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Groundwater Salinity in the Greater Green River Basin, Wyoming

Karl G. Taboga, James E. Stafford, James R. Rodgers, Seth J. Wittke, and Charles P. Samra

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INTRODUCTION

Groundwater quality varies widely throughout Wyoming's large intermountain structural basins where most of the state's population resides and the greater part of economic activity occurs. Basin aquifers typically produce high-quality groundwater along their margins in close proximity to mountainous recharge areas (Huntoon, 1993) and lower-quality water from their interiors (Clarey and others, 2010; Taucher and others, 2012, 2013; Taboga and others, 2014a, b, 2019). The most commonly used measure of groundwater quality in Wyoming wells is salinity (Wyoming State Engineer's Office, 2019).

This is the third report in a series by the Wyoming State Geological Survey (WSGS) that examines groundwater salinity in selected Wyoming energy-producing basins. In Wyoming, saline waters are most frequently produced in the state's energy basins during oil and gas production (table 1). In practice, the use of saline waters for industrial applications instead of freshwater depends on the availability and cost of using freshwater. Previous WSGS studies looked at groundwater quality in the Powder River (Taboga and others, 2018) and Denver-Julesburg basins (Taboga and others, 2016). This report considers groundwater salinity at depths of 1,000–7,000 feet (ft) below ground surface (bgs) in the Greater Green River Structural Basin (GGRB) and Overthrust Belt of southwestern Wyoming. Special emphasis is placed on saline groundwaters suited to industrial uses, thereby conserving higher-quality waters for municipal, domestic, and agricultural uses.

Table 1. 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

Salinity is a measure of the "total dissolved solids" (usually abbreviated and referred to as the singular noun TDS) that remain as residue after a water sample evaporates. TDS includes dissolved salts, minerals, metals, cations, anions, and molecules that can pass through a 2-micrometer filter. TDS is measured in units of mass per volume (milligrams/liter, abbreviated as mg/L). The terms "salinity" and "TDS" are used interchangeably in this report. A TDS concentration does not specify the type or amounts of the particular chemical compounds that make up solids in the residue. Therefore, it is only a general predictor of water quality. Low TDS groundwater can contain harmful levels of pesticides and other manufactured chemicals, or naturally occurring toxins such as heavy metals and radioactive elements. Even so, salinity is a useful measure of general water quality, particularly if it is part of a complete water chemistry analysis that specifies the type and concentrations of the many different chemical constituents present in a single water sample.

Saline groundwater in Wyoming is encountered most frequently as a byproduct of oil and gas exploration in deep basin aquifers. By comparison, domestic, irrigation, and livestock users seek higher-quality groundwater in shallow wells in order to conserve development and operational costs (Taboga and others, 2014a, b, 2019). There has never been a geospatially extensive deep-drilling and water-sampling program conducted by the scientific community or any government agency in Wyoming. Almost all water quality data for the state's deep aquifers have been obtained from energy exploration and development.

BACKGROUND

Water Quality Standards, Groundwater Classification, and TDS Levels

The Wyoming Department of Environmental Quality (WDEQ), U.S. Environmental Protection Agency (EPA), and Wyoming Oil and Gas Conservation Commission (WOGCC) regulate groundwater use in the state of Wyoming. The WDEQ, which regulates groundwater quality for most uses of the state's aquifers, classifies groundwater suitability for domestic, agricultural, and livestock uses based on water quality standards (WDEQ, 2019). The WDEQ prescribes maximum TDS concentrations of 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-grade groundwaters are classified by TDS concentration as Class IV A (TDS≤10,000 mg/L) and Class IV B (TDS>10,000 mg/L). Current WDEQ water quality standards are contained in chapter 8 of the WDEQ Water Quality Rules and Regulations, available at http://deq.wyoming.gov/wqd/resources/rules-regs/.

The EPA Region 8 Office, headquartered in Denver, Colorado, regulates public water systems in Wyoming that provide water for human consumption through at least 15 service connections or regularly serve at least 25 individuals. The EPA standard for TDS is set as a Secondary Maximum Contaminant Level (SMCL) of 500 mg/L (U.S. Environmental Protection Agency, 2019). SMCLs are non-enforceable guidelines for contaminants that may cause aesthetic problems such as degradation of taste, odor, or appearance. A full explanation of the EPA's drinking water standards is available on the EPA's website.

The WOGCC regulates the underground disposal of wastewater co-produced with oil and gas development that is not suitable for other uses through the issuance of underground injection control permits (Class II UIC permits). WOGCC rules require the applicant for a Class II disposal well permit to provide a, "Standard laboratory analysis of the water to be disposed and the water in the formation into which disposal is taking place," (chap. 4, sec. 5c [ix]). Specific water quality parameters that include TDS concentrations must be provided in the Water Analysis Report (WOGCC Form 17) filed with the permit application. The WOGCC also regulates the Wyoming Groundwater Baseline Sampling, Analysis and Monitoring Program. See current WOGCC regulations governing both programs at http://pipeline.wyo.gov/wogcchelp/commission.html.

Current Beneficial Uses of Saline Groundwater in Wyoming

The U.S. Geological Survey (USGS) estimates that in 2015 the amount of saline groundwater (TDS>1,000 mg/L) used beneficially in Wyoming was about 96.8 million gallons per day (Dieter and others, 2018), a 44 percent increase from 2010 (Maupin and others, 2014). It is unknown whether this increase is the result of better reporting or the more frequent use of saline water for industrial applications. Both studies report that all of the saline water was used by the mining industry, which includes oil and gas production by USGS definition (Maupin and others, 2014; Dieter and others, 2018). However, neither study specifies the particular application for which the water was used.

Industrial Applications for Saline Groundwater

Oil and gas development

The most common industrial application of saline groundwater is for oil and gas exploration and production (E&P). The industry requires substantial amounts of water to drill and develop new wells during exploration at the same time it coproduces large volumes of saline groundwater during production (WOGCC, 2020). In some cases, new development and production operations are located in the same field or in close geographic proximity. Therefore, the ability to use saline produced water for new drilling and development may be cost effective. This approach has the added advantage of managing coproduced water, a key component of the federal and state environmental permits required for E&P operations (WDEQ, 2019; WOGCC, 2020). These benefits also conserve and protect fresh water resources that would otherwise be used to meet E&P water demands. Recognizing this fact, the states of Texas and New Mexico encourage the reuse of saline water by waiving permits to inject produced saline waters downhole if certain water quality standards are met.

Oil and gas producers have used saline water for hydraulic fracturing and secondary and tertiary oil recovery (stream flooding) for a number of years (AGI, 2015). Energy companies, state agencies, and the EPA continue to study the use of saline water for hydraulic fracturing (AGI, 2015; Godsey, 2017; Scanlon and others, 2020), driven by the cost of using up to 10 million gallons of fresh water required to fracture one well (Allison and Mandler, 2018). These large volumes of water can stress local water resources, even in humid environments like the Marcellus Shale play in Pennsylvania and West Virginia. The problem is further exacerbated in semi-arid western basins (Allison and Mandler, 2018; table 1 in this report) where fresh groundwater is largely unavailable, average annual precipitation is less than 20 inches, and surface water flows may be (over) allocated to holders of existing water rights.

Saline groundwater must be treated for total suspended solids, free and colloidal oil, and microbes prior to reuse in fracturing fluid. Additionally, chemical interactions between additives in the fracturing fluid and some ions in saline groundwater may limit the use of saline water for hydraulic fracturing (LeBas and others, 2013; AGI, 2015; Godsey, 2017). Elevated iron concentrations can interfere with flocculation formers, divalent ions such as calcium, magnesium, and sulfate can cause scale build-up, and boron can disrupt cross-link additives. Many times, adjusting the fracking chemicals used for treating the saline water on-site can remedy these problems. In practice, effective mixtures of saline water and frack fluid additives must be developed for each producing formation individually by an experienced hydraulic fracturing contractor. Despite these challenges, energy corporations are using saline waters for hydraulic fracturing (Allison and Mandler, 2018), and their use is expected to grow as further technical and economic obstacles are resolved.

The American Geosciences Institute (AGI) provides a free short online course, "Making Produced Water More Productive", on its Geoscience Online Learning Initiative platform at mailto:goli@americangeosciences.org. Course presentations discuss the environmental, legal, and economic issues involved with recycling and reusing saline water co-produced with oil and gas development (AGI, 2015).

Other industrial applications

Saline water can be used in the coal, aggregate, and ore mining industries for quarrying, ore handling and processing, equipment wash-down, and on-site dust suppression (WDEQ, 2020). Saline waters may be used in manufacturing for fabricating, processing, washing, or cooling where water quality is not a limiting factor or in cases where minimal water treatment is required prior to application.

METHODS

The WSGS used the Static Spontaneous Potential (SSP) Method (Schlumberger Well Services, 1989; Schnoebelen and others, 1995) to estimate groundwater TDS levels from oil and gas well logs. Initially, the WSGS used Petra® 4.3.0.283 geologic interpretation software to identify almost 2,100 candidate wells with static spontaneous potential (SSP) logs among more than 22,000 oil and gas wells in the Greater Green River Basin and Overthrust Belt as delineated by WOGCC records (2019).

Next, the WSGS examined candidate well records for: 1) legible SSP logs with coherent shale baselines, 2) corresponding gamma ray logs, 3) borehole bottom temperatures, 4) mud filtrate resistivity data, and 5) the use of drilling muds that did not contain saline or petroleum-based compounds. Final analysis involved evaluating SSP deflections in sandstone strata that are more than 20 ft thick to a depth of 7,000 ft in the 1,606 wells that met the above selection criteria (figure 1). A set of fitted mathematical algorithms developed by Brown and others (1980) was used to calculate TDS levels from observed SSP deflections. The final SSP dataset consisted of 1,617 calculated TDS levels at varying depths up to 7,000 ft bgs. Additionally, this study uses data obtained from almost 36,000 Wyoming water chemistry analyses provided by the USGS (2019a, b) and WOGCC (2019). Taboga and others (2016, 2018) provides a full explanation of the manner used to process the USGS/WOGCC water quality data. The resultant water quality dataset used in this report provided water quality analyses for 612 qualified wells in the Greater Green River Basin and Overthrust Belt. The final dataset generated by well log and water quality analyses contained 2,229 combined data points from oil and gas well fields (see the WSGS Oil and Gas Interactive Map, https://www.wsgs.wyo.gov/energy/oil-gas-resources) and from the USGS National Water Information System (NWIS, at https://waterdata.usgs.gov/nwis).

The resultant dataset includes wide ranges of TDS concentrations (1,021–169,944 mg/L) and reported depths (1,021–6991 ft). Challenges to the analysis include often-inconsistent driller-provided stratigraphic data, and the large 22,327-square-mile surface area of the combined Greater Green River Basin and Overthrust Belt. The WSGS addressed these issues as follows:

- 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. In depth intervals that contained more than one observed SP deflection or water quality analysis, the least saline groundwater is shown.

- Groundwater salinities in this report have been aggregated into categories adapted from WDEQ (2019) classes of use:

    ° Slightly saline water suitable for Class II agricultural use (1,000–2,000 mg/L TDS)

    ° Moderately saline water suitable for Class III livestock use (2,000–5,000 mg/L TDS)

    ° Industrial-grade groundwater suitable for Class IVA industrial use (5,000–10,000 mg/L TDS) or Class IVB industrial use (>10,000 mg/L TDS).

- Stratigraphic units were determined from geologic markers listed for particular wells (WOGCC, 2019), where available. Otherwise, the WSGS used in-house stratigraphic studies (Ver Ploeg and others, 1983; Lynds and Lichtner, 2016) and USGS data (Freethey and others, 1988; Martin, 1996; Glover and others, 1998). Stratigraphic markers within the complex Eocene stratigraphy were often lacking, and therefore assigned to a single group: Tertiary, Eocene rocks, undivided (Te). Formation symbols (table 2) are shown for saline waters in each depth interval when the depth of occurrence could be correlated to a Wyoming stratigraphic unit (Love and others, 1993). Qualifying wells that could not be assigned to a stratigraphic unit, referred to as "undesignated" in the text, are shown without formation symbols on the map figures.

- Due to the size of the Greater Green River Basin, the results are presented in two parts: 1) the Overthrust Belt and Green River Basin to the western edge of the Rock Springs Uplift and 2) the Rock Springs Uplift, Washakie Basin, and Great Divide Basin.

