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Groundwater Salinity in the Denver-Julesburg Basin, Wyoming

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

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INTRODUCTION

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

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

This report examines the salinity of groundwaters that occur at depths of 5000 ft or less "below ground surface" (bgs) in the Denver-Julesburg structural basin (D-J Basin) of southeastern Wyoming. Special emphasis is placed on saline groundwaters (TDS ≥ 5000 mg/L) that may be suited to industrial uses thereby conserving higher quality waters for domestic, agricultural and livestock uses. Saline groundwaters are encountered most frequently during oil and gas exploration and production operations (Kharaka and others, 2003) in deep basin aquifers located more than 1,000 feet bgs. In contrast, due to costs, few deep wells are drilled by domestic, irrigation or livestock water users looking for good quality groundwaters which are generally found in shallow wells close to recharge areas located along basin margins and alluvial deposits (Taboga and others, 2014a, b).

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

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

1. Saline waters make up ~40 percent of all deep (>1000 ft. bgs) groundwaters in Wyoming (USGS, 2015a; WOGCC, 2015).

2. The presence of saline groundwaters provides information about the evolution of groundwater quality in the host aquifer and structural basin of occurrence.

3. Federal and state environmental regulatory agencies permit the disposal of wastewater produced from resource development (http://wogcc.state.wy.us/Injection) and other industrial operations (http://deq.wyoming.gov/wqd/UIC/) by injection into saline aquifers.

4. In Wyoming, saline aquifers may be located in proximity to aquifers targeted for in-situ recovery (ISR) of uranium, trona and potentially lithium (Taboga and others, 2015).

5. Since it commonly occurs in deeply buried formations, saline groundwater is frequently geothermal (http://www.wsgs.wyo.gov/Research/Energy/Geothermal.aspx).

6. Saline groundwaters are frequently (but not always) co-produced with hydrocarbons.

7. Geoscience research groups throughout the world are looking into the feasibility of sequestering carbon dioxide in deep saline aquifers (http://www.uwyo.edu/cmi/). Some of these technologies involve extracting saline waters to enhance carbon sequestration in the target aquifer.

8. In the future, Wyoming industries may choose to use saline waters, as fresh water resources become harder to access and demands for public use increase.

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

MEASURING TDS

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

Residue on evaporation method

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

Computational method

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

$$TDS = kEC$$

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

Accurate calculation of TDS by summation of the concentrations of constituents requires a complete chemical analysis that includes major ions, metals and, in some cases, organic chemicals. Summation may provide more accurate estimates than residue on evaporation analysis in water samples that have TDS concentrations above 1000 mg/L and contain significant levels of organics or acids, or yield hygroscopic (water retaining) crystals. Although summation can be the most accurate method, the multiple analyses required to determine concentrations of the major ions make it expensive and time consuming.

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

WATER QUALITY STANDARDS, GROUNDWATER CLASSIFICATION AND TDS LEVELS

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

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

WDEQ regulations (WDEQ, 2015) classify a groundwater's suitability for domestic, agricultural and livestock uses based on water quality standards for specified inorganic chemicals, radionuclides and physical characteristics. Maximum concentrations of total dissolved solids are 500 mg/L for domestic use (Class I), 2,000 mg/L for agricultural use (Class II), and 5,000 mg/L for livestock (Class III). Groundwaters deemed suitable for industrial uses are classified by TDS concentration as Class IV A (TDS not in excess of 10,000 mg/L) and Class IV B (TDS greater than 10,000 mg/L).

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

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

Table 1. USGS water salinity classification.

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

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

EVOLUTION OF GROUNDWATER WITH DEPTH IN SEDIMENTARY BASINS

Groundwater salinity generally increases along with the depth of burial of the host aquifer in a structural basin. The rates of increase differ greatly, however, within different parts of the same basin, among basins and among different hydrostratigraphic units in the same basin (Kharaka and others, 2003). Increasing salinity levels with depth result primarily from increases in sodium and chloride concentrations (fig. 1) likely derived from the dissolution of evaporitic materials contained in the host rock (Kharaka and others, 2003). In some cases, groundwater salinity levels may decrease with depth within a particular formation (Kharaka and others, 2003). Also, occasionally older underlying formations may have lower TDS concentrations than overlying, younger formations (table 2).

