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Groundwater Salinity in the Powder River Basin, Wyoming

By Karl G. Taboga, James E. Stafford, and James R. Rodgers

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Table of Contents

INTRODUCTION 1
Residue on evaporation method 2
Computational method 3
EVOLUTION OF GROUNDWATER WITH DEPTH IN SEDIMENTARY BASINS 4
Beneficial Uses of Saline Waters. 6
Resource Development Uses. 7
Industrial Uses 7
METHODS 7
RESULTS AND DISCUSSION 10
References 22

List of Figures

Figure 1. TDS, sodium and chloride levels versus depth in two geologic formations, Wyoming 5
Figure 2. Powder River Basin wells for all TDS concentrations. 9
Figure 3. Saline waters in the 1,000–2,000 ft depth interval. 12
Figure 4. Saline waters in the 2,000–3,000 ft depth interval. 13
Figure 5. Saline waters in the 3,000–4,000 ft depth interval. 14
Figure 6. Saline waters in the 4,000–5,000 ft depth interval. 15
Figure 7. Saline waters in the 5,000–6,000 ft depth interval. 16
Figure 8. Saline waters in the 6,000–7,000 ft depth interval. 17
Figure 9. Prevalence of saline groundwater by depth interval. 18
Figure 10. Depth to first saline (TDS >5,000 mg/L) groundwater in study wells. 20

List of Tables

Table 1. USGS water salinity classification. 4
Table 2. TDS levels and depths for three oil-producing formations in the western Bighorn Basin, Wyoming . . . 6
Table 3. Hydrocarbon production, precipitation, and population statistics for Wyoming's structural basins 6
Table 4. Geologic units and corresponding symbols examined in this study. 10
Table 5. Summary table for salinity levels by depth intervals. 18

INTRODUCTION

Groundwater quality, and subsequently the use(s) for which it is suited, varies widely throughout Wyoming. This is most evident in the large sedimentary structural basins, where the majority of the state's population resides and the greater part of economic activity occurs. An aquifer may produce high-quality groundwater suited for human consumption at a basin's margin, while water pumped from the same aquifer a few miles basinward may be unfit for livestock usage. One measure of water quality is its "salinity," which is the amount of dissolved material that remains as residue after the liquid portion of a water sample evaporates. Also called "total dissolved solids," or TDS, salinity is commonly measured in units of mass per volume (milligrams/liter, abbreviated as mg/L); in this report, the terms "salinity" and "TDS" are used interchangeably. A TDS concentration provides a measure of the total solids contained in a water sample but does not specify the type or amounts of the particular chemical compounds that make up the solids. A complete water chemistry analysis is required to determine the type and concentration of the many different chemical constituents present in a single water sample.

TDS consist of any salts, minerals, metals, cations or anions, or inorganic or organic molecules dissolved in water that can pass through a 2-micrometer filter. TDS do not include dissolved gases such as oxygen and hydrogen. Because salinity is a non-specific measure of water quality, it is a poor predictor of water potability (suitability for human consumption). Groundwater with low TDS levels can contain harmful levels of naturally occurring or manmade toxins such as arsenic, lead, pesticides, or radioactive elements. Still, salinity is an expedient and useful measure of general water quality, especially when accompanied by a complete water chemistry analysis.

This report examines the salinity of groundwater that occurs at depths of 7,000 feet (ft) or less below ground surface (bgs) in the Powder River structural basin (PRB) of northeastern Wyoming. Special emphasis is placed on saline groundwaters (TDS ≥5,000 mg/L) that may be suited to industrial uses, thereby conserving higher-quality waters for domestic, agricultural, and livestock uses. Saline groundwaters are encountered most frequently during oil and gas exploration and production operations (Kharaka and Hanor, 2003) in deep basin aquifers located more than 1,000 ft bgs. In contrast, due to costs, few deep wells are drilled by domestic, irrigation, or livestock water users looking for quality groundwaters, which are generally found in shallow wells close to recharge areas located along basin margins and alluvial deposits (Taboga and others, 2014a, b).

Two approaches were utilized to determine groundwater salinity. First, the Wyoming State Geological Survey (WSGS) obtained water quality data from three government datasets associated with oil and gas production: 1) the United States Geological Survey (USGS) Produced Water Database (PWD), 2) the USGS National Water Information System Database (NWIS), and 3) the Wyoming Oil and Gas Conservation Commission (WOGCC) Water Analysis Database (WADB). Second, using the Static Spontaneous Potential Method (Schlumberger Well Services, 1989; Schnoebelen and others, 1995), the WSGS estimated TDS levels from spontaneous potential data obtained from nearly 200 WOGCC oil and gas well logs. Thus, in this report, the location of saline water is largely based on data obtained during oil and natural gas exploration and production. Groundwater salinities in overlying geologic formations that do not contain oil and gas deposits must be estimated from geophysical logs of oil field wells that penetrate these units; there is no geospatially extensive deep drilling and water sampling program in Wyoming outside of hydrocarbon operations.

The USGS (Maupin and others, 2014) reports saline groundwater, which accounts for about one percent of all water use in the United States, is utilized primarily for mining operations, thermoelectric power generation, and industrial operations. Still, an understanding of saline groundwater occurrence is beneficial for several reasons:

1. Saline waters make up ~40 percent of all deep (>1,000 ft bgs) groundwaters in Wyoming (USGS, 2017a; WOGCC, 2017).
2. The presence of saline groundwaters provides information about the evolution of groundwater quality in the host aquifer and structural basin of occurrence.

3. Federal and state environmental regulatory agencies permit the disposal of wastewater produced from resource development and other industrial operations by injection into saline aquifers.
4. In Wyoming, saline aquifers may be located in proximity to aquifers targeted for in-situ recovery (ISR) of uranium, trona, and potentially lithium (Gallegos and others, 2015; Taboga and others, 2015).
5. Since it commonly occurs in deeply buried formations, saline groundwater is frequently geothermal.
6. Saline groundwaters are frequently, but not always, co-produced with hydrocarbons.
7. Geoscience research groups throughout the world are looking into the feasibility of sequestering carbon dioxide in deep saline aquifers (http://www.uwyo.edu/cmi/). Some of these technologies involve extracting saline waters to enhance carbon sequestration in the target aquifer.
8. In the future, Wyoming industries may choose to use saline waters as fresh water resources become harder to access and demands for public use increase.

Saline waters co-produced or created in association with resource development (items 4–7, above) must be managed in compliance with local, state, and federal environmental regulations. In many cases, the most cost-effective management method is to inject the produced water into another saline aquifer onsite. Alternatively, the produced water may be conveyed by pipeline or tank truck to another area for reinjection into a relatively deep saline aquifer that is no longer productive or to a water treatment facility. Injection/disposal wells are commonly repurposed oil and gas wells regulated by the WOGCC.

MEASURING TDS

Although, the concept of "salinity" is simple, the actual measurement of TDS in natural waters itself is complicated by chemical changes resulting from the analytical processes used. Two methods of measurement are commonly employed.

Residue on evaporation method

This method involves actively evaporating the volatile portion of the water sample and then measuring the remaining residue. Historically, various public agencies and research bodies specified several differing procedures for this method. The USGS, which has assembled the most extensive water quality database for natural waters of the United States, has used two evaporative procedures: a higher temperature (180 °C) method and lower temperature (105–110 °C) analysis (Skougstad and others, 1979). The 180 °C evaporation temperature is meant to withdraw a higher fraction of the water retained in the crystalline structures of some salts, notably those containing sulfates such as gypsum ($CaSO_4$). The mass added by the water of crystallization is offset to some degree by the partial evaporation (volatilization) of organic compounds, acids, and ions (particularly bicarbonate) during the drying process. In fact, the high and low temperature analyses do not yield markedly different results for even slightly saline (<3,000 mg/L TDS) natural waters (Hem, 1985). Generally, evaporation methods yield the most accurate and precise results regardless of temperature, especially in low TDS waters where inorganic salts constitute the greater part of dissolved solids. However, evaporation methods are time consuming and expensive.

Computational method

This method calculates TDS levels indirectly either by measuring the electric conductance (EC) of the sample and multiplying by an appropriate conversion coefficient, or by summing the concentrations of the major constituent ions. Each computational method has benefits and limitations. Measuring electrical conductance is quick and convenient with properly maintained and calibrated instruments. EC is directly related to the concentration of dissolved ions in the sample. The approximate relationship between EC and TDS is given by the equation:

$$TDS = kEC$$

where k is a conversion coefficient. Accurate calculation of TDS with the EC conversion method requires the application of the appropriate conversion factor (k). In practice, this is complicated by the fact that the value of k differs widely with ion composition and sample temperature. For example, at 25 °C, a 1,000 mg/L TDS solution of sodium chloride will exhibit a TDS/EC ratio of about 0.5, while a 1,000 mg/L TDS solution of sodium bicarbonate has a TDS/EC ratio of 0.9. In fact, the value of k typically falls somewhere between these extremes as most groundwater samples contain a diverse mixture of ions. Combination EC/TDS monitoring instruments typically use a conversion factor around 0.65, but more sophisticated devices allow the user to specify a conversion factor for certain applications. If required, precise values of k can be calculated for specific types of groundwater by dividing sample EC levels by corresponding TDS concentrations obtained from supplemental analyses, such as residue on evaporation or summation methods, and then entered into the instrument. Sample temperature variations are less problematic; combination EC/TDS/temperature meters typically adjust for temperature automatically. Although the use of an EC meter is convenient, the resulting estimation of TDS concentration is typically accurate only to within 10 percent.