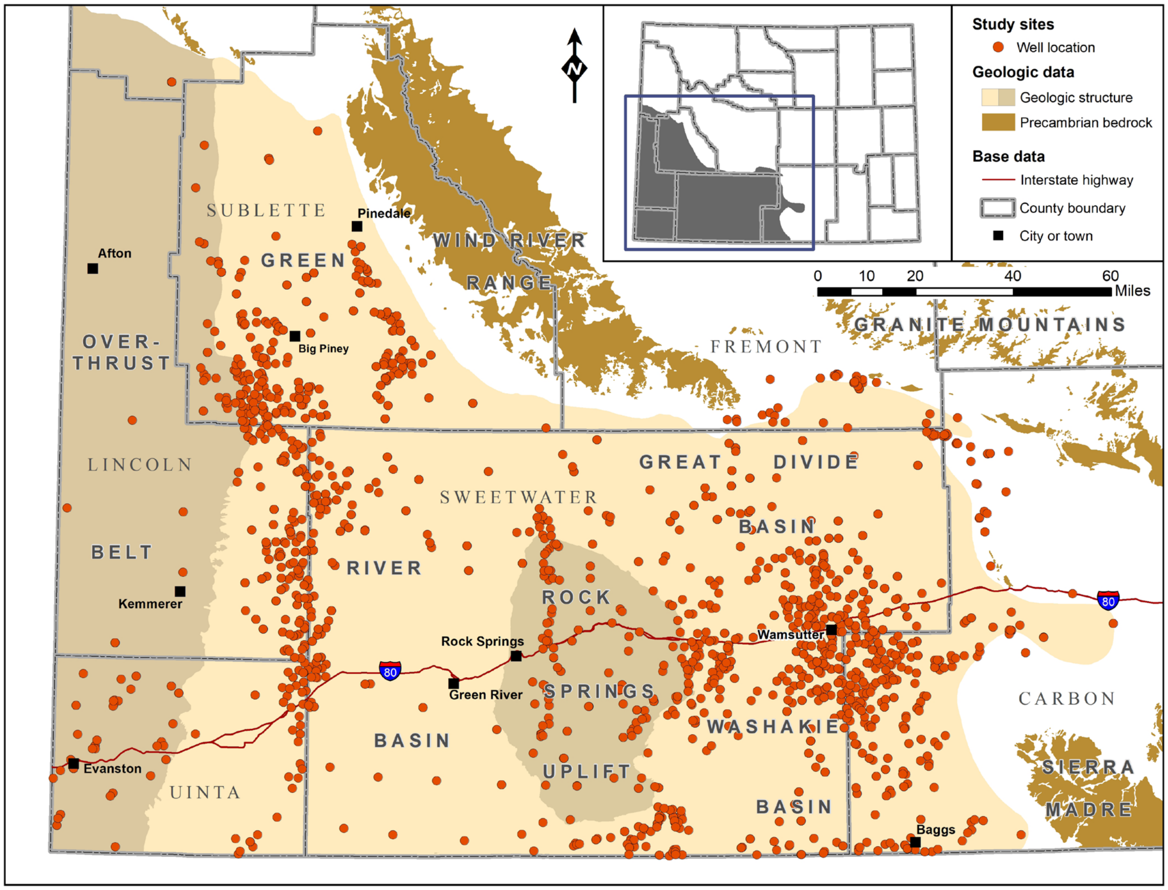

Figure 1. Qualified wells in Greater Green River Basin and Overthrust Belt used in this study. TDS concentrations were estimated using the Static Spontaneous Potential (SSP) Method (Schlumberger Well Services, 1989; Schnoebelen and others, 1995) or obtained from the USGS (2019a) and WOGCC (2019).

Table 2. Geologic units and corresponding symbols examined in this study.

Formation	Symbol	Formation	Symbol
Eocene rocks, undivided	Te	Aspen Shale	Ka
Wasatch Formation	Tw	Cloverly Formation	KJc
Green River Formation	Tgr	Morrison Formation	Jm
Fort Union Formation	Tfu	Sundance Formation	Js
Hoback Formation	Th	Twin Creek Limestone	Jtc
Lance Formation	Kl	Nugget Sandstone	JTRn
Fox Hills Sandstone	Kfh	Ankareh Formation	TRa
Lewis Shale	Kle	Thaynes Limestone	TRt
Mesaverde Group	Kmv	Woodside Shale	TRw
Steele Shale	Ks	Dinwoody Formation	TRd
Baxter Shale	Kba	Phosphoria Formation	Pp
Niobrara Formation	Kn	Weber Sandstone	PPw
Frontier Formation	Kf	Madison Limestone	Mm

RESULTS AND DISCUSSION

Green River Basin and Overthrust Belt

Most of the qualified wells in the Green River Basin are located in two areas (fig. 1). The greatest number of wells are located in a cluster of more than 70 well fields that predominately target natural gas reservoirs along the western border of Sweetwater County from the Utah state line into southwestern Sublette County. There are fewer wells in two large natural fields south of Pinedale. Although, fields in these two areas target natural gas reservoirs in Cretaceous formations (Toner and others, 2018), most of the groundwater salinity results are obtained from overlying Cenozoic units. Qualified wells in the Overthrust Belt are located in about 20 small oil and gas fields in western Uinta County (Toner and others, 2018).

Table 3 provides summary statistics for saline waters in the Green River Basin and Overthrust Belt by depth interval, and lists percentages of salinity grouped by WDEQ class of use (agricultural, livestock, and industrial).

Table 3. Summary table for salinity levels in the Green River Basin and Overthrust Belt 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 occurences**	**Percent**				
1,000–2,000	1,050	4,746	20,531	52	17	50	25	8	33
2,000–3,000	1,189	7,022	48,199	75	7	33	44	16	60
3,000–4,000	1,164	8,135	34,949	86	10	28	36	26	62
4,000–5,000	1,172	9,992	41,980	89	7	15	41	37	78
5,000–6,000	1,256	10,171	36,625	73	7	16	37	40	77
6,000–7,000	1,318	12,712	44,459	67	3	19	25	52	77

Salinity at 1,000–2,000 ft bgs

In this shallowest depth interval, a large group of slightly saline (TDS 1,000–2,000 mg/L) and moderately saline (TDS 2,000–5,000 mg/L) Tertiary sites extends from the southwestern corner of Sublette County into northern Lincoln and Sweetwater Counties (fig. 2). A smaller cluster of industrial-class (TDS>5,000 mg/L) waters occurs along the southern boundary between Lincoln and Sweetwater counties. Most of the saline groundwaters in this interval occur in undivided Eocene rocks (Te; table 4), a lithologically diverse assemblage of rocks distributed throughout the GGRB (Love and others, 1993).

Slightly and moderately saline waters comprise 67 percent of all results in this interval (table 3). The large group of wells in the north is likely freshened by recharge from nearby major groundwater recharge areas (Martin, 1996; Clarey and others, 2010 p. 5–55).

A few agricultural-, livestock-, and industrial-use waters are widely scattered throughout the Overthrust Belt. Many of the qualified wells in the Overthrust Belt lacked geologic marker data.

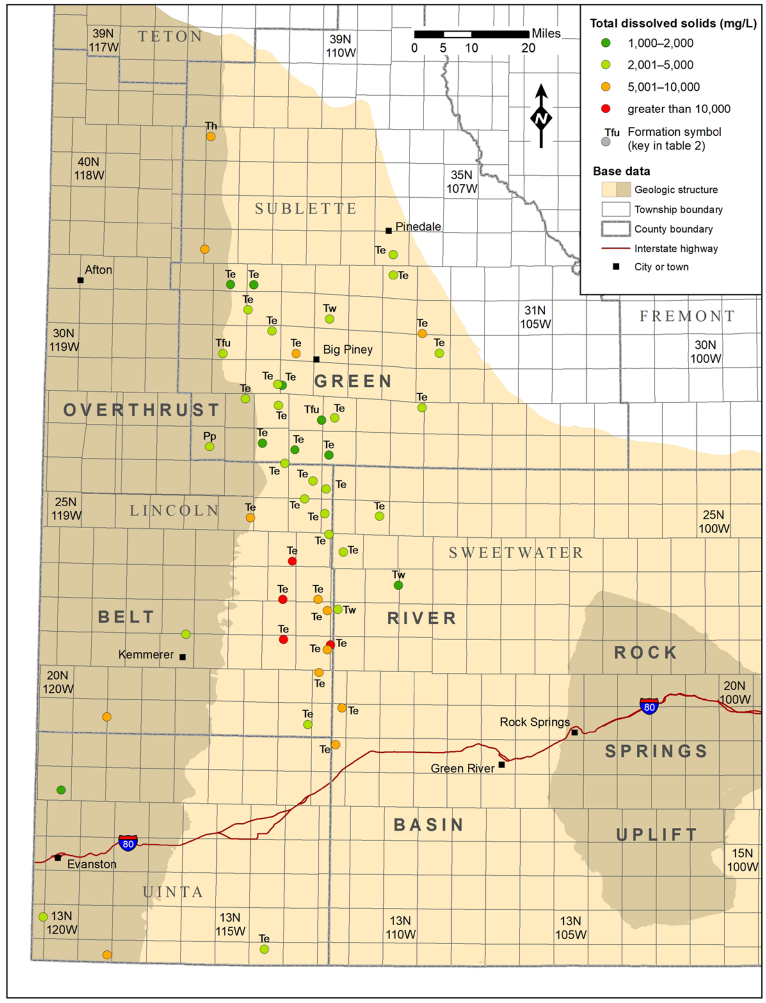

Figure 2. Saline waters in the 1,000–2,000-ft depth interval in the Green River Basin and Overthrust Belt.

Table 4. Summary statistics for all stratigraphic units in the Green River Basin and Overthrust Belt with qualified saline well sites (see methods section of this report for selection criteria) in the 1,000–2,000-ft depth interval.

Geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Eocene rocks, undivided	Eocene	39	1,401	5,035	20,531	13
Wasatch Formation	Eocene	3	1,050	2,778	4,775	0
Fort Union Formation	Paleocene	2	1,542	2,531	3,519	0
Hoback Formation	Paleocene	1	7,537	7,537	7,537	1
Phosphoria Formation	Permian	1	2,945	2,945	2,945	0
Unspecified unit	Unspecified	6	2,000	4,428	8,051	3

Salinity at 2,000–3,000 ft bgs

In the Green River Basin, a small cluster of industrial-grade (TDS>5,000 mg/L) wells exists in south-central Sublette County (fig. 3). To the west of this cluster, a long interspersed band of moderately saline (TDS 2,000–5,000 mg/L) and industrial-grade wells extends from southwestern Sublette County southward along the western boundary of Sweetwater County to U.S. Interstate 80 (I-80). Most of the industrial-grade groundwaters occur in undivided Eocene units and in specified Wasatch Formation wells (table 5). However, industrial groundwaters are also seen in the Paleocene Fort Union Formation, particularly along the western margin of the basin.

Six industrial-grade wells are scattered around Evanston in the southern Overthrust Belt. A few moderately saline and industrial-grade wells are located on the eastern edge of the Overthrust Belt.

Industrial-grade groundwaters occur in 60 percent of all wells in this interval (table 3).

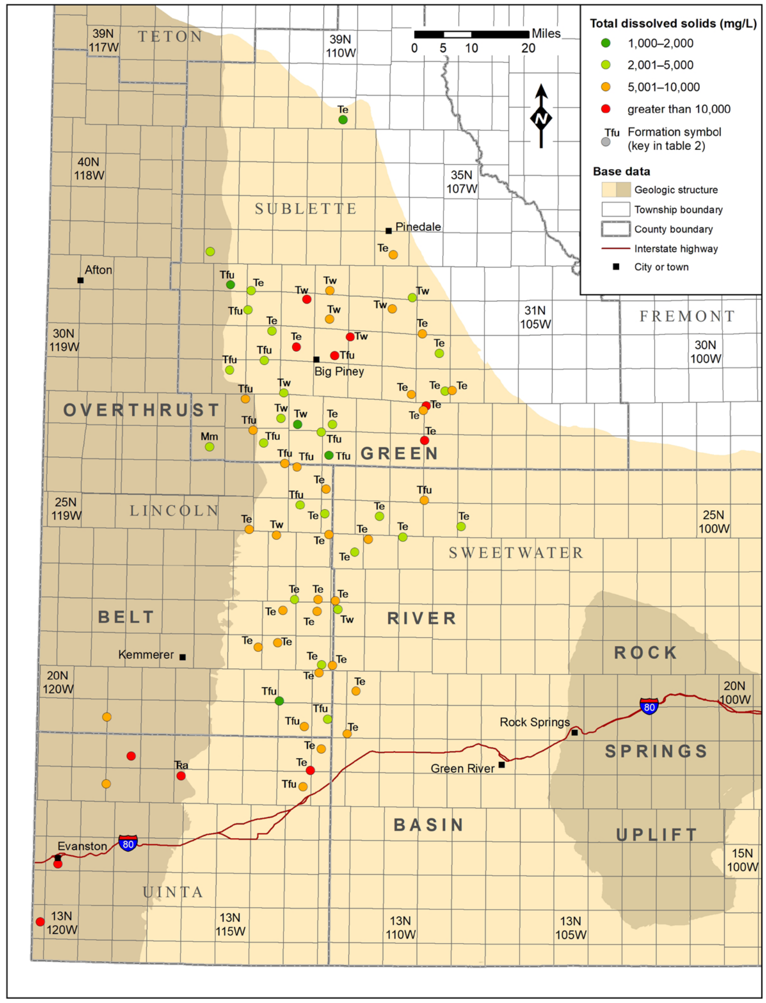

Figure 3. Saline waters in the 2,000–3,000-ft depth interval in the Green River Basin and Overthrust Belt.

Table 5. Summary statistics for all stratigraphic units in the Green River Basin and Overthrust Belt with qualified saline well sites (see methods section of this report for selection criteria) in the 2,000–3,000-ft depth interval.

Geologic unit	Geologic age	Count	TDS (mg/L) Minimum	TDS (mg/L) Mean	TDS (mg/L) Maximum	Count TDS>5,000 mg/L
Eocene rocks, undivided	Eocene	37	1,539	6,274	13,828	24
Wasatch Formation	Eocene	11	1,189	6,198	15,116	6
Fort Union Formation	Paleocene	19	1,624	7,046	48,199	9
Ankareh Formation	Triassic	1	29,263	29,263	29,263	1
Madison Limestone	Mississippian	1	2,899	2,899	2,899	0
Unspecified unit	Unspecified	6	3,653	10,042	20,056	5

Salinity at 3,000–4,000 ft bgs

Industrial-grade waters (TDS>5,000 mg/L) at this depth are found in about 60 percent of all wells (table 6); however, they are more saline than in the previous (2,000–3,000 ft) interval. These wells show an increase in the percentage of Class IVB groundwaters (TDS>10,000 mg/L) in conjunction with a corresponding decrease in the frequency of Class IVA groundwaters (TDS 5,000–10,000 mg/L). Industrial-grade waters are found in wells distributed throughout the western Green River Basin, with the exception of a narrow band of slightly and moderately saline wells that are concentrated in southwestern Sublette County (fig. 4). The lower salinities in these wells, observed at all depth intervals, are likely due to the proximity of important recharge areas (Clarey and others, 2010, p. 5–55; Taboga and Stafford, 2016, p. 10). In fact, the host rock unit does not appear to have a substantive effect on salinity; both saline industrial waters and the cluster of less saline wells in southwestern Sublette County occur in each of the dominant Tertiary units (table 6): Eocene Rocks, undivided (Te); Wasatch (Tw); and Fort Union (Tfu).