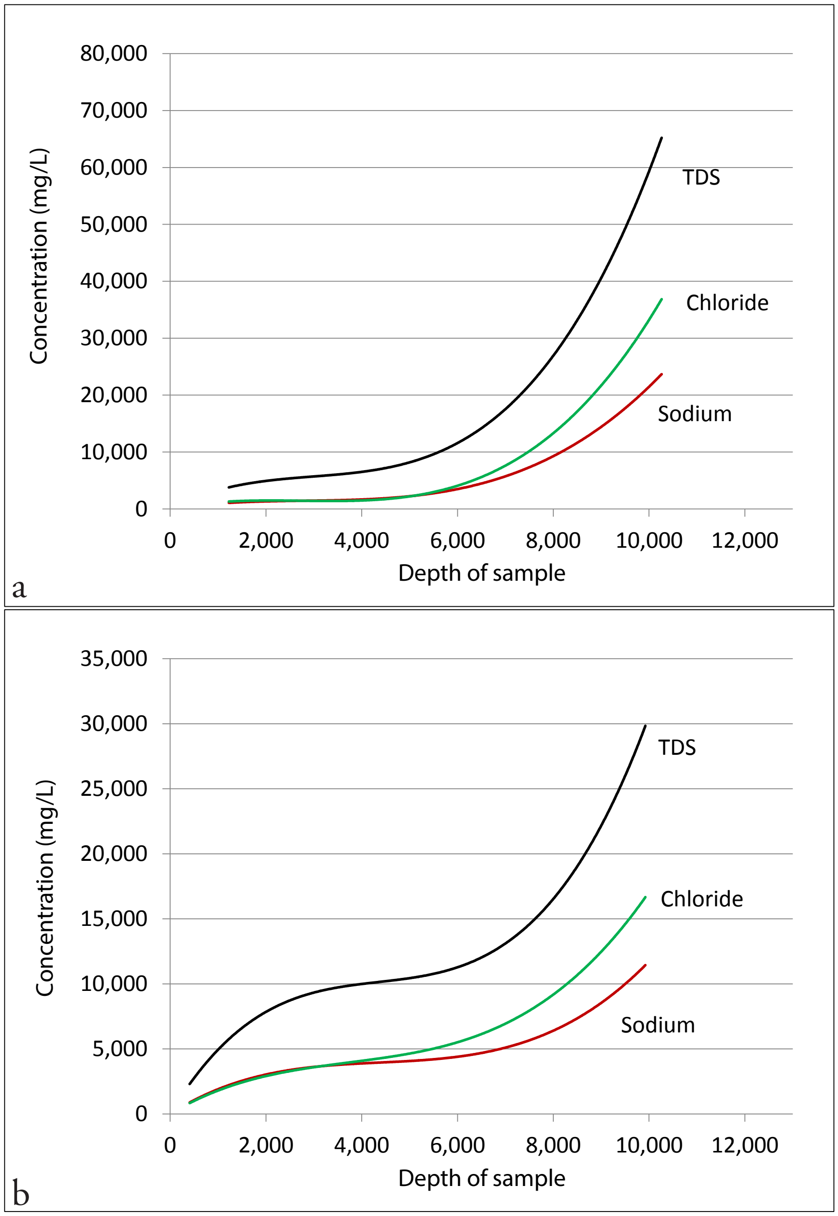

Figure 1. Trends in TDS, sodium and chloride levels with depth of sample in the a) Casper-Tensleep Formation of the Laramie Basin, and b) Newcastle Sandstone of the Powder River Basin, Wyoming.

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

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

[a] USGS, 2015

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

BENEFICIAL USES OF SALINE WATERS

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

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

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

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

[a] WOGCC, 2015

[b] PRISM, 2015

[c] WDAIEAD, 2014

Resource Development Uses

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

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

Industrial Uses

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

METHODS

WSGS estimated groundwater TDS levels from oil and gas well logs using the Static Spontaneous Potential (SSP) Method (Schnoebelen, 1995; Schlumberger Well Services, 1989). Initially, geophysical logs from 987 WOGCC D-J Basin wells were examined for: 1) legible spontaneous potential profiles, 2) borehole bottom temperatures, 3) mud filtrate resistivity data, 4) the use of drilling muds that did not contain saline or petroleum based compounds, and 5) a legible shale baseline. Subsequently, spontaneous potential data was manually extracted from logs for 234 wells that met the selection criteria. Because some well logs provide more than one data point over the length of the borehole, these analyses yielded 946 calculated TDS levels at varying depths up to 5,000 ft bgs.

WSGS also compiled over 35,000 records of Wyoming water quality data from the USGS PWD (USGS, 2015a), the USGS NWIS database (USGS, 2015b) and the WOGCC WADB (WOCGG, 2015). Water quality data was screened to identify and remove records that: 1) did not provide sample geospatial coordinates or depth of sample, 2) indicated that the sample was not a representative groundwater sample (injection water, commingled samples, reserve pit, backflow, etc.), 3) exhibited conflicting or questionable water quality analyses (ion balances exceeding 5 percent, pH values less than 4.5 units, and TDS values less than 100 mg/L). WSGS removed redundant records; in cases where multiple samples were drawn and analyzed from the same site, WSGS retained the sample with the single lowest TDS value. WSGS joined the PWD, NWIS and WADB data into a singular database from which it removed interagency duplicates (records shared by both agencies); there was considerable overlap of records from the two agencies since WOGCC provides produced water quality data to the USGS for incorporation into the Produced Water Database. The final WSGS Saline Water Database contains TDS data for over 11,000 sites statewide; more than 7,600 of these sites have TDS concentrations that exceed 5,000 mg/L. However, only 76 samples were obtained from D-J Basin wells and only fourteen of these were collected from depths of 5,000 ft or less.

The salinity data obtained from the above analyses were plotted into contours over 500 foot depth intervals in Arc GIS using a third power Inverse Distance Weighted (IDW) contouring model with a variable search radius of 20 neighboring wells. The contour maps were reviewed and logs from wells that exhibited anomalous results were examined to confirm that they met the designated selection criteria. This second evaluation which involved a thorough inspection of all well log data as well as field narratives resulted in the removal of 187 data points. In total, 709 TDS observations (695 estimates from the SSP Method and 14 USGS water quality analyses) were input into the IDW model to generate another set of contours. Finally, reasonable manual adjustments were made to this second set of contour maps to produce figures A-1–A-9.

