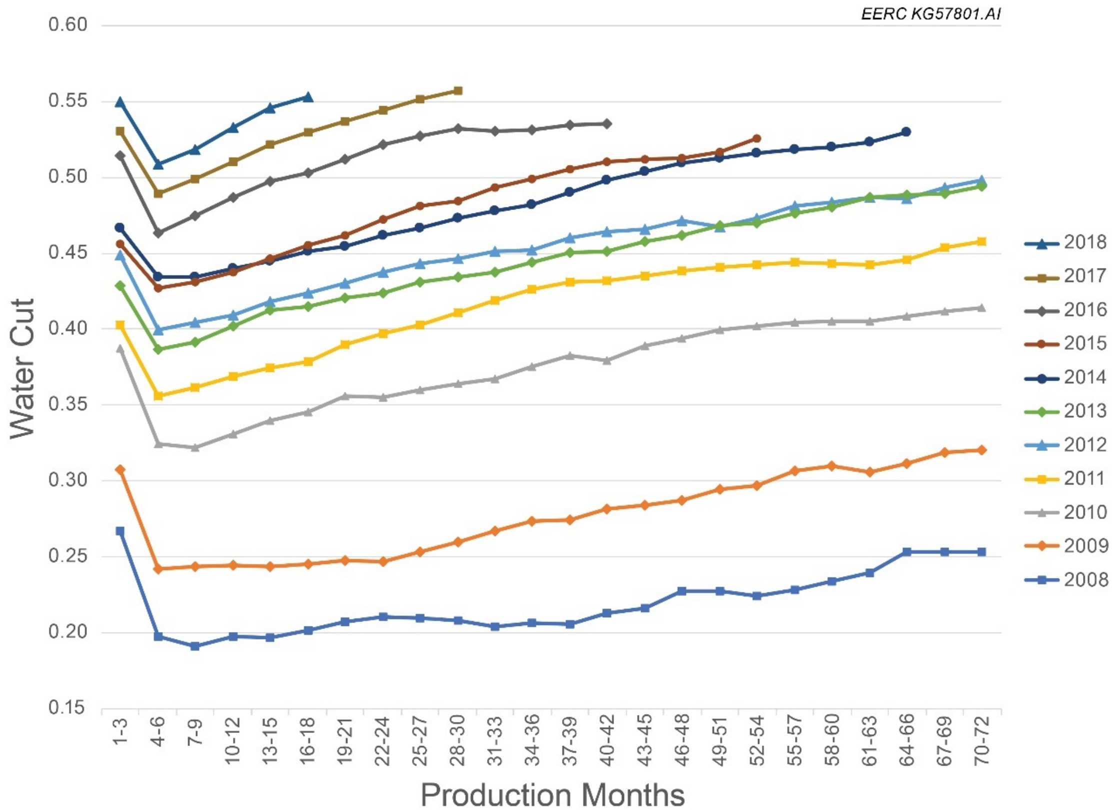

Figure 12. Average water cut by quarter for wells completed between 2008 and 2018 (data source: North Dakota Industrial Commission, 2019).

