Environmental Science & Technology

Article

pubs.acs.org/est

Water Use and Management in the Bakken Shale Oil Play in North Dakota

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S *Supporting Information*

ABSTRACT: Oil and natural gas development in the Bakken shale play of North Dakota has grown substantially since 2008. This study provides a comprehensive overview and analysis of water quantity and management impacts from this development by (1) estimating water demand for hydraulic fracturing in the Bakken from 2008 to 2012; (2) compiling volume estimates for maintenance water, or brine dilution water; (3) calculating water intensities normalized by the amount of oil produced, or estimated ultimate recovery (EUR); (4) estimating domestic water demand associated with the large oil services population; (5) analyzing the change in wastewater volumes from 2005 to 2012; and (6) examining existing water sources used to meet demand. Water use for hydraulic fracturing in the North Dakota Bakken grew 5-fold from 770 million gallons in 2008 to 4.3 billion gallons in 2012. First-year wastewater volumes grew in parallel, from an annual average of 1 135 000 gallons per well in 2008 to 2 905 000 gallons in 2012, exceeding the mean volume of water used in hydraulic fracturing and surpassing typical 4-year wastewater totals for the Barnett, Denver, and Marcellus basins. Surprisingly, domestic water demand from the temporary oilfield services population in the region may be comparable to the regional water demand from hydraulic fracturing activities. Existing groundwater resources are inadequate to meet the demand for hydraulic fracturing, but there appear to be adequate surface water resources, provided that access is available.

1. INTRODUCTION

Oil extraction from the Bakken shale oil deposit, or *play*, of western North Dakota and surrounding areas has increased rapidly since development began about a decade ago. This rapid development has greatly affected local economies, communities, and environments. The City of Williston, at the center of the Bakken development, experienced less than 2.5% annual population growth prior to 2009.[1] In 2013, it was the fastest growing micropolitan area in the country, with 10.7% growth over the previous year.[2] Local water resources are impacted by this rapid development, through both an increased demand for water—which is used for oil extraction and to support the burgeoning population of workers—and an increased production of saline wastewater from the oil-bearing formation.

Bakken oil is contained within low-permeability shale and is extracted through hydraulic fracturing, in which a mixture of water and other ingredients pumped at high pressure causes the rock to fracture, opening connecting pathways between pores, and enabling oil to flow back to the well. Hydraulic fracturing of a single shale well can use 2−8 million gallons of water or more, and is highly dependent on the play.[3−5] Recent comprehensive studies show that the variability in water use between, and even within, different plays may be even greater.[6,7] Hundreds to thousands of wells are being drilled in the Bakken play every year, and the water use is substantial. After a well is hydraulically fractured, much of the injected water returns to the surface, along with naturally occurring water released from

Received: August 21, 2015
Revised: December 29, 2015
Accepted: February 11, 2016
Published: February 11, 2016