RESULTS AND DISCUSSION

Results are presented in figure 2, table 4 and figures A-1–A-9 in the Appendix. Figure 2 shows the geospatial distribution of D-J Basin wells used in the TDS analyses. The majority of these sites are associated with oil and gas exploration. Table 4 provides summary statistics (minimum, mean and maximum TDS concentrations for 701 data points in nine 500 ft depth intervals from 500 to 5,000 ft. The 0-500 ft interval was represented by only four

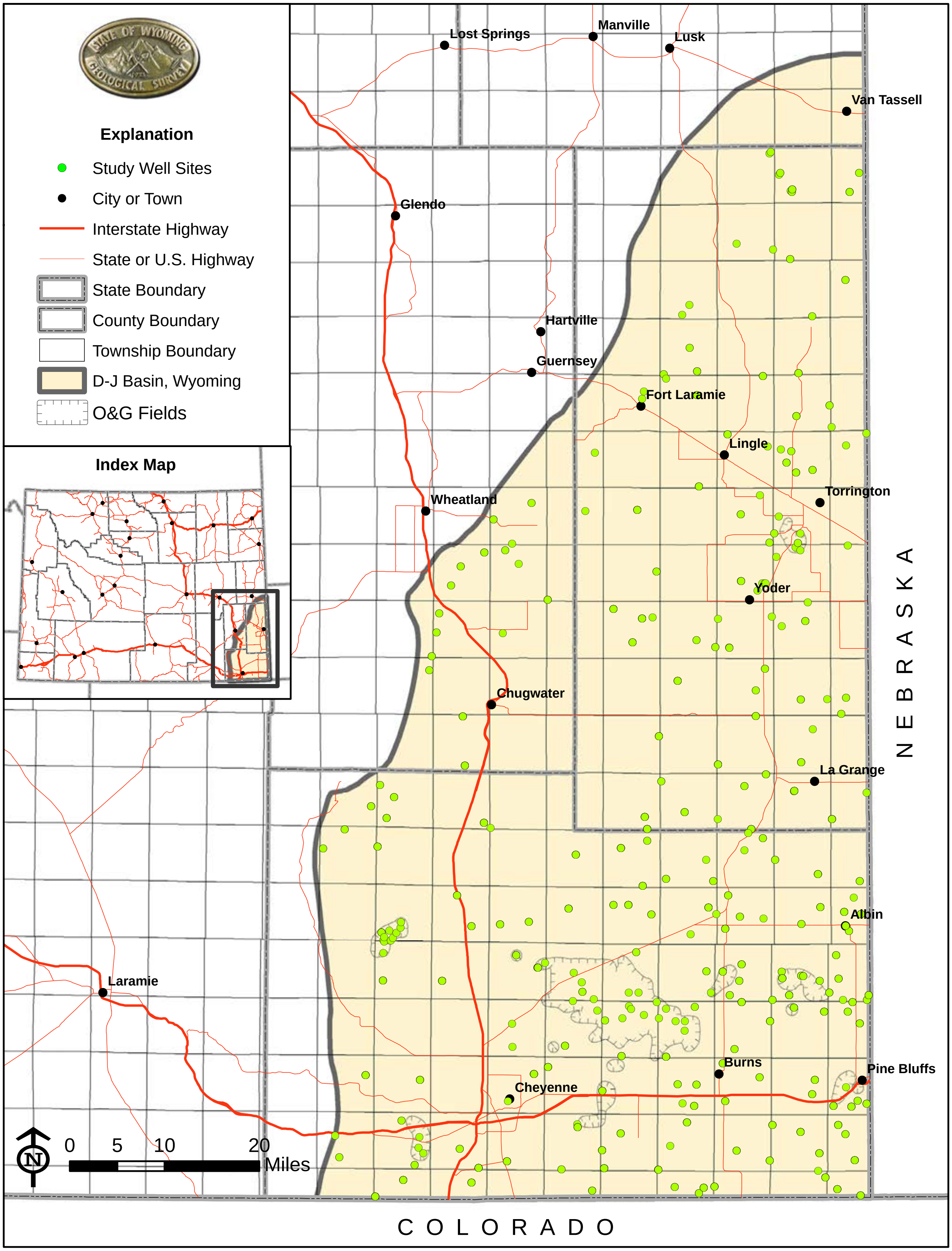

Figure 2. D-J Basin wells for all TDS concentrations.

data points and was not considered further; salinity data for shallow groundwater can be obtained from the USGS Water Resources website (http://www.usgs.gov/water/). The manner in which results are displayed on the contours are generally indicative of the method used to determine TDS levels. Salinities calculated from SP logs are interpolated from a series of parallel logarithmic scales called nomographs; results can only be determined to the nearest 100 mg/L for smaller values or nearest 1,000 mg/L for values above 10,000 mg/L. In contrast, results obtained from water analyses are commonly displayed as unrounded values. Examples of both are apparent in table 4.

Table 4. Summary statistics for 500 ft depth intervals.

Depth (ft)	Salinity as TDS (mg/L) Minimum	Mean	Maximum	Count
Under 500	1,400	1,750	2,400	4
500 - 999	369	2,549	5,300	92
1000 - 1499	1,100	2,714	4,800	91
1500 - 1999	700	2,663	5,100	85
2000 - 2499	529	2,802	4,500	76
2500 - 2999	1,250	2,806	4,300	59
3000 - 3499	1,400	2,792	5,000	66
3500 - 3999	1,600	3,107	6,600	78
4000 - 4499	1,600	3,421	7,600	93
4500 - 5000	1,300	4,713	30,833	54

Mean calculated TDS concentrations in the D-J Basin generally increase over the 500-5,000 ft depth range (fig. 3). The rate of increase is about 125 mg/L per 500 ft interval from depths of 550–4,500 ft. Mean TDS concentration jumps nearly 1,300 mg/L in the deepest interval (4,500–5,000 ft). The increases in mean TDS levels with depth are driven largely by elevated TDS levels observed in clusters of wells located largely along the western margin and in northern and southcentral areas of the basin.