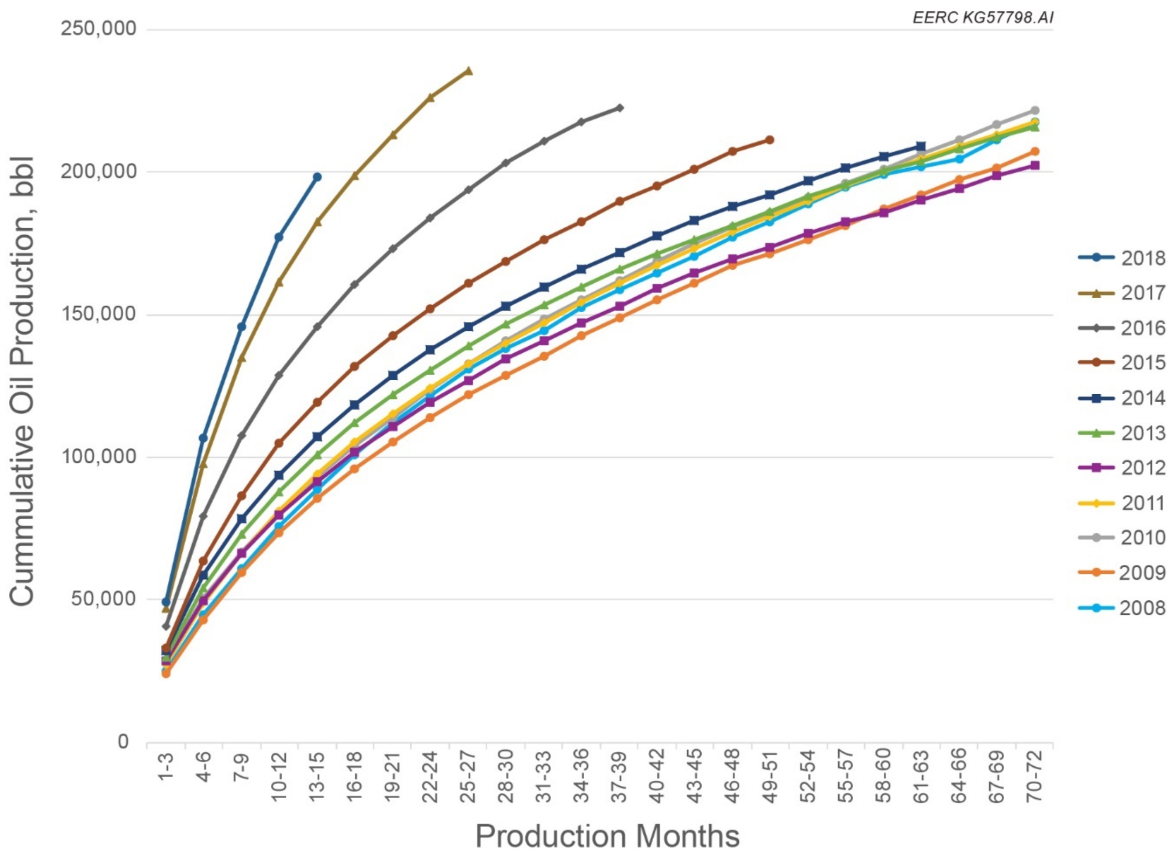

Figure 13. Average cumulative oil production by quarter for wells completed between 2008 and 2018 (data source: North Dakota Industrial Commission, 2019).

PRODUCED WATER DISPOSAL

SWD Trends

The number of water disposal wells and the annual saltwater injection volumes (including produced water and flowback water) have risen proportionally to annual produced water volumes in the North Dakota portion of the Bakken. Just as freshwater supply locations have increased as a result of the expanding oil and gas industry, so has the number of produced water disposal wells in the Bakken region. Typical transport mechanisms for moving produced water generated from Bakken wells to SWD well locations are semi-tractor trailers and saltwater pipelines. Saltwater pipelines are used to collect and aggregate produced water from various operators' well locations to operator-owned or third party-owned SWD sites. Trucking volumes are restricted to tanker capacity and weight restrictions with typical hauling volumes of approximately 75 to 140 bbl per truck, depending on the weight of the fluid. As a result of these restrictions and increasing SWD demand, saltwater pipeline use has increased.

Table 2 and Figure 14 show the total injection volumes for SWD wells in North Dakota from 2008 through 2018. The primary injection zones are the Dakota Group, the Minnelusa Group, and the Madison Group (Figures 15 and 16) . As of 2018, the total disposal volumes were more than 600 million bbl/yr, 95% (by volume) of which was injected into the Dakota Group, which contains the Inyan Kara Formation. To date, over 5.8 billion barrels have been injected into the Inyan Kara Formation (North Dakota Industrial Commission, 2019).

Table 2. Total SWD Injection Volumes from 2008 to 2018 (million bbl/year)*

	Dakota Group	Madison Group	Minnelusa Group	Other	Total
2008	84.7	1.1	17.9	3.1	106.8
2009	89.6	1.2	18.8	4.2	113.8
2010	109.6	1.2	19.6	5.1	135.5
2011	147.4	1.3	19.0	6.6	174.3
2012	215.9	1.4	14.9	7.7	239.9
2013	277.3	1.2	14.4	8.4	301.3
2014	361.1	1.0	18.1	7.9	388.1
2015	413.3	0.9	18.6	8.0	440.8
2016	383.0	0.9	17.0	9.0	409.9
2017	439.1	0.8	16.2	8.7	464.8
2018	574.3	0.8	17.3	9.5	601.9

* Data source: North Dakota Industrial Commission, 2019.