Accurate calculation of TDS by summation of the concentrations of constituents requires a complete chemical analysis that includes major ions, metals, and, in some cases, organic chemicals. Summation may provide more accurate estimates than residue on evaporation analysis in water samples that have TDS concentrations above 1,000 mg/L and contain significant levels of organics or acids, or yield hygroscopic (water retaining) crystals. Although summation can be the most accurate method, the multiple analyses required to determine concentrations of the major ions make it expensive and time consuming.

The accurate determination of TDS concentration is not obtained from a single analysis but through a process that involves completing and comparing several analyses for TDS as well as major ions. For example, the USGS lists water quality data for nearly 400,000 sites on the National Water Information System website (http://nwis.waterdata.usgs.gov/usa/nwis/qwdata). For many of the sites listed, TDS concentrations are provided using both residue on evaporation and computational methods. The databases used in this report do not specify the method(s) used to determine TDS concentrations, and WSGS did not ascertain the method(s) used.

WATER QUALITY STANDARDS, GROUNDWATER CLASSIFICATION, AND TDS LEVELS

Groundwater quality in the state of Wyoming is regulated by three agencies. The Wyoming Department of Environmental Quality (WDEQ) Water Quality Division regulates groundwater quality for most uses of the state's aquifers. Public groundwater systems are regulated by the U.S. Environmental Protection Agency (EPA) Region 8 Office, headquartered in Denver, Colorado. Both agencies have instituted chemical standards for groundwater uses under their regulation. The standards are reviewed periodically and updated as new scientific information becomes available. The WOGCC regulates the underground disposal of wastewater unfit for domestic, livestock, irrigation, and other general uses. Additionally, WOGCC manages and regulates the Wyoming Groundwater Baseline Sampling, Analysis and Monitoring Program. Current Wyoming state water quality standards are contained in chapter 8 of WDEQ Water Quality Rules and Regulations and chapters 3 and 4 of the WOGCC Rules. The EPA's current drinking water regulations are found under Title 40 of the Code of Federal Regulations (http://water.epa.gov/lawsregs/rulesregs/sdwa/currentregulations.cfm).

Groundwater standards for TDS concentration are based on the specific use under regulation. The Safe Drinking Water Act authorizes the EPA to set National Primary Drinking Water Regulations (NPDWR) for contaminants that may have adverse effects on the health of persons. The EPA has specified Maximum Contaminant Levels (MCLs) for the contaminants listed in the NPDWR. MCLs (EPA, 2015) are legally enforceable standards that apply to public water systems that provide water for human consumption through at least 15 service connections or regularly serve at least 25 individuals. Although MCLs do not apply to groundwater for livestock, irrigation, or self-supplied domestic use, they do provide a valuable reference when assessing the suitability of water for these uses. The EPA has also established Secondary Maximum Contaminant Levels (SMCLs) within the National Secondary Drinking Water Regulations. SMCLs are non-enforceable guidelines for contaminants that can cause aesthetic problems such as degradation of taste, odor, or appearance. Currently, there is no MCL for TDS concentrations in public drinking water systems, however, the EPA has established SMCL for TDS of 500 mg/L.

WDEQ regulations (2015) classify a groundwater's suitability for domestic, agricultural, and livestock uses based on water quality standards for specified inorganic chemicals, radionuclides, and physical characteristics. Maximum concentrations of TDS are 500 mg/L for domestic use (Class I), 2,000 mg/L for agricultural use (Class II), and 5,000 mg/L for livestock (Class III). Groundwaters deemed suitable for industrial uses are classified by TDS concentration as Class IV A (TDS ≤10,000 mg/L) and Class IV B (TDS >10,000 mg/L).

WOGCC regulations govern the issuance of underground injection control permits (UIC permits) of various types of wastewaters co-produced with oil and gas development operations into very saline aquifers (TDS > 10,000 mg/L). In certain cases, the WOGCC can authorize an exemption for an aquifer that has a TDS concentration between 5,000 and 10,000 mg/L and "is not reasonably expected to be used as fresh or potable water" (WOGCC Rules chap. 4, sec. 12 (a.v.)).

Table 1 shows the USGS salinity classification (Heath, 1983) for surface water and groundwater.

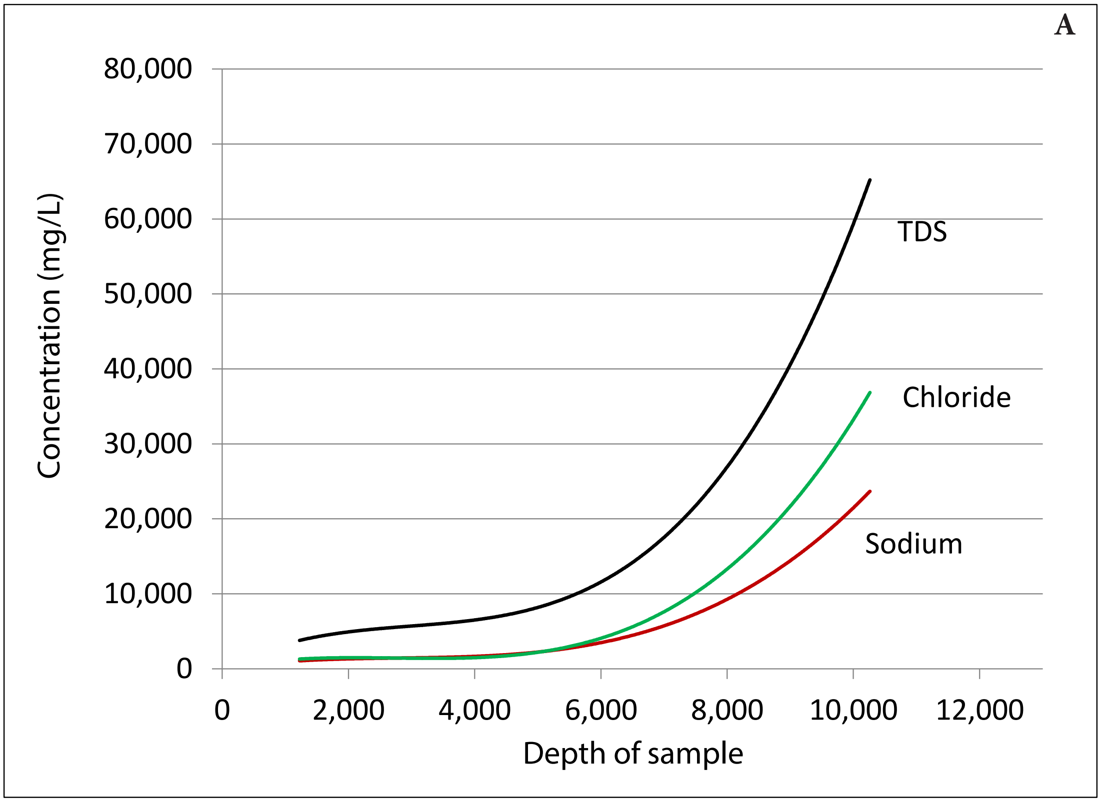
Table 1. USGS water salinity classification.

Classification	TDS (mg/L)
Fresh	0–999
Slightly saline	1,000–2,999
Moderately saline	3,000–9,999
Very saline	10,000–34,999
Briny	more than 34,999

The manner in which TDS is incorporated into the EPA, WDEQ, and WOGCC water quality standards gives regulatory context to the measurement and interpretation of TDS concentrations in natural waters. As an independent property, TDS concentration provides a convenient but incomplete initial assessment of water suitability for domestic, agricultural, livestock, and industrial uses. Frequently, an approximation of TDS levels obtained from electrical conductance measurements is the only water quality analysis conducted on a newly drilled well in Wyoming. A complete water chemistry analysis ensures that a groundwater resource will meet the health, safety, and aesthetic requirements of its intended use.