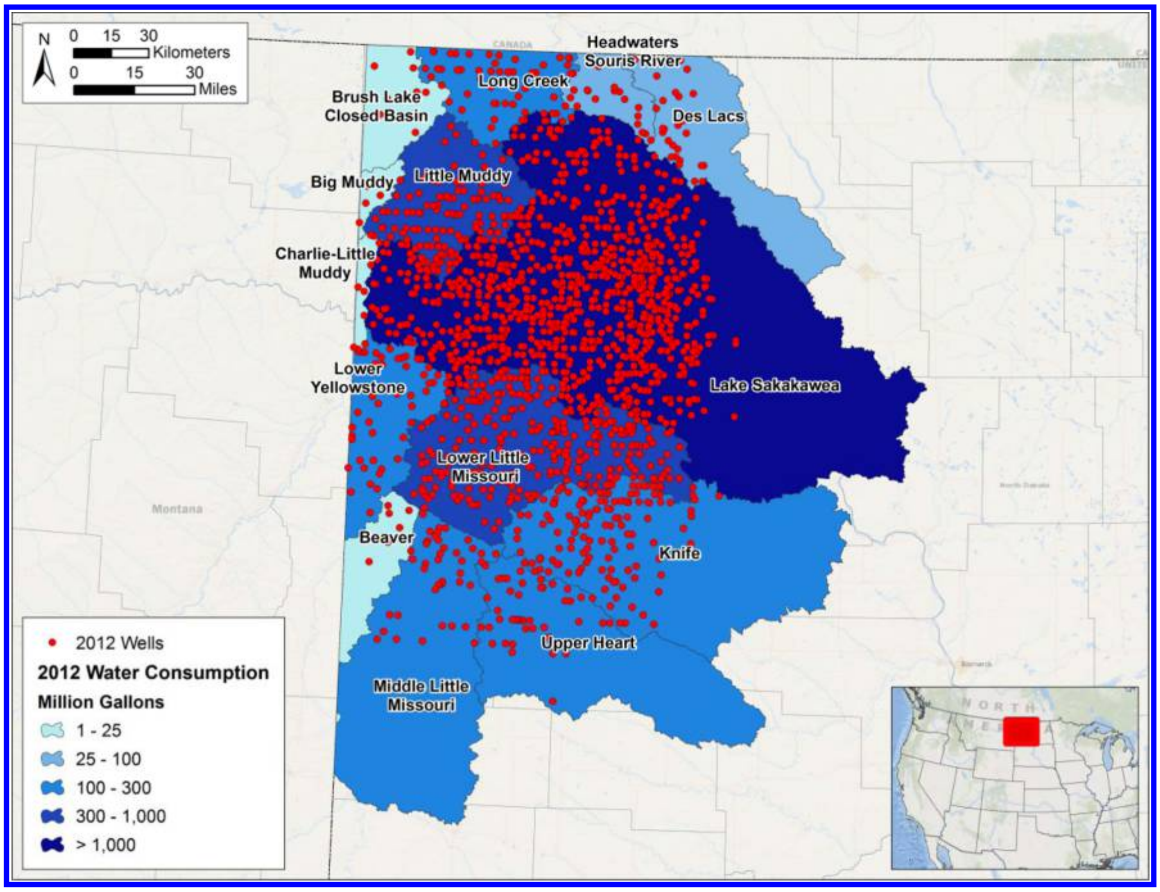

Figure 1. 2012 Hydraulic Fracturing Locations and Water Use by HUC-8 Subbasin in the North Dakota Bakken Shale Play. This figure overlays well installations in 2012 upon the estimated water use for hydraulically fracturing those wells, summed by HUC-8 watershed subbasin.

the rock formation. This wastewater normally contains high levels of total dissolved solids (TDS) and must be treated, disposed of, and/or recycled.[8,9]

This study serves as a comprehensive analysis and overview of water use and management for oil development in the North Dakota portion of the Bakken play. We estimate water demand for hydraulic fracturing activities since 2008 using publicly available well installation and water injection data from FracFocus.org and the North Dakota Department of Mineral Resources (NDDMR). We calculate water intensities for hydraulic fracturing and maintenance water normalized using data for scenarios of estimated ultimate recovery (EUR) over the lifetime of the well. We also calculate the increased domestic water demand attributable to growth in the human population associated with oil field services in the area. We examine the amount of water available for hydraulic fracturing by comparing hydraulic fracturing water demands with annual streamflow volumes for the U.S. Geological Survey (USGS) Hydrologic Unit Code 8 (HUC-8) watershed subbasins where the wells have been installed and by identifying other potential sources of water. Finally, we use data from the North Dakota Industrial Commission (NDIC) to analyze how flowback and produced water volumes from Bakken wells changed from 2005 to 2012 and discuss water management issues specific to the Bakken play.

2. MATERIALS AND METHODS

Analyses described in this article quantify the water used for all hydraulic fracturing that occurred in the North Dakota region of the Bakken play from 2008 to 2012, as well as the amount of water produced from North Dakota Bakken wells from 2005 to 2013 (with date ranges constrained by data availability). As described below, the water consumed over the lifetime of a North Dakota Bakken oil well is normalized to its oil production using data from currently producing wells, and changes in domestic water consumption due to growth of the oil services population in the Bakken region are estimated.