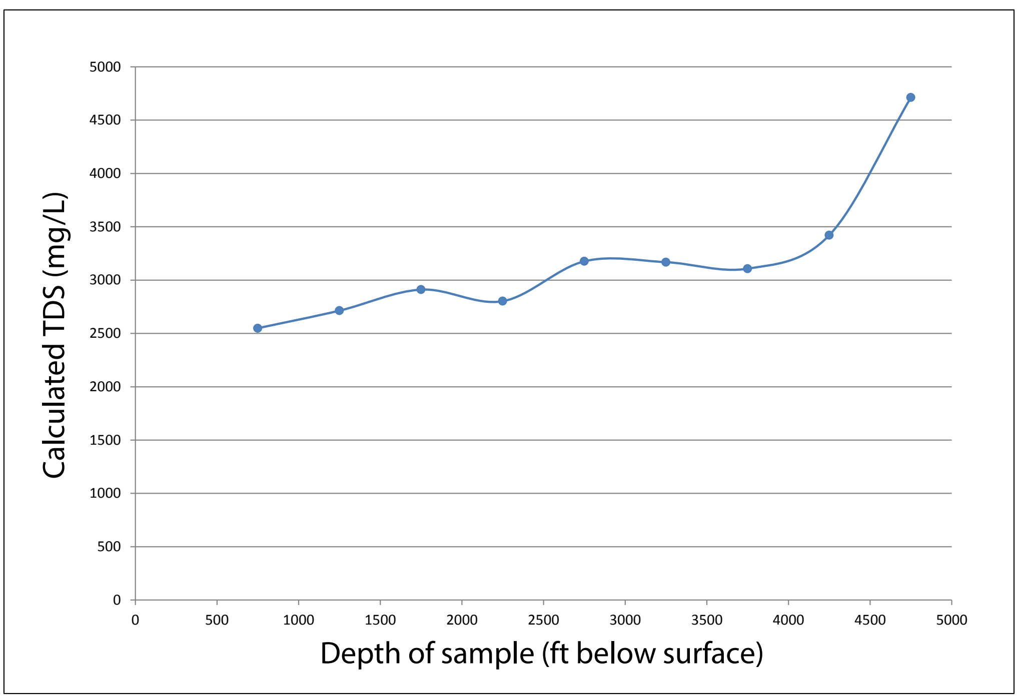

Figure 3. Mean calculated TDS levels versus depth of sample.

500–999 ft interval: Estimated TDS levels in this interval are below 5,000 mg/L except one well located on the northeastern edge of the basin in an area characterized by TDS concentrations that exceed 5,300 mg/L.

1,000–1,499 ft interval: All estimated TDS concentrations within this interval fall below 5,000 mg/L. However, several areas with TDS levels above 4,000 mg/L are scattered along the western margin of the basin and at one site in the southcentral area.

1,500–1,999 ft interval: One moderately saline well (TDS > 5,000 mg/L) occurs on the northwestern margin of the basin. Areas with TDS levels above 4,000 mg/L are found in the northwest and southwest.

2,000–2,499 ft interval: All estimated TDS concentrations within this interval fall below 5,000 mg/L. Several wells located in the southcentral and western basin exceed 4,000 mg/L.

2,500–2,999 ft interval: Estimated TDS concentrations within this interval also fall below 5,000 mg/L. Several areas with TDS levels above 4,000 mg/L are located on the northern, western and eastern basin margins.

3,000–3,499 ft interval: Only one well, located in the northcentral part of the basin exhibits a salinity of 5,000 mg/L. All other data points fall below 5,000 mg/L. Again, several areas with TDS levels above 4,000 mg/L are scattered throughout the basin.

3,500–3,999 ft interval: Three wells in the northeast and one well on the western margin are moderately saline (5,000 < TDS < 10,000 mg/L).

4,000–4,499 ft interval: Several moderately saline (5,000 < TDS < 10,000 mg/L) wells are located in the southeast and two occur in the north.

4,500–5,000 ft interval: Within this interval, areas with moderate to high salinity have expanded over wider geospatial extents than in the shallower zones discussed above. Two highly saline wells (16,000 and 30,833 mg/L) and one moderately saline (7,000) well occur on the western margin of the basin. Other moderately saline wells are located in northeastern (5,000 and 6,600 mg/L), eastern (5,600, 8,000 and 9,100 mg/L) and southcentral (5,000 and 8,500 mg/l) areas. Additionally, elevated (> 4,000 mg/L) TDS concentrations of peripheral wells illustrate the expansion of saline zones within this interval and suggest that saline waters may occur with increasing frequency at greater depths.

Generally, lower salinity groundwaters are more prevalent at depths to 5,000 ft bgs in a broad band that stretches across the southern half of the D-J Basin, most notably in the vicinity of Cheyenne and Pine Bluffs. The causes of this regional trend (figs A-1–A-9) are not yet known but are likely related to environmental factors not considered in this report.