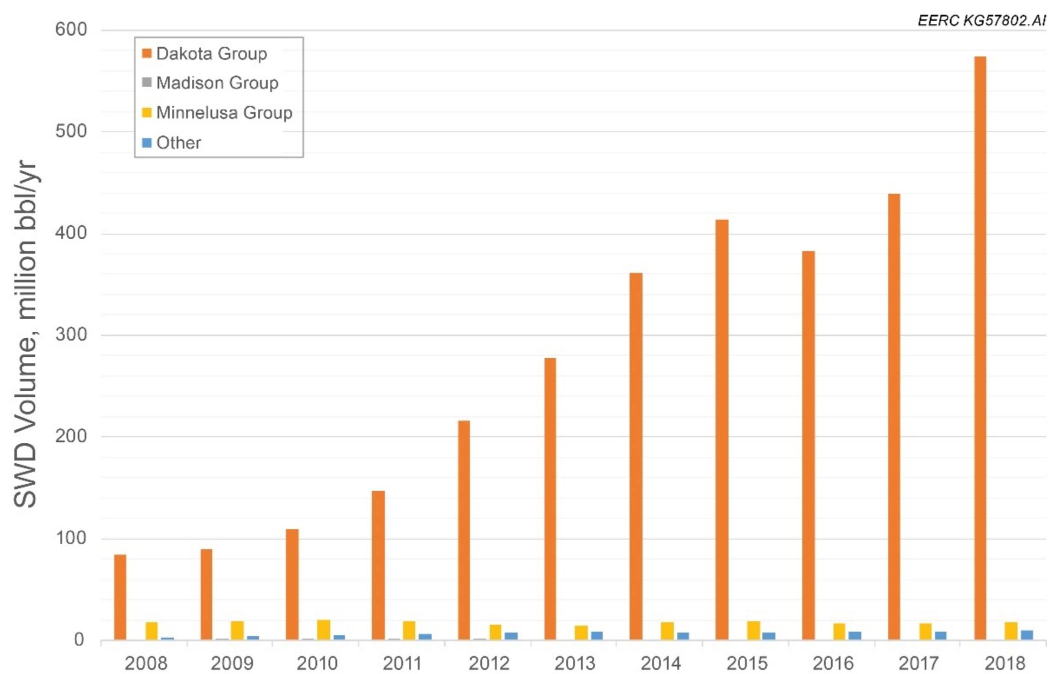

Figure 14. Annual SWD injection volume by geologic group from 2008 to 2018 (data source: North Dakota Industrial Commission, 2019).