EVOLUTION OF GROUNDWATER WITH DEPTH IN SEDIMENTARY BASINS

Groundwater salinity generally increases along with the depth of burial of the host aquifer in a structural basin. The rates of increase differ greatly, however, within different parts of the same basin, among basins, and among different hydrostratigraphic units in the same basin (Kharaka and Hanor, 2003). The rise in salinity levels with depth results from increases in sodium and chloride concentrations as evaporitic materials in the host rock dissolve (Kharaka and Hanor, 2003; fig. 1). In contrast, groundwater salinity levels may decrease with depth within a particular formation



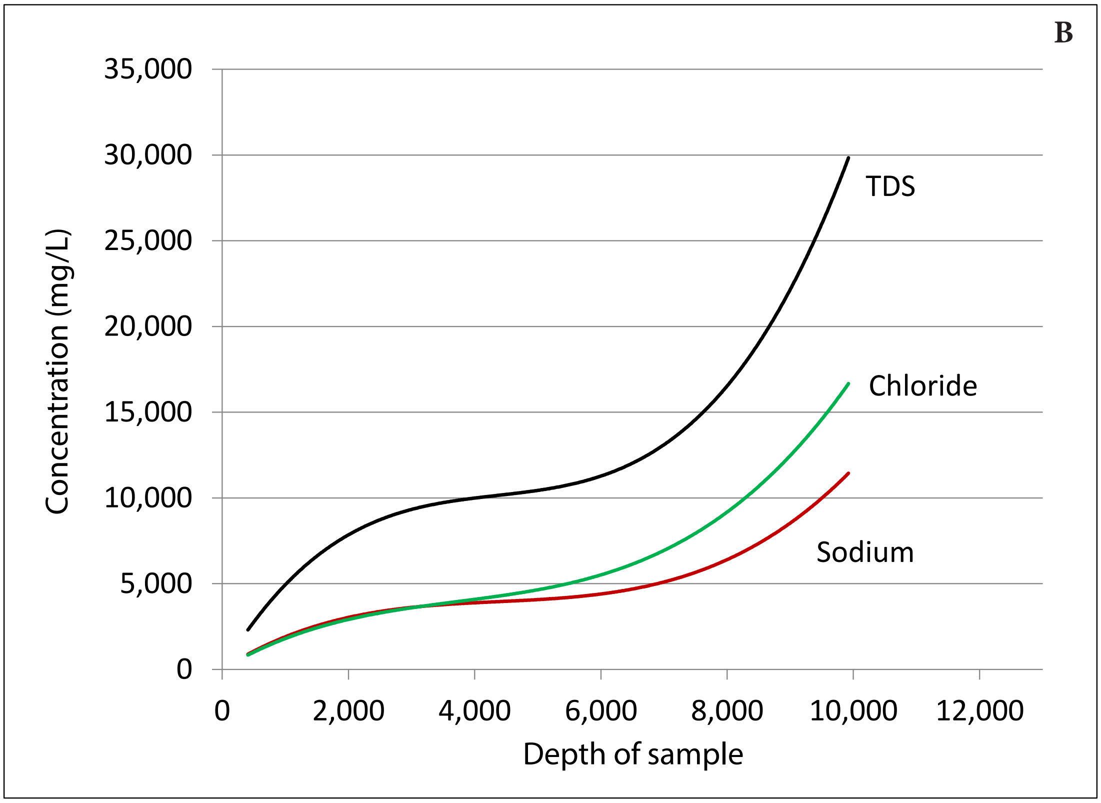


Figure 1. Trends in TDS, sodium and chloride levels with depth of sample in the a) Casper Formation of the Laramie Basin and b) Newcastle Sandstone of the Powder River Basin, Wyoming.

(Kharaka and Hanor, 2003). In other instances, older underlying formations have lower TDS concentrations than overlying, younger formations (table 2).

Table 2. Mean TDS concentrations and depths of sample for three hydrocarbon producing formations in the Oregon Basin Oil Field located in the western Bighorn Structural basin, Wyoming. Mean TDS levels are progressively higher in the younger Tensleep and Dinwoody-Phosphoria production intervals than in the more deeply buried, older Madison formations.

Formation	Age	Number of samples	Mean TDS[a] (mg/L)	Mean depth[a] (ft bgs)
Dinwoody-Phosphoria	Permian	121	8,070	3,768
Tensleep	Pennsylvanian	63	6,650	3,882
Madison	Mississippian	78	3,924	4,975

[a] USGS, 2015

The hydrochemical evolution of groundwater is affected by numerous physical and chemical properties of the solids (aquifer matrix) and fluids (water, gas, and oil) that constitute the aquifer. Some properties that control salinity include host rock geochemistry, depth of burial, aquifer residence time, geological structure, proximity to recharge areas, groundwater flow rates and patterns, diagenetic processes, and interactions between fluid and solid geo-materials.

BENEFICIAL USES OF SALINE WATERS

The USGS reports (Maupin and others, 2014) surface and groundwater withdrawals of saline water totaled 48.3 billion gallons per day (Bgal/d) in the United States in 2010, constituting approximately 14 percent of all water used. About 7 percent (3.29 Bgal/d) of the saline waters withdrawn came from groundwater sources. The extracted saline groundwater was used in mining operations, including oil and natural gas exploration and development (93.9 percent), thermoelectric power generation (4.5 percent), and industrial operations (1.6 percent).

In Wyoming, saline waters are most often encountered during resource development operations located in semi-arid structural basins (table 3) where most of the state's population and industry is concentrated and where saline water is most likely to be used beneficially. The use of saline waters for industrial applications as an alternate to fresh water is dependent on the availability of and the costs associated with obtaining, transporting, and storing fresh water.

Table 3. Hydrocarbon and co-produced water production levels in 2013, average annual precipitation, and population for Wyoming's five top resource producing structural basins.

Basin	Oil [a] (BBLs)	Gas [a] (MCF)	Water [a] (BBLs)	Average annual precipitation [b] (in)	Estimated population [c]
Denver Julesburg	1,420,597	1,095,676	2,340,103	11–20	104,900
Wind River	4,659,699	146,733,934	242,795,089	6–10	39,900
Bighorn	11,547,252	13,505,269	1,009,545,661	6–10	36,800
Greater Green River	14,336,780	1,208,678,067	159,948,934	6–15	62,300
Powder River	30,433,643	367,986,763	637,105,294	13–15	126,900

[a] WOGCC, 2015

[b] PRISM, 2015

[c] WDAIEAD, 2014

Resource Development Uses

Saline water is frequently suitable for use in mineral extraction operations such as quarrying, milling and other ore processing, injection of water for secondary and tertiary oil recovery, and unconventional oil and gas recovery (hydraulic fracturing, also known as fracking or frac job). During the last decade, resource development corporations and their consultants have been examining the use of saline water for fracking operations, largely motivated by the volumes of water required for a frac job (variously estimated at 2 to 10 million gallons per well). This can increase competition for local water resources even in areas with moister climates such as the Marcellus Shale play in Pennsylvania and West Virginia. The problem is further exacerbated in semi-arid western basins where annual precipitation averages 6 to 20 inches, fresh groundwater is largely unavailable, and surface water flows are allocated to holders of existing water rights.

Successful fracking with saline groundwater depends on the chemistry of the water and its interactions with the geologic formations under development. High concentrations of common ions can reduce frac fluid effectiveness (http://www2.epa.gov) by causing scale build-up (Ca, Ba, Mg, SO_4, HCO_3, and Fe) or by interfering with performance enhancing chemicals contained in the fracking fluid (Ca, Mg, Ba, Sr, Cl, and PO). In some cases, the fracking chemicals added can be adjusted or saline water can be treated on site to render it suitable for use in a particular fracking operation. Waters with salinities up to 100,000 mg/L can be used for fracking (http://cen.acs.org). Effective mixtures of saline waters and fracking chemicals must be customized for each producing field. Despite these challenges, resource corporations are conserving freshwater by using saline waters (http://m.amarillo.com/news/texas,) and their use is expected to grow as technical and economic obstacles are successfully addressed (LeBas and others, 2013; McGovern and others 2014).

Industrial Uses

Saline waters are suitable for non-mining industrial applications such as fabricating, processing, washing, or cooling manufactured product where water quality is not a limiting factor. As in mining applications, saline waters may require treatment prior to their use in industry.

METHODS

For this project, the WSGS estimated groundwater TDS levels from oil and gas well logs using the Static Spontaneous Potential (SSP) Method (Brown and others, 1980; Schlumberger Well Services, 1989; Schnoebelen and others, 1995). The WSGS used Petra® 4.3.0.283 geologic interpretation software to identify wells with spontaneous potential (SP) logs among the 65,000 oil and gas wells in the Powder River Basin (PRB). This provided almost 1,000 identified candidate wells that were evaluated for: 1) legible SP logs with coherent shale baselines and corresponding gamma ray logs, 2) borehole bottom temperatures, 3) mud filtrate resistivity data, and 4) the use of drilling muds that did not contain saline or petroleum-based compounds. Next, SP and gamma ray logs from 355 wells that met the selection criteria were checked for SP deflections in sandstone strata to a depth of 7,000 ft. For this study, TDS levels were calculated from SP deflections by application of fitted mathematical algorithms developed by Brown and others (1980). These analyses yielded 2,480 calculated TDS levels at varying depths up to 7,000 ft bgs.

The WSGS also compiled more than 35,000 records of Wyoming water quality data from the USGS PWD (USGS, 2017a), the USGS NWIS database (USGS, 2017b), and the WOGCC WADB (WOCGG, 2017). Water quality data were screened to identify and remove records that: 1) did not provide sample geospatial coordinates or depth of sample, 2) indicated the sample was not a representative groundwater sample (injection water, commingled samples, reserve pit, backflow, etc.), and 3) exhibited conflicting or questionable water quality analyses (ion balances exceeding 5 percent, pH values less than 4.5 units, and TDS values less than 100 mg/L). The WSGS removed redundant records; in cases where multiple samples were drawn and analyzed from the same site, the WSGS retained the sample with the single lowest TDS value. The WSGS joined the PWD, NWIS, and WADB data into a singular database from which it removed interagency duplicates (records shared by both agencies); there was considerable overlap of records from the two agencies since WOGCC provides produced water quality data to the USGS for incorporation into the Produced Water Database. The final WSGS Saline Water Database contains TDS data for more than 11,000 sites statewide; more than 7,600 of these Wyoming sites have TDS concentrations exceeding 5,000 mg/L. Nearly 420 water analysis samples were obtained from PRB wells; 204 of those samples were qualified for use in this study.