CONCLUSIONS

WSGS used 695 spontaneous potential (SP) measurements from 234 borehole geophysical logs and 14 water quality analyses from qualified oil and gas wells to approximate the geospatial distribution of groundwater salinity (TDS) in the Denver-Julesburg Basin of southeastern Wyoming. Salinity estimates (as NaCl equivalents) were obtained from SP wellbore logs using the Static Spontaneous Potential (SSP) Method (Schnoebelen, 1995; Schlumberger Well Services, 1989) over a depth range of 500-5,000 ft bgs at nine 500 ft intervals. The resultant salinity data were plotted into contours by 500 foot depth interval in Arc GIS using a third power Inverse Distance Weighted (IDW) contouring model with a variable search radius of 20 neighboring wells.

Average groundwater salinity was observed to increase about 125 mg/L per 500 ft interval from 500-4,500 ft in depth. The rate of increase jumped to nearly 1,300 mg/l over the final (4,500-5,000 ft bgs) depth interval examined. The contour maps generally show that below 4,500 ft bgs moderately (5,000- 10,000 mg/L) to highly (>10,000 mg/L) saline groundwater occurs across wide areas located in the north and northwest of the basin. A second area of more limited extent is found in the southcentral basin. These areas exhibit the highest potential to provide industrial groundwaters with salinity levels that exceed WDEQ TDS requirements for domestic, agricultural and livestock uses.

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 D-J 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 D-J Basin will be developed as oil and gas exploration expands with higher oil prices and the continued advancement of drilling technology. This report is intended to provide a preliminary approximation of salinity levels at depths of 500 to 5,000 feet below ground surface in the Denver–Julesburg Basin of southeastern Wyoming. WSGS makes no guarantees regarding the accuracy of the data contained herein and encourages readers of this report to consult other reports, publications, 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 southeastern Wyoming (Platte River Basin) can be found in Taucher and others, (2013) available at: http://www.wsgs.wyo.gov/Research/Water-Resources/River-Basin-Plans.aspx.