2.1. Hydraulic Fracturing Water Volumes. Water is used in many aspects of well installation and operation; it is a primary constituent of drilling mud and the cement used to case and seal the well from nontarget rock formations. However, the volume of water used for the hydraulic fracturing phase dwarfs that of all other phases of well installation and development.[4] Therefore, this analysis focuses on water used for hydraulic fracturing. The amount of water was quantified using oil well data acquired from two sources: FracFocus.org[10] and the NDDMR's well database.[11] FracFocus.org is a privately hosted online registry where oil and gas developers may disclose information to the public regarding hydraulic fracturing activities. Included in the disclosed information are the latitude and longitude location data and volume of water used for hydraulic fracturing for each well. In addition, the American Petroleum Institute (API) number is included, which provides a unique identifier for any well drilled in the United States. The NDDMR has a more comprehensive database of wells that reports location data and API number (along with other data such as vertical depth) for every well that is legally drilled in the

DOI: 10.1021/acs.est.5b04079
Environ. Sci. Technol. 2016, 50, 3275−3282

state, but the basic data set at the time of this study did not report hydraulic fracturing water volumes.

Well data for the North Dakota portion of the Bakken play was obtained from FracFocus.org and compared to well data acquired from NDDMR. To estimate the water used for hydraulic fracturing for all wells in the North Dakota portion of the Bakken play, the two data sets were merged by API number using a Geographical Information System (GIS) program. Duplicate entries and outliers in well depth and water volumes were deleted (see Figure 1 for an example of the resulting wells plotted geographically). Of the 4624 wells identified as having been installed in the North Dakota portion of the Bakken play from 2008 to 2012, approximately 1578 were reported in FracFocus.org at the time of our data gathering. To estimate overall hydraulic fracturing water use for the North Dakota portion of the Bakken play, annual per-well averages from the FracFocus.org data were assigned to the 3046 remaining wells that were missing this information because they were only reported by NDDMR. However, because very few wells installed in 2008, 2009, and 2010 were reported in the FracFocus.org data (1, 2, and 7, respectively), the more-robust 2011 average was used for wells installed in those years that lacked water volume data. Variability in the FracFocus.org data is characterized in the water intensity analysis described in Section 2.3.

The data were also used to report the number of wells installed and amount of water used within each HUC-8 watershed subbasin overlying the Bakken play. The HUC-8 subbasins were used to organize the data so that surface water flow volumes could be compared to water used for hydraulic fracturing in the same geographic area (see Figure 1 for a visual example). This comparison is for purposes of illustration only, because there is no easy way to link hydraulic fracturing activities to their specific water sources. As discussed in Section 4, much of the water used for hydraulic fracturing in North Dakota comes from public or private water depots. Records indicating which water depots were used for each hydraulic fracturing occurrence could not be found consistently for individual wells. Although the locations of the water depots are known,[12] it cannot be assumed that the closest water depot was utilized because, as a brief review of North Dakota State Water Commission (NDSWC) permit applications show, the amount of water available and its intended use varies widely among sources.[13] Therefore, it should not be assumed that all of the water used for hydraulic fracturing within a HUC-8 subbasin was sourced from the same subbasin.

2.2. Maintenance Water. The high salinity of the formation water within the Bakken play (see Section 5) necessitates injection of water in some wells to eliminate salt buildup within the well bore, which can negatively impact production rates. The water used for this process is known as maintenance water,[14,15] or brine dilution fluid.[15,16] Very little has been published concerning the volumes of water used for this purpose or the specifics of such water's application. We examined the existing literature and interviewed industry sources to obtain estimates that we used for scenarios to calculate the water intensity of oil production in the Bakken.[16] Also, a representative of a major Bakken oil producer provided some general information under the condition of anonymity.

2.3. Water Intensity. To calculate the water intensity of oil production, lifetime water consumption for Bakken shale oil wells was normalized by the estimated lifetime amount of oil produced (EUR), using the unit gallons of water required per gallon of oil produced.[5] Because of wide variability in the FracFocus.org hydraulic fracturing water volume data described in Section 2.1, the volume of water required was calculated using the 25th, 50th, and 75th percentiles of all reported data. These volumes were added to maintenance water requirement scenarios gleaned from research (see Section 3.2). Literature estimates of EUR for the Bakken vary widely, from 270 000 to 550 000 barrels per well.[17,18] So, new estimates of EUR were generated by using two commonly used fit functions—hyperbolic and stretched exponential—on production history data of 5773 currently producing wells in North Dakota derived from McNally and Brandt (see Table S1 in the Supporting Information).[19] Total water use (maintenance water calculated over the well lifetime plus hydraulic fracturing water volume) was divided by EUR to obtain water intensity. Water intensities were calculated for different combinations of hydraulic fracturing volume, maintenance water, well lifetime and EUR.