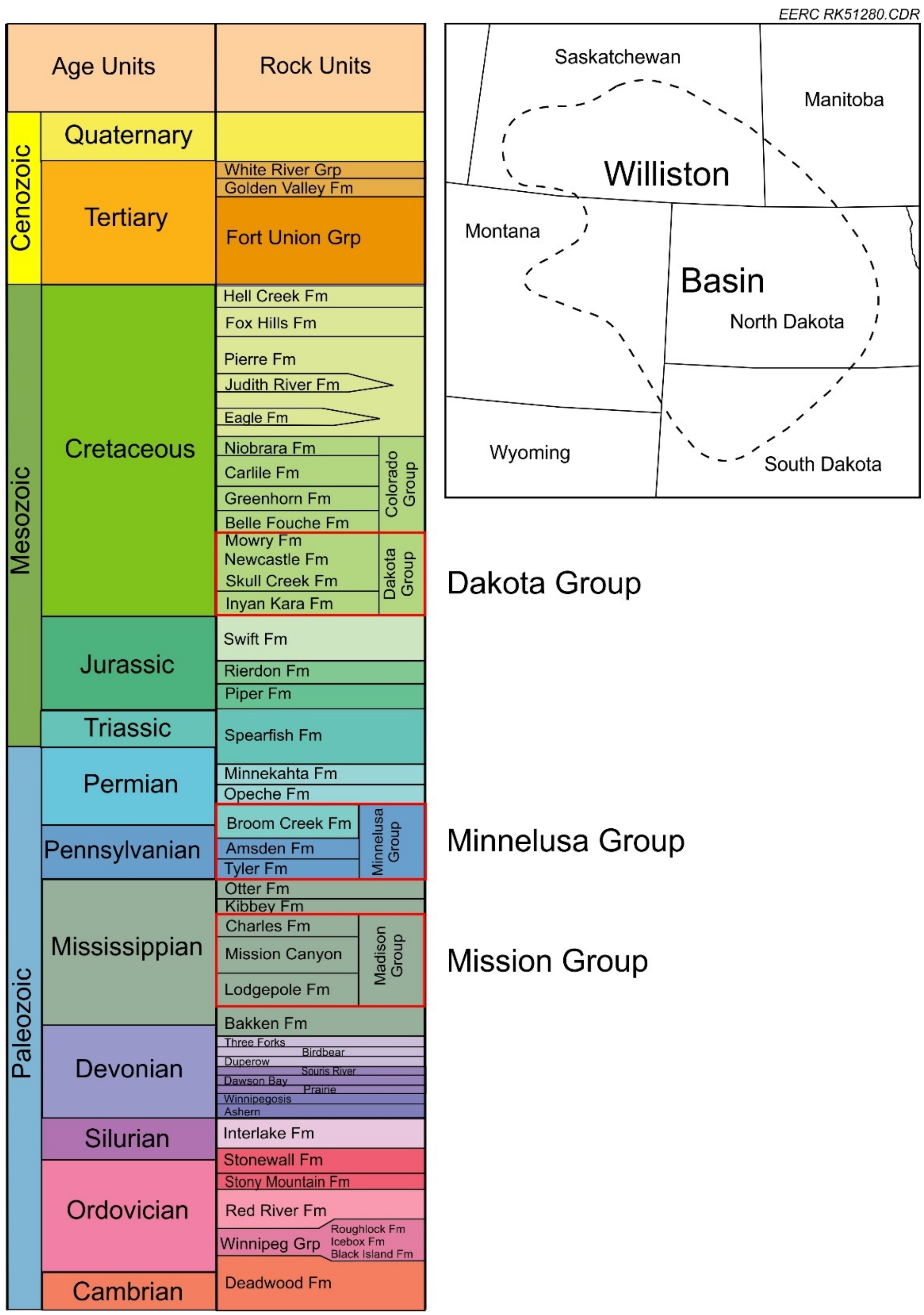

Figure 15. Modified image of North Dakota stratigraphic column.