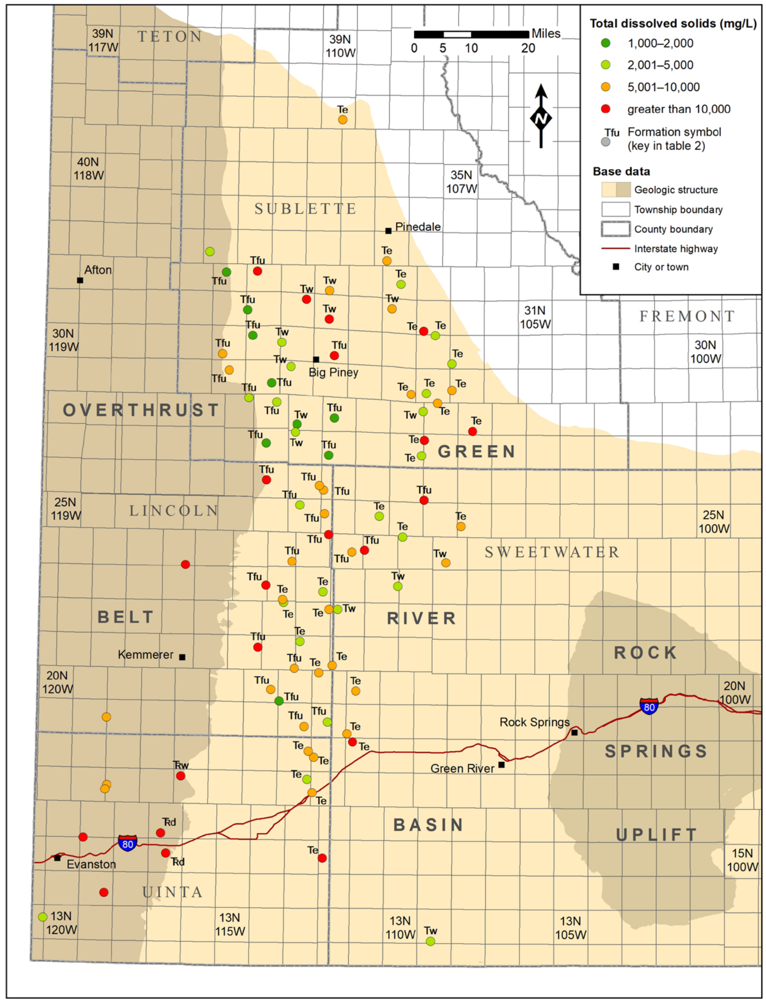

Figure 4. Saline waters in the 3,000–4,000-ft depth interval in the Green River Basin and Overthrust Belt.

The number of industrial-grade wells in the southern Overthrust Belt has increased to eight when compared to the previous shallower interval. Groundwaters with salinities exceeding 10,000 mg/L are found at three Triassic sites east of Evanston on the margin of the Overthrust Belt. Geologic markers are unavailable for wells that are more than a few miles west of the margin.

In the 3,000–4,000-ft depth interval, the great majority of saline samples were drawn from undivided Eocene rocks as well as from the Fort Union and Wasatch formations (table 6).

Table 6. Summary statistics for all stratigraphic units in the Green River Basin and Overthrust Belt with qualified saline well sites (see methods section of this report for selection criteria) in the 3,000–4,000-ft depth interval.

Geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Eocene rocks, undivided	Eocene	31	2,202	7,310	19,082	20
Wasatch Formation	Eocene	13	1,164	6,193	16,663	5
Fort Union Formation	Paleocene	30	1,256	7,547	21,723	18
Woodside Shale	Triassic	1	17,220	17,220	17,220	1
Dinwoody Formation	Triassic	2	15,399	16,104	16,809	2
Unspecified unit	Unspecified	9	3,396	12,963	34,949	7

Salinity at 4,000–5,000 ft bgs

Industrial-grade waters (TDS>5,000 mg/L) comprise nearly 80 percent of all groundwater at this depth interval (table 3). Slightly and moderately saline wells are limited, for the most part, to southern and western Sublette County. Even so, the combined incidence of waters with salinities of 1,000–5,000 mg/L in this limited area has declined when compared to the previous depth interval (fig. 5). The great majority of Green River Basin wells in this interval are still within Tertiary units, particularly the Fort Union Formation and in undivided Eocene rocks (table 7). Several wells along the southern border of Sublette County penetrate into the underlying Cretaceous Mesaverde (Kmv) and Frontier (Kf) units.

In the southern Overthrust Belt, the number of industrial-grade wells near Evanston has increased to 10, including four in the Paleozoic Weber Sandstone (PIPw).

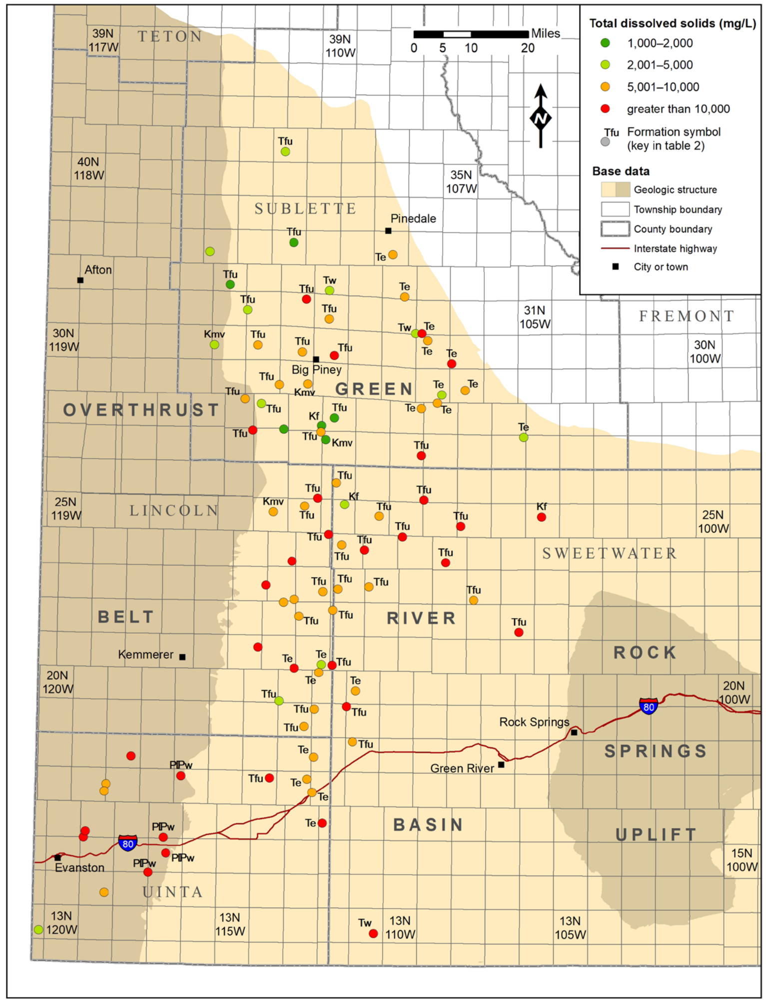

Figure 5. Saline waters in the 4,000–5,000-ft depth interval in the Green River Basin and Overthrust Belt.

Table 7. Summary statistics for all stratigraphic units in the Green River Basin and Overthrust Belt with qualified saline well sites (see methods section of this report for selection criteria) in the 4,000–5,000-ft depth interval.

Geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Eocene rocks, undivided	Eocene	19	4,230	11,103	40,362	16
Wasatch Formation	Eocene	3	3,309	9,054	19,010	1
Fort Union Formation	Paleocene	42	1,172	9,595	41,980	35
Mesaverde Group	Cretaceous	4	1,739	5,108	8,297	2
Frontier Formation	Cretaceous	3	1,643	8,180	19,825	1
Weber Sandstone	Pennsylvanian	4	14,139	15,627	16,948	4
Unspecified units	Unspecified	14	1,329	10,048	22,469	11

Salinity at 5,000–6,000 ft bgs

The principal spatial and statistical patterns observed in the previous interval continue in this depth range. Industrial-grade (TDS>5,000 mg/L) saline groundwaters constitute about 80 percent of all waters and appear throughout the Green River Basin and Overthrust Belt (fig. 6). Slightly and moderately saline wells are still limited, largely, to southwestern Sublette County. Most saline waters in this depth interval still occur in Tertiary units (table 8) excepting a few Cretaceous sites in southern Sublette County.

The total number of qualified saline wells decreases to 73 from 89 in the previous interval because fewer wells are being drilled to this depth (table 3). Groundwater salinity levels are rising along with increasing depths; the number of Class IVB (TDS>10,000 mg/L) wells exceeds the number of Class IVA (TDS 5,001–10,000 mg/L) wells for the first time. The number of Green River Basin wells without geologic markers continues to increase (table 8).

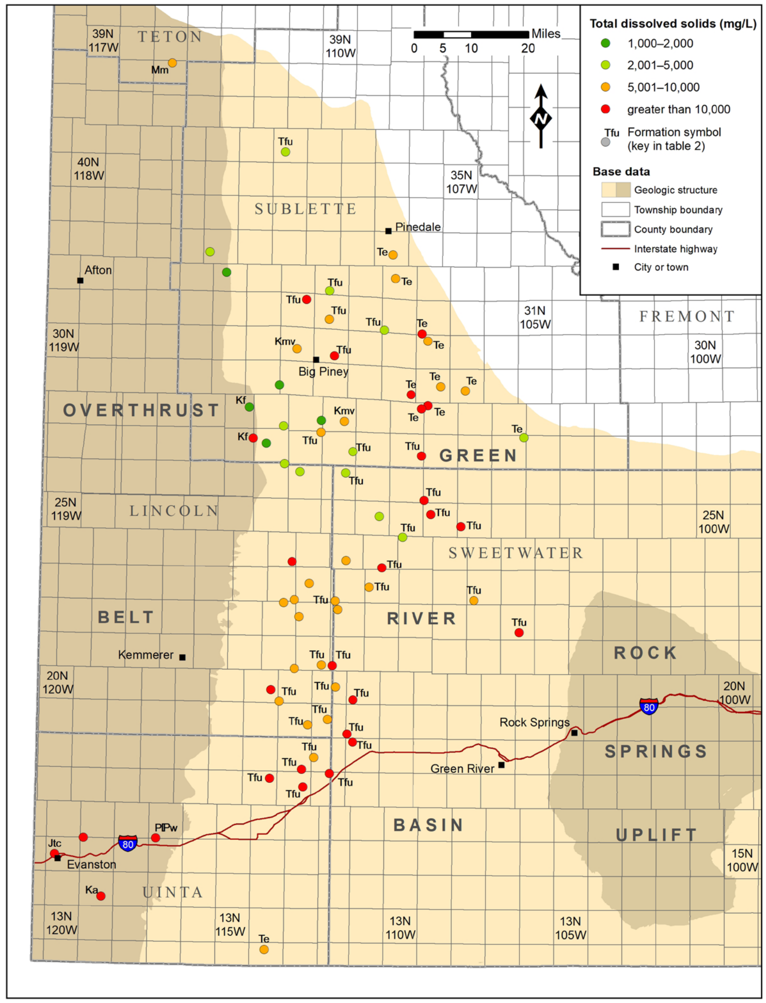

Figure 6. Saline waters in the 5,000–6,000-ft depth interval in the Green River Basin and Overthrust Belt.

Table 8. Summary statistics for all stratigraphic units in the Green River Basin and Overthrust Belt with qualified saline well sites (see methods section of this report for selection criteria) in the 5,000–6,000-ft depth interval.

Geologic unit	Geologic age	Count	TDS (mg/L) Minimum	TDS (mg/L) Mean	TDS (mg/L) Maximum	Count TDS>5,000 mg/L
Eocene rocks, undivided	Eocene	12	4,184	11,193	36,625	11
Fort Union Formation	Paleocene	34	2,435	11,603	33,348	28
Mesaverde Group	Cretaceous	2	5,147	6,583	8,019	2
Frontier Formation	Cretaceous	2	1,468	6,060	10,652	1
Aspen Shale	Cretaceous	1	28,887	28,887	28,887	1
Twin Creek Limestone	Jurassic	1	15,219	15,219	15,219	1
Weber Sandstone	Pennsylvanian	1	19,051	19,051	19,051	1
Madison Limestone	Mississippian	1	5,605	5,605	5,605	1
Unspecified units	Unspecified	19	1,256	6,296	14,665	12

Salinity at 6,000–7,000 ft bgs

The total number of saline wells examined in this interval has decreased to 67; however, the frequency of industrial-grade wells remains about 80 percent (table 3). Most of the saline waters shown still occur in Tertiary units (table 9), although a few saline waters in this interval appear to be sourced from Upper Cretaceous units such as the Frontier (Kf), Mesaverde (Kmv), and Lewis Shale (Kl).

A small number of Class IVB (TDS>10,000 mg/L) wells cluster near Evanston (fig. 7). The small cluster of slightly and moderately saline waters persists in southwestern Sublette County.

The cluster of industrial-grade wells that extends along the western boundary of Sweetwater County has narrowed toward the east as the number of saline wells in eastern Lincoln County has been reduced to six compared to 12 in the previous interval. This reduction occurs because some wells in this area penetrate into the underlying Cretaceous Hilliard Shale (WOGCC, 2020). The Static Spontaneous Potential (SSP) Method used in this study estimates groundwater salinity only for sandstone strata but not for shales (Schlumberger Well Services, 1989; Schnoebelen and others, 1995).