The final dataset generated by well log and water quality analyses contained 2,669 data points in PRB oil and gas well fields (see the WSGS Oil and Gas Interactive Map, http://www.wsgs.wyo.gov/) and 15 data points from USGS environmental samples (NWIS).

Stratigraphic units were determined and named from geologic markers listed for each well (WOGCC, 2017), and from USGS cross sections (Fox, 1993a, b, c, d, and references therein) and structure contours (Lewis and Hotchkiss, 1981). In two cases, adjacent stratigraphic units were combined into single hydrostratigraphic units: 1) The early Tertiary Wasatch, exposed throughout the PRB, and Fort Union formations form a regional aquifer system (Thamke and others, 2014) and are combined into a single hydrostratigraphic unit in this report. The exposures of the Wasatch/Fort Union hydrostratigraphic unit were used in this study to represent the boundaries of the Powder River Structural Basin shown in **figures 2–9.** 2) The relatively shallow Lance Formation and underlying Foxhills Sandstone form the Upper Cretaceous regional aquifer system (Thamke and others, 2014) and are undifferentiated as well.

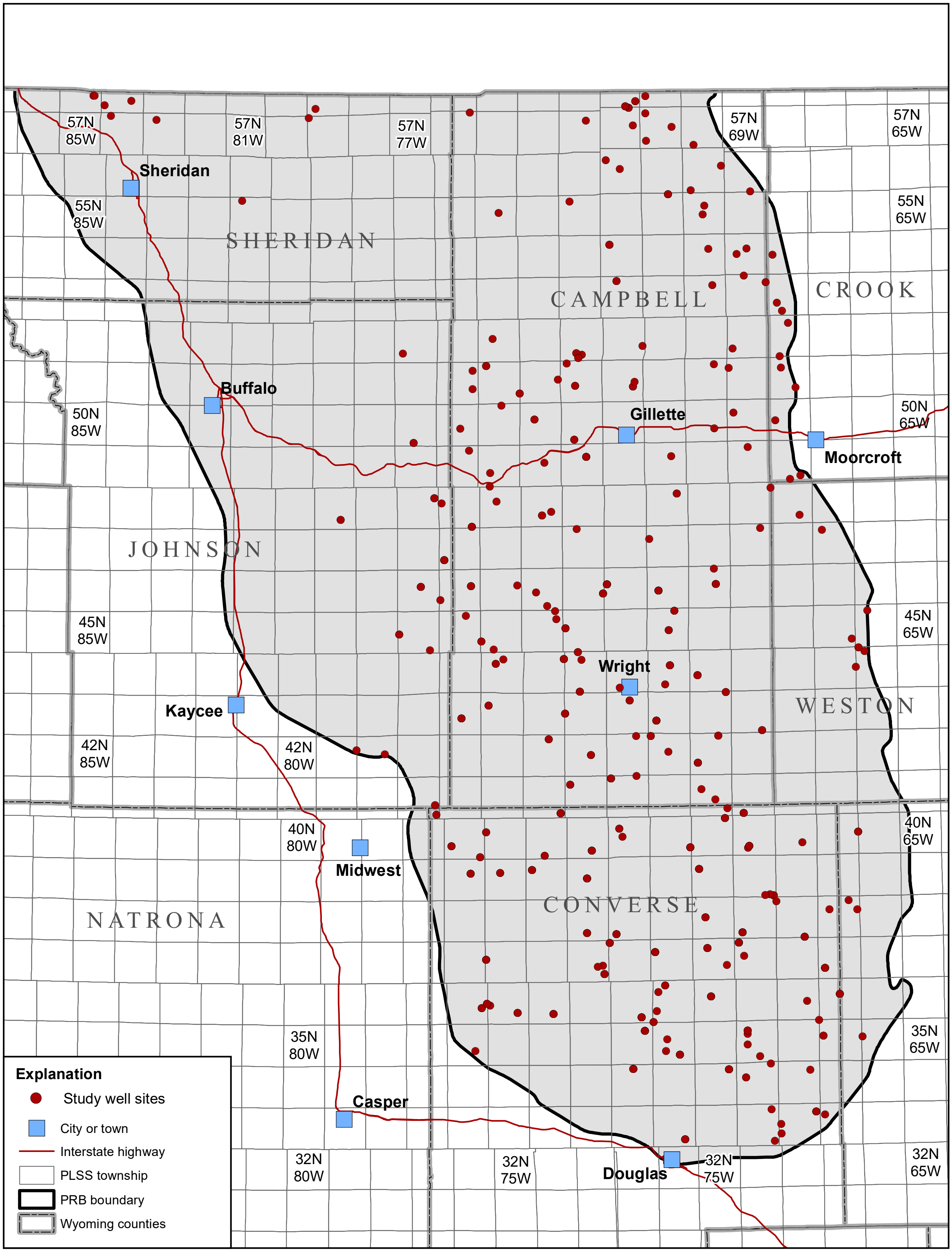


Figure 2. Powder River Basin wells for all TDS concentrations.

Results are presented by 1,000 ft intervals from 1,000 to 7,000 ft in depth, and by depth of first encountered industrial grade (TDS>5,000 mg/L) saline groundwater.

RESULTS AND DISCUSSION

Results are presented in figures 2–8, table 5, and the data table in the appendix. Figure 2 shows the geospatial distribution of PRB wells used in the TDS analyses. Table 5 provides summary statistics (minimum, mean, and maximum TDS concentrations, and depth range of occurrence) for each of the six 1,000 ft depth intervals.

Salinity Levels by Depth Intervals

Figures 3–8 show wellbore TDS levels by 1,000 ft depth intervals from 1,000 to 7,000 ft below ground surface (bgs). The least saline groundwater is shown in depth intervals that exhibit multiple results. Groundwaters less than 1,000 ft deep are generally of good quality in the PRB and were not considered in this report. Formation symbols (table 4) next to each well denote the stratigraphic unit in which the saline water occurred. TDS levels are sorted into categories consistent with Wyoming Department of Environmental Quality (WDEQ) requirements for agricultural (Class II, TDS ≤ 2,000 mg/L), livestock (Class III, TDS ≤ 5,000 mg/L), and industrial uses (Class IV-A ,TDS ≤10,000 mg/L, and Class IV-B, TDS >10,000 mg/L).

1,000–2,000 ft bgs (fig. 3): Estimated TDS levels in this interval are all less than 10,000 mg/L. A broad band of moderately saline (5,001 – 10,000 mg/L) sites in the Tertiary Wasatch/Fort Union (Twf) hydrostratigraphic units extends from the south central PRB to the northwest. Moderately elevated (2,001–5,000 mg/L) salinities appear in the Upper Cretaceous Lance/Fox Hills aquifer system (Klf) at the remaining four wellsites, located along the eastern margin of the PRB.

Table 4. Geologic units and corresponding symbols examined in this study.

Formation	Symbol
Belle Fourche Shale	Kbf
Carlile Shale	Kcl
Chugwater Formation	TRc
Frontier Formation	Kf
Greenhorn Formation	Kgh
Inyan Kara Group	Kjik
Lance Formation/Fox Hills Sandstone	Klf
Lewis Shale	Kle
Mesaverde Formation	Kmv
Minnelusa Formation	PIPm
Morrison Formation	Jm
Mowry Formation	Kmr
Muddy/Newcastle sandstones	Kmn
Niobrara Formation	Kn
Pierre Shale	Kp
Skull Creek Shale	Ksc
Steele Shale	Ks
Sundance Formation	Js
Wasatch/Fort Union formations	Twf

2,000–3,000 ft bgs (fig.4): Slightly to very saline groundwaters occur in the Klf aquifer system along the entire eastern margin of the PRB. One slightly saline (1,000–2,000 mg/L) Pierre Shale (Kp) wellsite is found on the edge of the basin in southwest Crook County. The belt of saline Twf sites, observed in the previous interval, has extended further to the west. Most Twf sites are moderately saline (2,001–5,000 mg/L), although a few industrial grade (>5,000 mg/L) groundwaters are scattered throughout the basin.

3,000–4,000 ft bgs (fig.5): At this depth interval, industrial grade (>5,000 mg/L) groundwater is found in the Cretaceous Pierre (Kp) and Lewis (Kle) shales along the eastern margin of the PRB and in Twf wells in western Campbell and eastern Johnson counties south of U.S. Interstate 90. Moderately saline groundwaters (2,001–5,000 mg/L) occur in the Klf unit in the southeast and in the Twf system in the western half of the basin.

4,000–5,000 ft bgs (fig. 6): Industrial grade (>5,000 mg/L) groundwaters occur in the Pierre (Kp), Lewis (Kle), and Carlile (Kcl) shales and the Greenhorn Formation (Kgh) on the eastern and western basin margins and are scattered throughout the Twf and Klf units. Groundwater in eastern Converse County is slightly to moderately saline (1,000–5,000 mg/L).