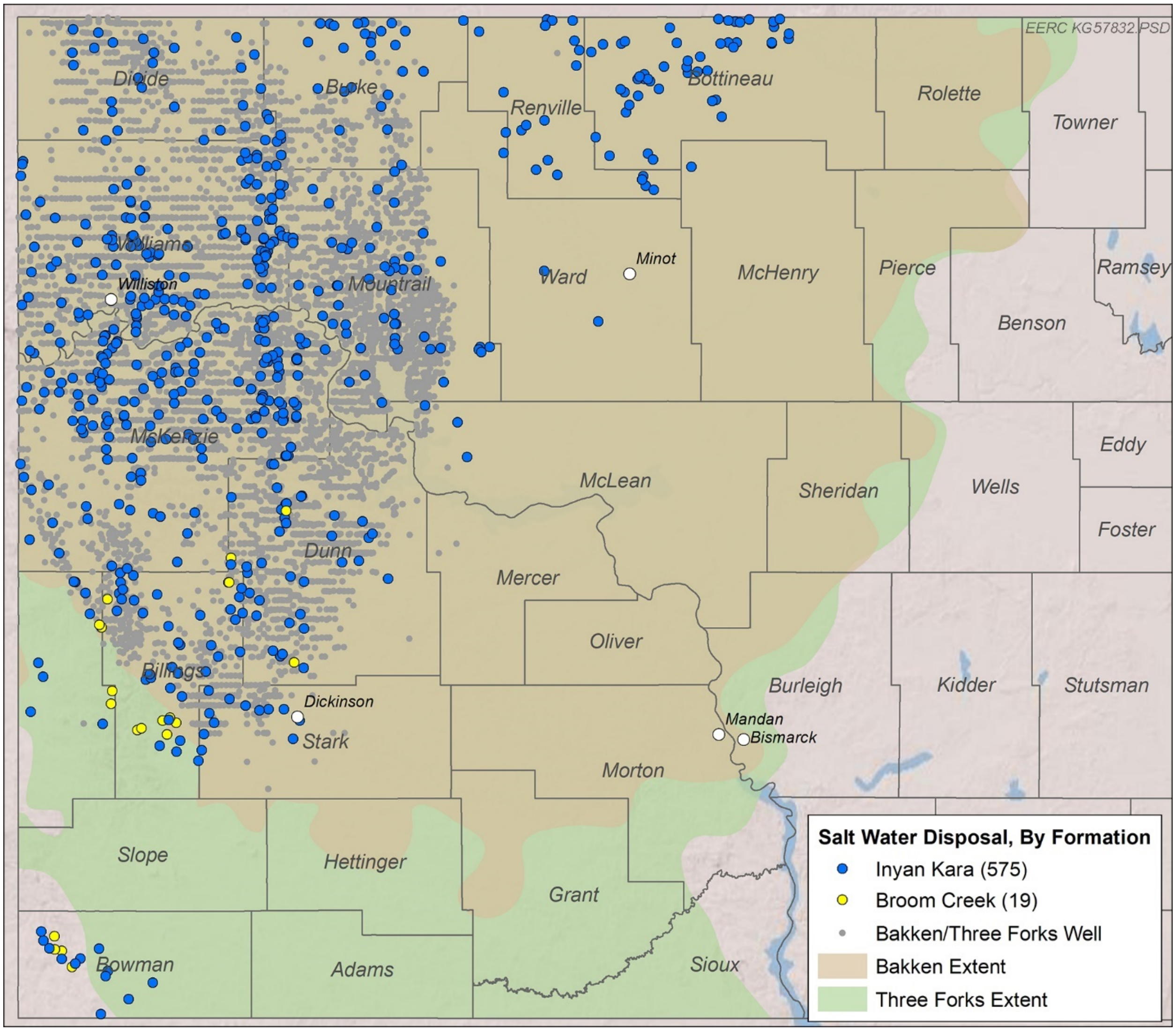

Figure 16. Active SWD wells by formation in 2019 (North Dakota Industrial Commission, 2019).

The lower Cretaceous Inyan Kara Formation is a porous sandstone formation with varying total dissolved solids (TDS) depending on location. In eastern North Dakota, TDS values are typically below 10,000 mg/L; however, in western North Dakota, values can be in the 10,000–30,000-mg/L range, making it an acceptable formation for injection. The Inyan Kara is approximately 1500 to 2000 feet shallower than other saline formations, and with the formation's excellent disposal capacity and geographic extent, the Inyan Kara has historically been a suitable, economical, primary geologic target for SWD.

Figure 17 shows the total volume of water injected into North Dakota SWD wells by year since 1956, illustrating a recent dramatic increase in SWD volumes as a result of the Bakken development. Figure 18 illustrates the 58% increase in the number of active SWD wells between 2008 (297) and 2018 (512). During that time period, disposal volumes increased over 500% from 106.8 to 601.9 million barrels (North Dakota Industrial Commission, 2019). In 2008, Bakken produced water accounted for only 6% of all SWD, whereas in 2018, Bakken produced water disposal accounted for over 80% of all SWD (Table 3).

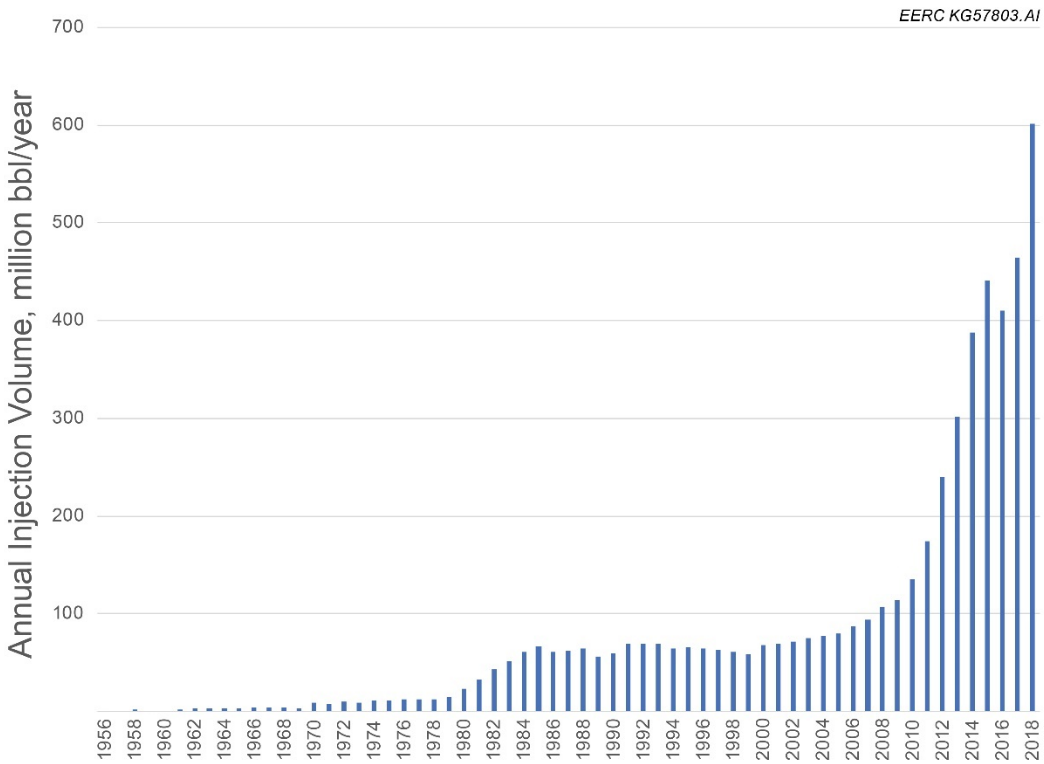

Figure 17. Volumes of all water injected into North Dakota SWD wells since 1956 (data source: North Dakota Industrial Commission, 2019).

