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Groundwater Salinity in Wyoming

By Karl G. Taboga and James E. Stafford

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INTRODUCTION

Groundwater quality is highly variable in the intermountain structural basins that serve as home to most of Wyoming's population and economic activity (https://www.wsgs.wyo.gov/energy/oil-gas-basins). Typically, good quality groundwater is found along basin margins in close proximity to mountainous recharge areas while lower quality water occurs in the basin's interior (Clarey and others, 2010; Taucher and others, 2012, 2013; Taboga and others, 2014a, b, 2019). This report examines groundwater salinity in these large sedimentary structural basins. The most commonly used measure of groundwater quality in Wyoming wells is salinity (Wyoming State Engineer's Office, 2018). This report specifically examines saline groundwaters suited to industrial uses, thereby conserving higher-quality waters for domestic, agricultural, and livestock uses.

Salinity, measured in milligrams/liter (mg/L) as "total dissolved solids," or TDS, consists of the dissolved mineral residue that remains after evaporation of the liquid portion of a water sample. Dissolved salts, minerals, metals, cations and anions, and inorganic and organic molecules that can pass through a 2-micrometer filter make up TDS. A TDS concentration, however, does not specify the type or amounts of the individual chemical compounds that make up the residue. Instead, a complete water chemistry analysis must be conducted to determine the presence and concentrations of the chemical constituents present in a single water sample. Salinity is a poor predictor of water potability (suitability for human consumption). Low TDS waters can contain harmful levels of naturally occurring or man-made toxins such as arsenic, lead, pesticides, or radioactive elements. When accompanied by a complete water chemistry analysis, however, salinity is an expedient and useful measure of general water quality.

Saline groundwater is encountered most frequently during oil and gas exploration in geologic units that occur more than 1,000 feet (ft) below ground surface (bgs). Therefore, this study uses water quality data from the U.S. Geological Survey Produced Water Database (USGS, 2018) and the Wyoming Oil and Gas Conservation Commission (WOGCC) Water Analysis Database (WOGCC, 2018). Doubtlessly, saline waters occur at locations other than reported here, but these remain unconfirmed because there is currently no spatially extensive deep drilling and sampling program outside of hydrocarbon exploration.

In other states and U.S territories, saline groundwater is utilized primarily for thermoelectric power generation as well as mining and industrial operations. In Wyoming, saline groundwater accounts for 1.2 percent of all water used (Dieter and others, 2018), all of which (96.8 million gallons per day) is used by the mining industry. Still, understanding the occurrence and extent of groundwater salinity in Wyoming is beneficial for several reasons:

1. Nearly 40 percent of all deep (>1,000 ft bgs) groundwaters in Wyoming are saline (USGS, 2018; WOGCC, 2018),

2. The occurrence of saline groundwater provides insight into the processes that determine groundwater quality in basin aquifers,

3. State of Wyoming regulations permit the injection of wastewater co-produced with petroleum and natural gas (http://pipeline.wyo.gov/legacywogcce.cfm) and other industrial operations (http://deq.wyoming.gov/wqd/UIC/) into saline aquifers,

4. Saline aquifers may be in proximity to aquifers subject to in-situ recovery of uranium and trona,

5. Saline groundwater is frequently geothermal (http://www.wsgs.wyo.gov/energy/geothermal), and

6. Saline groundwater may be used for hydraulic pressure stimulation (fracturing) of hydrocarbons.

Saline waters co-produced during hydrocarbon and mineral development (4–6, above) have to be managed in compliance with local, state, and federal environmental regulations. Frequently, the most economic method is to inject the produced water into another saline aquifer on-site or to pipe or truck it to a commercial injection well located elsewhere. Injection/disposal wells are commonly repurposed oil and gas wells that are regulated by the WOGCC.

Measuring TDS

The method used for measuring the TDS concentration in a natural water sample is largely determined by the cost, time, and precision requirements. Two types of measurement commonly employed are residue-on-evaporation (also called gravimetric) and computational techniques.

In the residue-on-evaporation method, a known volume of water is evaporated to dryness in an oven heated to either 105°C or 180°C. The remaining residue is treated in a desiccator and promptly weighed (Skougstad and others, 1979). The 180°C method removes a higher fraction of the water retained in the crystalline structures of some salts such as gypsum ($CaSO_4$), but may partially evaporate (volatilize) some organic compounds, acids, and salts. The 105°C method avoids the volatilization of solids to some extent, but takes more time and may be less precise (Skougstad and others, 1979). Hem (1985) noted that the 105°C and 180°C analyses do not yield markedly different results even for slightly saline (<3,000 mg/L TDS) natural waters. Although the residue-on-evaporation method is time consuming, it yields the most accurate results notably for low TDS (<1,000 mg/L) natural waters where inorganic salts constitute the largest fraction of dissolved solids.

Computational methods are used to estimate TDS levels indirectly by either multiplying the measured electric conductance of a sample by an appropriate conversion coefficient or by summing the concentrations of the major chemical constituents. Each computational method has its advantages and limitations. Measuring electrical conductance (EC) is quick and convenient with properly maintained and calibrated instruments. EC is directly related to the TDS concentration of the sample by the equation:

$$\mathrm{TDS} = k\mathrm{EC},$$

where *k* is a conversion coefficient that varies widely with ion composition and sample temperature. Accurate estimation of TDS concentration using the EC conversion technique requires an understanding of the appropriate conversion factor (k). Inexpensive monitoring instruments typically estimate TDS from electrical conductance levels using a conversion factor around 0.65, while more sophisticated instruments allow the user to specify a conversion factor usually obtained by dividing sample EC levels with corresponding TDS concentrations obtained from laboratory (residue-on-evaporation or summation) analyses. Sample temperature variations are less problematic; combination EC/TDS/temperature meters typically adjust for temperature automatically. However, estimating TDS concentrations from EC measurements, even using a high-quality instrument, is typically accurate only to within 10 percent, which may be sufficient for many monitoring projects.

Another computational technique, the summation method, estimates TDS concentration by adding the concentrations of the major ions, metals and, in some cases, organic chemicals present in the sample. This method requires chemical analyses for these chemical components. In practice, however, a reasonable estimate of TDS can be obtained in most natural waters by summing concentrations for calcium, magnesium, sodium, potassium, ammonium, silicate, alkalinity, chloride, sulfate, nitrate, and fluoride; contributions from other elements are considered negligible. 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, acids, or yield hydrated (water-retaining) crystals. TDS estimation by summation frequently replaces gravimetric analysis when a water sample has been submitted to a laboratory for major ions analyses.

Comparing TDS concentrations obtained from more than one analysis of a particular water sample provides the best measure of TDS. Many water quality analyses shown on the USGS National Water Information System website (http://nwis.waterdata.usgs.gov/usa/nwis/qwdata) provide TDS concentrations using both residue-on-evaporation and computational methods. The USGS Produced Water Database (USGS, 2018) and the WOGCC Water Analysis

Database (WOGCC, 2018) do not specify the methods used to determine TDS concentrations. It should be noted that the data from the USGS and WOGCC databases were collected by different operators over seven decades using any of the methods discussed above. The lack of strict quality control may have biased some of the statistical analyses presented in this report.

WATER QUALITY STANDARDS, GROUNDWATER CLASSIFICATION, AND TDS LEVELS

Groundwater quality in Wyoming is regulated by three agencies. The U.S. Environmental Protection Agency (EPA) Region 8 Office, headquartered in Denver, Colorado, regulates public groundwater systems. The Wyoming Department of Environmental Quality (WDEQ) Water Quality Division regulates water quality for most other uses of the state's groundwater. Both agencies have instituted chemical standards for groundwater uses under their jurisdiction. The standards are reviewed periodically and updated as new scientific information becomes available. The WOGCC regulates the underground injection of wastewater unfit for domestic and agricultural uses and administers the Wyoming Groundwater Baseline Sampling, Analysis and Monitoring rule. Wyoming water quality standards, listed in chapter 8 of the WDEQ Water Quality Rules and Regulations and chapters 3 and 4 of the WOGCC Rules, are available at http://soswy.state.wy.us/Rules/default.aspx. EPA drinking water regulations and water quality standards are found under Title 40 of the Code of Federal Regulations at http://water.epa.gov/lawsregs/rulesregs/sdwa/currentregulations.cfm.

Groundwater standards for TDS are based on the specific use under regulation. The EPA has established a secondary maximum contaminant level (SMCL) of 500 mg/L for TDS in public drinking water systems. An SMCL is a non-enforceable guideline for contaminants that can cause aesthetic problems in drinking water such as degradation of taste, odor, or appearance, but do not have adverse effects on the health of persons.

WDEQ regulations (WDEQ, 2018) specify that maximum TDS concentrations should not exceed 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). Industrial groundwaters are classified by TDS concentration as Class IV A (TDS not in excess of 10,000 mg/L) and Class IV B (TDS greater than 10,000 mg/L).

The WOGCC issues underground injection permits (UIC permits) for the disposal of water co-produced with oil and gas development operations by injection into saline aquifers (TDS>10,000 mg/L). In certain cases, the WOGCC can authorize exemptions to inject co-produced water into an aquifer with a TDS concentration between 5,000–10,000 mg/L that "is not reasonably expected to be used as fresh or potable water" (WOGCC Rules, chap. 4, Sec. 12 [a. v.]).

The USGS salinity classification system (Heath, 1983) is shown in table 1.

Table 1. USGS water salinity classification.

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

A TDS concentration provides a convenient but non-specific initial assessment of water suitability for domestic, agricultural, 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. The WSGS encourages all groundwater users to obtain a complete water chemistry analysis to ensure that a groundwater resource will meet the health, safety, and aesthetic requirements of its intended use. The Wyoming Department of Agriculture Analytical Services Lab provides reasonably priced water analyses. Check http://agriculture.wy.gov/divisions/asl/testing/water-analyses for more information about the analytical services offered by the lab.

EVOLUTION OF GROUNDWATER WITH DEPTH IN SEDIMENTARY BASINS

Generally, groundwater salinity increases with depth of burial in basin aquifers. However, this is not always the case; decreases in salinity with depth have been observed in some formations (Kharaka and Hanor, 2003). Moreover, older underlying formations may have lower TDS concentrations than younger formations (table 2). The change in salinity with depth can vary greatly between basins, within different parts of the same basin, and among different hydrostratigraphic units in a particular basin (Kharaka and Hanor, 2003). Salinity increases with depth usually result from rising sodium and chloride concentrations as evaporitic materials in the host rock dissolve (Kharaka and Hanor, 2003).

Table 2. Mean TDS concentrations and depths-of-sample for three hydrocarbon-producing formations in the Oregon Basin Oil Field in the western Bighorn Structural Basin, Wyoming. Mean TDS levels are higher in the younger Tensleep and Dinwoody-Phosphoria [b] (listed as Embar formation in WOGCC records) formations production intervals than in the more deeply buried Madison Formation. [a] WOGCC, 2018; [b] Sheldon, 1957.

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

Aquifer physical and chemical properties such as host rock geochemistry, depth of burial, aquifer residence time, geological structure, proximity to recharge areas, groundwater flow rates, and water/rock interactions drive the relationship between groundwater quality and depth.

BENEFICIAL USES OF SALINE WATERS

According to USGS estimates (Dieter and others, 2018), total withdrawals of saline surface water and groundwater in the United States in 2015 were about 41 billion gallons per day (Bgal/d), which represent approximately 13 percent of all water used. About 6 percent (2.34 Bgal/d) of the total withdrawn came from groundwater sources. Most of the saline groundwater was utilized for mining operations (79.5 percent), with lesser amounts used in thermoelectric power generation (7.4 percent) and industrial operations (1.8 percent).

In Wyoming, most saline waters (>5,000 mg/L) are co-produced with oil and gas in semi-arid basins (table 3), where the state's population and industry are concentrated and where saline water is most likely to be used beneficially. In contrast, waters produced from Wyoming coal mines typically have salinities of 3,000 mg/L or less (WDEQ, 2019). Generally, the use of saline water for industrial applications in Wyoming is driven by two factors. The first factor is the availability and the costs of using fresh water. Secondly, some industrial applications such as washing equipment or suppressing dust on unpaved facility roads provide low cost means to dispose of saline waters co-produced with oil or gas.