5,000–5,999 ft bgs (fig. 7): Wells in this interval penetrate geologic units that underly the Klf in a broad belt that extends northwestward from eastern Converse County to northern Sheridan County. In fact, wells at this depth range enter Lower Cretaceous, Jurassic, and Pennsylvanian–Permian formations in the northeastern PRB near the Black Hills Uplift. To the west of this belt, saline groundwater occurs largely in the Klf system and in a few Twf sites.

Industrial grade (>5,000 mg/L) saline groundwaters appear more frequently in all formations within this interval. There are areas with high concentrations of industrial grade groundwater along the basin margin in Converse County, in the central PRB and near Black Hills Uplift. A zone of moderately saline (2,001–5,000 mg/L) Klf groundwater appears in northcentral Converse County.

6,000–7,000 ft bgs (fig. 8): In the eastern two thirds of the PRB, saline waters are found in geologic units underlying the Klf and, further west, in the Klf system. Although industrial grade (>5,000 mg/L) groundwaters are scattered throughout the PRB within this interval, they occur most frequently in the northeastern PRB near the Black Hills Uplift and across northern Converse County.

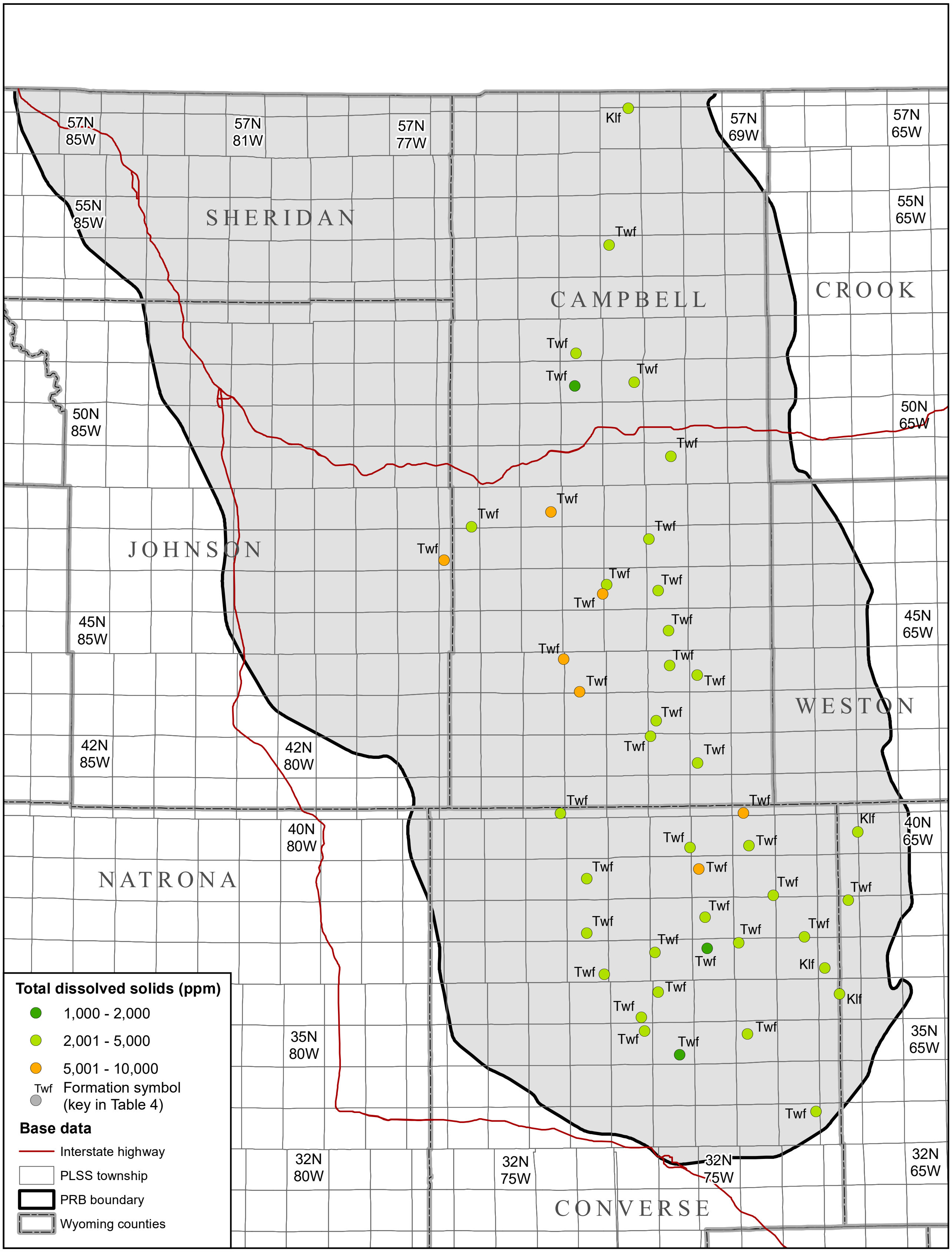


Figure 3. Saline waters in the 1,000–2,000 ft depth interval.

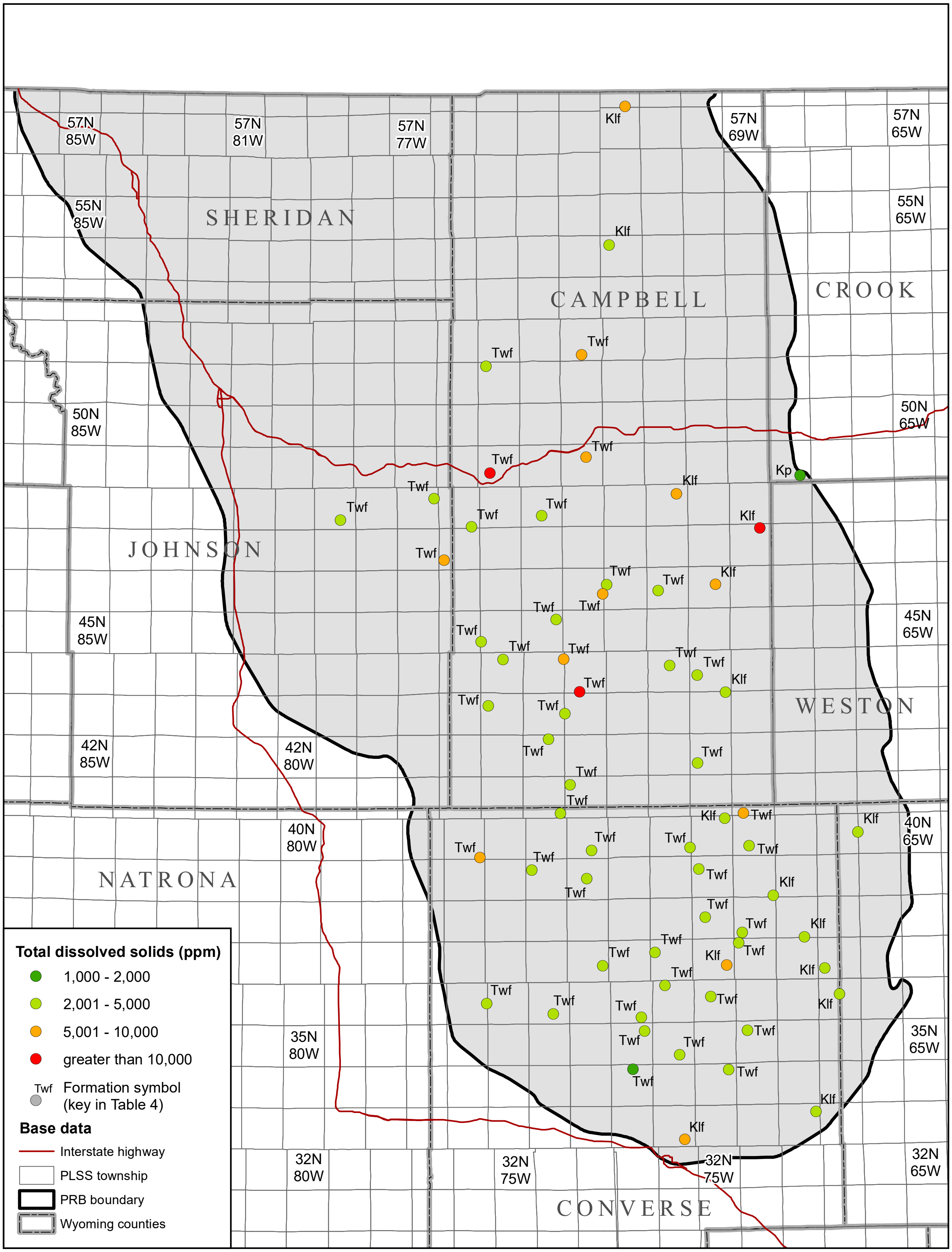


Figure 4. Saline waters in the 2,000–3,000 ft depth interval.