SWD Needs

Bakken oil, gas, and water production is projected to continue to increase for the coming decades (Department of Mineral Resources, 2020), driving a need for SWD or alternative recycle and reuse options. While advances are being made, produced water recycle and reuse remains a challenge in the Bakken region and has yet to be economically deployed in North Dakota at scale. As SWD into the Inyan Kara continues to increase, capacity issues are beginning to develop. This will necessitate SWD transport to areas further away from producing well locations (resulting in additional traffic in local communities and increased transportation costs), use of alternative deeper and less desirable SWD formation targets, or applications of recycle and reuse. Table 1 shows the increase in the total number of Bakken wells since 2008 and the concurrent increase in produced water generation, which influence SWD requirements.

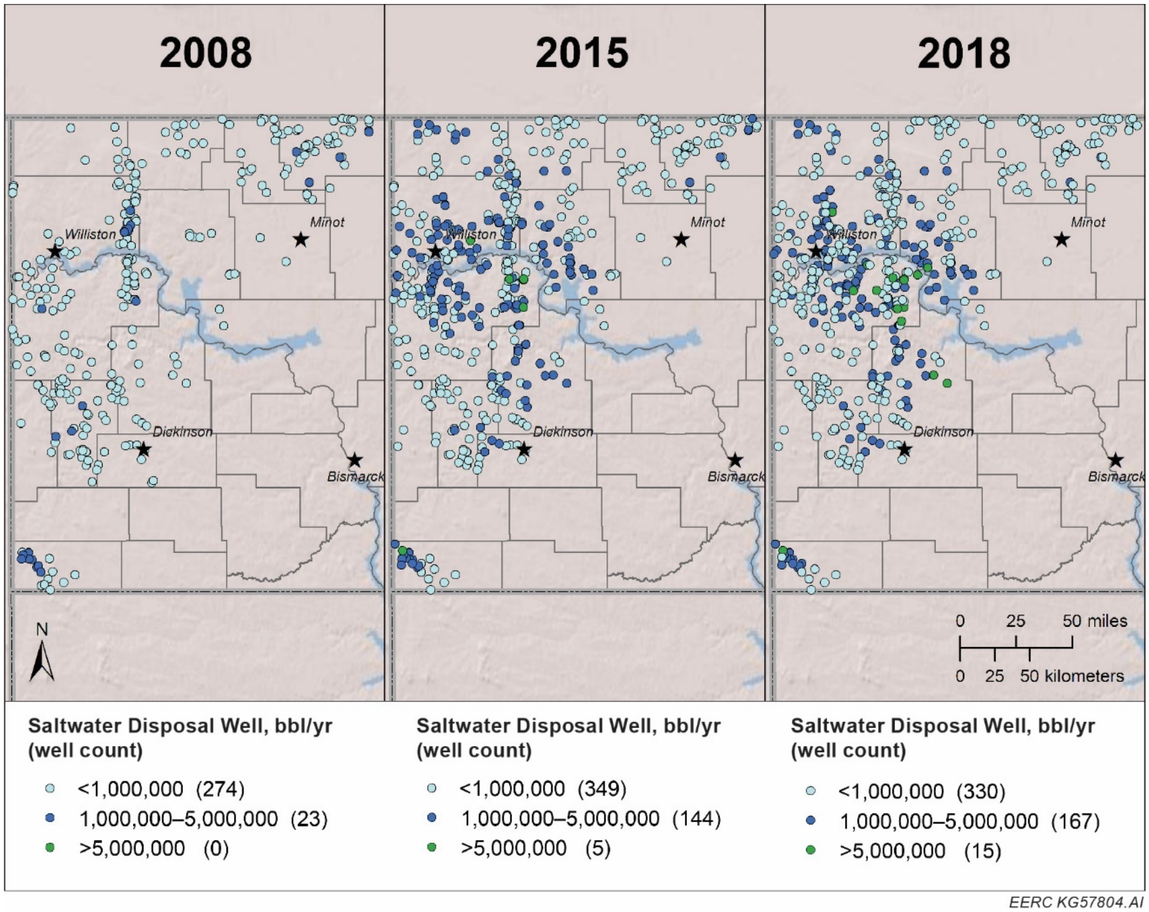

Figure 18. Comparison of active SWD well locations between 2008 and 2018 (data source: North Dakota Industrial Commission, 2019).