Table 3. Oil, gas, and associated water production levels (2018) compared to average annual precipitation and population in Wyoming's top four energy-producing basins. [a] WOGCC, 2019; [b] PRISM Climate Group, 2017; [c] Wyoming Department of Administration and Information Economic Analysis Division, 2019.

Basin	Oil (BBLs) [a]	Gas (MCF) [a]	Water (BBLs) [a]	Average annual precipitation (In)[b]	Estimated population [c]
Wind River	4,128,845	154,178,941	236,378,932	6–10	40,000
Bighorn	9,987,294	11,467,039	902,593,050	6–10	37,000
Greater Green River	14,115,390	1,083,682,005	163,025,314	6–15	62,000
Powder River	48,738,293	243,769,073	368,948,481	13–15	127,000

Resource development—Common uses in the petroleum industry include the injection of raw or treated saline water for enhanced oil recovery and hydraulic fracturing (fracking) of oil and gas wells. During the last decade, oil and gas developers have studied the use of saline water for hydraulic fracturing (Godsey, 2017), motivated by the economic and regulatory costs of using up to 10 million gallons of freshwater to frack a single well (Allison and Mandler, 2018). In particular, freshwater supplies for fracking may be severely restricted in semi-arid western basins where average annual precipitation is less than 13 inches and both groundwater and surface water rights may have been fully allocated for more than a century. The use of raw or treated saline water for fracking or enhanced oil recovery may be an economically viable option to dispose or repurpose produced water. Such was the case when Anadarko began construction of a high-capacity pipeline in 2005 to carry produced saline water from Powder River coal bed methane fields to its Salt Creek and Teapot Dome oilfields for tertiary oil recovery (Oil and Gas Journal, 2006).

The use of saline water for hydraulic fracturing does present some technical problems, however. Chemical interactions between saline source water, additives in the frack fluid, and the geologic formations under development may precipitate sulfate, carbonate, and silicate scales or affect the performance of fracking fluid additives. In some cases, these problems can be resolved by adjusting the additives used or by treating the saline water on-site. In practice, this means that effective mixtures of saline water and frack fluid additives must be customized for each producing formation by an experienced hydraulic fracturing contractor. Despite these challenges, energy corporations currently use saline waters for hydraulic fracturing (Allison and Mandler, 2018), and their use will increase as the technical problems are resolved.

Industrial uses—Raw or treated saline waters are used for fabricating, processing, washing, or cooling manufactured product in non-mining industries applications.

METHODS

This study uses water quality data from almost 36,000 records of Wyoming water quality data provided by the USGS (2018) and WOGCC (2018). A full explanation of the manner used to process the USGS/WOGCC water quality data is provided in Taboga and others (2016, 2018). The resultant water quality dataset used in this report consists of TDS data obtained from more than 11,500 Wyoming well sites.

In many cases, the names of the producing geologic units provided by petroleum operators to the USGS/WOGCC databases do not agree with currently accepted Wyoming stratigraphic nomenclature (Love and others, 1993; Geolex, 2018). Many of the producing formation names provided by industry refer to nomenclature that is outdated or borrowed from producing units encountered in neighboring states or basins. For example, the USGS has replaced the “Embar Formation,” a term used by petroleum producers until the 1990s, with the “Park City, Dinwoody, and, Chugwater Formations” (Geolex, 2018). In this report, Embar Formation wells are assigned to the Dinwoody Formation, where present, and to the Chugwater Formation elsewhere. Similarly, Tensleep Sandstone wells in the Laramie and Hanna basins are assigned to the Casper Formation (Love and others, 1993).

Tables in the following section use the stratigraphic nomenclature from Love and others (1993) with specific exceptions noted in the text. The WSGS assigned petroleum-producing units to the appropriate Wyoming stratigraphic unit based on the U.S. Geological Names Lexicon (Geolex, 2018). For clarity, however, the text may refer to specific members of a formation, such as the “Shannon Member of the Cody Shale.”

This study also investigates the relationship between groundwater salinity and depth-of-sample in 61 stratigraphic units throughout Wyoming. Salinity levels were charted against corresponding depth data in scatter plots for each stratigraphic unit with 10 or more samples. First, all plotted data were evaluated by application of the Linear Regression analysis tool in the Microsoft Excel Analysis ToolPak. Scatter plots that displayed a coefficient of determination (R^2) greater than 0.30 were then visually examined for data point clusters, outliers, and non-linear trends that could exert disproportionate influence on R^2 (Anscombe, 1973). Statistical significance was assigned to qualified datasets where p-values<0.05. Plots with apparent non-linear trends (Brown, 2000) were evaluated with the

Generalized Reduced Gradient algorithm in the Excel Solver platform by minimizing the difference between model estimates and observed salinities.

RESULTS AND DISCUSSION

Statewide results are presented in figures 1 and 2. Figure 1 shows the distribution of all examined sites throughout Wyoming. The great majority of these sites are situated within Laramide basins and the Overthrust Belt, consistent with oil and gas exploration and production sites. A small number of samples were obtained from moderately uplifted areas between basins such as the Casper Arch, Rawlins Uplift, Owl Creek Mountains, and Black Hills.

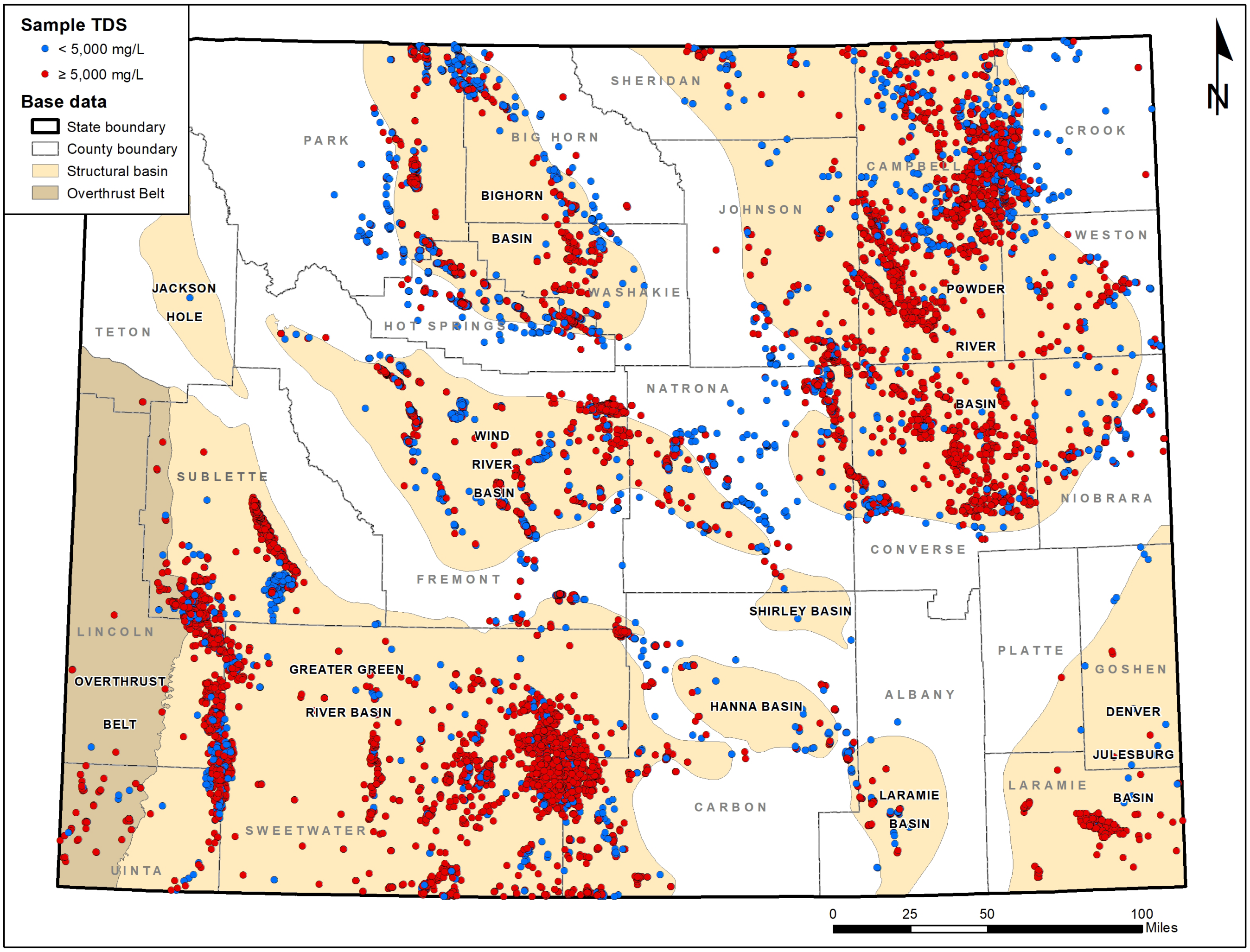


Figure 1. Wyoming sampling sites for all TDS concentrations (USGS, 2018; WOGCC, 2018).

Figure 2 shows the statewide spatial distribution of all water samples grouped by geologic era. About one quarter of these samples were obtained from Paleozoic formations. Paleozoic samples are concentrated in the northeastern Powder River Basin and along the margins of the Bighorn Basin. Almost 66 percent of all samples come from Mesozoic formations clustered in the southern Powder River Basin, the Great Divide and Washakie basins, and in three dense groups in the Green River Basin. In addition, small groups of Mesozoic samples were obtained from wells scattered throughout every Wyoming basin. Cenozoic samples occur most frequently in the northeastern Wind River Basin, north central part of the Powder River Basin, and northwestern and southern parts of the Greater Green River Basin.

This report examines identically named geological units present in differing basins independently; for example, the Tensleep Formation in the Bighorn and Wind River basins is considered separately. Figures 1 and 2 show the geospatial distribution of 11,540 sample points (wells), which had TDS data from 59 Wyoming stratigraphic units (Love and others, 1993). However, only 33 different stratigraphic units had 10 or more samples; units with fewer than 10 samples were treated as being underrepresented in this report.

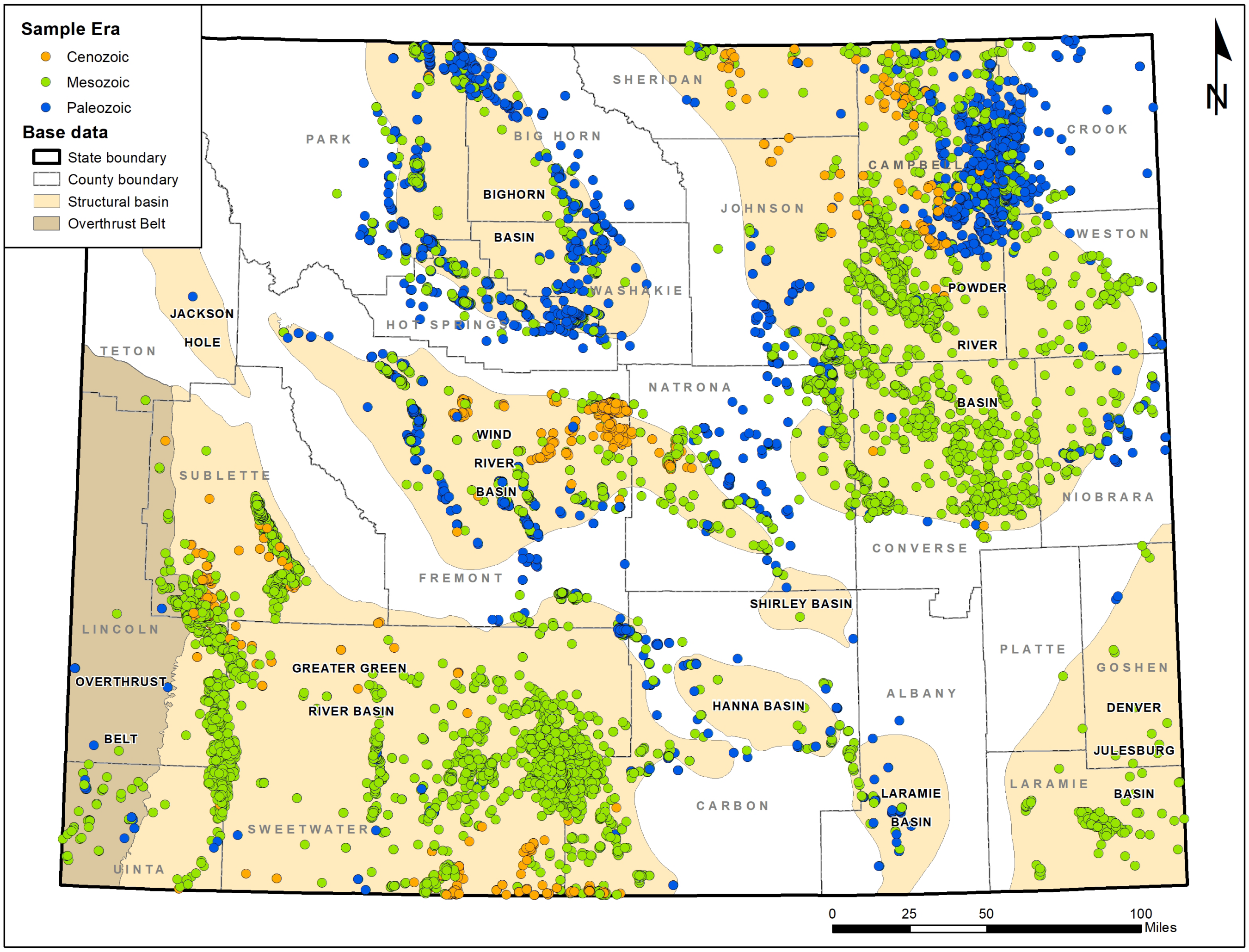


Figure 2. Wyoming sampling sites for all TDS concentrations shown by geologic era of unit sampled.