A number of scenarios were generated to explore uncertainty in the EUR, the volume of maintenance water required, and typical well lifetime. The hydraulic fracturing volumes used for all scenarios were the 25th, 50th, and 75th percentiles described above. Two EUR estimates were used—one from each fit function mentioned above. Three different estimates were used for maintenance water volume: the 400−600 gallons per day from Helms[20] and the 85 gallons per day used by the NDSWC,[15] discussed in Section 3.2 To account for the uncertainty in estimates of the production life of hydraulically fractured wells, well lifetimes of 15 and 30 years were used.[4,19]

2.4. Domestic Water Demand. The rapid growth in oil development in the Bakken play has led to large increases in the local population, which, along with the direct needs of oil production, has also increased water consumption in the area. To our knowledge, no previous quantitative analysis of the water requirements of unconventional oil production has included increased domestic water use. Domestic water demand in the region has increased due to the daily personal needs of the oilfield workers—a population whose size is substantial in comparison to the permanent population of the area. To be complete, it is important that any analysis of the increased regional water demand caused by oil development in the Bakken play include demand for domestic water use by oilfield service workers who would not otherwise be in the region.

Due to the transient presence of many Bakken oilfield workers, the most recent U.S. decennial census failed to count them, and no estimates for this population were found for the entire Bakken region.[21] However, an estimate does exist for Williams County, ND, which contains the City of Williston, the commercial center of activity in the Bakken region. From 2010 to 2012, it is estimated that Williams County added 23 980 temporary service workers and 4683 permanent residents—a ratio of approximately 5:1.[21] We used this growth ratio combined with U.S. Census population estimates for 2010 and 2012[22] to estimate the growth in temporary service worker populations for the eight additional ND counties in the Bakken region: Burke, Divide, Dunn, McKenzie, McLean, Mountrail, Stark, and Ward. Because no estimates for service worker populations in 2010 were found for these counties, we conservatively used our calculated estimate for 2010−2012 growth as the estimated total temporary service worker population for the North Dakota Bakken in 2012.

Domestic water demand for the temporary oilfield services population in the North Dakota Bakken was then calculated by

DOI: 10.1021/acs.est.5b04079
Environ. Sci. Technol. 2016, 50, 3275−3282

multiplying the temporary service worker population estimate by per-capita domestic water use estimates for Williams County from the USGS[23] (79.5 gal person^{-1} day^{-1}) and for the Bakken region from the Western Area Water Supply Project[24] (160 gal person^{-1} day^{-1}). We use both estimates because of the large difference between them.

2.5. Wastewater Volumes. Wastewater produced from oil and gas wells is often classified into two categories: *flowback* water and *produced* water. In general, flowback describes fluid that flows from a well soon after hydraulic fracturing occurs and prior to the well being put into production. This fluid is primarily constituted of what was used to fracture the well.[25] Produced water is produced along with the oil and gas over the lifetime of the well. For the purposes of this paper we will use these two definitions, along with the more general term *wastewater* when discussing these two quantities combined.

Average water production over the lifetime of oil wells in the Bakken play was analyzed using data from the Oil and Gas division of the NDDMR. Data were acquired for produced water from wells with a first production date between 2005 and 2013, though only data through 2012 were included in the analysis for consistency between data sets. For each annual cohort, we analyzed the produced water for the first year of production through 2012, leading to a maximum of 7 years of data for wells drilled in 2005. These data were processed such that only wells from the Bakken play were included.

Because NDIC reports monthly data for every well in production, it was necessary to sum the produced water monthly and then by year to obtain lifetime totals for each well. Since the process of flowback occurs before the well is put into production, the volume of flowback water is not included in the reported produced water volumes. Flowback water volumes were estimated using the mean values for the amount of water used in hydraulic fracturing in the Bakken for a given year (see Table 1) combined with previous estimates that 25% of hydraulic fracturing water there returned to the surface as flowback water.[24]

Table 1. Annual Total Water Consumption for Hydraulic Fracturing in the North Dakota Bakken Play

year	total water consumed (millions of gallons)	number of wells	average volume per well (millions of gallons)
2008	770	401	[a]
2009	894	465	[a]
2010	1457	758	[a]
2011	2304	1199	1.92
2012	4274	1801	2.37

[a] Insufficient data to determine an accurate annual average volume per well; total consumption is calculated using the 2011 average volume per well for 2008–2011 (see Section 2.1).