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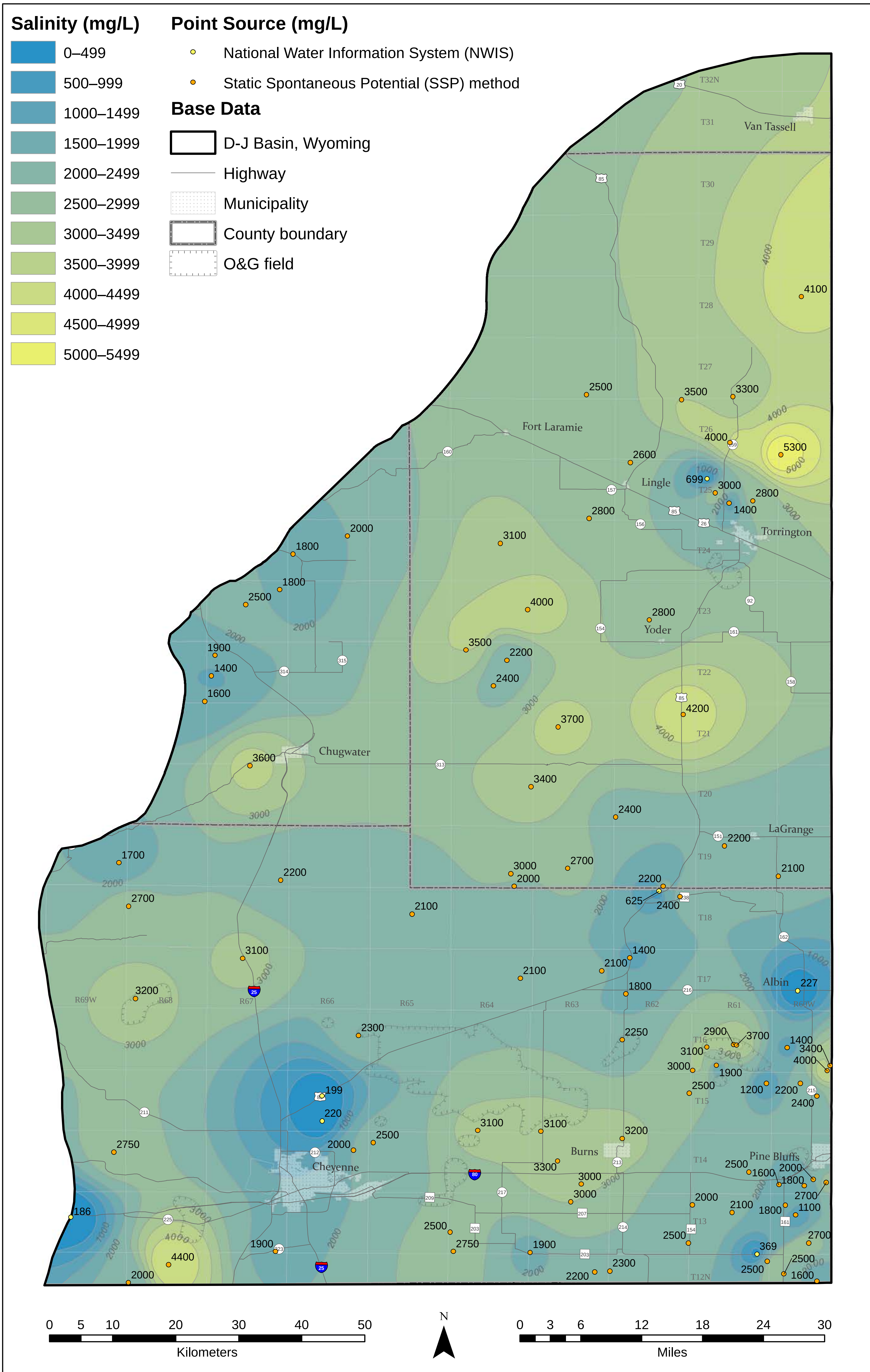
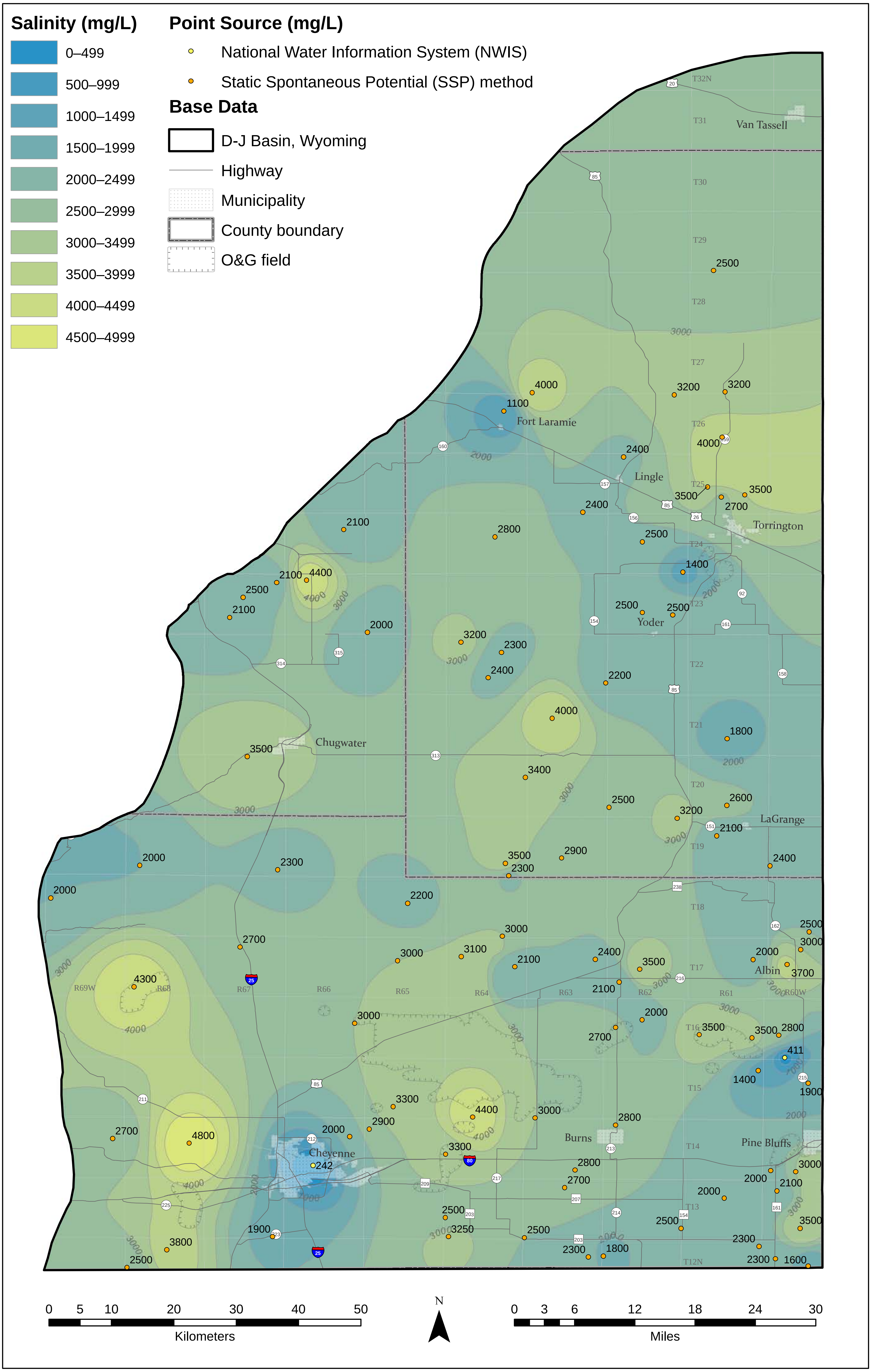
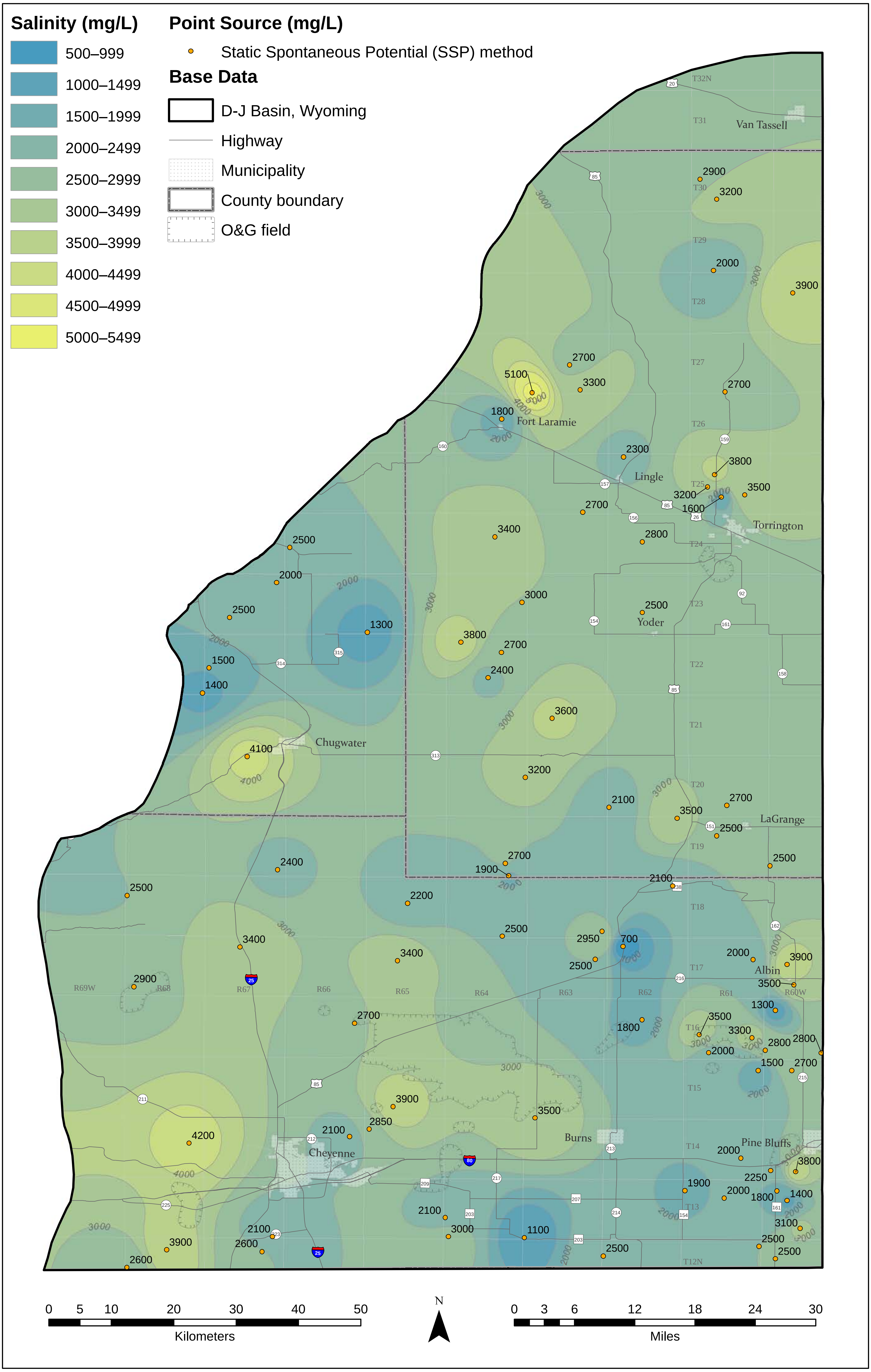
Appendix