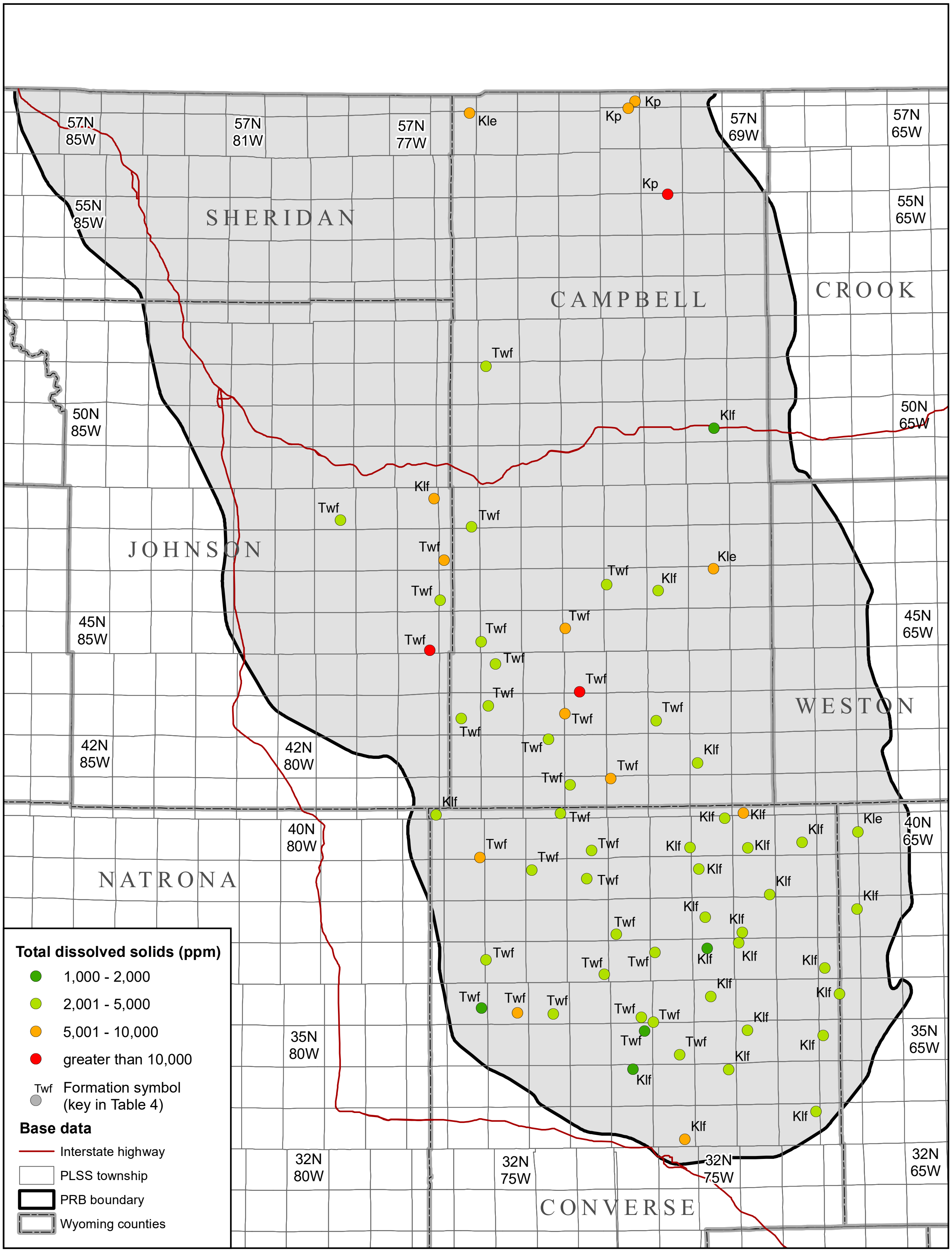


Figure 5. Saline waters in the 3,000–4,000 ft depth interval.

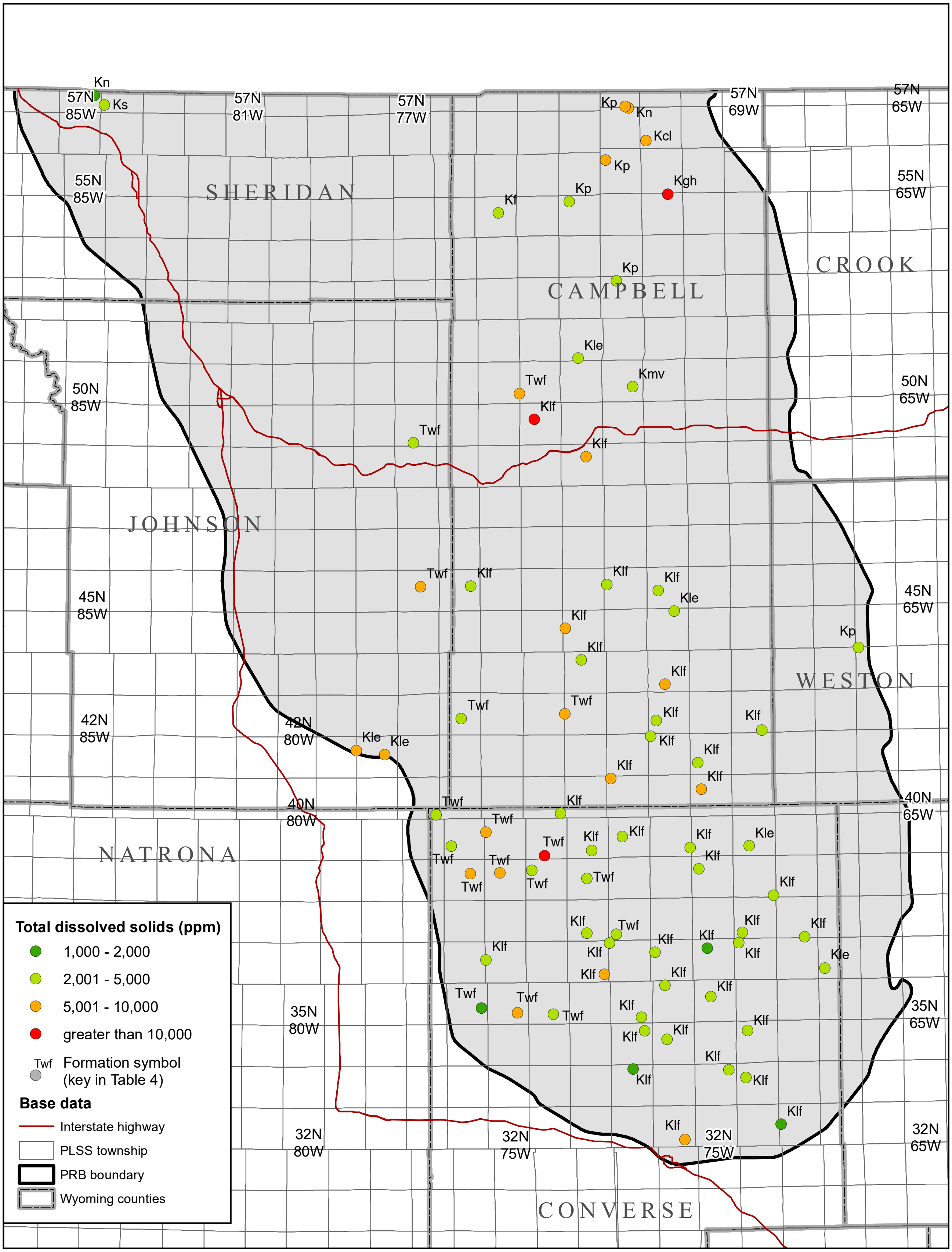


Figure 6. Saline waters in the 4,000–5,000 ft depth interval.