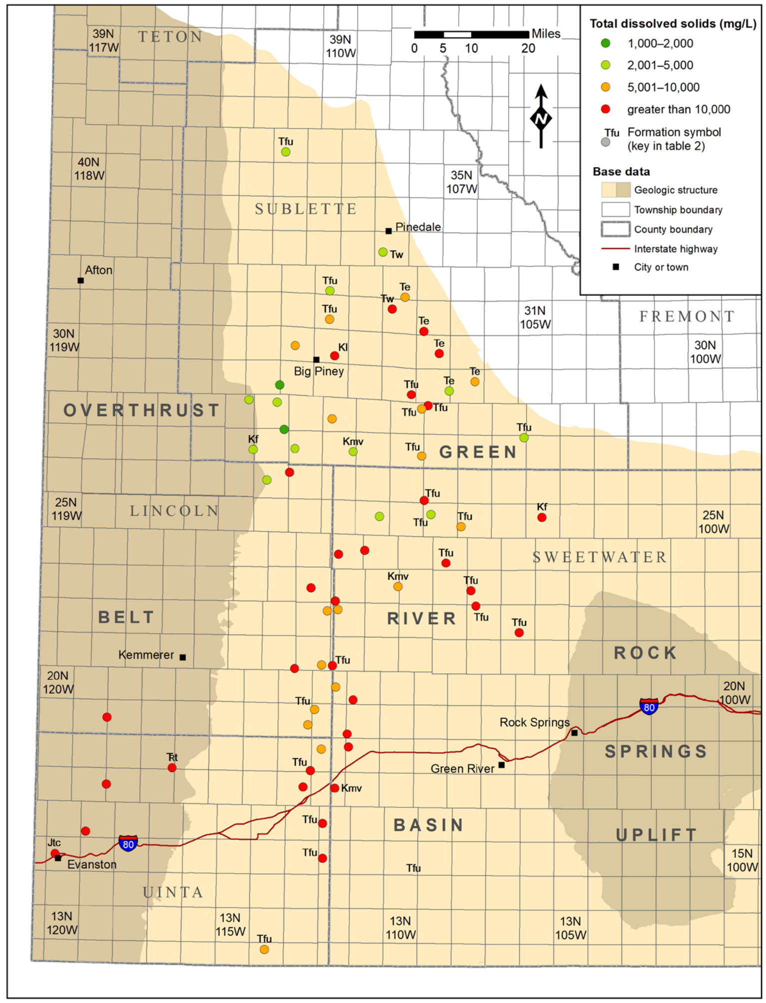

Figure 7. Saline waters in the 6,000–7,000-ft depth interval in the Green River Basin and Overthrust Belt.

Table 9. Summary statistics for all stratigraphic units in the Green River Basin and Overthrust Belt with qualified saline well sites (see methods section of this report for selection criteria) in the 6,000–7,000-ft depth interval.

Geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Eocene rocks, undivided	Eocene	5	2,884	10,281	21,892	4
Wasatch Formation	Eocene	2	2,840	9,814	16,787	1
Fort Union Formation	Paleocene	22	2,297	13,440	32,608	18
Lance Formation	Cretaceous	2	11,417	27,938	44,459	2
Mesaverde Group	Cretaceous	3	3,451	8,222	13,472	2
Frontier Formation	Cretaceous	2	3,550	12,150	20,749	1
Twin Creek Limestone	Jurassic	2	29,826	36,058	42,289	2
Thaynes Limestone	Triassic	1	26,390	26,390	26,390	1
Unspecified unit	Unspecified	28	1,318	10,058	24,270	21

Discussion for Wells in the Green River Basin and Overthrust Belt

Figure 8 illustrates the statistical trends associated with the occurrence of saline groundwater in the Green River Basin and Overthrust Belt.

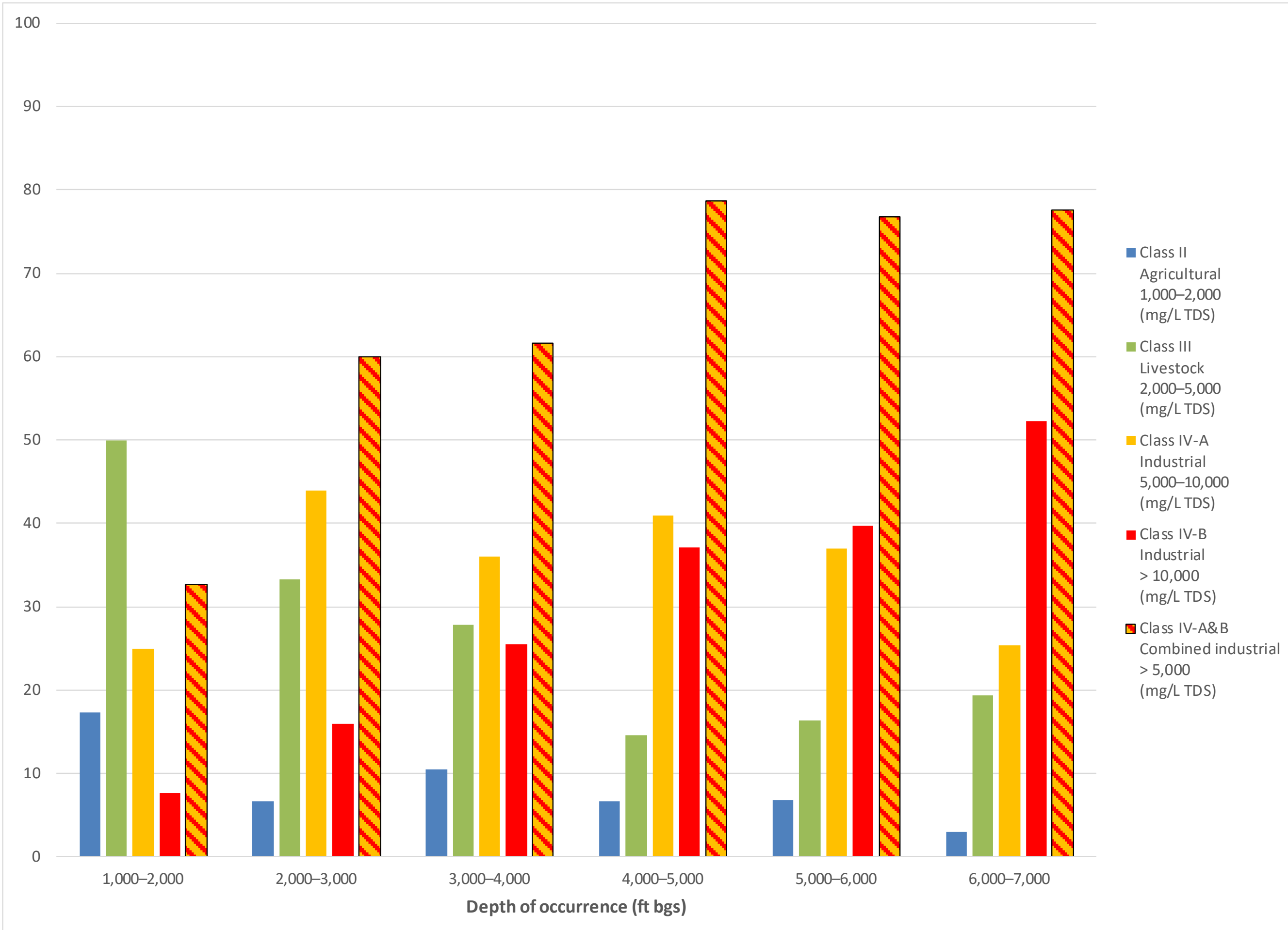

Figure 8. Prevalence of saline groundwater by depth interval found in the Green River Basin and Overthrust Belt.

Tables 3-9 and figures 2-8 illustrate the following important points:

- In each of the first four-depth intervals, the incidence of industrial-grade (TDS>5,000 mg/L) groundwaters increases substantially with a concurrent decrease in the occurrence of Classes II and III waters (TDS<5,000 mg/L). This is consistent with the general observation that groundwater salinity increases with depth-of-burial in sedimentary basins in North America (Kharaka and Hanor, 2003) and Wyoming (Taboga and Stafford, 2020).

- The prevalence of industrial-grade groundwaters remains relatively steady at nearly 80 percent in the three deepest intervals. Although, this appears to run counter to the previous observation and mean salinity levels for these intervals increase with depth of burial (table 3). Furthermore, the occurrence of Class IV-B waters (TDS>10,000 mg/L) increases in each subsequent interval between 4,000–7,000 ft at the expense of less saline industrial-grade Class IV-A waters (5,000<TDS≤10,000 mg/L; fig. 8).

- Industrial-grade waters (TDS>5,000 mg/L) occur most frequently at all depth intervals in the oil fields of the southern Overthrust Belt, and in Green River Basin natural gas wells at depths greater than 4,000 feet particularly along the western boundary of Sweetwater County, and in south-central Sublette County.

- Slightly and moderately saline waters (TDS<5,000 mg/L) are found at every depth interval examined (figs. 2–7); however, they occur most frequently in an area that extends from southwestern Sublette County to the far northwestern corner of Sweetwater County. This area is downgradient of prolific recharge zones located along the northern perimeter of the Green River Basin in western Sublette County. These zones provide up to 2.5 inches of annual recharge to exposures of the Wasatch Formation (Martin, 1996; Clarey and others, 2010 p. 5-55), which then flows predominately to the southeast (Martin, 1996; Clarey and others, 2010 p. 5-51).

- In the Green River Basin, industrial-grade waters are observed most often in the most frequently encountered geologic units, which are the lower Tertiary Fort Union and Wasatch formations, and in undifferentiated Eocene rocks. These lower Tertiary geologic units are more than 7,000 ft thick in much of the Green River Basin (Clarey and others, 2010). Cretaceous formations are most frequently encountered along basin margins at depths exceeding 4,000 ft.

Great Divide and Washakie Basins, and Rock Springs Uplift

The qualified wells in this portion of the study area are more evenly distributed than in the Green River Basin and Overthrust Belt (fig. 1). The greatest number of wells are located in a wide band that extends along the border between Sweetwater and Carbon counties from the Colorado state line into southern Fremont County (Toner and others, 2018). Additionally, a large number of wells are located in natural gas fields on the western Rock Springs Uplift and the western perimeters of the Great Divide and Washakie basins. Although fields in these areas generally target natural gas reservoirs in Cretaceous formations (Toner and others, 2018), most of the groundwater salinity results are obtained from overlying Cenozoic units.

Table 10 provides summary statistics for saline waters in the Great Divide and Washakie basins, and on the Rock Springs Uplift by depth interval, and lists percentages of salinity grouped by WDEQ class of use (agricultural, livestock, and industrial).

Table 10. Summary table for salinity levels in the Washakie and Great Divide basins, and on the Rock Springs Uplift 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 occurences**	**Percent**				
1,000–2,000	1,320	6,357	58,769	75	5	57	23	15	38
2,000–3,000	1,174	8,226	98,380	109	5	57	17	21	38
3,000–4,000	1,021	9,768	67,566	121	4	40	29	27	56
4,000–5,000	1,121	13,211	114,526	116	3	33	23	41	64
5,000–6,000	1,343	12,208	97,249	101	3	35	20	42	62
6,000–7,000	2,110	16,198	169,944	94	0	20	28	46	74

Salinity at 1,000–2,000 ft bgs

There are 75 qualified wells in this interval. Numerous moderately saline waters (TDS 2,000–5,000 mg/L) are interspersed with industrial-grade waters (TDS>5,000 mg/L) throughout the Washakie and Great Divide basins, and on the Rock Springs Uplift. Industrial-grade waters occur most frequently in the southern Great Divide Basin north of Wamsutter, the central Washakie Basin, and on the Rock Springs Uplift. Widely scattered clusters of moderately saline groundwaters stretch from the far northern Rock Springs Uplift eastward into the western Great Divide Basin and across the northern Washakie Basin.

Most of the saline waters shown in the Washakie and Great Divide basins occur in undivided Eocene rocks (Te) and in the Wasatch Formation (Tw; table 11). A few moderately saline Mesaverde Group (Kmv) sites cluster on the north end of the Rock Springs Uplift (fig. 9).

Slightly and moderately saline wells (47) account for a little more than 60 percent of all wells (75) examined at this depth interval (table 10).