3. WATER DEMANDS

3.1. Hydraulic Fracturing. The amount of water consumed annually for hydraulic fracturing activities in the Bakken play has increased more than 5-fold, from 770 million gallons to 4.27 billion gallons, over the 5 years from 2008 to 2012 (Table 1). The annual rate of well installation has more than quadrupled. However, the increase in water consumption is not wholly due to an increasing number of wells drilled per year; the amount of water used for hydraulic fracturing per well in the Bakken play increased by 23% from 2011 to 2012 (Table 1). Increasing lateral lengths (the length of the well bore extending horizontally within the reservoir), which require more stages of hydraulic fracturing, may explain much of the increasing volume per well. Lateral lengths in the Bakken increased approximately 25% from 2009 to 2013.[26]

3.2. Maintenance Water. Actual data on the amount of water used for brine dilution maintenance could not be found among publically available information. An early study[27] estimated maintenance water needs at over 1400 gallons/well/day at wells requiring maintenance water, which was estimated to be 10% of Bakken wells. A later estimate[14] referenced NDDMR estimates and showed the water volumes required to be lower: on the order of 400–600 gallons/well/day.[20] However, maintenance water estimates published by NDSWC[15] show a seemingly lower average of approximately 85 gallons/well/day. Conversations with NDSWC revealed that this lowest value takes into account the estimate that only 10–15% of Bakken wells require maintenance water (meaning that, among wells that do require maintenance water, approximately 570–850 gallons/well/day is needed) and that more maintenance water is generally required per well the further to the west the well is located within the North Dakota portion of the Bakken play.[16]

Much uncertainty remains in the publicly available information regarding maintenance water volumes. One major producer in the Bakken contacted by the authors (who asked not to be named) stated that its wells currently require significantly less water than estimated in Kiger.[14] The producer also stated that the water used for such activities is often brackish and thus less likely to stress freshwater resources. The producer stated that even within the oil industry, a clear and consistent definition of maintenance water is lacking.

3.3. Water Intensity. Combining the data on water use with EUR data from different scenarios shows that water intensity in the Bakken ranges from 0.10 gallons of water per gallon of crude oil produced (25th percentile of HF water use, no maintenance water requirements, and high EUR) to 0.82 gallons of water per gallon of crude oil produced (75th percentile of HF water use, high maintenance water requirements, and low EUR). The full range and results of this analysis are displayed in Table 2. The addition of maintenance water has a substantial impact on the normalized lifetime water consumption and thus needs to be better understood (see Section 3.2). When the low estimate of maintenance water is used, the range of water consumption values falls in a narrower range: 0.16–0.33 gallons of water per gallon of crude oil. These results assume that a well is only hydraulically fractured once. It is likely that in the future some wells will be refractured, which will increase the water consumption, lifetime, and EUR of the well. Other stages such as well drilling, transportation, and processing were not included in our estimates; however, previous analyses have shown that the water requirements for these stages of well development and production tend to be small relative to those for hydraulic fracturing.[4]

3.4. Domestic Water Demand. Domestic water use by temporary oilfield service workers is a substantial contributor to the overall water use impact of Bakken oil development. The lower bound to our estimate—2.19 billion gallons (Table 3)—is over half the estimated water used for hydraulic fracturing in the North Dakota portion of the Bakken play for that year—4.27 billion gallons (Table 1). The upper bound to our estimate exceeds the amount used for hydraulic fracturing. Uncertainties not captured in this analysis include possible differences