Tables 4–12 provide summary statistics (sample count, minimum, mean, and maximum TDS concentrations), and available depth-of-sample data for stratigraphic units with 10 or more records in each basin and the Overthrust Belt. Additional information for all samples contained in the WSGS saline water database, including geospatial distribution, is available on the WSGS Groundwater Atlas interactive map on the WSGS website at https://www.wsgs.wyo.gov/water/river-basin-plans. Additionally, the following sections discuss geologic units with 10 or more saline samples by basin.

Regression analyses of salinity and depth-of-sample data in 61 stratigraphic units located in Wyoming hydrocarbon-producing basins indicated that only seven units exhibited substantive relationships ($p<0.05$) that could be adequately modeled with linear or exponential regressions. These results are shown in the following sections, as well.

Southeastern Wyoming

A complete description of the hydrogeology of southeastern Wyoming, which includes the four basins discussed in this section, can be found in Taucher and others (2013), available at http://www.wsgs.wyo.gov/Research/Water-Resources/River-Basin-Plans.aspx. Figures 3A and 3B show the locations of saline wells in Mesozoic and Paleozoic units, respectively. There are no saline Cenozoic units recorded in the Denver-Julesburg, Laramie, Hanna, or Shirley basins.

Denver-Julesburg Basin

Saline groundwater is present in three Cretaceous, producing geologic units (table 4): the Niobrara Formation (101 wells), Muddy Sandstone (30 wells), and Codell Sandstone Member (26 wells) of the Carlile Shale.

Table 4. Summary statistics for stratigraphic units with 10 or more saline well sites in the Denver-Julesburg Basin.

Geologic unit	Geologic age	Count	TDS (mg/L)			Range, depths-of-sample, ft-bgs [#wells with depths]
			Minimum	Mean	Maximum	
Niobrara	Cretaceous	101	5,150	39,983	111,609	7,360
Carlile	Cretaceous	26	20,300	31,770	57,914	Insufficient data
Muddy	Cretaceous	30	5,071	13,856	51,969	5,284–9,760 [22]

The mean TDS level in the Muddy Sandstone (~14,000 mg/L) is markedly lower than in the Carlile Shale (~32,000 mg/L) and the Niobrara Formation (~40,000 mg/L). The similar mean values of the Carlile Shale and Niobrara Formation may be due, in part, to the fact that hydrocarbons and produced water are frequently extracted and commingled from both units (Nelson and Santus, 2011). Muddy Sandstone wells are located generally in western Laramie County along the margin of the DJ Basin. Niobrara and Carlile Shale (Codell) wells are concentrated in several oil fields in central Laramie County (Toner and others, 2018).

Laramie Basin

Saline water has been produced from 31 wells in the Casper Formation and 10 wells in the Muddy Sandstone (table 5). Note that Casper Formation wells include those listed in WOGCC and USGS records as completed in the equivalent Tensleep Sandstone (Mallory, 1967; Richter 1981). The Tensleep Sandstone, historically the most prolific petroleum-producing formation in much of Wyoming, has been only moderately productive in the Laramie Basin.

Hanna Basin

Saline water was produced from 20 Casper Formation wells (table 6). Love and others (1993) group the stratigraphic nomenclature of the Hanna and Laramie basins together; the Casper Formation includes Tensleep Sandstone listed wells in this section. All saline samples were collected from wells located along the perimeter (figs. 3A and B) of the small but anomalously deep (~30,000 ft) Hanna Basin (WSGS, 2018).

Shirley Basin

Relatively little is known about groundwater quality in the sparsely populated Shirley Basin. Saline water samples were collected from one well each in the Frontier and Dinwoody formations and the Tensleep Sandstone, all located on the northwestern margin of the Shirley Basin (figs. 3A and B). Oil and gas development has been limited to two small fields in the northwest (Toner and others, 2018), and groundwater wells are thinly scattered throughout the basin (Stafford and others, 2017).

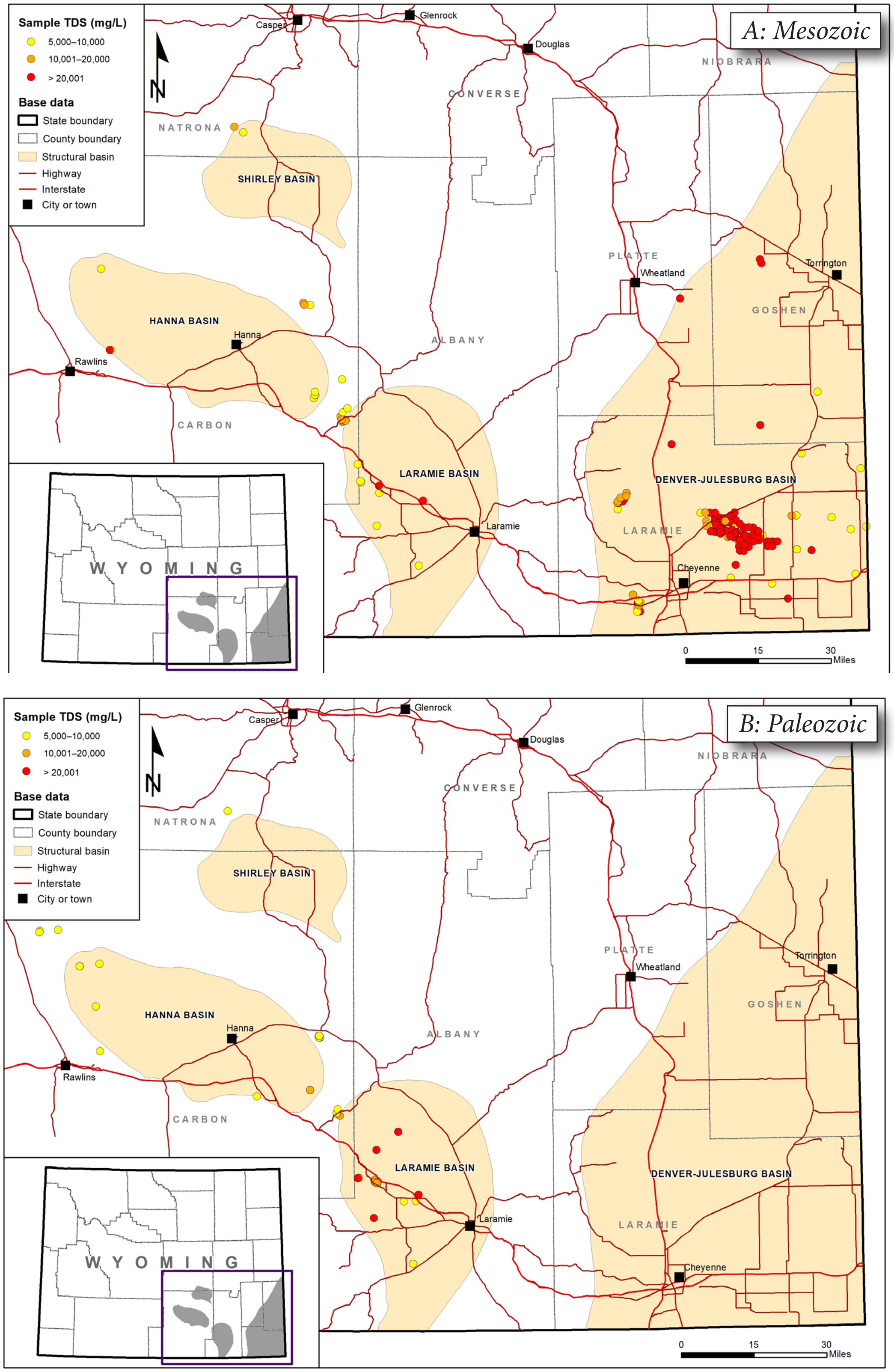


Figure 3. Saline samples from (A) Mesozoic and (B) Paleozoic geologic units in southeastern Wyoming. There are no saline Cenozoic units recorded in the Denver-Julesburg, Laramie, Hanna, or Shirley basins.

Table 5. Summary statistics for producing units with 10 or more saline well sites in the Laramie Basin.

Geologic unit	Geologic age	Count	TDS (mg/L)			Range, depths-of-sample, ft-bgs [#wells with depths]
			Minimum	Mean	Maximum	
Muddy	Cretaceous	10	5,225	8,673	13,379	756
Casper	Pennsylvanian-Permian	31	6,758	18,546	77,439	947–10,262 [28]

Table 6. Summary statistics for producing units with 10 or more saline well sites in the Hanna Basin.

Geologic unit	Geologic age	Count	TDS (mg/L)			Range, depths-of-sample, ft-bgs [#wells with depths]
			Minimum	Mean	Maximum	
Casper	Pennsylvanian-Permian	20	5,014	7,731	15,913	3,966–8,939 [16]

Depth and salinity—In southeast Wyoming, a statistically significant ($p<0.001$) relationship between depth and groundwater salinity is observed only in the Casper Formation of the Laramie Basin (fig. 4).