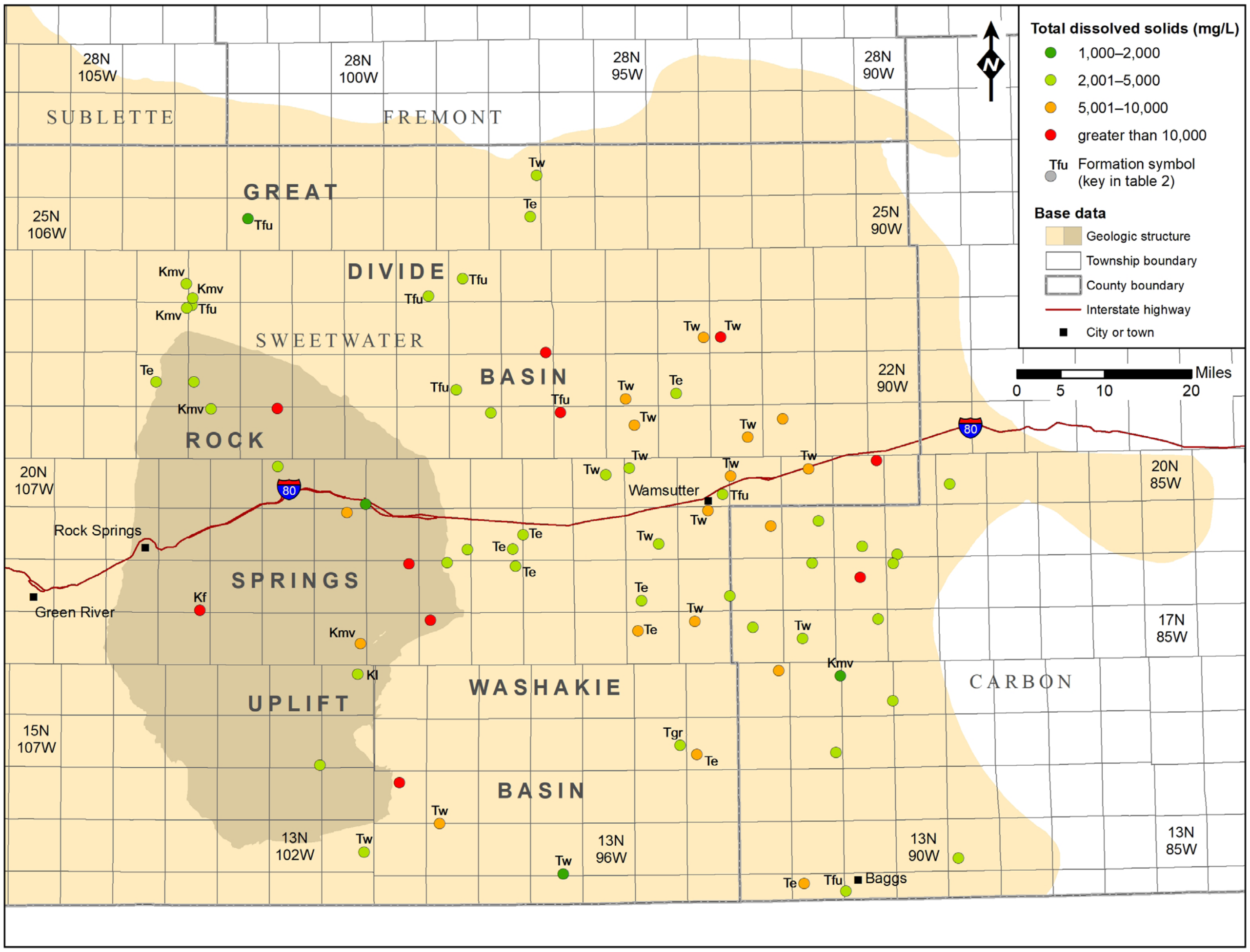

Figure 9. Saline waters in the 1,000–2,000-ft depth interval in the Washakie and Great Divide basins, and on the Rock Springs Uplift.

Table 11. Summary statistics for all stratigraphic units on the Rock Springs Uplift, and Washakie and Great Divide basins with qualified saline well sites (see methods section of this report for selection criteria) in the 1,000–2,000-ft depth interval.

Geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Eocene rocks, undivided	Eocene	10	2,433	4,863	8,458	3
Wasatch Formation	Eocene	17	1,320	4,971	10,611	10
Green River Formation	Eocene	1	2,241	2,241	2,241	0
Fort Union Formation	Paleocene	8	1,938	4,690	14,366	1
Lance Formation	Cretaceous	1	3,161	3,161	3,161	0
Mesaverde Group	Cretaceous	6	1,670	3,756	6,967	1
Frontier Formation	Cretaceous	2	25,259	42,014	58,769	2
Unspecified units	Unspecified	30	1,950	6,472	25,838	11

2,000–3,000 ft bgs

There are 109 qualifying wells at this depth interval distributed across the Washakie and Great Divide basins (table 10). A large cluster of moderately saline waters (TDS 2,000–5,000 mg/L) is located around Wamsutter. Industrial-grade (TDS>5,000 mg/L) waters appear most frequently in the Paleocene Fort Union Formation (Tfu) and various Eocene units (Tw, Tgr, and Te) in the southern Washakie Basin and central Great Divide Basin (fig. 10; table 12). This large group of wells is likely freshened by direct and streamflow recharge from upland areas in western Carbon County (Freethey and Cordy, 1991; Glover and others, 1998; Clarey and others, 2010 p. 5-62, 5-65, and 5-75).

A narrow band of industrial-grade waters extends northward along the western edge of the Rock Springs Uplift in the Cloverly (KJc), Frontier (Kf), and Mesaverde (Kmv) formations.

As in the previous interval, industrial-grade saline wells (TDS>5,000 mg/L) constitute about 40 percent of all wells examined (table 10).

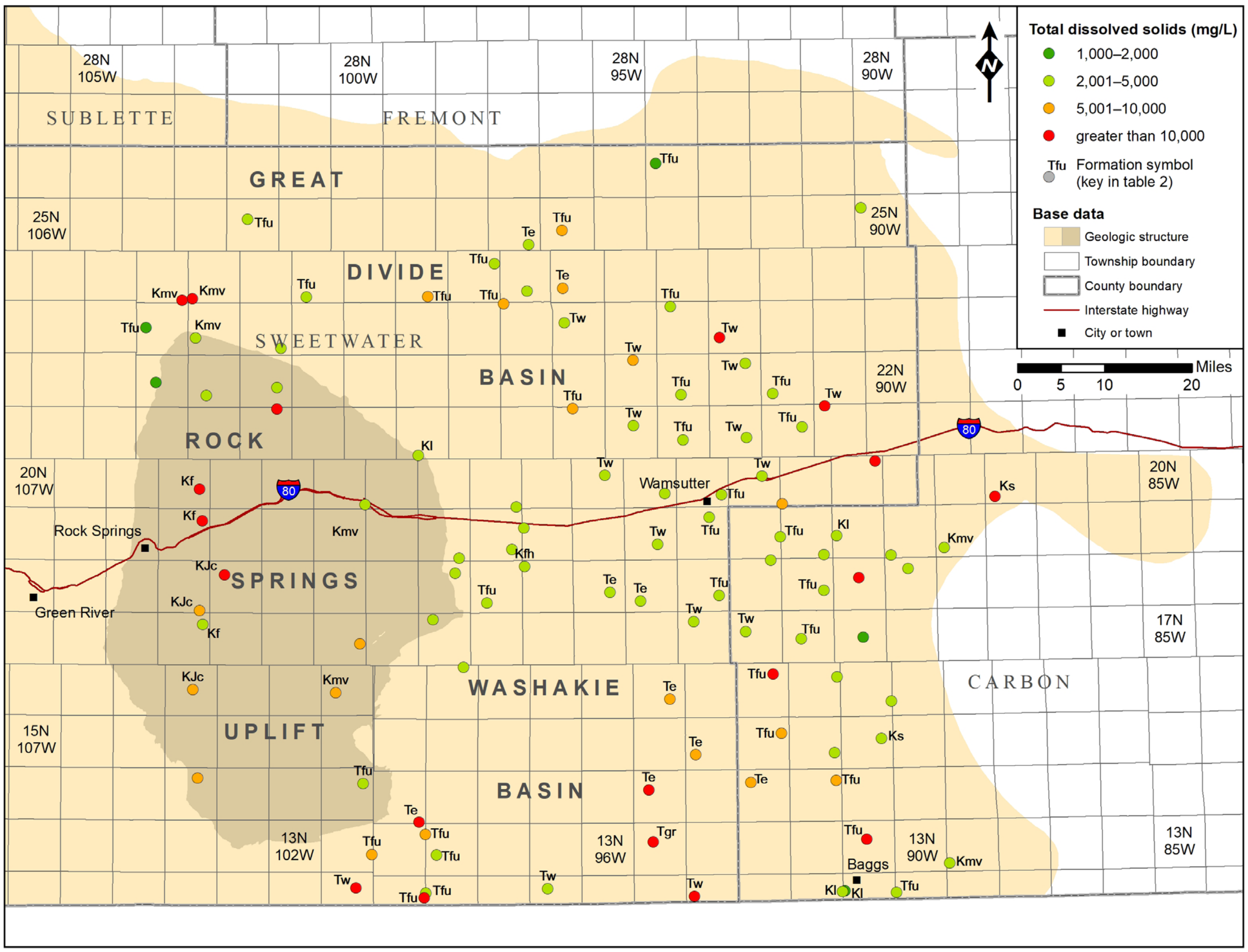

Figure 10. Saline waters in the 2,000–3,000-ft depth interval in the Washakie and Great Divide basins, and on the Rock Springs Uplift.

Table 12. Summary statistics for all stratigraphic units on the Rock Springs Uplift, and in the Washakie and Great Divide basins with qualified saline well sites (see methods section of this report for selection criteria) in the 2,000–3,000-ft depth interval.

Geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Eocene rocks, undivided	Eocene	9	2,407	7,317	18,421	6
Wasatch Formation	Eocene	15	2,053	7,060	25,111	5
Green River Formation	Eocene	1	17,775	17,775	17,775	1
Fort Union Formation	Paleocene	33	1,174	8,134	98,380	12
Lance Formation	Cretaceous	4	1,629	3,488	4,934	0
Fox Hills Sandstone	Cretaceous	2	3,228	19,483	35,738	1
Mesaverde Group	Cretaceous	7	2,020	14,282	48,046	4
Steele Shale	Cretaceous	2	4,230	8,006	11,781	1
Frontier Formation	Cretaceous	3	4,519	17,767	28,626	2
Cloverly Formation	Cretaceous	3	5,634	8,577	12,162	3
Unspecified units	Unspecified	30	1,790	6,358	37,604	7

3,000–4,000 ft bgs

Several spatial patterns first seen in the 2,000–3,000-ft interval continue here, although at these greater depths there are substantial increases in both the total number of qualified wells (121) and the proportion (56 percent) of industrial-grade wells (TDS>5,000 mg/L; table 10). Spatially, the sampled sites are well distributed across the Washakie and Great Divide basins, and Rock Springs Uplift (fig. 11). As in the previous interval, there is a wide cluster of moderately saline waters centered on Wamsutter. Most of these occur in basinward Tertiary units (table 13) located downgradient from upland recharge areas in western Carbon County and southern Fremont County (Glover and others, 1998). Moderate salinity is also seen in a few Cretaceous wells on the basin perimeter in western Carbon County adjacent to Mesozoic exposures that receive recharge from streamflow and direct precipitation (Freethey and Cordy, 1991).

Industrial-grade waters appear most frequently in the southern Washakie Basin, central Great Divide Basin, and on the Rock Springs Uplift. The highly variable salinity observed in Mesozoic units on and near the Rock Springs Uplift is driven by interactions between lithologic, structural, geochemical, groundwater flow (horizontal and vertical), and recharge controls (Freethey and Cordy, 1991).

4,000–5,000 ft bgs

At this depth range, industrial-grade wells constitute nearly two-thirds of all qualified wells, and the incidence of Class IV-B (TDS>10,000 mg/L) wells is now almost 20 percent higher than Class IV-A (TDS 5,001–10,000 mg/L) sites (table 10). The cluster of slightly saline wells around Wamsutter covers a smaller area than in the previous depth intervals while the number of industrial-grade water sites has increased elsewhere.

Figure 12 and table 14 show that nearly all interior basin samples are drawn from the Tertiary Fort Union (Tfu) and Wasatch (Tw) formations, and undivided Eocene rocks (Te). The Upper Cretaceous Mesaverde (Tmv), Lance (Tl), and Fox Hills (Tfh) formations provided the majority of saline samples along the basin margins. Samples were obtained from Cretaceous through Triassic units on the Rock Springs Uplift. Even at this deeper interval, it appears that groundwater salinity is driven, at least in part, by proximity to recharge zones (fig. 12). Basinward Cretaceous and Tertiary units located in proximity to each other share similar salinity characteristics.

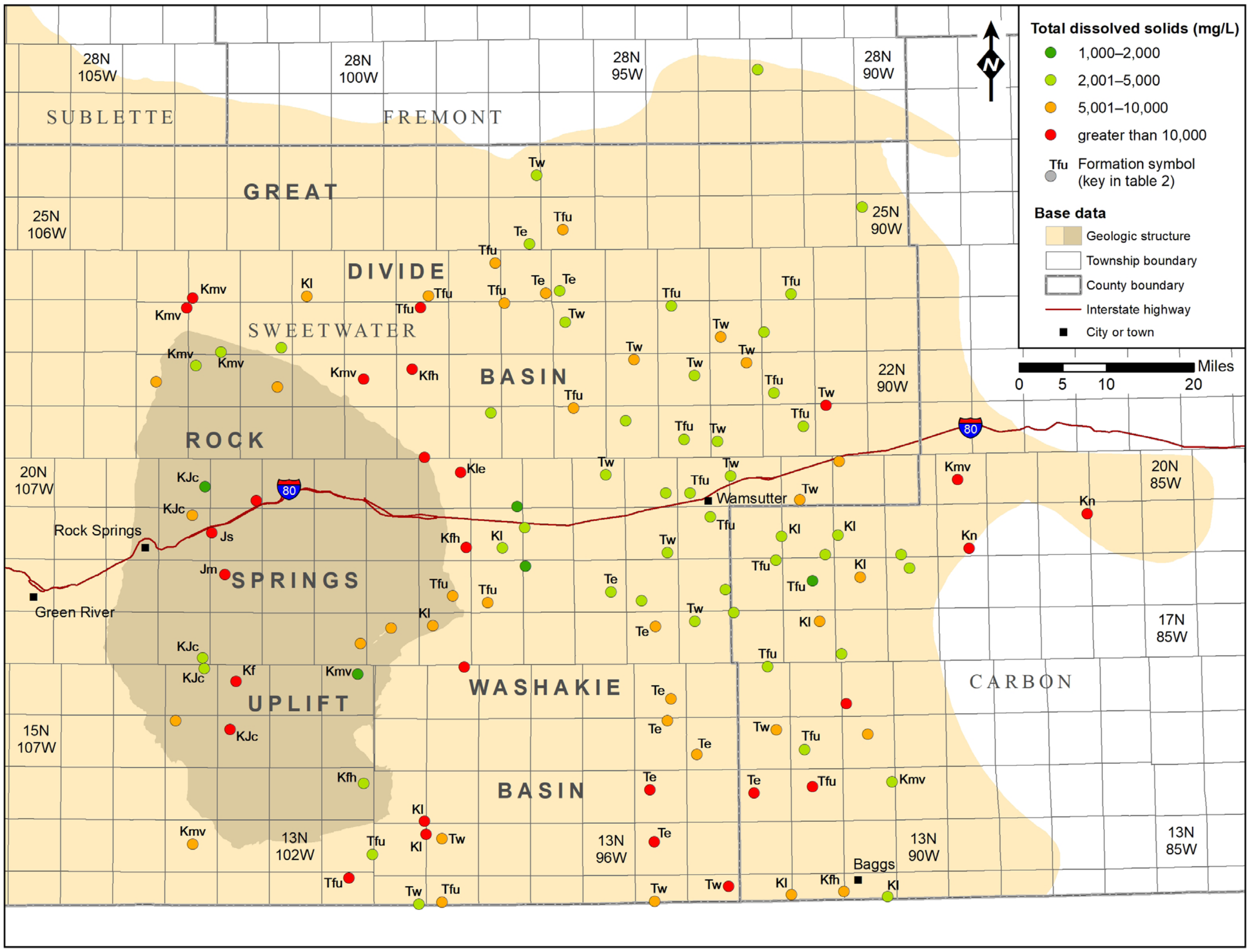

Figure 11. Saline waters in the 3,000–4,000-ft depth interval in the Washakie and Great Divide basins, and on the Rock Springs Uplift.