Table 3. Produced Water Generation & Disposal*

Year	Total Annual SWD Injection Volume, million bbl/yr	Volume of Produced Water Generated from Bakken Wells, million bbl	Total SWD from Bakken Produced Water, %
2008	106.8	6.4	6.0
2009	113.8	12.2	10.7
2010	135.5	32.6	24.1
2011	174.3	64.1	36.8
2012	239.9	135.3	56.4
2013	301.3	194.1	64.4
2014	388.0	283.9	73.2
2015	440.8	337.4	76.5
2016	409.9	313.3	76.4
2017	464.8	367.9	79.2
2018	601.9	485.6	80.7

* Data source: North Dakota Industrial Commission, 2019.

2018 data indicates that nearly 602 million bbl/yr of produced water is being injected into the subsurface, primarily the Inyan Kara Formation, via 512 active disposal wells. This equates to an average annual injection volume at each disposal well of 1.2 million bbl for 2018. However, Figure 18 illustrates injection volumes are not evenly distributed throughout all the SWD wells in the state. As the map shows, in 2008, while there were 297 active wells within the state, 38% of the total volume of injected fluids was injected via 23 wells. In 2018, the number of SWD wells injecting over 1 million barrels each year rose to 182, representing 84% of the total disposal volume for the year. Historic trends have suggested that rather than the number of SWD wells increasing proportionally to the volume of produced water being generated, instead the volume of brine injected at individual SWD wells is increasing substantially. These trends will be evaluated in the produced water quality assessment report.

With the increasing volumes of SWD into the Inyan Kara, capacity issues are starting to emerge that suggest SWD at some point could become constrained as Bakken operators are seeing challenges with the formation being pressurized in certain areas when drilling new Bakken wells. The pressurization is forcing operators to run an additional casing string to isolate the formation to continue drilling (Basu and others, 2019), as illustrated in Figure 19. This increases the cost to drill new Bakken wells by $300,000 to $700,000 per well (Industrial partners, discussions, 2019). Given the emerging trends, a more in-depth look at the long-term sustainability and techno-economics of the Inyan Kara Formation and the emerging pressurization challenges will be pursued in the subsequent produced water quality assessment report.

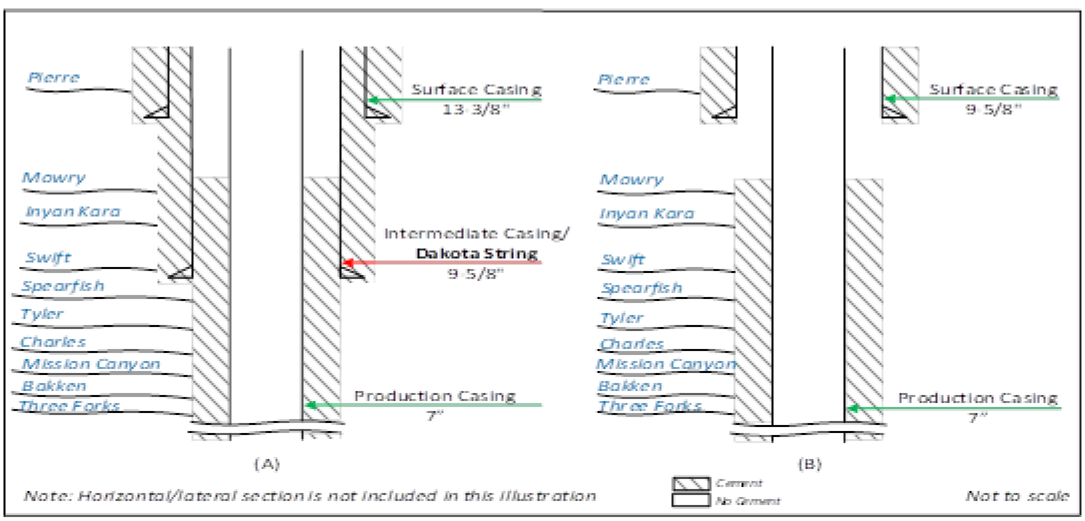

Figure 19. Illustrative well design for a well using the additional intermediate casing string or "Dakota string" (A), and a typical well design without the addition of a Dakota string (B).

OPPORTUNITIES AND ISSUES ASSOCIATED WITH PRODUCED WATER RECYCLING AND REUSE IN THE BAKKEN

Drivers and Deterrents for Recycling and Reuse

Commercial adaptation of produced water recycling and reuse practices in the oil and gas industry is influenced by cost and availability of freshwater and produced water injection/disposal options. Freshwater availability will vary by region and depend upon factors such as climate and competing water use (e.g., irrigation, domestic). Injection/disposal availability will depend on factors such as disposal formation capacity (e.g., limited by induced seismicity, formation pressurization, and injection rates and pressures), produced water transportation costs, and surface storage costs.