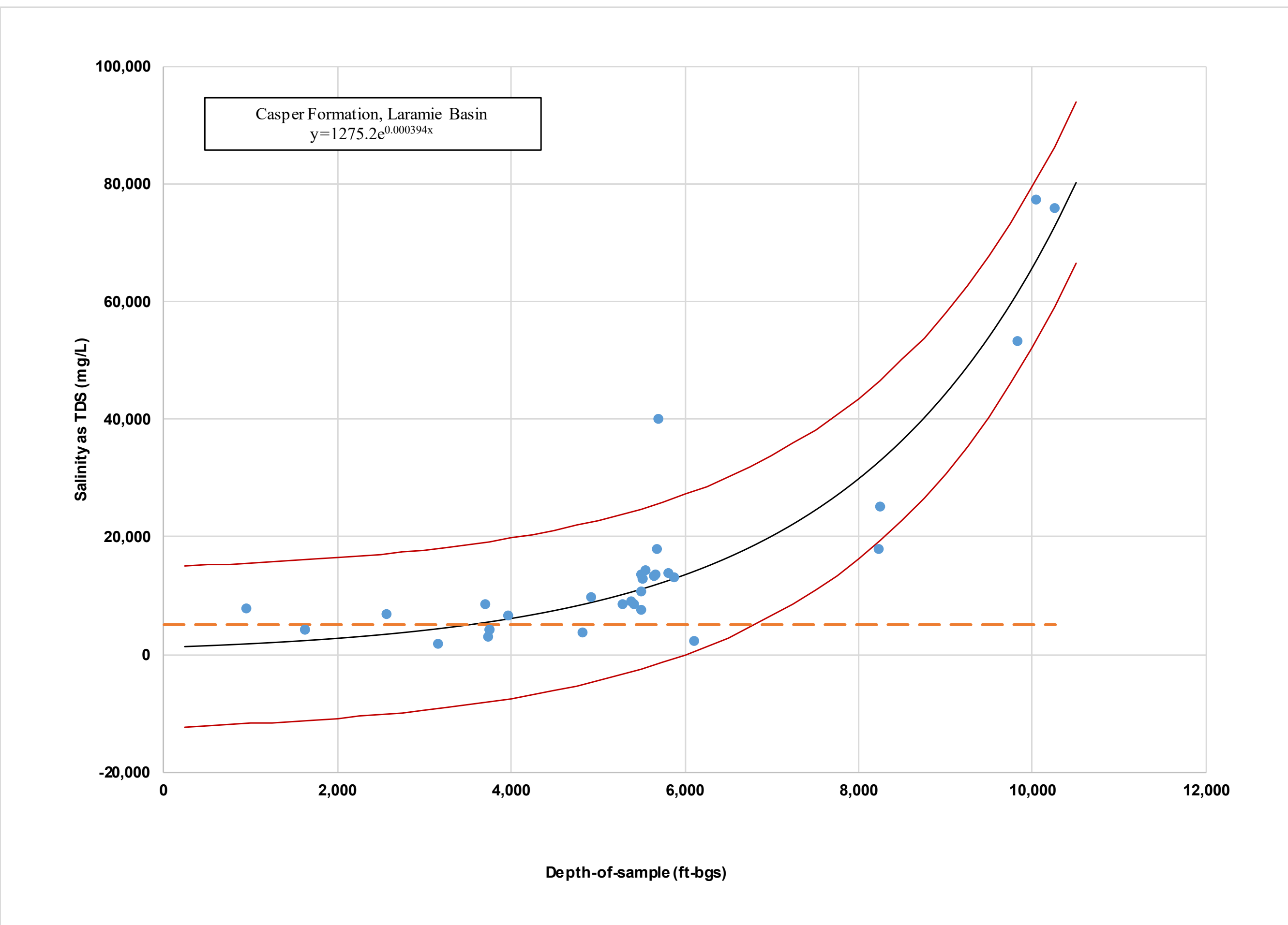


Figure 4. Relationship between salinity and depth-of-sample in the Casper Formation of the Laramie Basin. Regression trend line shown in black; 95 percent confidence intervals are shown in red. The dashed orange line indicates the 5,000 mg/L TDS concentration.

Northeastern Wyoming

Powder River Basin and western flank of the Black Hills

The Powder River Basin (PRB) has been the site of extensive oil and gas development since the late-1800s. Saline groundwaters are found in 14 geologic formations with 10 or more samples (figs. 5A and B, and table 7). Two adjustments were made in this report to accommodate the variations of PRB stratigraphic nomenclature that are used by the USGS, the WSGS (Love and others, 1993), and oil and gas drillers. First, the Cloverly Group and equivalent Inyan Kara Group were combined into the Cloverly-Inyan Kara because the two units share the Lakota, Dakota, and Fall River formations. Second, the Steele Shale, recognized in the basin by the USGS (Fox, 1993; Geolex, 2018) but not Love and others (1993), was included in the PRB because the Ash Creek and Fishtooth sandstone members are assigned by the USGS (Geolex, 2018) solely to the Steele Shale.

Numerous water samples (642) were obtained from wells completed in the Paleozoic Minnelusa Formation, which is partly correlated to the Tensleep, Casper, and Hartville formations (Foster, 1958). The Minnelusa wells, located on

Table 7. Summary statistics for producing units with 10 or more saline well sites in the Powder River Basin.

Geologic unit	Geologic age	Count	TDS (mg/L)			Range, depths-of-sample, ft-bgs [#wells with depths]
			Minimum	Mean	Maximum	
Lewis	Cretaceous	43	5,618	10,262	14,360	5,504–7,330 [18]
Mesaverde	Cretaceous	467	5,028	15,142	178,000	68–11,950 [155]
Steele	Cretaceous	26	5,069	8,406	11,042	703–7,057 [23]
Cody	Cretaceous	336	5,024	22,069	76,100	306–9,752 [66]
Niobrara	Cretaceous	133	5,534	24,645	69,659	1,215–8,750 [4]
Carlile	Cretaceous	78	5,956	39,933	67,100	4,005–6,000 [6]
Frontier	Cretaceous	157	5,334	18,483	121,000	1,116–12,626 [90]
Muddy	Cretaceous	232	5,030	15,166	44,504	2,412–12,570 [179]
Newcastle	Cretaceous	69	5,325	12,890	29,003	499–8,340 [59]
Cloverly-Inyan Kara	Cretaceous	190	5,025	12,459	70,351	2,368–11,032 [146]
Morrison	Jurassic	12	8,671	11,521	15,000	2,610–3,696 [8]
Sundance	Jurassic	79	5,012	9,827	33,661	970–12,230 [62]
Minnelusa	Pennsylvanian-Permian	642	5,031	60,629	307,713	2,138–15,332 [341]
Tensleep	Pennsylvanian-Permian	32	5,186	8,824	20,946	2,444–12,371 [26]

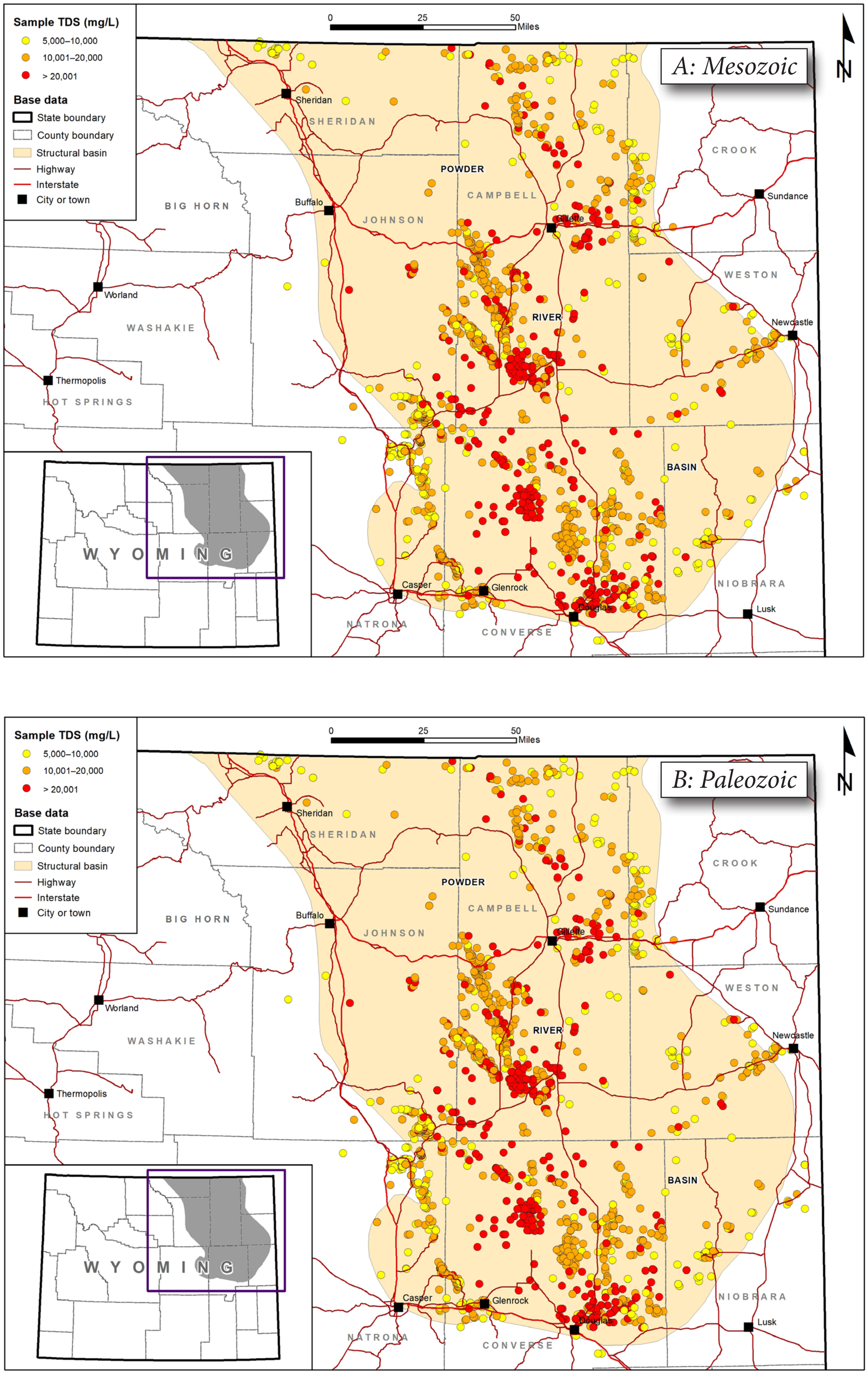


Figure 5. Saline samples from (A) Mesozoic and (B) Paleozoic geologic units in northeastern Wyoming. There are no saline Cenozoic units recorded in the Powder River Basin.

the eastern margin of the PRB, exhibit the second highest mean TDS level (60,629 mg/L) and highest maximum (307,713 mg/L) TDS values of all formations examined in this report. The high-mean salinity in the Minnelusa is likely due to the presence of extensive evaporite beds rather than its mean sample depth (7,851 ft-bgs). For comparison, mean depth-of-sample in the Cloverly-Inyan Kara Formation is 6,927 ft-bgs, but median salinity is less than 13,000 mg/L.

Other saline producing geologic units (followed by mean TDS in parentheses) with over 100 wells sampled are the Mesaverde (15,142 mg/L), Cody Shale (22,069 mg/L), Muddy Sandstone (15,166 mg/L), Cloverly-Inyan Kara (12,459 mg/L), Frontier Formation (18,483 mg/L), and Niobrara Formation (24,645 mg/L).

Depth and salinity—A statistically significant ($p<0.001$) relationship between depth and groundwater salinity is observed only in the Newcastle Sandstone of the Powder River Basin (fig. 6).

Complete descriptions of the hydrogeology of the Powder River Basin (HKM Engineering Inc., 2002; Taboga and others, 2019) are available at http://waterplan.state.wy.us/.

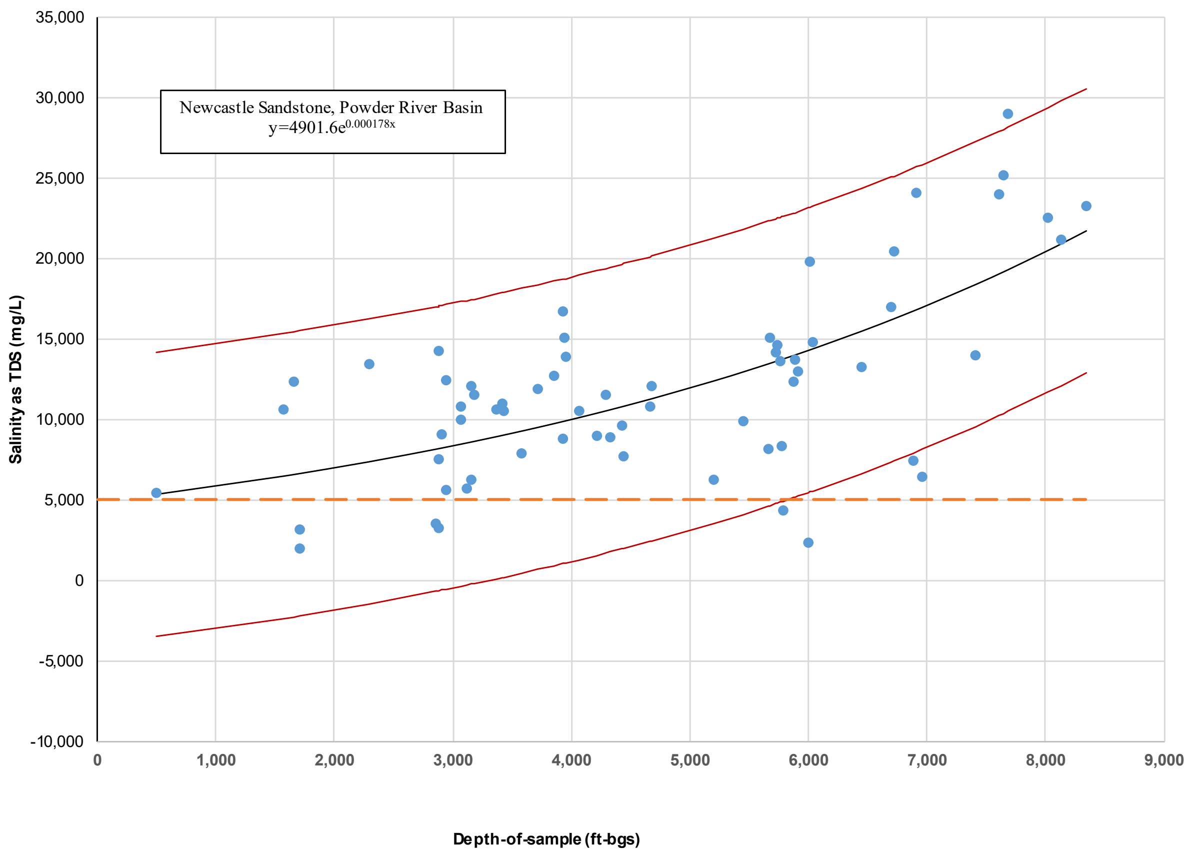


Figure 6. Relationship between salinity and depth-of-sample in the Newcastle Sandstone of the Powder River Basin. Regression trend line shown in black; 95 percent confidence intervals are shown in red. The dashed orange line indicates the 5,000 mg/L TDS concentration.