Table 13. Summary statistics for all stratigraphic units on the Rock Springs Uplift, and in the Washakie and Great Divide basins with qualified saline well sites (see methods section of this report for selection criteria) in the 3,000–4,000-ft depth interval.

Geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Eocene rocks, undivided	Eocene	11	4,527	11,298	29,778	8
Wasatch Formation	Eocene	19	3,274	7,566	33,661	10
Fort Union Formation	Paleocene	25	1,789	9,105	48,615	12
Lance Formation	Cretaceous	11	2,543	7,903	25,883	7
Fox Hills Sandstone	Cretaceous	4	3,535	8,432	14,961	3
Lewis Shale	Cretaceous	1	14,842	14,842	14,842	1
Mesaverde Group	Cretaceous	11	1,021	19,691	67,566	7
Niobrara Formation	Cretaceous	2	16,363	22,323	28,282	2
Frontier Formation	Cretaceous	1	26,570	26,570	26,570	1
Cloverly Formation	Cretaceous	6	1,274	10,210	36,132	3
Morrison Formation	Jurassic	1	10,811	10,811	10,811	1
Sundance Formation	Jurassic	1	15,870	15,870	15,870	1
Unspecified units	Unspecified	28	1,438	6,249	21,754	11

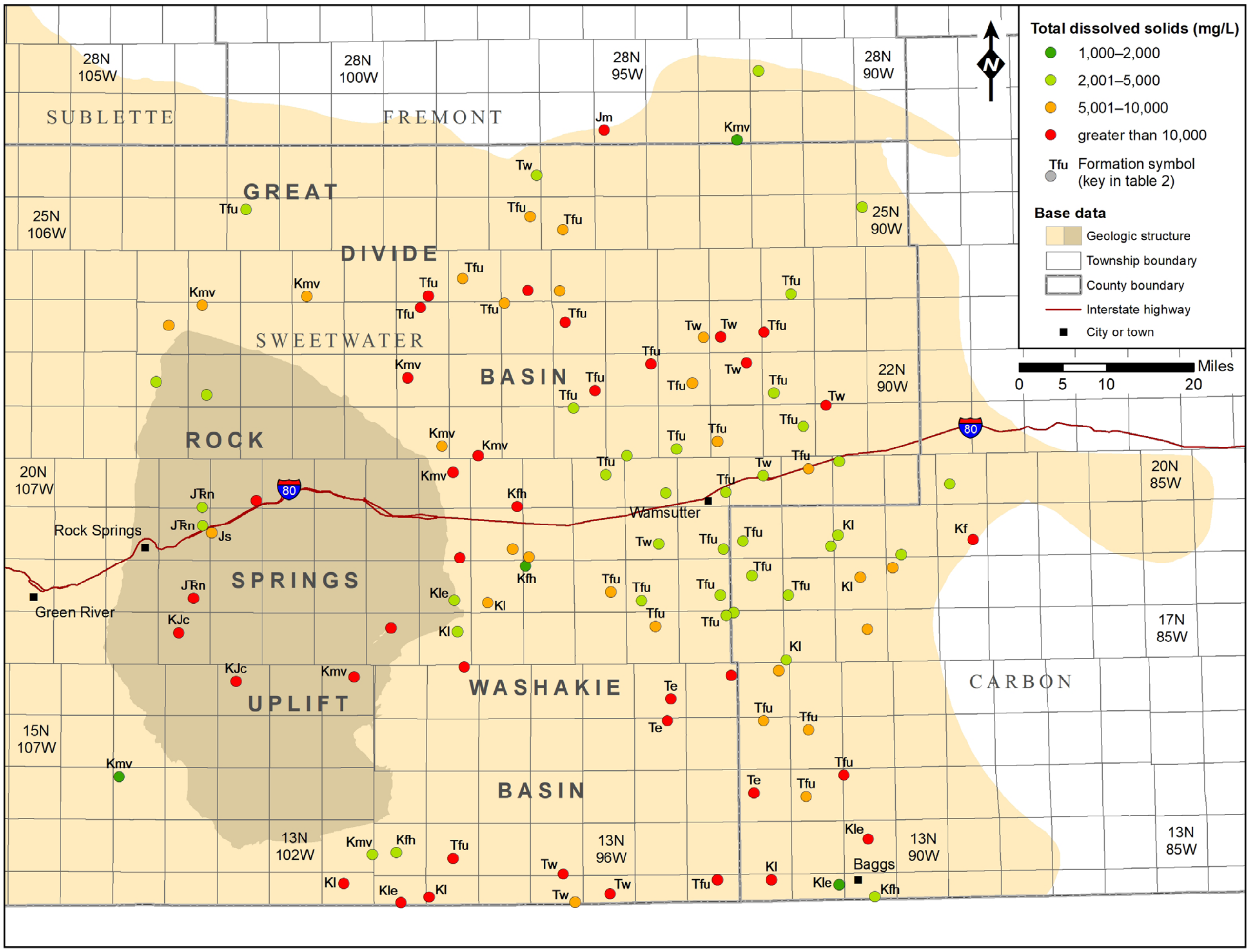

Figure 12. Saline waters in the 4,000–5,000-ft depth interval in the Washakie and Great Divide basins, and on the Rock Springs Uplift.

Table 14. Summary statistics for all stratigraphic units on the Rock Springs Uplift, and in the Washakie and Great Divide basins with qualified saline well sites (see methods section of this report for selection criteria) in the 4,000–5,000-ft depth interval.

Geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Eocene rocks, undivided	Eocene	4	11,871	19,282	34,137	4
Wasatch Formation	Eocene	12	2,364	19,361	86,265	9
Fort Union Formation	Paleocene	38	2,064	9,196	37,858	23
Lance Formation	Cretaceous	8	2,981	10,352	19,757	5
Fox Hills Sandstone	Cretaceous	5	1,436	14,220	43,086	2
Lewis Shale	Cretaceous	4	1,121	11,048	27,717	2
Mesaverde Group	Cretaceous	11	1,766	20,155	114,526	8
Frontier Formation	Cretaceous	2	28,819	47,104	65,388	2
Cloverly Formation	Cretaceous	3	27,476	42,215	71,543	3
Morrison Formation	Jurassic	1	10,887	10,887	10,887	1
Sundance Formation	Jurassic	1	9,286	9,286	9,286	1
Nugget Sandstone	Jurassic/Triassic	3	3,020	6,594	11,764	1
Unspecified units	Unspecified	24	2,207	8,040	24,800	13

5,000–6,000 ft bgs

Results for all salinity levels in this interval duplicate, within a few percentage points, the incidence of salinities in the 4,000–5,000-ft depth range (table 10). The incidence of industrial-grade waters (62 percent) is still nearly two-thirds of all qualifying well sites. The occurrence of Class IV-B (TDS>10,000 mg/L) sites (43 percent) increased slightly with a corresponding 20 percent decrease in the frequency of Class IV-A (TDS 5,000–10,000 mg/L) wells. The total number of qualified sample sites has decreased (table 10).

The spatial trends observed in the 4,000–5,000-ft depth range persist in this interval (fig. 13). The Fort Union Formation (Tfu) provided the greatest number of basinward samples, however, a substantial number of samples along the eastern margins of the Washakie Basin and Rock Springs Uplift were obtained from Upper Cretaceous Lance (Kl), Fox Hills (Kfh), Mesaverde (Kmv), and Frontier (Kf) formations (table 15). The sudden appearance of several slightly saline (2,000–5,000 mg/L) Cretaceous Mesaverde Formation (Kmv) wells that border the north-eastern Rock Springs Uplift may be the result of recharge to one of its massive sandstone members exposed on the flanks of the uplift.

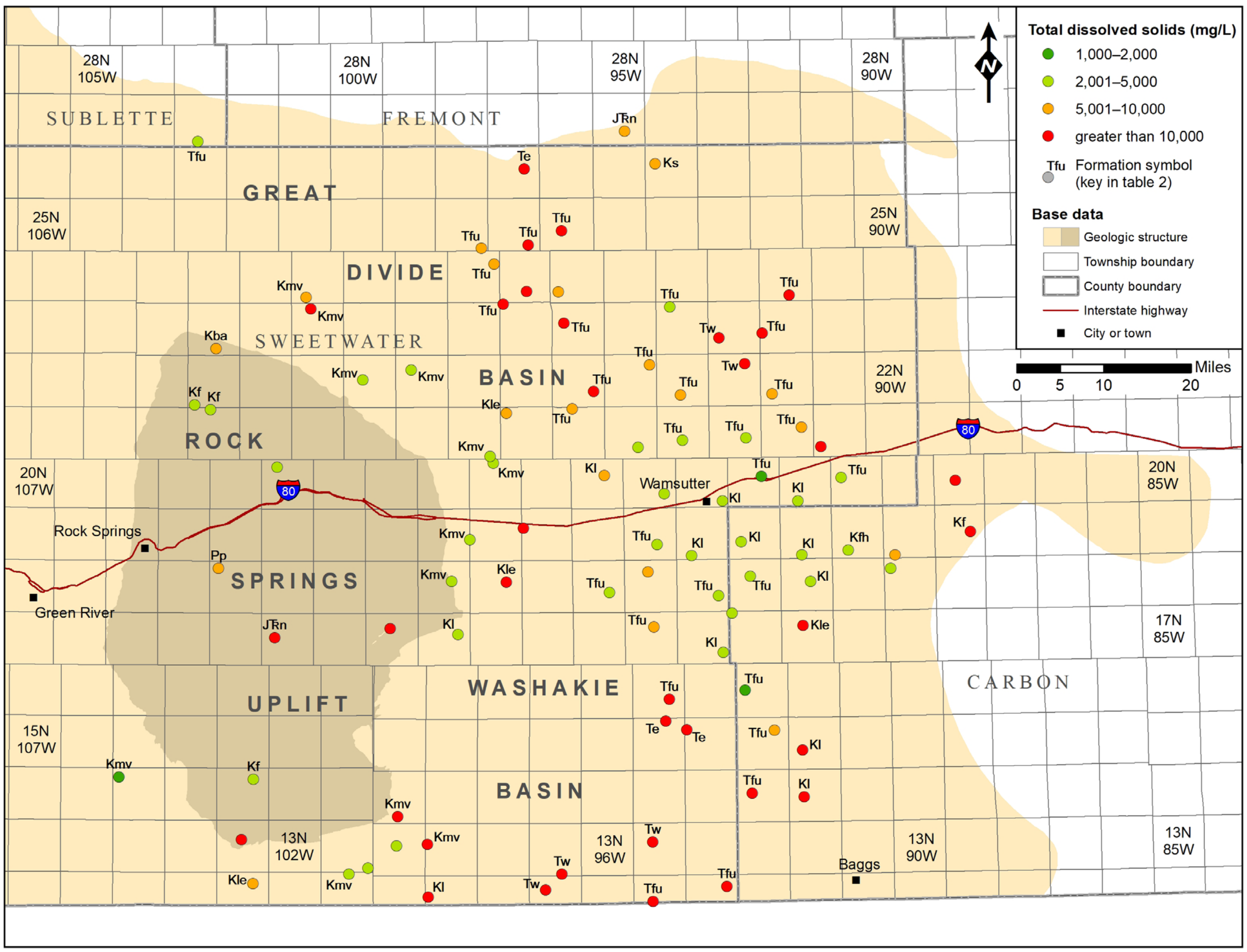

Figure 13. Saline waters in the 5,000–6,000-ft depth interval in the Washakie and Great Divide basins, and on the Rock Springs Uplift.

Table 15. Summary statistics for all stratigraphic units on the Rock Springs Uplift, and in the Washakie and Great Divide basins with qualified saline well sites (see methods section of this report for selection criteria) in the 5,000–6,000-ft depth interval.

Geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Eocene rocks, undivided	Eocene	3	11,114	17,132	22,779	3
Wasatch Formation	Eocene	5	10,326	15,140	22,584	5
Fort Union Formation	Paleocene	33	1,343	10,560	45,496	22
Lance Formation	Cretaceous	14	2,806	11,613	35,078	6
Fox Hills Sandstone	Cretaceous	1	3,219	3,219	3,219	0
Lewis Shale	Cretaceous	5	5,317	13,286	31,140	5
Mesaverde Group	Cretaceous	15	1,837	20,918	97,249	6
Steele Shale	Cretaceous	1	9,468	9,468	9,468	1
Baxter Shale	Cretaceous	1	5,910	5,910	5,910	1
Frontier Formation	Cretaceous	4	3,113	9,424	26,390	1
Nugget Sandstone	Jurassic/Triassic	2	8,789	9,547	10,304	2
Phosphoria Formation	Permian	1	7,045	7,045	7,045	1
Unspecified units	Unspecified	16	2,205	8,263	22,467	9

6,000–7,000 ft bgs

The incidence of industrial-grade waters has increased to almost 80 percent of all qualified wells sampled in this deepest interval with corresponding declines in the frequency of Class II (zero percent) and III (20 percent) groundwaters (table 10).

The spatial effects of the large increase in the occurrence of industrial-grade waters are readily observed in figure 14. Industrial-grade waters (TDS>5,000 mg/L) occur in nearly all of the sites examined in the Great Divide Basin and have replaced many of the moderately saline (TDS 2,000–5,000 mg/L) sites in the northern Washakie Basin around Wamsutter. At this depth interval, saline waters in the central Washakie and Great Divide basins occur most frequently in Upper Cretaceous units, particularly the Mesaverde (Kmv), Lance (Kl), and Lewis (Kle) formations (fig. 14, table 16). Saline waters occur in several different Mesozoic formations and in the Paleozoic Weber Formation (PIPw) and Madison Limestone (Mm) on the Rock Springs Uplift.

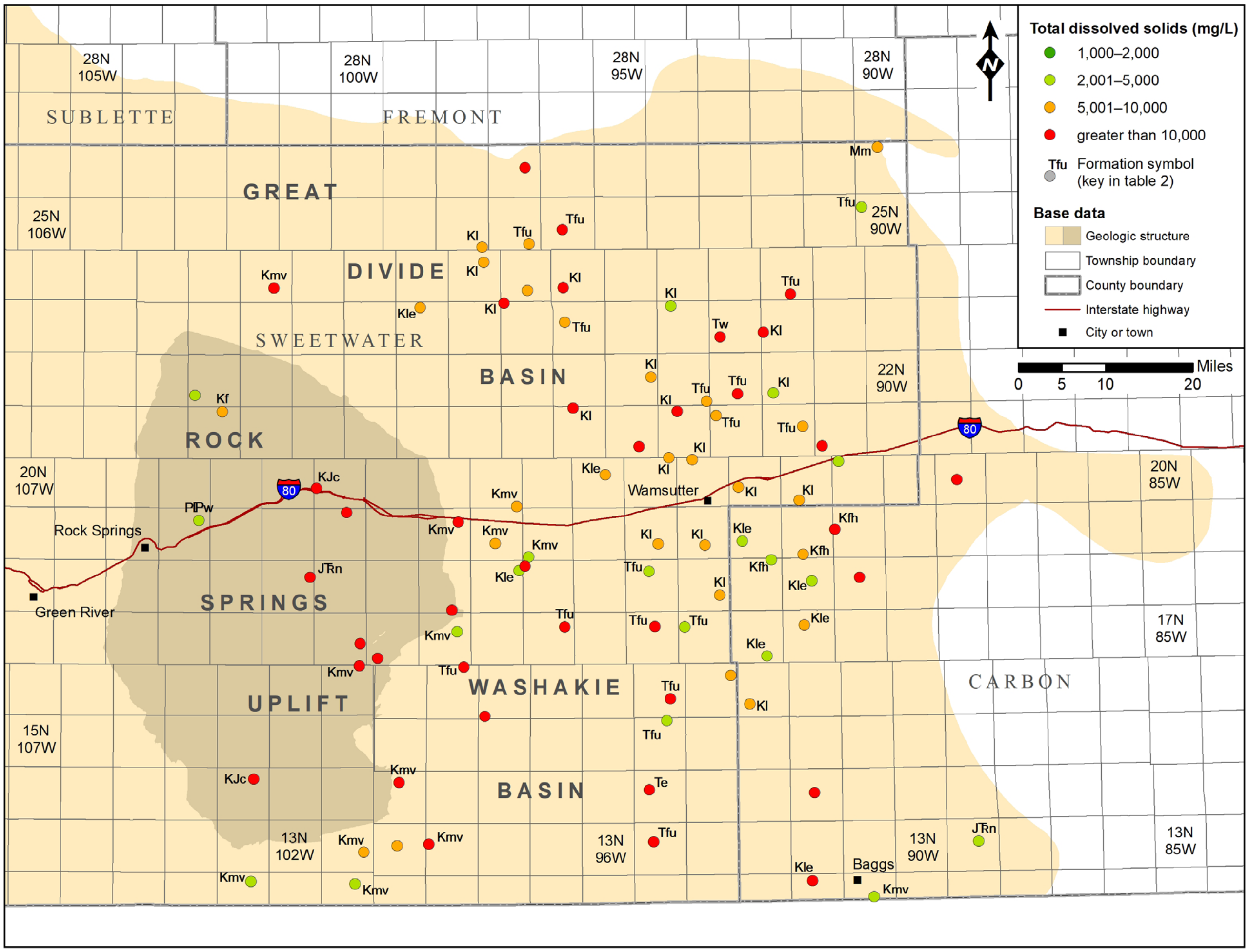

Figure 14. Saline waters in the 6,000–7,000-ft depth interval in the Washakie and Great Divide basins, and on the Rock Springs Uplift.

Table 16. Summary statistics for all stratigraphic units on the Rock Springs Uplift, and in the Washakie and Great Divide basins with qualified saline well sites (see methods section of this report for selection criteria) in the 6,000–7,000-ft depth interval.

Geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Eocene rocks, undivided	Eocene	1	29,767	29,767	29,767	1
Wasatch Formation	Eocene	2	15,769	42,255	68,741	2
Fort Union Formation	Paleocene	17	2,734	10,646	24,447	13
Lance Formation	Cretaceous	20	3,001	12,563	58,988	18
Fox Hills Sandstone	Cretaceous	3	3,115	6,506	10,314	2
Lewis Shale	Cretaceous	8	2,513	7,793	21,700	4
Mesaverde Group	Cretaceous	17	2,110	28,082	169,944	12
Frontier Formation	Cretaceous	2	8,483	34,326	60,169	2
Cloverly Formation	Cretaceous	2	12,824	17,480	22,135	2
Nugget Sandstone	Jurassic/Triassic	2	4,432	14,447	24,462	1
Weber Sandstone	Pennsylvanian	1	3,395	3,395	3,395	0
Madison Limestone	Mississippian	1	8,525	8,525	8,525	1
Unspecified units	Unspecified	16	6,549	7,004	7,271	16

Discussion for Wells in the Washakie and Great Divide Basins, and on the Rock Springs Uplift

Figure 15 illustrates the statistical trends associated with the occurrence of saline groundwater on the Rock Springs Uplift, and in the Washakie and Great Divide basins.

Tables 10–16 and figures 9–15 illustrate the following important points:

- In this part of the study area, the incidence of industrial-grade groundwater (TDS>5,000 mg/L) increases from 38 percent in the shallowest interval (1,000–2,000 ft) to 74 percent in the 6,000–7,000-ft interval (table 10). However, the increase in salinity with depth is not constant but varies between depth intervals (fig. 15). In the Washakie and Great Divide basins, this increase is typically associated with a concurrent decrease in the occurrence of Classes III waters (2,000<TDS<5,000 mg/L). There is a slight reversal of this trend in the 5,000–6,000-ft interval resulting from the appearance of several moderately saline Mesaverde (Kmv) wells on the eastern edge of the Rock Springs Uplift (fig. 13).

- Conversely, slightly and moderately saline waters (TDS<5,000 mg/L) constitute about 40–60 percent of groundwater at depths of less than 6,000 ft (fig. 15) due to the presence of a large and persistent cluster of lower TDS wells that is centered on Wamsutter (figs. 9–13). This area receives recharge from permeable upland Tertiary and Cretaceous exposures along the eastern perimeter of the Washakie Basin in southwestern Carbon County (Freethey and Cordy, 1991; Glover and others, 1998; Clarey and others, 2010). This freshening effect is still apparent but greatly diminished at the 6,000–7,000-ft interval, particularly north of Wamsutter (fig. 14).

- At depths of less than 6,000 ft, industrial-grade waters (TDS>5,000 mg/L) occur most consistently in wells sited on the Rock Springs Uplift and in areas of the Washakie and Great Divide basins located some distance away from Wamsutter (figs. 9–13). Industrial-grade waters are found throughout the study area in the 6,000–7,000-ft interval although with less frequency south of Interstate 80 in the northern Washakie Basin.

- In the Washakie and Great Divide basins, industrial-grade waters are observed most often in the most frequently encountered geologic units, which are the lower Tertiary Fort Union and Wasatch formations, and in undifferentiated Eocene rocks. Tertiary geologic units are up to 10,000 ft thick in the Great Divide and Washakie basins (Glover and others, 1998; Clarey and others, 2010). Cretaceous formations are most frequently encountered in these basins on the basin margins at depths exceeding 4,000 ft.

- In contrast, Cretaceous units are exposed on the greatest part of the heavily faulted Rock Springs Uplift (Love and Christiansen, 1985), and the magnitude of the uplift is large enough that Paleozoic units are less than 7,000 ft deep along its crest (Deng and others, 2013). This lithologic and structural heterogeneity likely accounts for the great variability in groundwater salinity seen at all depth intervals on the Rock Springs Uplift (figs. 9–14).

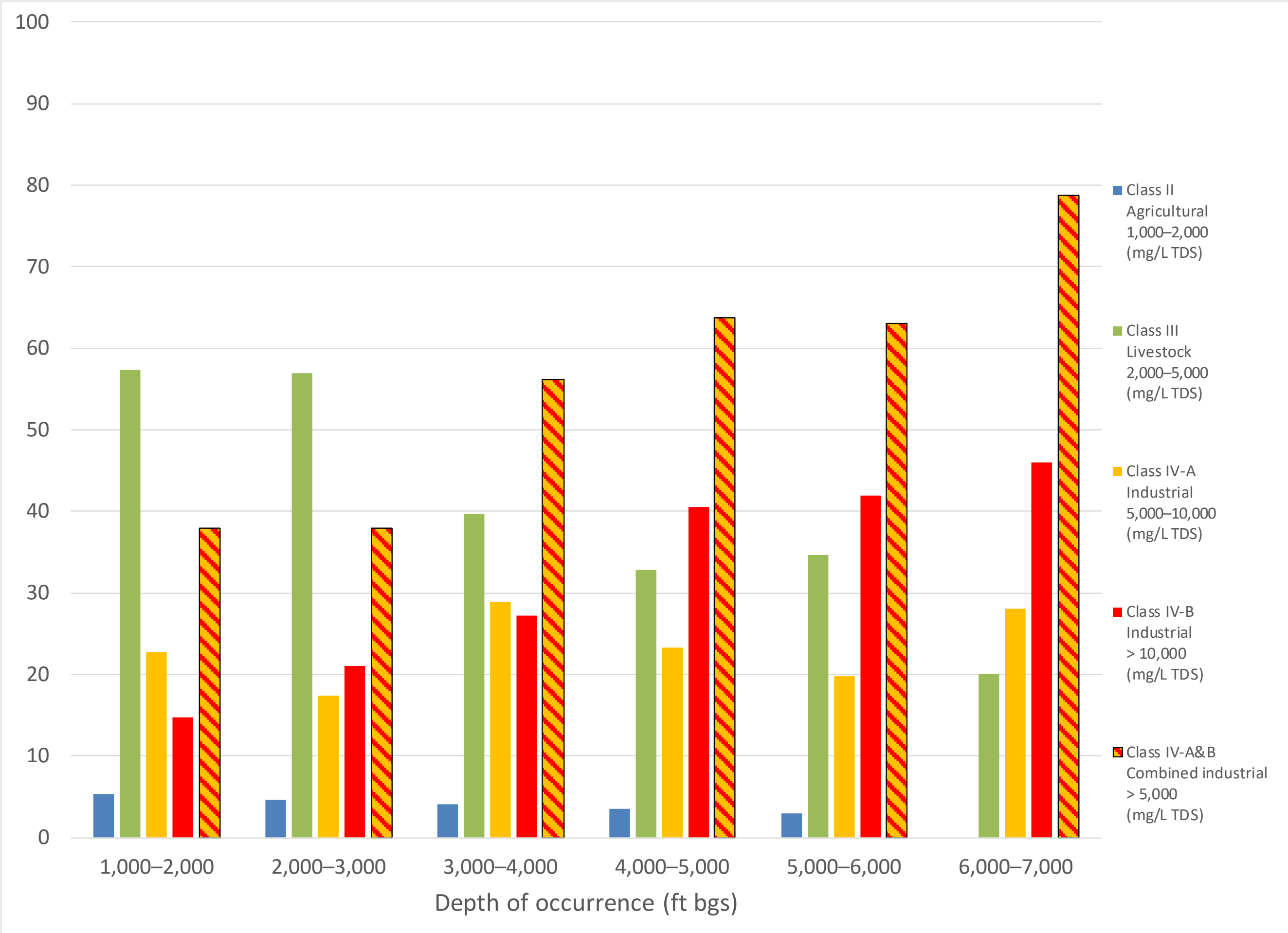

Figure 15. Prevalence of saline groundwater in the Washakie and Great Divide basins, and on the Rock Springs Uplift by depth interval.