DOI: 10.1021/acs.est.5b04079
Environ. Sci. Technol. 2016, 50, 3275–3282

Table 2. Bakken Well Water Consumption Normalized by Output

HF water[a] (Mgal/well)	maintenance water (gal/day)	EUR (bbl)	well lifetime (yr)	normalized lifetime water requirement (gal water/gal oil)
1.39, 2.14, 2.69	0	330 000[b]	30	0.10, 0.15, 0.19
1.39, 2.14, 2.69	0	270 000[c]	30	0.12, 0.19, 0.24
1.39, 2.14, 2.69	85[d]	330 000[b]	30	0.17, 0.22, 0.26
1.39, 2.14, 2.69	400[e]	330 000[b]	30	0.42, 0.47, 0.51
1.39, 2.14, 2.69	600[e]	330 000[b]	30	0.57, 0.63, 0.67
1.39, 2.14, 2.69	85[d]	270 000[c]	30	0.20, 0.27, 0.32
1.39, 2.14, 2.69	400[e]	270 000[c]	30	0.51, 0.58, 0.62
1.39, 2.14, 2.69	600[e]	270 000[c]	30	0.70, 0.77, 0.82
1.39, 2.14, 2.69	85[d]	270 000[b]	15	0.16, 0.23, 0.28
1.39, 2.14, 2.69	400[e]	270 000[b]	15	0.32, 0.38, 0.43
1.39, 2.14, 2.69	600[e]	270 000[b]	15	0.41, 0.48, 0.53
1.39, 2.14, 2.69	85[d]	230 000[b]	15	0.19, 0.27, 0.33
1.39, 2.14, 2.69	400[e]	230 000[b]	15	0.37, 0.45, 0.50
1.39, 2.14, 2.69	600[e]	230 000[b]	15	0.48, 0.56, 0.62

[a]25th, 50th, and 75th percentiles of all FracFocus.org data. [b]Hyperbolic function fit mean. [c]Stretched exponential function fit mean. [d]NDSWC (2015).[15] [e]Helms (2013).[20]

Table 3. Estimated 2012 Domestic Water Demand from Temporary Oilfield Service Population in the North Dakota Bakken

county	2010−2012 change in permanent population[a]	estimated temporary service population	estimated domestic water use (millions of gallons)
Burke	202	1,030	30.0[b]−60.4[c]
Divide	162	830	24.1[b]−48.4[c]
Dunn	438	2240	65.1[b]−131[c]
McKenzie	1605	8220	238[b]−480[c]
McLean	409	2090	60.8[b]−122[c]
Mountrail	1077	5520	160[b]−322[c]
Stark	2722	13 900	404[b]−814[c]
Ward	3805	19 500	565[b]−1,140[c]
Williams	4288	22 000	637[b]−1,280[c]
Total	14 708	75 300	2,190[b]−4,400[c]

[a]U.S. Census Bureau (2014).[22] [b]Assuming 79.5 gal person^{-1} day^{-1} domestic use as calculated from USGS (2014).[23] [c]Assuming 160 gal person^{-1} day^{-1} domestic use from Western Area Water Supply Project (2011).[24]

between the amount of use in the permanent and oilfield service populations and the difficulty in segregating the service from the permanent population. Given our conservative assumptions in estimating the temporary service population (see Section 2.4), it seems clear that domestic water use contributes substantially to overall water use for oil development in the Bakken—perhaps even more so than hydraulic fracturing.

4. WATER SOURCES

Much of the water used for hydraulic fracturing is sourced from public or private water distribution sites, known as water depots, and trucked to the well site.[28,29] Water depots can source their water from groundwater reserves or from surface water. However, the only reliable source of surface water in the western part of North Dakota is the Missouri River System—including Lake Sakakawea, the third-largest manmade reservoir in the country. Withdrawals from Lake Sakakawea are limited by the U.S. Army Corps of Engineers,[12,28] and development in the Bakken is spreading farther away from it geographically.[21] Transporting water is expensive and, as a result, many oil developers source their water from the closest water depot—often a private depot that uses groundwater.[29]

However, because of the volumes of water needed, groundwater depots alone cannot meet future demand.[24,30] As of August 2012, there were 85 permitted water depots in the Bakken region, 73 of which source from groundwater.[12] Up to 3.7 billion gallons of groundwater are permitted for withdrawal annually in North Dakota.[12] Already in 2012, 4.3 billion gallons were needed for hydraulic fracturing alone in the North Dakota Bakken play (Table 1). Therefore, North Dakota also requires surface water to meet its hydraulic fracturing demand.[28,30]

In contrast to the shortage of available groundwater, western North Dakota appears to have sufficient surface water availability in the Missouri River system to meet the increased demands.[14,28,29] Up to 10.3 billion gallons annually are permitted for withdrawal from surface waters in North Dakota.[12] Lake Sakakawea has at least 32.5 billion gallons of annual surplus water that are being made available by the U.S. Army Corps of Engineers (see below). The NDSWC believes there is adequate supply in surface resources, but notes that there are potential water access issues, including uncertainty in the long term management plan for Lake Sakakawea.[15] Figure 1 illustrates local water demand for hydraulic fracturing by overlaying the well installations in 2012 upon the estimated water use for hydraulically fracturing those wells by HUC-8 watershed subbasin (other years are illustrated in Figures S1−S4 in the Supporting Information). This demand ranged from 0.06% to 6.25% of surface flow in those subbasins (see Table S2 in the Supporting Information).[31]