Northwestern Wyoming

Bighorn Basin

Saline Mesozoic and Paleozoic wells are interspersed around the perimeter of the Bighorn Basin (figs. 7A, B, and C). Saline Paleozoic units are the Tensleep Sandstone, the Phosphoria Formation, and the Madison Limestone (table 8). Mesozoic formations make up the remaining saline geologic units. There are no saline Cenozoic units recorded in the Bighorn Basin. All saline wells assigned to the Dinwoody Formation (table 8) are identified in WOGCC and USGS records as completed in the Embar Formation. As noted previously, the unit name "Embar" has been abandoned and replaced by the Park City, Dinwoody, and Chugwater formations in the Bighorn and Wind River basins (Geolex, 2018).

There are no statistically significant relationships between depth and groundwater salinity in any of the geologic units of the Bighorn Basin (table 8).

Table 8. Summary statistics for producing units with 10 or more saline well sites in the Bighorn Basin.

Geologic unit	Geologic age	Count	TDS (mg/L)			Range, depths-of-sample, ft-bgs [#wells with depths]
			Minimum	Mean	Maximum	
Muddy	Cretaceous	11	5,008	7,335	11,921	3,130–8,633 [9]
Frontier	Cretaceous	78	5,087	10,493	44,700	316–10,130 [30]
Sundance	Jurassic	21	6,803	32,902	54,513	2,192–8,846 [19]
Chugwater	Triassic	29	5,387	30,932	47,705	1,614–10,060 [25]
Dinwoody	Triassic	190	5,009	13,802	163,347	905–13,000 [157]
Phosphoria	Permian	188	5,034	22,842	253,670	970–13,324 [146]
Tensleep	Pennsylvanian-Permian	139	5,005	8,400	34,486	1,228–15,176 [130]
Madison	Mississippian	19	5,133	19,809	141,832	2,060–15,627 [16]

Wind River Basin

Saline groundwater is found in 16 formations with 10 or more well sites in the Wind River Basin (table 9). While Mesozoic and Paleozoic wells are widely distributed throughout the basin, Cenozoic saline wells stretch northwesterly along a distinct band located along the basin's northern margin (figs. 7A, B, and C).

Depth and salinity— Statistically significant relationships between depth and groundwater salinity in the Wind River Basin are seen in the Dinwoody (fig. 8; $p<0.001$), Sundance (fig. 9; $p=.003$), Cloverly (fig. 10; $p<0.001$), and Wind River (fig. 11; $p<0.001$) formations.

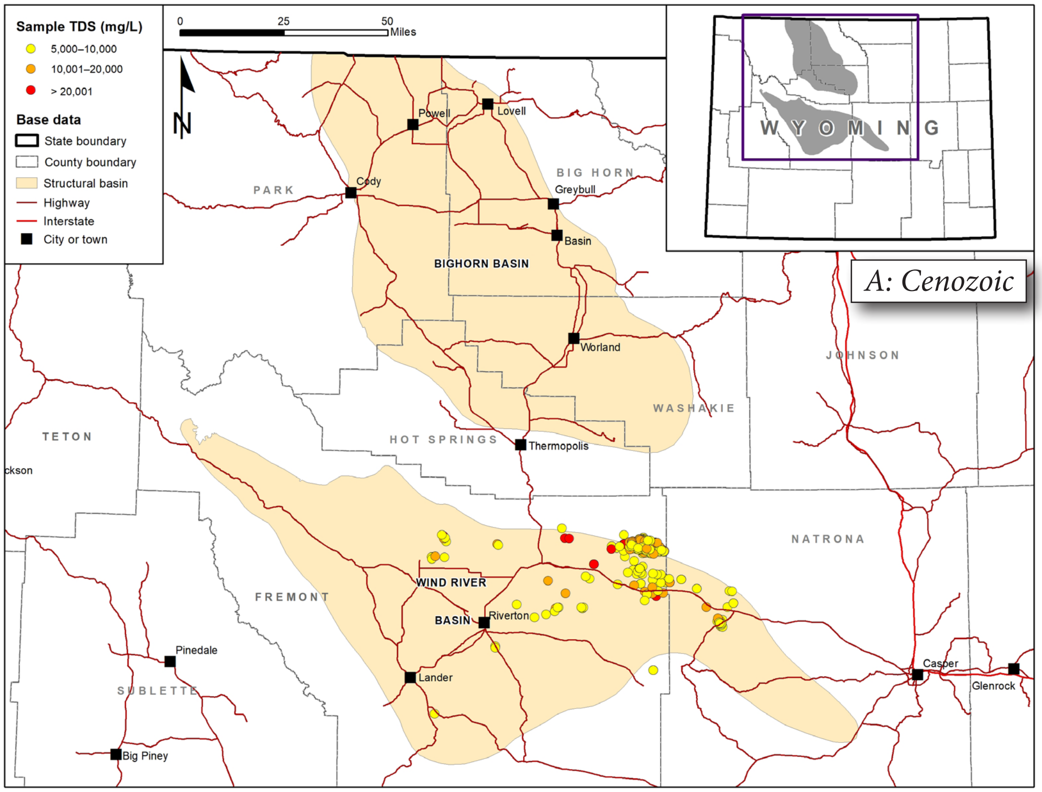


Figure 7. Saline samples from (A) Cenozoic, (B) Mesozoic, and (C) Paleozoic geologic units in northwestern Wyoming.

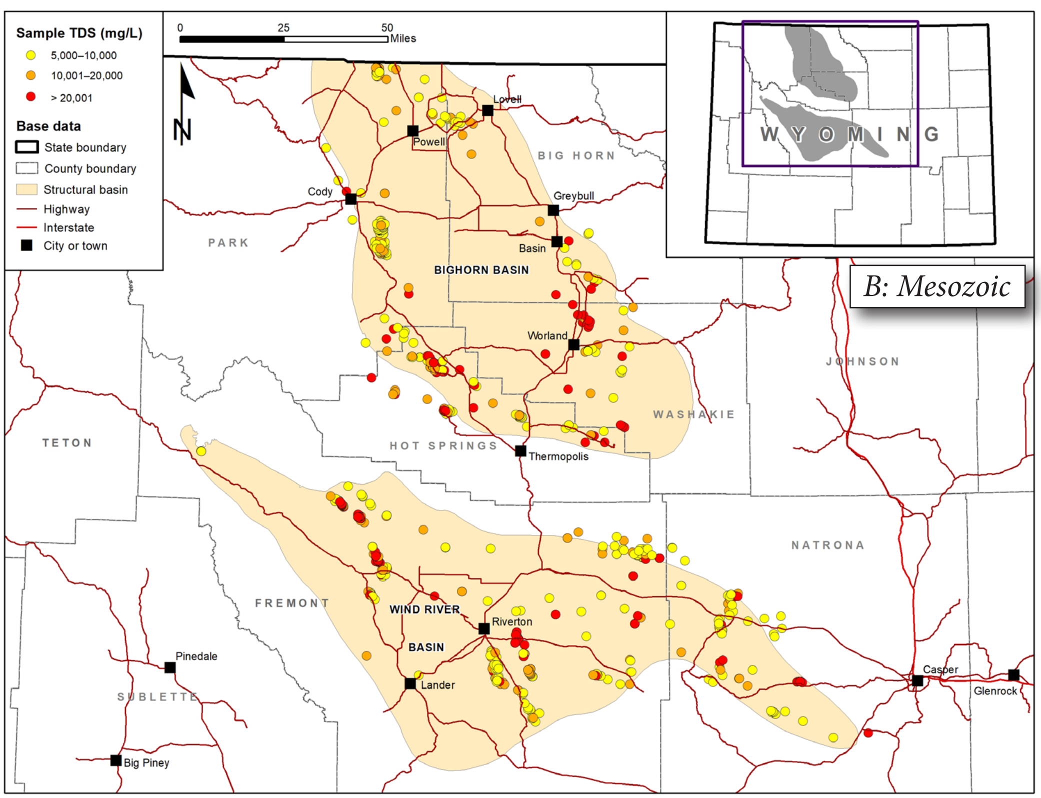


Figure 7 Continued. Saline samples from (C) Paleozoic geologic units in northwestern Wyoming.

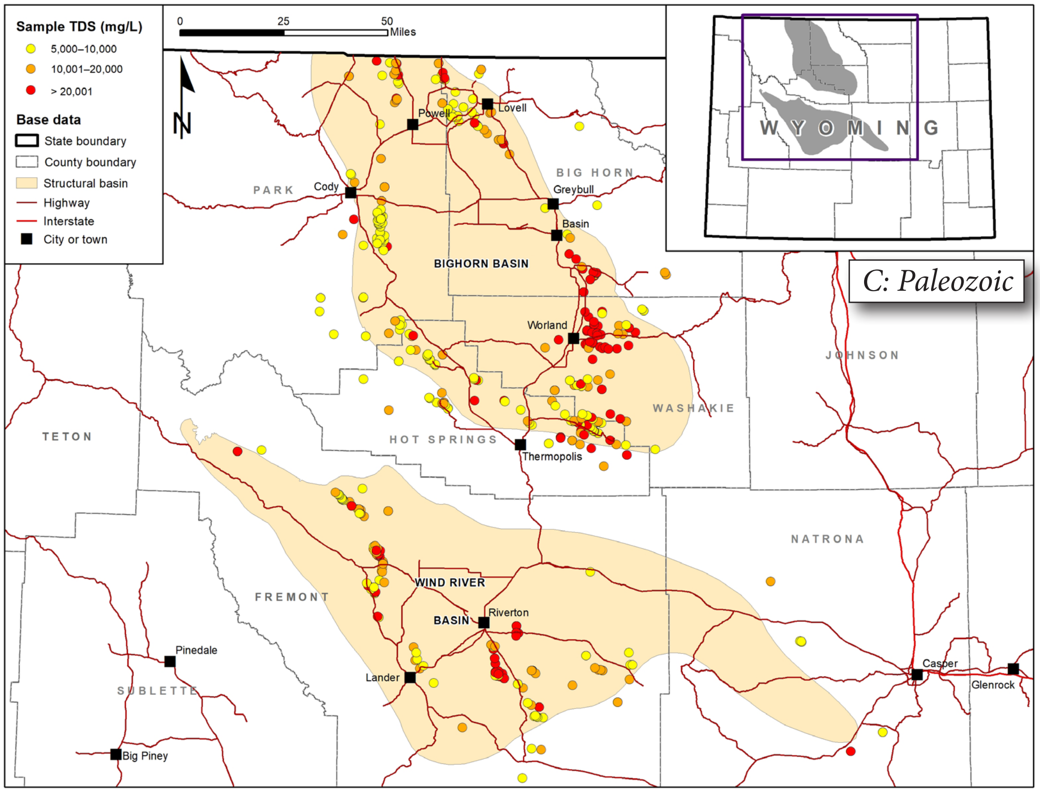


Table 9. Summary statistics for producing units with 10 or more saline well sites in the Wind River Basin.