In the Bakken region of western North Dakota, consistent low-cost freshwater supplies, economic transport options, and sufficient cost-effective disposal options in close proximity to oil production have not yet necessitated the adoption of produced water recycle and reuse as evidenced by nearly all produced water being injected into SWD wells. Available and relatively inexpensive freshwater supplies from the Missouri River system and Lake Sakakawea, along with the formation capacity and broad geographic extent of the Inyan Kara Formation has made produced water disposal the more economic option. Transportation-related costs and surface storage for produced water treatment and reuse remain significant barriers to implementing recycling or reuse. While there is oil and gas industry interest in produced water recycling or reuse from a sustainability perspective, the current techno-economic landscape does not make implementation an economically viable option.

Reusing produced water in hydraulic fracturing is a technically viable option (Schmidt and others, 2015). Although Bakken produced water recycling and reuse is challenging in the current landscape, as injection volumes continue to increase with Bakken development; and as Inyan Kara Formation capacity challenges emerge, there is a drive/need to develop prudent and economic produced water recycle and reuse practices. As localized areas of pressurization in the Inyan Kara expand, the substantial costs associated with running an additional casing string may provide an economic driver for produced water recycling and reuse. With Bakken SWD volumes forecasted to increase to 1.1 billion bbl/yr by 2035 (Kurz and others, 2016), understanding produced water recycle and reuse options and the economic conditions where they become viable are critical for assuring the viability of Bakken development for decades to come.

DISCUSSION AND CONCLUSIONS

Water is a valuable commodity in the Bakken region for drilling, completion, production, and production maintenance. From 2008 to 2018, North Dakota oil production has risen from ~35,000 bbl/day to over 1 million bbl/day (North Dakota Industrial Commission, 2019). As presented throughout this report, with increased oil production there has been a commensurate increase in freshwater demand, Bakken produced water generation, and resultant produced water disposal. Current state resources and infrastructure have been able to manage these increased volumes of water. Oil production is expected to continue to increase (North Dakota Industrial

Commission, 2019); however, produced water management represents a significant economic and technical challenge with the increased production. The increase in SWD volumes have resulted in localized areas of high pressure in the Inyan Kara Formation (Schmidt and others, 2019). The increased pressure impacts the economics and risk associated with the drilling of new wells which can now require additional intermediate casing strings, increasing well costs by $300,000 to $700,00 per well (Industrial partners, discussions, 2019), and alternative methods of dealing with the disposal volumes (i.e., recycling and reuse) will be necessary for sustainable oil and gas production in the future.

Traditional commercial techniques for treating produced water for reuse are challenged by the highly variable chemistries and high total dissolved solids content of Bakken formation water and hydraulic fracturing fluid flowback (Kurz and others, 2016). Further, the storage of large volumes of produced fluids on the surface is prohibitively expensive because of regulations borne of environmental concerns, effectively precluding adoption of traditional produced water recycling and reuse strategies. North Dakota currently has abundant freshwater available at low cost, limiting incentive to find solutions to these emerging challenges. However, with the increasing pressurization of the Inyan Kara Formation, increasing produced water volumes, and increasing demand for freshwater, this may not always be the case.

The EERC, in collaboration with Nuverra, NDIC OGRP, DOE NETL, and members of the BPOP, will assess the techno-economic viability of using GHCR as a means of addressing the challenges associated with produced water management in the Williston Basin. This approach, if viable, could take advantage of the natural processes to filter and condition produced water for reuse; enable subsurface, large-volume storage of produced water; reduce rate of pressurization of the Inyan Kara, thus reducing drilling costs; and provide an alternative source of water for the oil and gas industry, thus reducing demand on freshwater. A comprehensive produced water assessment will build upon the information contained in this report to provide an understanding of water challenges and opportunities facing the Bakken region in western North Dakota. This information will provide the metrics to evaluate the techno-economic viability of the GHCR concept and inform key conditions that will limit or drive the commercial adoption of GHCR. The water assessment will delve deeper into produced water chemistries, volumes, management practices, costs, and forecasts and will be reported in October 2020 via a produced water quality assessment report. Topics covered in that future report will include the following:

- Bakken produced water chemistry from water sampling and/or data collection to determine variability in water qualities throughout the region.

- Inyan Kara water chemistry from water sampling and/or data collection to determine the variability in native water qualities throughout the region.

- Water acquisition, disposal, storage, and transportation costs and considerations for operators in the Bakken region.

- Water treatment costs and considerations (e.g., surface storage, transportation) for potential recycling and reuse, including for hydraulic fracturing fluid makeup water.

- Evaluation of pressurization and capacity constraints associated with SWD in the Inyan Kara Formation.

- Water demand, supply, and disposal forecasts, challenges, and opportunities.

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