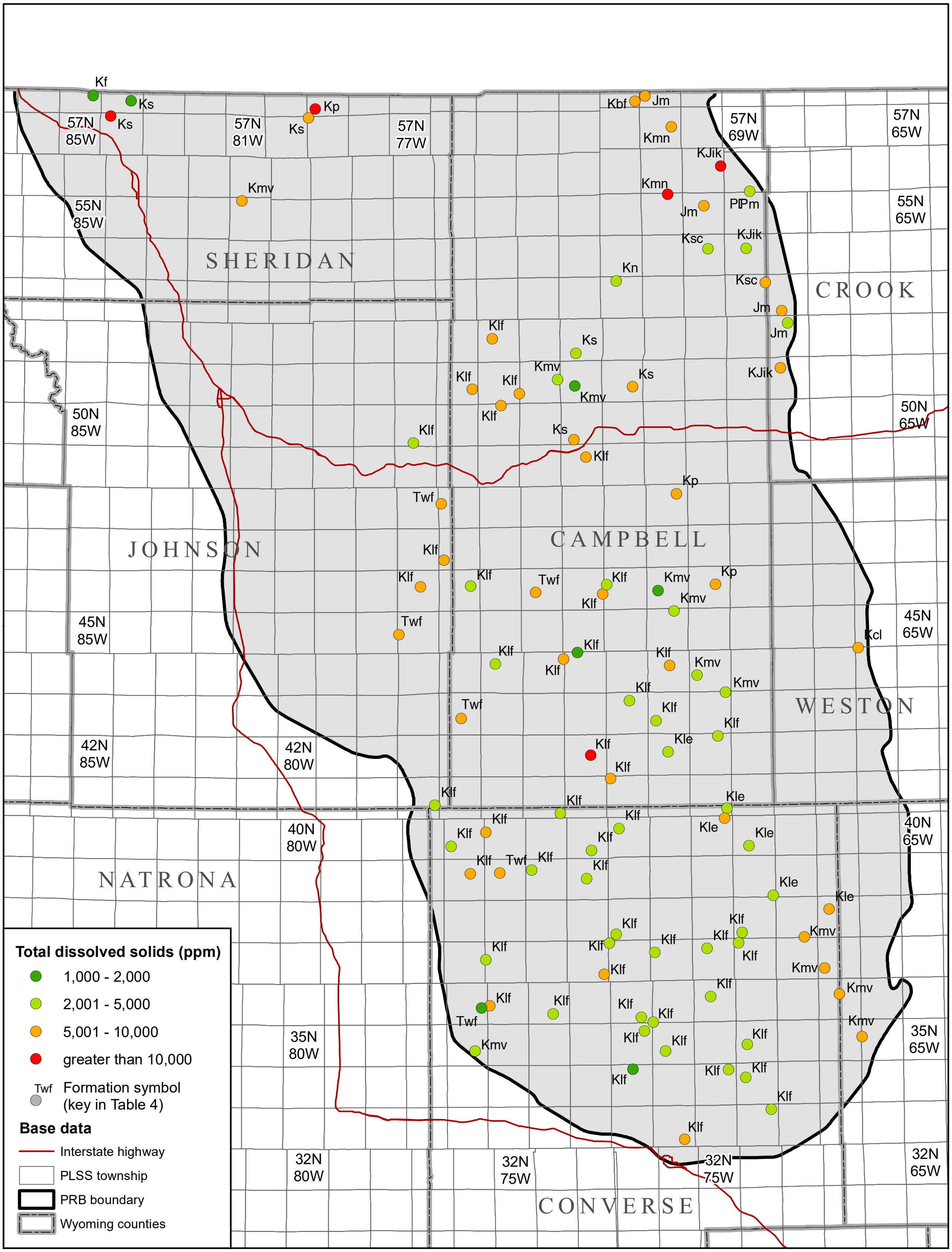


Figure 7. Saline waters in the 5,000–6,000 ft depth interval.

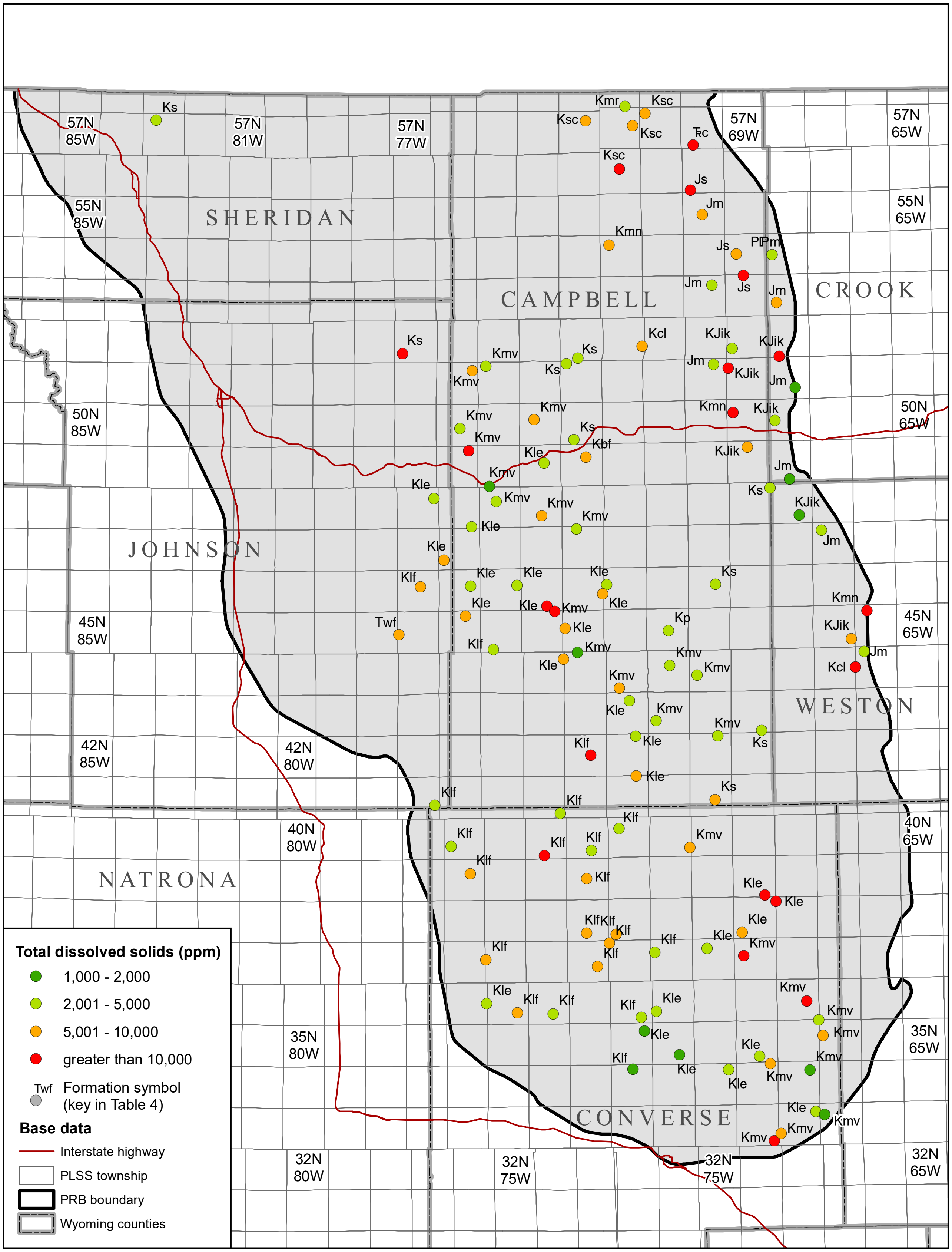


Figure 8. Saline waters in the 6,000–7,000 ft depth interval.

Table 5 provides summary statistics for each depth interval and lists percentages of salinity grouped by WDEQ class of use (agricultural, livestock, and industrial); figure 9 summarizes the class of use data shown in table 5.

The proportion of agricultural grade groundwater (1,000–2,000 mg/L) remains relatively constant at less than 10 percent within all depth intervals. The incidence of industrial grade waters (Classes IV-A & B, TDS >5,000 mg/L) rises with increasing depth, most notably at depths greater than 5,000 ft. This increase in the proportion of industrial waters coincides with a decline in the proportion of livestock grade (Class III) water. Nevertheless, TDS levels characteristic of Class III groundwater are most frequently encountered at depths less than 5,000 ft.

Table 5. Summary table for salinity levels by depth intervals.

Salinity as TDS (mg/L)					Class II Agricultural 1,000-2,000 (mg/L TDS)	Class III Livestock 2,000-5,000 (mg/L TDS)	Class IV-A Industrial 5,000-10,000 (mg/L TDS)	Class IV-B Industrial >10,000 (mg/L TDS)	Class IV-A&B Combined industrial >5,000 (mg/L TDS)
Depth (ft)	**Minimum**	**Mean**	**Maximum**	**Number of occurrences**	**Percent**				
1,000–2,000	1,828	3,815	8,347	45	7%	78%	16%	0%	16%
2,000–3,000	1,037	4,488	15,744	64	3%	73%	19%	5%	23%
3,000–4,000	1,029	4,880	25,848	66	8%	68%	20%	5%	24%
4,000–5,000	1,080	4,492	13,566	75	7%	63%	27%	4%	31%
5,000–6,000	1,347	5,035	15,275	99	7%	46%	41%	5%	46%
6,000–7,000	1,009	6,110	24,074	115	9%	42%	32%	17%	50%

Regarding the two classes of industrial groundwater, the proportion of Class IV-A industrial groundwater rises between 1,000 and 6,000 ft and then declines in the 6,000 to 7,000 ft interval. The three-fold increase in the occurence of Class IV-B industrial grade water at the 6,000 to 7,000 ft interval corresponds to observed declines in Class III and IV-A groundwaters.