Geologic unit	Geologic age	Count	TDS (mg/L)			Range, depths-of-sample, ft-bgs [#wells with depths]
			Minimum	Mean	Maximum	
Wind River	Tertiary	17	5,029	10,373	33,534	2,434–7,146 [11]
Fort Union	Tertiary	298	5,010	9,440	127,111	595–12,870 [106]
Lance	Cretaceous	87	5,034	10,973	49,442	5,972–11,328 [65]
Mesaverde	Cretaceous	41	5,229	10,769	48,422	3,010–16,472 [25]
Cody	Cretaceous	26	5,064	13,144	99,833	684–17,894 [13]
Frontier	Cretaceous	56	5,375	16,540	71,538	1,393–14,309 [42]
Muddy	Cretaceous	27	5,642	9,889	43,789	500–13,335 [18]
Cloverly	Cretaceous	25	5,020	12,330	45,960	1,592–11,532 [20]
Morrison	Jurassic	12	8,057	22,599	74,013	540–16,094 [7]
Sundance	Jurassic	11	6,384	26,074	58,294	4,915–6,748 10]
Nugget	Triassic-Jurassic	38	5,327	29,302	216,565	1,298–12,498 [37]
Chugwater	Triassic	27	5,009	20,070	40,132	120–5,908 [24]
Dinwoody	Triassic	34	5,055	10,260	24,197	1,330–11,931 [27]
Phosphoria	Permian	122	5,009	24,008	187,725	910–13,564 [107]
Tensleep	Pennsylvanian-Permian	32	5,022	10,575	32,994	1,714–12,258 [30]
Madison	Mississippian	15	5,409	11,793	31,205	2,469–12,686 [14]

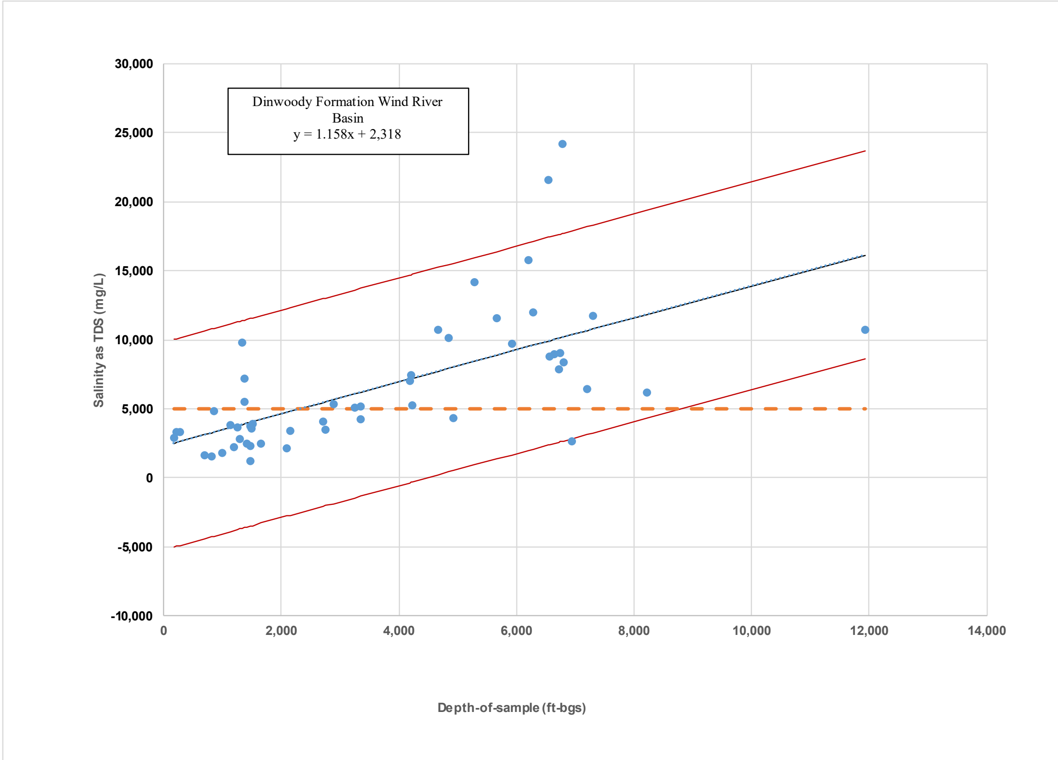


Figure 8. Relationship between salinity and depth-of-sample in the Dinwoody Formation of the Wind River Basin. Regression trend line shown in black; 95 percent confidence intervals are shown in red. The dashed orange line indicates the 5,000 mg/L TDS concentration.

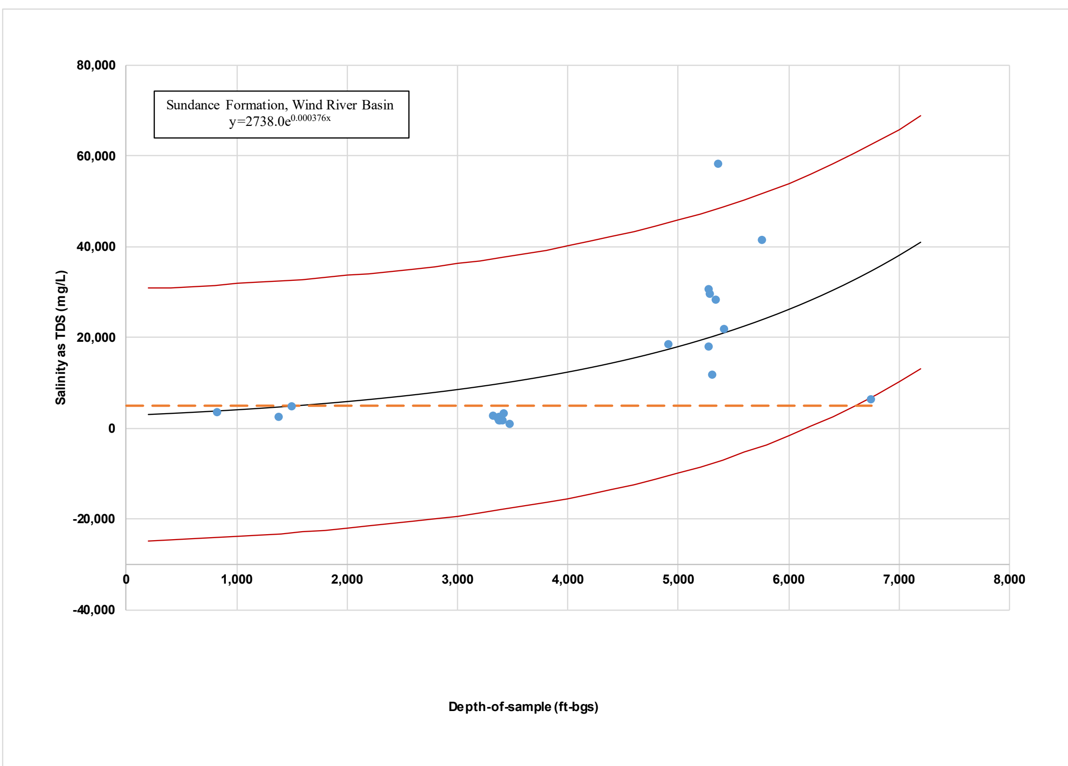


Figure 9. Relationship between salinity and depth-of-sample in the Sundance Formation of the Wind River Basin. Regression trend line shown in black; 95 percent confidence intervals are shown in red. The dashed orange line indicates the 5,000 mg/L TDS concentration.

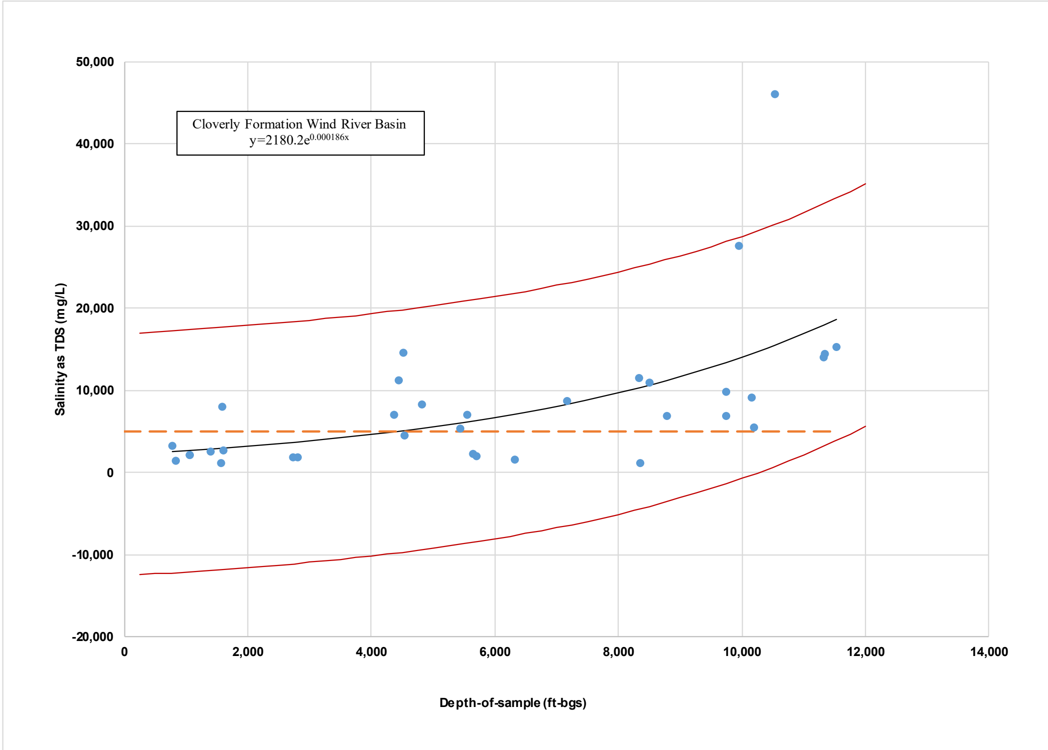


Figure 10. Relationship between salinity and depth-of-sample in the Cloverly Formation of the Wind River Basin. Regression trend line shown in black; 95 percent confidence intervals are shown in red. The dashed orange line indicates the 5,000 mg/L TDS concentration.

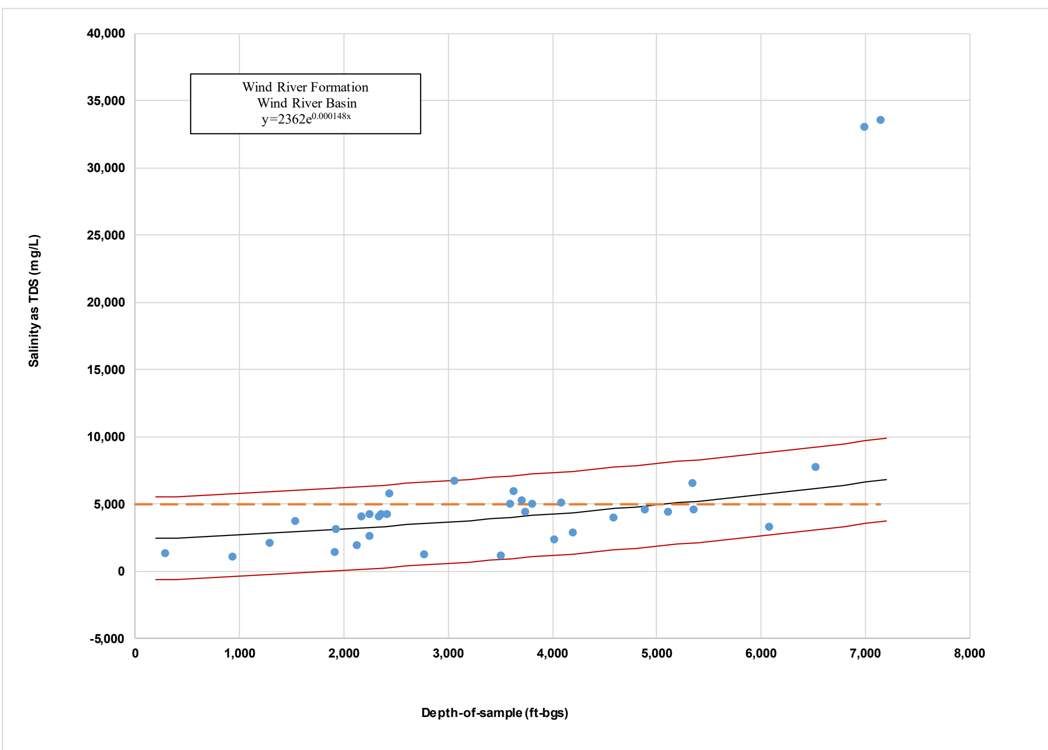


Figure 11. Relationship between salinity and depth-of-sample in the Wind River Formation of the Wind River Basin. Regression trend line shown in black; 95 percent confidence intervals are shown in red. The dashed orange line indicates the 5,000 mg/L TDS concentration. The two extreme values at the 7,000 depth (from the same well) were removed during regression optimization so that the non-linear model would reach convergence.