Although enough surface water is potentially available, accessing the water and transporting it to well sites—which can be far from the source—can be an issue. The Western Area Water Supply Project (WAWSP) is currently expanding the supply of potable water from the Missouri River system for municipal, rural, and industrial needs in a large area surrounding the City of Williston, which is a hub of Bakken activity in North Dakota.[14,32] Up to 20% of WAWSP water is allowed to be distributed and sold for hydraulic fracturing activities. In 2009 and 2010, permit applications were made to allow annual withdrawals totaling more than 7.8 billion gallons from Lake Sakakawea. The company applying for these permits planned to distribute the water via underground pipeline to areas where Bakken drilling is occurring.[22] In December 2010,

DOI: 10.1021/acs.est.5b04079
Environ. Sci. Technol. 2016, 50, 3275−3282

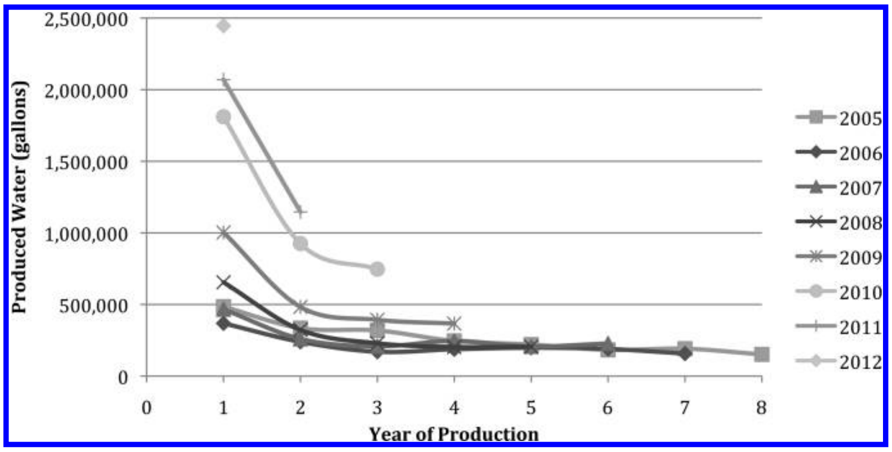

Figure 2. Average annual volume of produced water per well from North Dakota Bakken Oil Wells by year of installation.

the U.S. Army Corps of Engineers made available 32.5 billion gallons of annual surplus water for temporary withdrawal permits valid for five years, with the possibility of one five-year renewal.[33] In order to issue permanent withdrawal permits, a Missouri River System reallocation study, which is currently underway, needs to be completed.[34]

Another possible source of water for Bakken development is the use of brackish groundwater or reuse of saline flowback water from hydraulic fracturing activity. More information on these possibilities is contained in the next section. Use of saline flowback water appears to be a viable technology, but the economics of deploying it at scale in the Bakken are unclear.

5. WASTEWATER

5.1. Wastewater Quantity. Based on our analysis, wastewater production per well in the Bakken is increasing greatly and is much larger than that in other shale plays. The average volume of produced water per well in the first year of production from North Dakota Bakken oil wells increased 5-fold between 2005 and 2012 (Figure 2). Average volumes of produced water in the first year of production were 440 000 gallons/year for wells completed between 2005 and 2007. In contrast, first-year produced water volumes rose to 2 210 000 gallons/year on average for wells completed in 2011 and 2012. When flowback water is included in the wastewater estimates, the total amounts of wastewater generated per well in the first year was 2 905 000 gallons/year in 2012, as shown in Table 4. Totals of wastewater generated per well for the first year alone were comparable to or higher than 4-year totals for wells in the Barnett, Denver, and Marcellus basins.[5] Three-year totals of wastewater for wells completed in 2008 through 2011 were also rapidly increasing, as shown in Table 4. The 3-year total has nearly tripled, from 1 630 000 gallons per well in 2008 to 4 440 000 gallons in 2011 (Table 4).