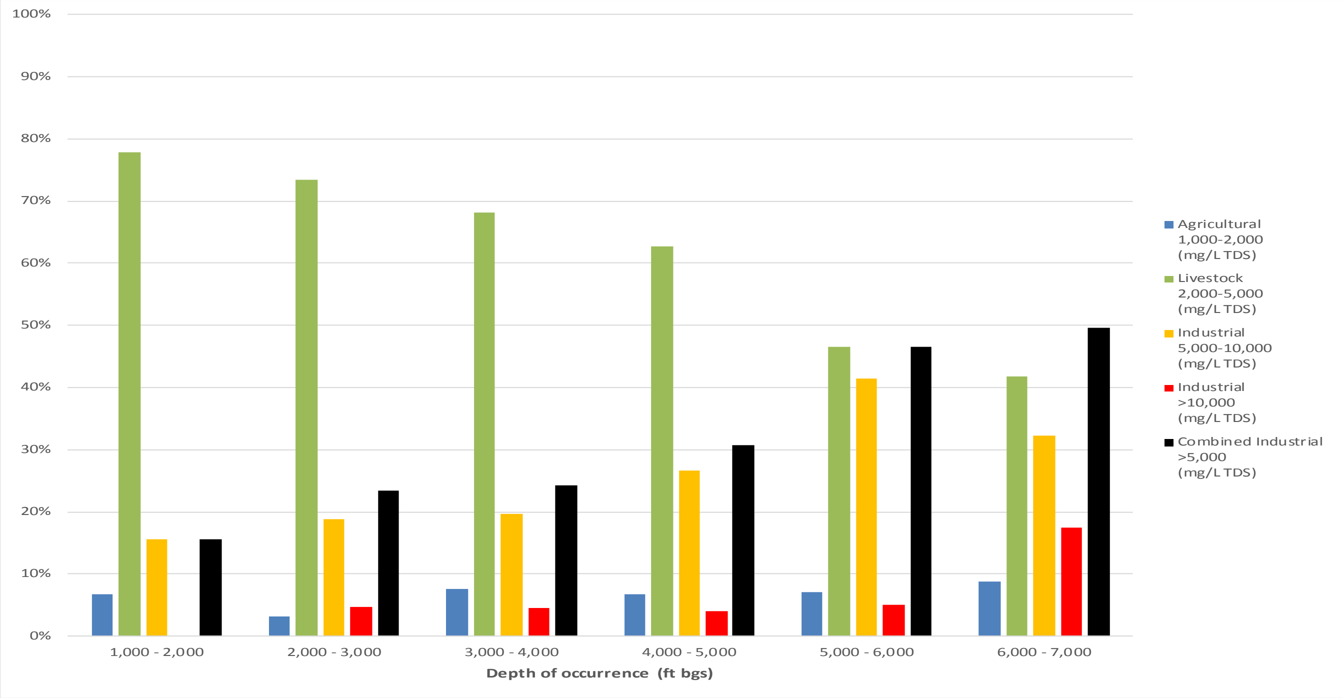


Figure 9. Prevalence of saline groundwater by depth interval.

First Encountered Saline Groundwater

Figure 10 shows the depth intervals where industrial grade saline groundwater (>5,000 mg/L) is first encountered in the wells analyzed for this report. Wells that did not exhibit salinity levels above 5,000 mg/L are not shown in figure 10.

Depths to first encountered saline groundwaters are substantial throughout the PRB. Industrial grade saline waters were first encountered at depths greater than 2,000 ft bgs in 92 percent of the wells shown in figure 10. This is supported by USGS water analyses that have shown that almost all shallow groundwaters (<2,000 ft bgs) in the PRB have TDS levels below 5,000 mg/L (Taboga and others, in press).

First encountered saline groundwaters are generally found at greater depths in the eastern half of the PRB than in the west. This is likely due to the close proximity of eastern wells to aquifer recharge areas along the basin margin. This effect is apparent along the entirety of the PRB margin but is most evident in the northeastern PRB near the Black Hills Uplift. In contrast, the longer residence times of groundwater drawn from basin interior wells allows those waters to dissolve more salts from the host rocks.

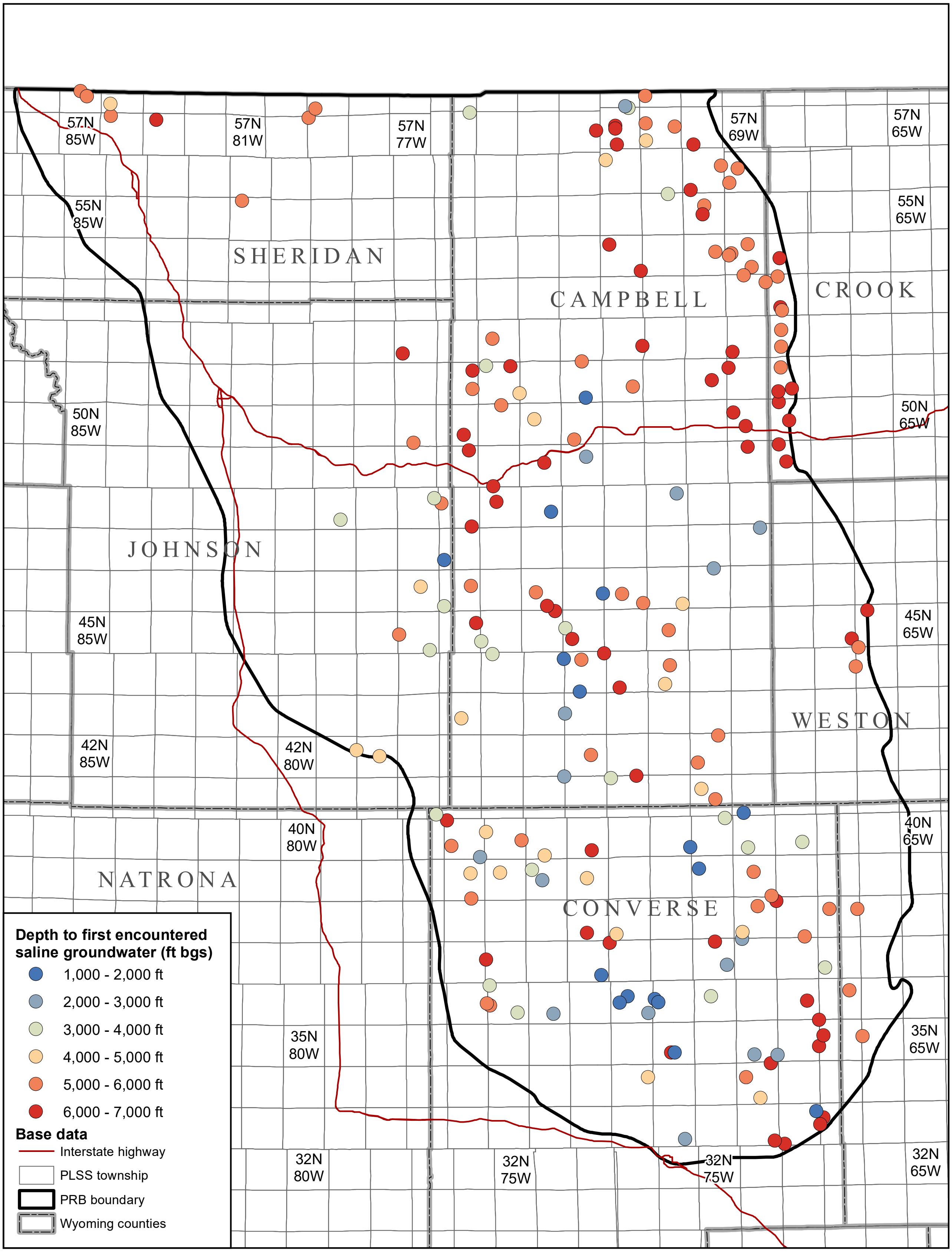


Figure 10. Depth to first saline (TDS >5,000 mg/L) groundwater in study wells.

Conclusions

WSGS used 2,480 spontaneous potential (SP) measurements from borehole geophysical logs and 204 USGS water quality analyses from 544 qualified wells to approximate the geospatial distribution of groundwater salinity (TDS) in the Powder River Basin of northeastern Wyoming. Salinity estimates (as NaCl equivalents) were obtained from SP wellbore logs using the Static Spontaneous Potential (SSP) Method over a depth range of 1,000–7,000 ft bgs at six 1,000 ft intervals. The resultant salinity data are shown in figures 3 through 10 and summarized in table 5.

Groundwater with estimated TDS levels of 2,000 to 5,000 are the most frequently encountered waters in the PRB to depths of less than 5,000 ft. The incidence of industrial grade waters (TDS>5,000 mg/L) increases with depth and occurs with the greatest frequency at depths greater than 5,000 ft. Depths to first encountered saline groundwaters are generally shallowest in the western interior of the PRB distant from the groundwater recharge areas located along the eastern margin of the basin. This study suggests that the most economic source of industrial grade water may be found in once-productive oil and gas wells completed more than 5,000 ft deep that can be repurposed for groundwater production.

Despite the large number of WOGCC well logs and USGS water quality analyses examined during the course of this project, this report does not constitute a comprehensive examination of saline waters in the PRB. The locations and geologic units of sites that produce saline waters were largely determined by the potential of those sites to yield economically recoverable reserves of oil and gas.

This document was prepared as a WSGS Open File Report that will be supplemented periodically as new information becomes available. It is expected that new data on saline groundwaters in the PRB will be developed as oil and gas exploration expands with higher oil prices and the continued advancement of drilling technology. This report is intended to provide a preliminary approximation of salinity levels to depths of 7,000 ft bgs in the Powder River Basin of northeastern Wyoming. The WSGS makes no guarantees regarding the accuracy of the data contained herein and encourages readers of this report to consult other reports, publications, and data sources, and to seek information from other qualified groundwater professionals before seeking to develop groundwater resources in this or any other area of the state. Additional information involving the hydrogeology of northeastern Wyoming can be found in technical memoranda contained in Wyoming Water Development river basin planning reports (HKM, 2002a, b; Taboga and others, in press), at (http://waterplan.state.wy.us/ basins/basins.html and in USGS publications (https://pubs.er.usgs.gov/).

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