Jackson Hole

There are no saline wells identified in the Jackson Hole.

A complete description of the hydrogeology of northwestern Wyoming (Wind, Bighorn, and Snake River basins) can be found in Taucher and others (2013) and Taboga and others (2014b), available at https://www.wsgs.wyo.gov/water/river-basin-plans.

Southwestern Wyoming

Overthrust Belt

The Nugget and Frontier formations each have more than 10 saline wells (table 10). Mean TDS concentration (49,362 mg/L) and depth-of-sample (10,426 ft-bgs) for Nugget Sandstone wells are the highest values observed in the southwestern region.

Table 10. Summary statistics for producing units with 10 or more saline well sites in the Overthrust Belt.

Geologic unit	Geologic age	Count	TDS (mg/L)			Range, depths-of-sample, ft-bgs [#wells with depths]
			Minimum	Mean	Maximum	
Frontier	Cretaceous	25	5,458	16,400	72,801	5,550–12,326 [22]
Nugget	Jurassic-Triassic	40	10,658	49,362	101,851	7,160–12,380 [20]

Green River Basin

Saline groundwaters are found in 12 formations with 10 or more samples (figs. 12A, B, and C and table 11). Mesozoic saline producing units are concentrated in areas around the Rock Springs Uplift, along Sweetwater County's western border, in southwestern Sublette County, and along the basin margin west of the Wind River Range near Pinedale. Saline Cenozoic units are largely in the southern part of the basin and near Pinedale. A few saline wells completed in Paleozoic units are scattered throughout the basin. Wells in the Cretaceous Lance, Frontier, and Mesaverde formations are the most frequent producers of saline waters.

Table 11. Summary statistics for producing units with 10 or more saline well sites in the Green River Basin.

Geologic unit	Geologic age	Count	TDS (mg/L)			Range, depths-of-sample, ft-bgs [#wells with depths]
			Minimum	Mean	Maximum	
Wasatch	Tertiary	77	5,030	8,071	30,060	1,084–4,055 [67]
Fort Union	Tertiary	62	5,249	16,308	52,100	839–10,906 [36]
Lance	Cretaceous	654	5,180	9,629	75,590	6,575–13,930 [9]
Mesaverde	Cretaceous	110	5,147	17,979	147,174	512–17,526 [60]
Hilliard	Cretaceous	10	10,357	21,934	66,100	2,030–2,260 [7]
Frontier	Cretaceous	433	5,002	12,348	66,500	113–12,287 [53]

Table 11. Continued.

Geologic unit	Geologic age	Count	TDS (mg/L)			Range, depths-of-sample, ft-bgs [#wells with depths]
			Minimum	Mean	Maximum	
Muddy	Cretaceous	11	6,717	14,395	23,482	7,729–8,306 [4]
Bear River	Cretaceous	21	6,226	16,600	40,155	7,532–8,890 [8]
Cloverly	Cretaceous	87	5,141	17,317	72,195	2,270–15,748 [66]
Morrison	Jurassic	15	7,016	23,472	45,831	3,097–8,576 [14]
Sundance	Jurassic	10	9,151	22,423	50,377	3,473–4,535 [8]
Nugget	Jurassic-Triassic	36	7,117	38,043	104,678	3,350–14,516 [31]

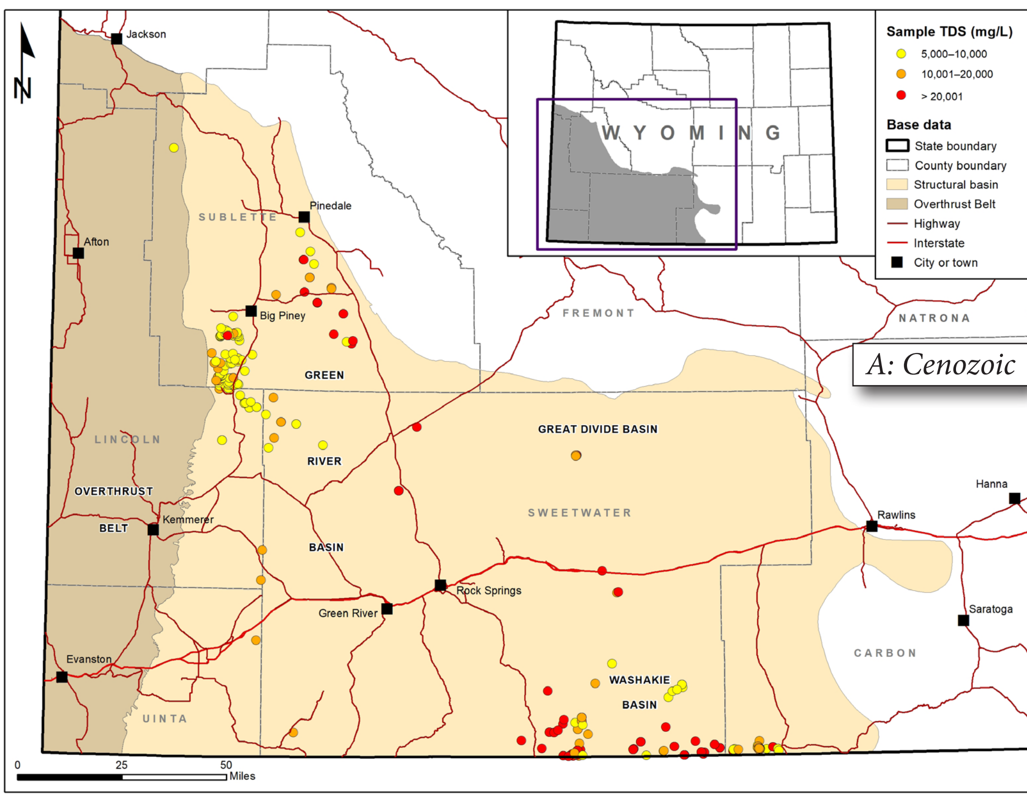
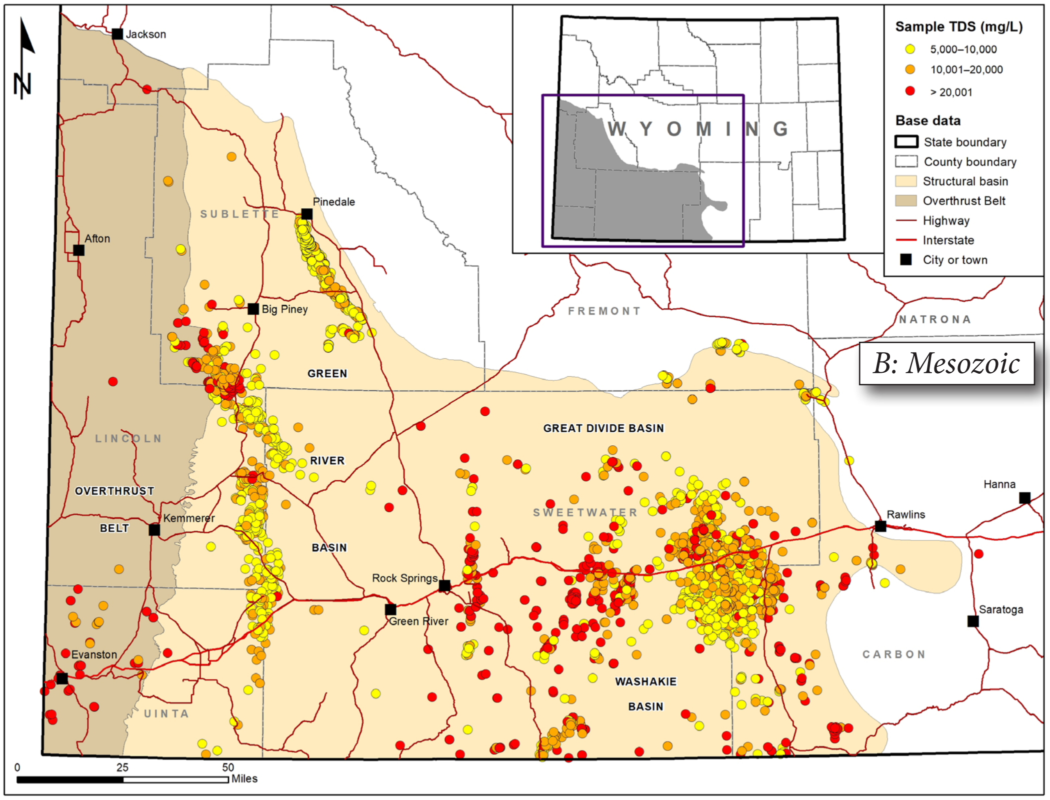
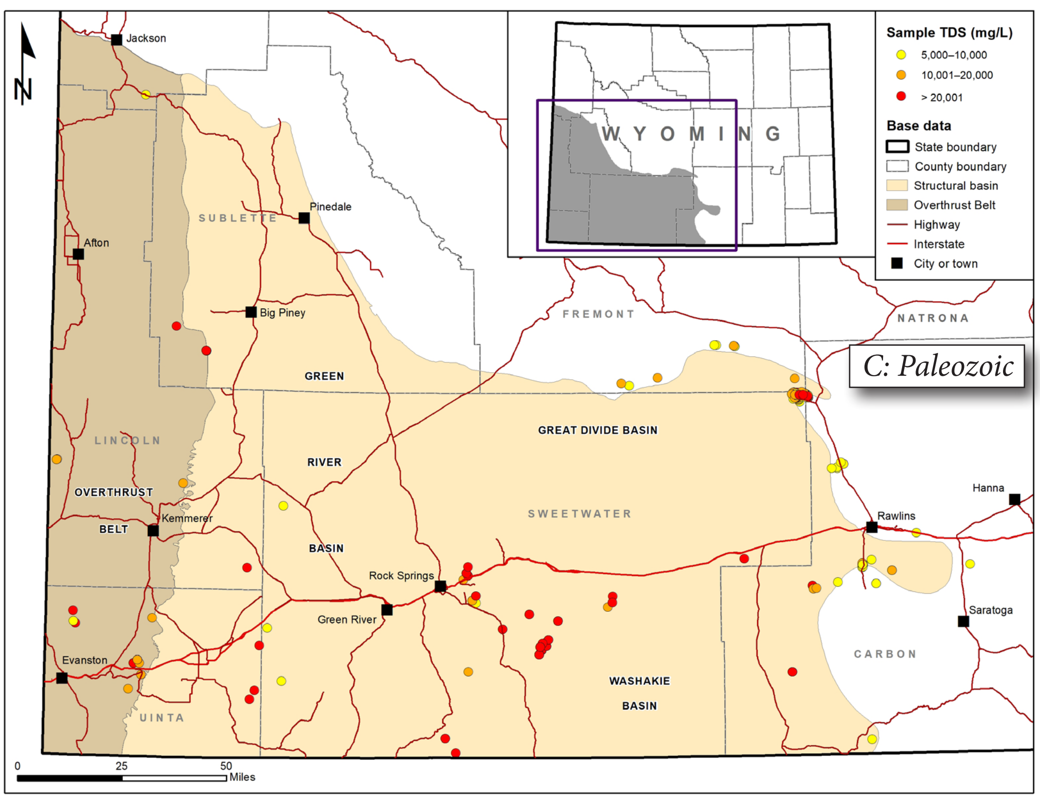


Figure 12. Saline samples from (A) Cenozoic, (B) Mesozoic, and (C) Paleozoic geologic units in southwestern Wyoming.