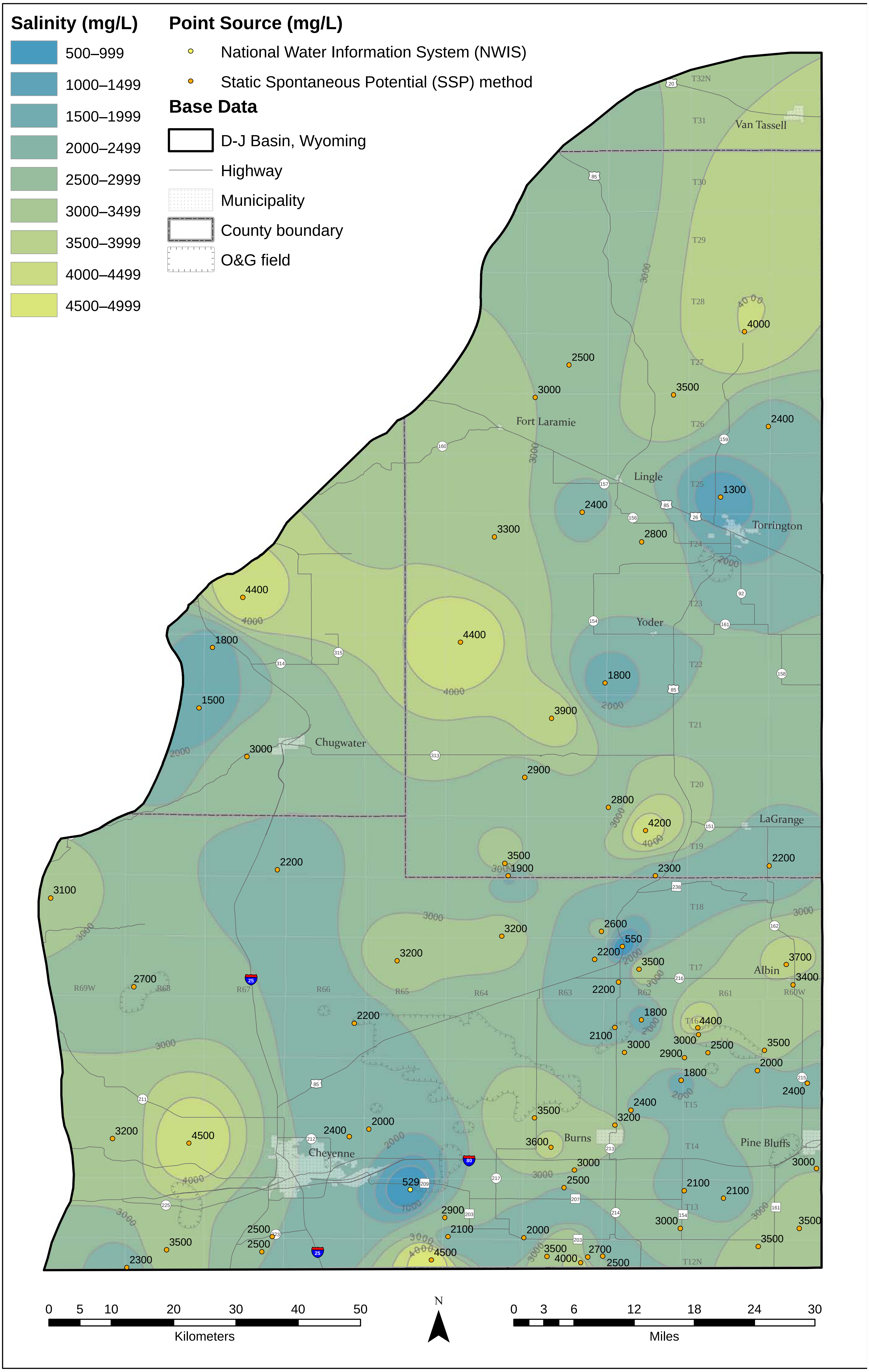
A-1. Salinity (mg/L) values at 500–999' below ground surface (bgs).