First Encountered Saline Groundwater

Figures 16 and 17 show the depth intervals where industrial-grade saline groundwater (TDS>5,000 mg/L) is first encountered in the wells analyzed for this report. Figures 16 and 17 do not show wells that did not exhibit salinity levels below 5,000 mg/L.

Generally, industrial-grade groundwaters are first encountered at less than 3,000 ft bgs in the west central Green River Basin along the boundary between Sweetwater and Lincoln counties and in a small cluster of wells south of Pinedale (fig. 16). In contrast, industrial-grade waters are first observed at depths greater than 3,000 ft bgs in southern Sublette County and northwestern Sweetwater County.

The higher incidence of slightly saline groundwaters at all depth intervals in this latter case is likely due to the presence of vigorous recharge zones along the upper reaches of the Green River and its tributaries that overlay surface exposures of the Wasatch zone of the Wasatch-Fort Union aquifer system (Clarey and others, 2010). In the basin interior, reduced recharge inputs and the presence of saltwater facies in some Eocene rocks (Clarey and others, 2010, p. 5-41) likely account, at least in part, for the narrow band of shallower saline wells that extends along the eastern boundary of Lincoln County.

In comparison to the western GGRB (fig. 16), depths of first occurrence are highly variable in the central and eastern GGRB (fig. 17). First occurrences ranging from the shallowest (1,000–2,000 ft) to the deepest (6,000–7,000 ft) intervals are interspersed in a broad band that extends from the entire Rock Springs Uplift eastward along the I-80

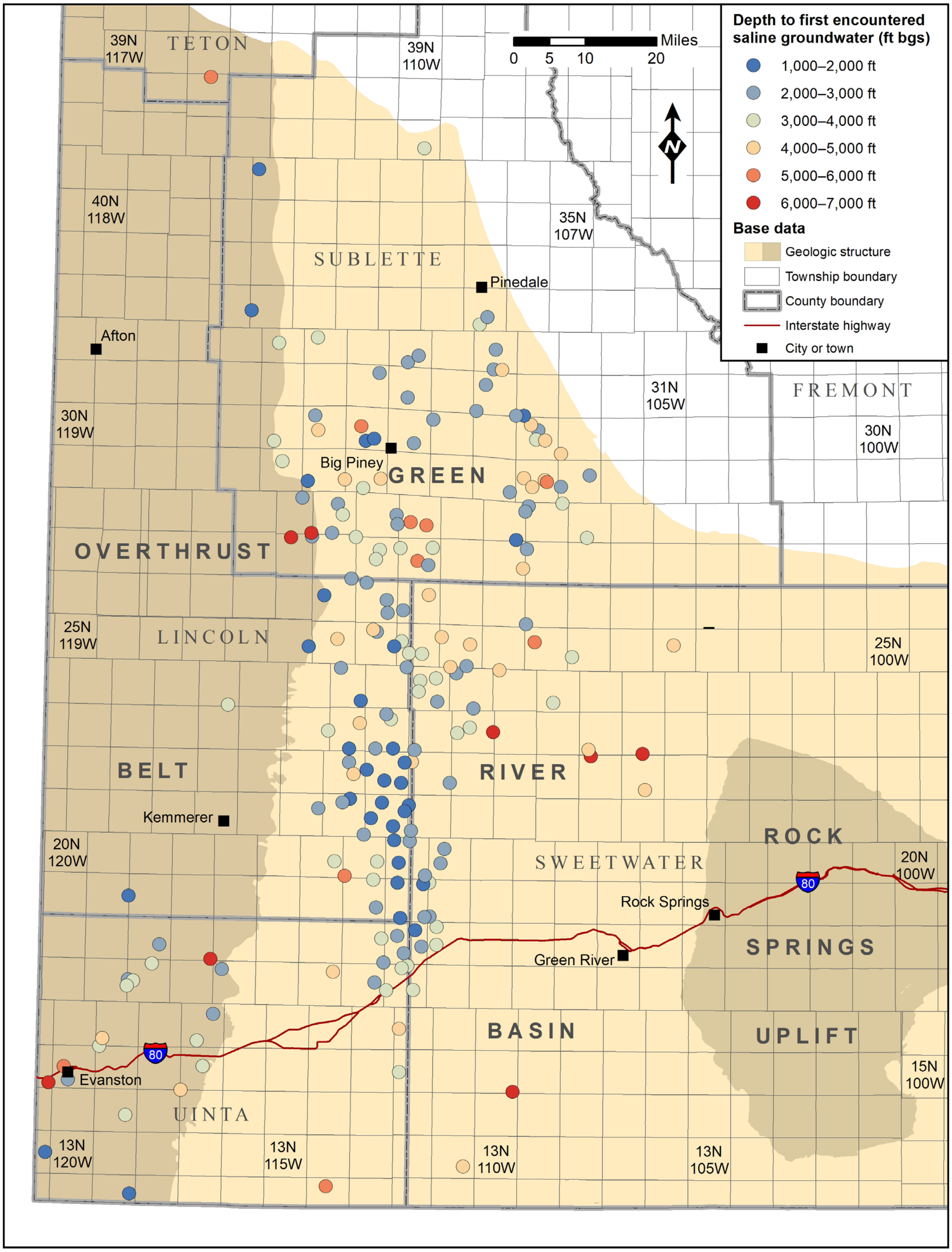

Figure 16. Depth to first industrial-grade (TDS>5,000 mg/L) groundwater in the Green River Basin and Overthrust Belt.

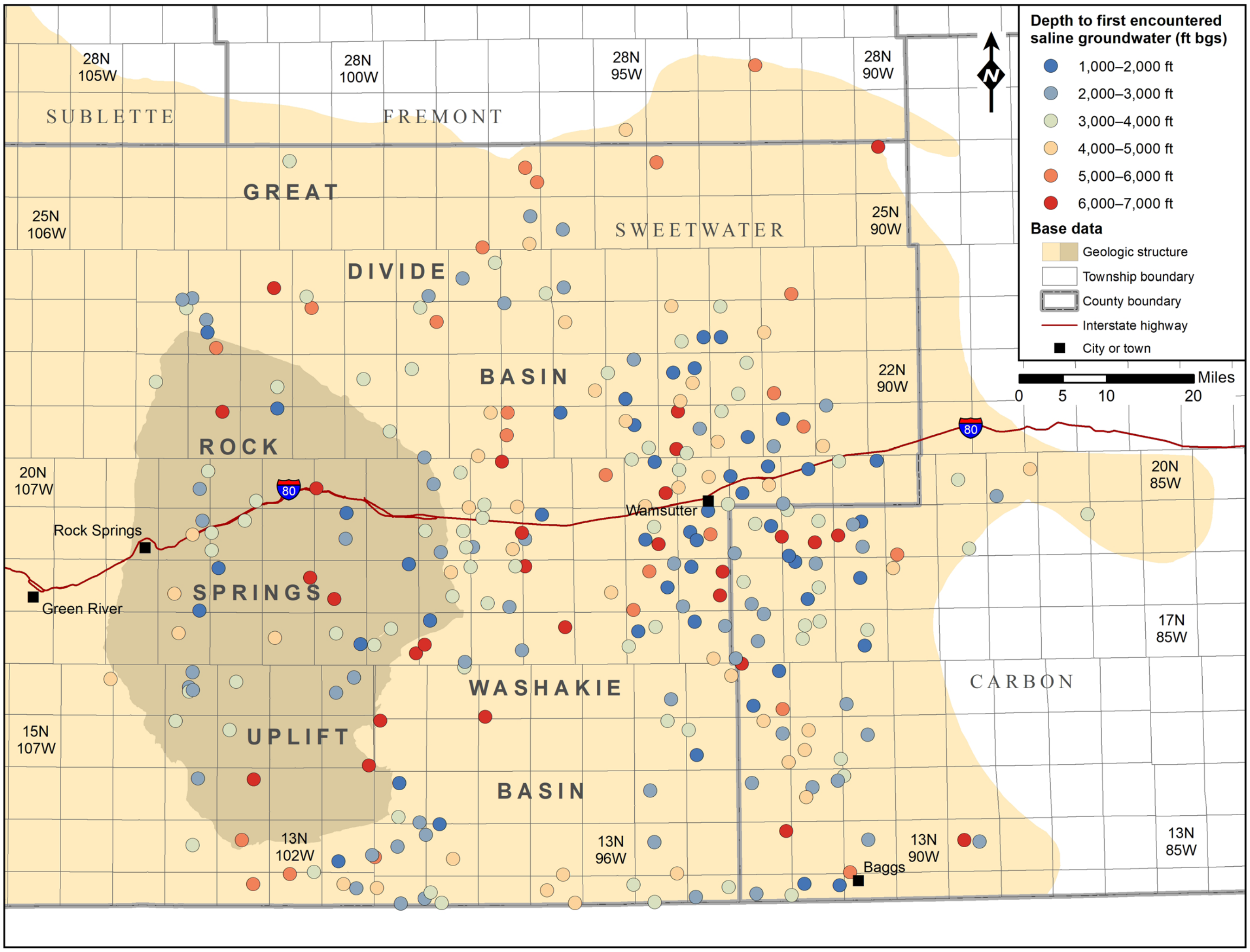

Figure 17. Depth to first industrial-grade (TDS>5,000 mg/L) groundwater in the Great Divide and Washakie basins, and on the Rock Springs Uplift.

corridor into northwestern Carbon County. The reasons for this high degree of variability are not known with any certainty and are likely complex; however, here are some geologic factors to consider:

Stratigraphic heterogeneity—Cretaceous formations are the most frequently targeted oil- and gas-producing units throughout the GGRB (Toner and others, 2018); however, the overlying Tertiary formations are generally thicker in the Green River Basin than in the Washakie and Great Divide basins (Clarey and others, 2010, p. 5-93). Mesozoic and Paleozoic rocks are nearer to the surface in the Washakie and Great Divide basins and therefore encountered more often within the 1,000–7,000-ft depth interval. This wider range of stratigraphic units (Paleozoic through Tertiary) penetrated by qualified wells on the eastern side of the GGRB likely accounts, in part, for the weaker relationship between location and depth to first saline groundwater there.

Location and proximity of recharge zones and groundwater flow—Clarey and others (2010, p. 5-38–5-93) used more than 50 figures modified from extensive USGS hydrogeologic studies (Freethey and others, 1988; Freethey and Cordy, 1991; Martin, 1996; Glover and others, 1998) to define the major aquifers and their recharge zones in the GGRB. In summary, these figures show that recharge and groundwater flow in the Tertiary and Mesozoic formations of the Washakie and Great Divide basins are more complex than in the western GGRB. Glover and others (1998) noted that sufficient data are not available to map recharge areas in the Washakie and Great Divide basins. They observed that highland areas to the north of the Great Divide Basin, Rock Springs Uplift, and Sierra Madre Range have the enhanced precipitation, snowpack, and permeable bedrock exposures required to serve as recharge zones. The somewhat greater depths of first occurrence in some qualified wells sited on the basin margins (fig. 17) appear to support this premise.

Lastly, vertical groundwater flows within Mesozoic formations and between Mesozoic and Paleozoic formations (Clarey and others, 2010, p. 5-76) may contribute to the wide variability observed in depths-of-first-occurrence throughout the Washakie and Great Divide basins.

SUMMARY

The WSGS used spontaneous potential (SP) measurements from borehole geophysical logs and USGS water quality analyses from more than 2,200 qualified wells to estimate the geospatial distribution of groundwater salinity (TDS) in the Greater Green River Basin of southwestern Wyoming.

Industrial-grade groundwaters (TDS>5,000 mg/L) are most frequently encountered in geologic units that are more than 2,000 ft deep in the Green River Basin and Overthrust Belt (fig. 8). In the Washakie and Great Divide basins, and on the Rock Springs Uplift, industrial-grade groundwaters comprise more than 60 percent of groundwaters at depths greater than 4,000 ft (fig. 15). The incidence of industrial-grade waters (TDS>5,000 mg/L) increases with depth and occurs with the 70–80 percent frequency at depths greater than 4,000 ft in the Green River Basin and Overthrust Belt, and more than 6,000 ft in the Washakie and Great Divide basins, and on the Rock Springs Uplift.

The summary tables (tables 3–9, 10–15) for each 1,000-ft interval shows that the formation of occurrence does not substantially affect the occurrence of industrial-grade groundwater (TDS>5,000 mg/L). It is important to note that industrial-grade waters are observed most often in the most frequently encountered geologic formation. In the western part of the GGRB, Tertiary formations are the most frequently sampled units at all depth intervals (tables 3–8). Industrial-grade waters occur most often in Tertiary formations in the eastern portion of the study area to a depth of 6,000 ft (tables 11–15). In the 6,000–7,000-ft interval, many qualified wells penetrate Tertiary formations completely, and industrial-grade waters are found most often in Cretaceous formations (table 16).

The shallowest depths to first encountered industrial-grade groundwaters in the Greater Green River Basin are found around Wamsutter, on the Rock Springs Uplift, and on the border of Sweetwater and Lincoln counties (figs. 16 and 17). However, in many cases, shallow industrial-grade water sites are interspersed with deeper sites especially in the Washakie and Great Divide basins (fig. 17). The results strongly suggest that once-productive oil and gas wells can be repurposed as economic, low-risk sources of industrial-grade water following careful water quality and production evaluations.

DISCLAIMER

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 Greater Green River Basin. 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 GGRB may be developed as oil and gas exploration responds to market demand 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 Greater Green River Basin of southwestern 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 southwestern Wyoming can be found in technical memoranda contained in Wyoming Water Development river basin planning reports (States West Water Resources, 2001; Clarey and others, 2010; Taboga and others, 2014a, b), at (http://waterplan.state.wy.us/basins/basins.html and in USGS publications (https://pubs.er.usgs.gov/).

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