Figure 12. Continued. Saline samples from (B) Mesozoic and (C) Paleozoic geologic units in southwestern Wyoming.





Great Divide and Washakie basins

Second only to the Powder River Basin in the number of saline wells, the Great Divide and Washakie basins contain 16 saline geologic units with 10 or more wells (figs. 12A, B, and C and table 12). Saline Mesozoic wells are frequently encountered in the Great Divide Basin, while saline Cenozoic wells are located mostly in the southern Washakie Basin. Saline units range in age from the Mississippian Madison Limestone to the Eocene Wasatch Formation. Wells completed in the Mesaverde Group account for nearly 67 percent of all saline wells in the Great Divide/Washakie Basin. On the western margin of the Washakie Basin, wells completed in the Weber Sandstone, partly equivalent to the Tensleep Sandstone (Love and others, 1993), exhibit the highest mean TDS concentration (86,038 mg/L) and depth-of-sample (14,592 ft-bgs) in all of Wyoming.

Table 12. Summary statistics for producing units with 10 or more saline well sites in the Great Divide and Washakie basins.

Geologic unit	Geologic age	Count	TDS (mg/L)			Range, depths-of-sample, ft-bgs [#wells with depths]
			Minimum	Mean	Maximum	
Wasatch	Tertiary	45	5,410	26,373	96,661	1,356–6,056 [38]
Fort Union	Tertiary	69	5,497	26,837	153,364	1,100–7,701 [37]
Lance	Cretaceous	27	5,932	24,423	80,420	3,602–8,885 [17]
Fox Hills	Cretaceous	16	5,213	22,381	64,783	3,398–7,637 [7]
Lewis	Cretaceous	105	5,045	15,218	100,026	3,805–13,258 [27]
Mesaverde	Cretaceous	1,169	5,074	16,654	292,810	1,063–13,746 [254]
Cody	Cretaceous	10	20,218	26,878	34,962	3,401–3,640 [3]
Frontier	Cretaceous	54	5,172	20,386	60,169	412–13,474 [38]
Muddy	Cretaceous	14	5,000	12,241	30,093	2,920–8,556 [11]
Cloverly	Cretaceous	47	5,368	15,177	98,462	1,985–14,209 [31]
Nugget	Jurassic - Triassic	49	5,120	46,465	138,221	2,358–14,940 [30]
Phosphoria	Permian	12	5,241	12,964	25,893	2,878–10,100 [10]
Weber	Pennsylvanian-Permian	25	5,577	86,038	162,989	10,066–18,112 [20]
Tensleep	Pennsylvanian-Permian	88	5,074	14,013	100,982	3,796–12,000 [73]
Amsden	Pennsylvanian-Mississippian	14	5,945	14,536	38,566	6,365–6,889 [8]
Madison	Mississippian	35	5,644	16,084	120,469	4,444–15,211 [30]

Depth and salinity—A statistically significant (p-value<0.05) relationship between depth and groundwater salinity is seen in the Nugget Sandstone of the Green River Basin (fig. 13).

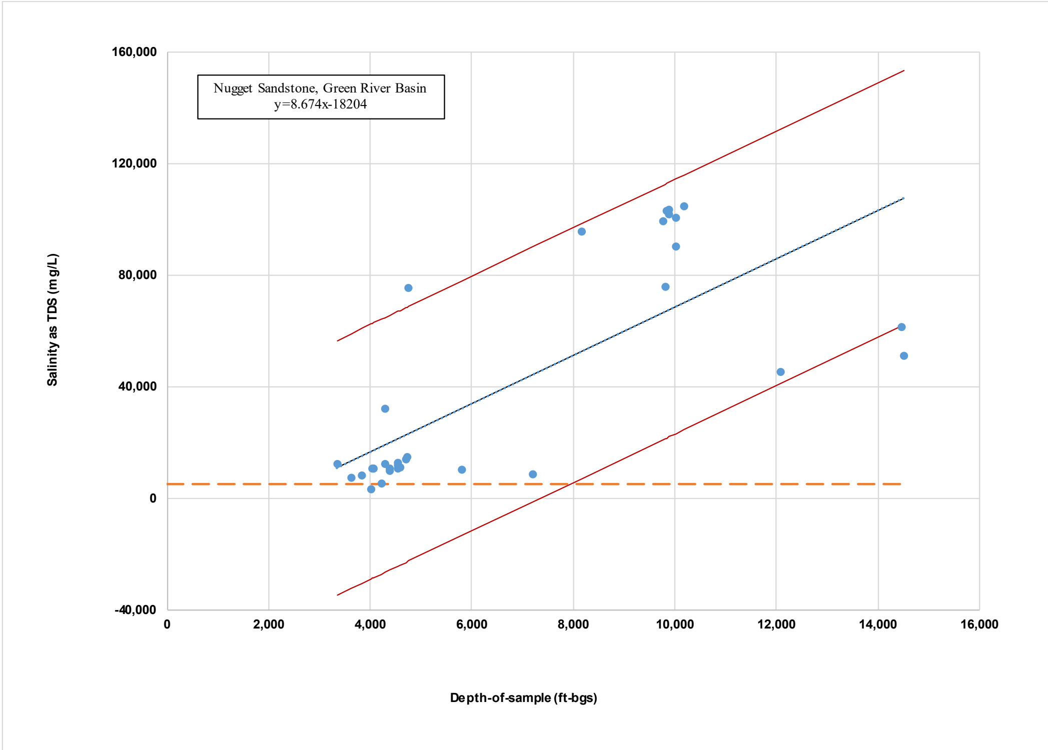


Figure 13. Relationship between salinity and depth-of-sample in the Nugget Sandstone of the Green River Basin. Regression trend line shown in black; 95 percent confidence intervals are shown in red. The dashed orange line indicates the 5,000 mg/L TDS concentration.

Complete descriptions of the hydrogeology of the Green River, Washakie, and Great Divide basins (Clarey and others, 2011) and the Overthrust Belt (Taboga and others (2014a, b) are available at http://www.wsgs.wyo.gov/Research/Water-Resources/River-Basin-Plans.aspx.

SUMMARY

The WSGS reviewed almost 36,000 records of Wyoming water quality data from the USGS Produced Water Database (USGS, 2018) and the WOGCC Water Analysis Database (WOGCC, 2018). After conducting a screening process that removed incomplete and duplicate records, The WSGS compiled a database that contains TDS data for over 11,500 unique sites, of which 7,848 had TDS concentrations of 5,000 mg/L or greater.

Despite the large number of sites contained in the WSGS saline water database, this report does not constitute a comprehensive examination of saline groundwater in Wyoming. The locations and geologic units of sites that produce saline waters were largely determined by exploratory oil and gas drilling. Consequently, the sample sites shown in the figures presented in this report are clustered in Wyoming's oil and gas fields (Toner and others, 2018).

Comparative percentages indicate that saline groundwaters occur most frequently in the Denver-Julesburg Basin (43 percent of all wells tested) and the Overthrust Belt (30 percent), followed by the Powder River (27 percent), Laramie (23 percent), Great Divide and Washakie (22 percent), and Bighorn (21 percent) basins. Saline wells are found with less frequency in the Wind River (20 percent), Green River (18 percent), and Hanna (11 percent) basins. No saline wells are recorded in the Jackson Hole, where oil and gas exploration has been limited.

In the Denver-Julesburg Basin, wells completed in the Cretaceous Niobrara Formation, Carlile Shale, and Muddy Sandstone produce saline water with 79–100 percent frequency. Mean TDS levels in Niobrara Formation and Carlile Shale wells, sited predominately in central Laramie County, exceed 30,000 mg/L. In contrast, the Cretaceous Muddy Sandstone produces less saline water (mean TDS ~14,000 mg/L) from 30 wells, generally located across southern Laramie County.

In the western Laramie Basin, wells completed in the Paleozoic Casper Formation (mean TDS 18,546 mg/L) and the Cretaceous Muddy Sandstone (mean TDS 8,673 mg/L) produce saline groundwater from 41 wells.

The Casper Formation has also produced moderately saline water (mean TDS 7,731 mg/L) in the eastern Hanna Basin from 20 wells.

In contrast to the limited number of saline wells in southeastern Wyoming basins, the Powder River Basin produces saline groundwater from 2,529 widely distributed wells completed in 26 different geologic units. More than 600 saline wells are found in the Paleozoic Minnelusa Formation, located for the most part in the northeast portion of the basin. Minnelusa wells have the second highest mean salinity level (60,629 mg/L) observed among all Wyoming formations. Completions in Cretaceous geologic units comprise more than 1,750 of the remaining saline wells in the PRB.

Paleozoic and Mesozoic saline wells are interspersed around the perimeter of the Bighorn Basin. About 70 percent of wells completed in the Phosphoria (69 percent) and Dinwoody (74 percent) formations produce saline groundwater, whereas only a minor portion of Tensleep Sandstone (26 percent), Madison Limestone (40 percent), and Frontier Formation (25 percent) wells yield saline water.

In comparison, more than 850 saline wells are distributed widely across the Wind River Basin. The largest portion (44 percent) are completed in varied Mesozoic units. However, one-third of all saline wells are completed in the Tertiary Fort Union Formation. The remaining saline wells produce water from Paleozoic units (the Phosphoria Formation, Tensleep Sandstone, and Madison Limestone) scattered across the southern basin margin.

In the Overthrust Belt, deep wells (average depth 10,426 ft-bgs) in the Nugget Sandstone produce saline groundwater with 95 percent frequency. The Frontier Formation is a reliable source of saline water also.

Wells completed in the Cretaceous Lance, Frontier, Mesaverde, Cloverly, Tertiary Wasatch, and Fort Union formations produce moderately saline groundwater (mean salinities less than 20,000 mg/L) in the Green River Basin. Saline wells are heavily concentrated on the Pinedale Anticline and along the western border of Sweetwater County into southwestern Sublette County.

The Cretaceous Mesaverde Group of the Washakie and Great Divide basins is the most prolific producer of saline water in Wyoming. Furthermore, 15 other Paleozoic through Cenozoic stratigraphic units generate saline water from 10 or more wells. Geospatially, saline wells are heavily concentrated in two clusters that lie in eastern Sweetwater County along the Wamsutter Arch, along the eastern side of the Rock Springs Uplift, and along the southern edge of the Washakie Basin. Lastly, groundwater produced from the Paleozoic Weber Sandstone, partly equivalent to the Tensleep Sandstone, exhibits the highest mean salinity (86,038 mg/L) of any formation examined in this report.

The WSGS used regression analysis to relate salinity to depth of sample in 61 stratigraphic units located in major Wyoming hydrocarbon producing basins. Only seven units exhibited substantive relationships that could be adequately modeled with linear or exponential regressions (table 13). The geochemical complexity of Wyoming's basins as well as the lack of quality control in the compiled dataset may account for the apparent lack of correlation between these variables.

The lack of discernible substantive relationships between depth of sample and salinity in the majority of the 61 stratigraphic units examined in this report is likely due to the geochemical and hydrogeologic complexity of Laramide structural basins as well as the questionable quality of the data, which were collected by different operators using varied methods over seven decades. Still, the compiled data provide useful information regarding groundwater salinity levels.

Table 13. Best-fit regressions for depth-of-sample and salinity data in selected stratigraphic units in Wyoming basins. Coefficients of determination (R^2), shown for linear regressions only, is not a valid goodness-of-fit measure for non-linear regressions (Spiess and Neumeyer, 2010).

Basin	Stratigraphic unit	Type of trend	Function	R^2
Laramie	Casper Formation	Exponential	$y=1275.2e^{0.000394x}$	---
Powder River	Newcastle Sandstone	Exponential	$y=4901.6e^{0.000178x}$	---
Green River	Nugget Sandstone	Linear	$y = 8.67x - 18{,}204$	0.54
Wind River	Dinwoody Formation	Linear	$y = 1.158x + 2{,}318$	0.41
Wind River	Sundance Formation	Exponential	$y=2738.0e^{0.000376x}$	---
Wind River	Cloverly Formation	Exponential	$y=2180.2e^{0.000186x}$	---
Wind River	Wind River Formation	Exponential	$y=2362.0e^{0.000148x}$	---

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