Table 4. Average Flowback and Produced Water per Well in the First 1 and 3 Years of Production

year of first production	flowback water (gallons)	produced water in first year (gallons)	total wastewater in first year (gallons)	total wastewater in first 3 years (gallons)
2008	480 000	655 000	1 135 000	1 685 000
2009	480 000	1 000 000	1 480 000	2 362 000
2010	480 000	1 810 000	2 290 000	3 960 000
2011	480 000	2 070 000	2 550 000	4 380 000
2012	595 000	2 310 000	2 905 000	

5.2. Wastewater Quality and Management. The salinity of wastewater varies among different shale plays. It also differs based on factors such as well location and volume of water produced.[5,24,35−37] Therefore, wastewater TDS levels can vary widely within a play. Nevertheless, some plays clearly produce water with higher TDS levels than others (see Table S3 in the Supporting Information). Reported wastewater TDS values across major plays in the U.S. range from 3000 to over 400 000 mg/L. Wastewater in the Bakken play tends to be among the most saline of all the major plays in the United States.[38,39]

Currently, wastewater in the Bakken play is primarily disposed through deep-well injection.[28] In this method, the wastewater is pumped back underground into depleted oil formations or deep saline water reservoirs. With more than 1000 oil wells per year currently being drilled and hydraulically fractured in the Bakken, many disposal wells are required to handle the high volume of wastewater. More than 400 saltwater disposal wells are currently operating in North Dakota, over 100 of which have been installed since the beginning of 2008.[40]

An alternative disposal/source option is the reuse of wastewater for hydraulically fracturing other wells. Such recycling is practiced to varying degrees in other shale plays. Little or no recycling occurs in the Haynesville shale, but close to 90% of produced water is recycled in the Marcellus.[4] Currently, no wastewater is recycled during normal operations in the Bakken play. Stepan et al.[24] determined that widespread recycling of wastewater in the Bakken play is not likely to become economically viable, primarily due to the water's very high salinity, which makes it difficult, energy intensive, and expensive to treat. In contrast, disposal through the use of injection wells is relatively cheap. In August 2013, Halliburton unveiled a water recycling process specifically developed for the Bakken play,[41] which was incorporated into a Statoil pilot test announced in December 2013 as the "first significant pilot test of recycling water for hydraulic fracturing in the Bakken."[42] The pilot ran successfully in the Spring of 2014, but a review of Bakken producers in April 2015 revealed that none of them are currently using recycled wastewater for hydraulic fracturing in the Bakken. Despite technical success, the process is not yet economically competitive.[43]

DOI: 10.1021/acs.est.5b04079
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6. IMPLICATIONS

Unconventional oil and gas development can impact local water resources in many ways: water demands have increased in the Bakken for direct uses such as hydraulic fracturing and brine dilution and for indirect uses such as domestic water use from the temporary oilfield services population; increasing amounts of wastewater must be disposed of or reused (volumes that now exceed those injected for hydraulic fracturing); and water demands must be balanced against expected amounts of oil or gas production. By analyzing the suite of issues associated with water use in a specific unconventional oil or gas play, an accurate and comprehensive picture of water impacts in that geographic area can emerge. The North Dakota Bakken shale oil play has several features that differentiate it from other unconventional plays in North America: the high salinity and volume of wastewater, the need for brine dilution using maintenance water, and the large relative increase in local population and water use as a direct result of oilfield development. Yet what we learn about impacts in the Bakken may help in analyzing impacts for other plays. While no other play may have experienced an increase in local population as proportionally large and easy to define as the Bakken, temporary oilfield service populations have an impact everywhere. Much can be learned from contrasts with other plays—the Marcellus play produces water with high salinity (though not quite as high as the produced water in the Bakken), yet has a 90% recycle rate. More data collection and further study in the Bakken and elsewhere is needed to better understand, quantify, and minimize water impacts of unconventional oil and gas development in the future.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b04079.

Additional data and annual figures mapping well installations onto watershed subbasins(PDF)

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

Argonne National Laboratory's work was funded by U.S. Department Energy under contract DE-AC02-06CH11357. We also acknowledge the Natural Resources Defense Council, Stanford University, and Stanford's Natural Gas Initiative for support. Scott Schlueter, Argonne GIS analyst, generated the figures in the report and in the Supporting Information.

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