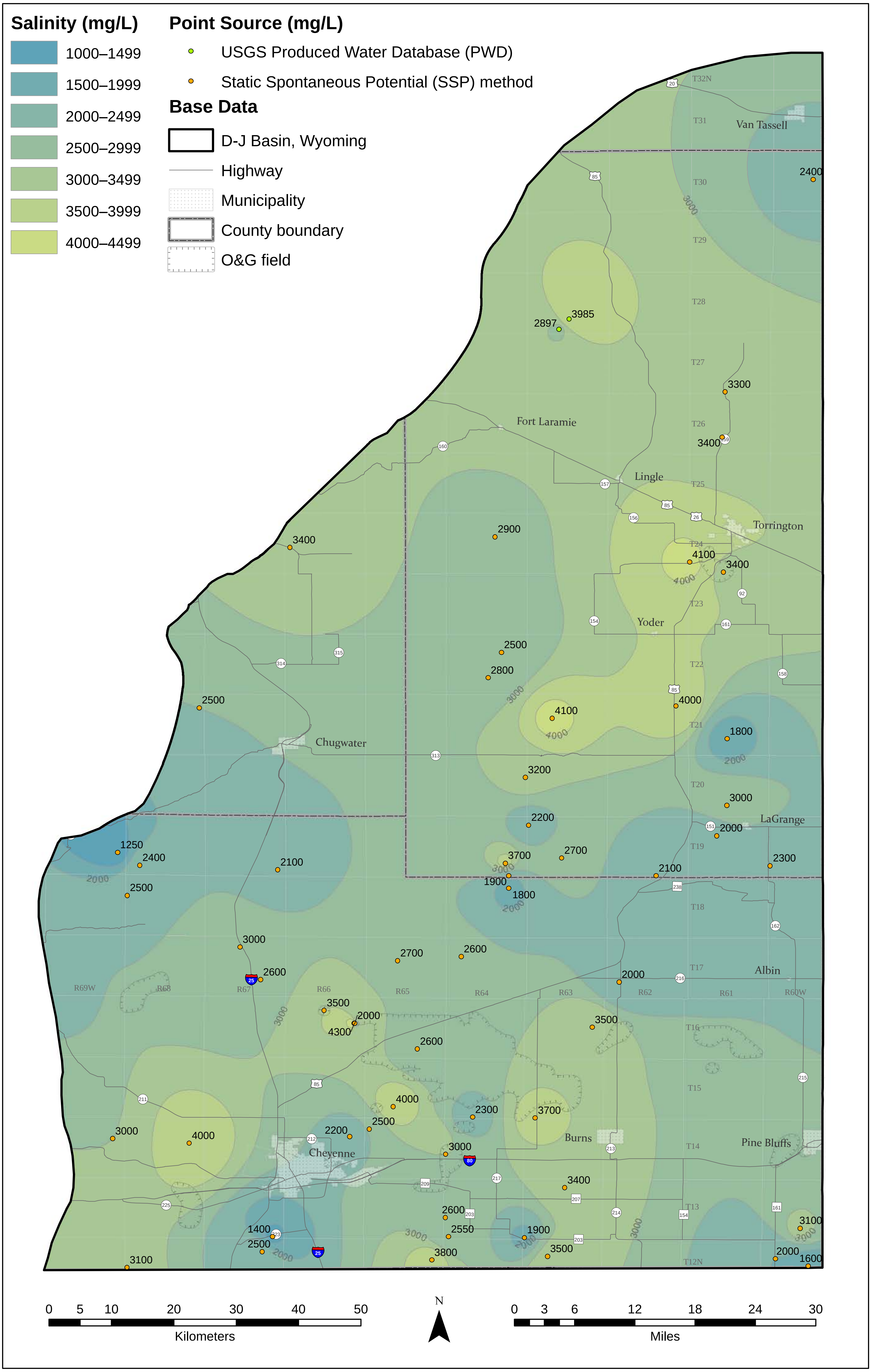
A-2. Salinity (mg/L) values at 1,000–1,499' below ground surface (bgs).



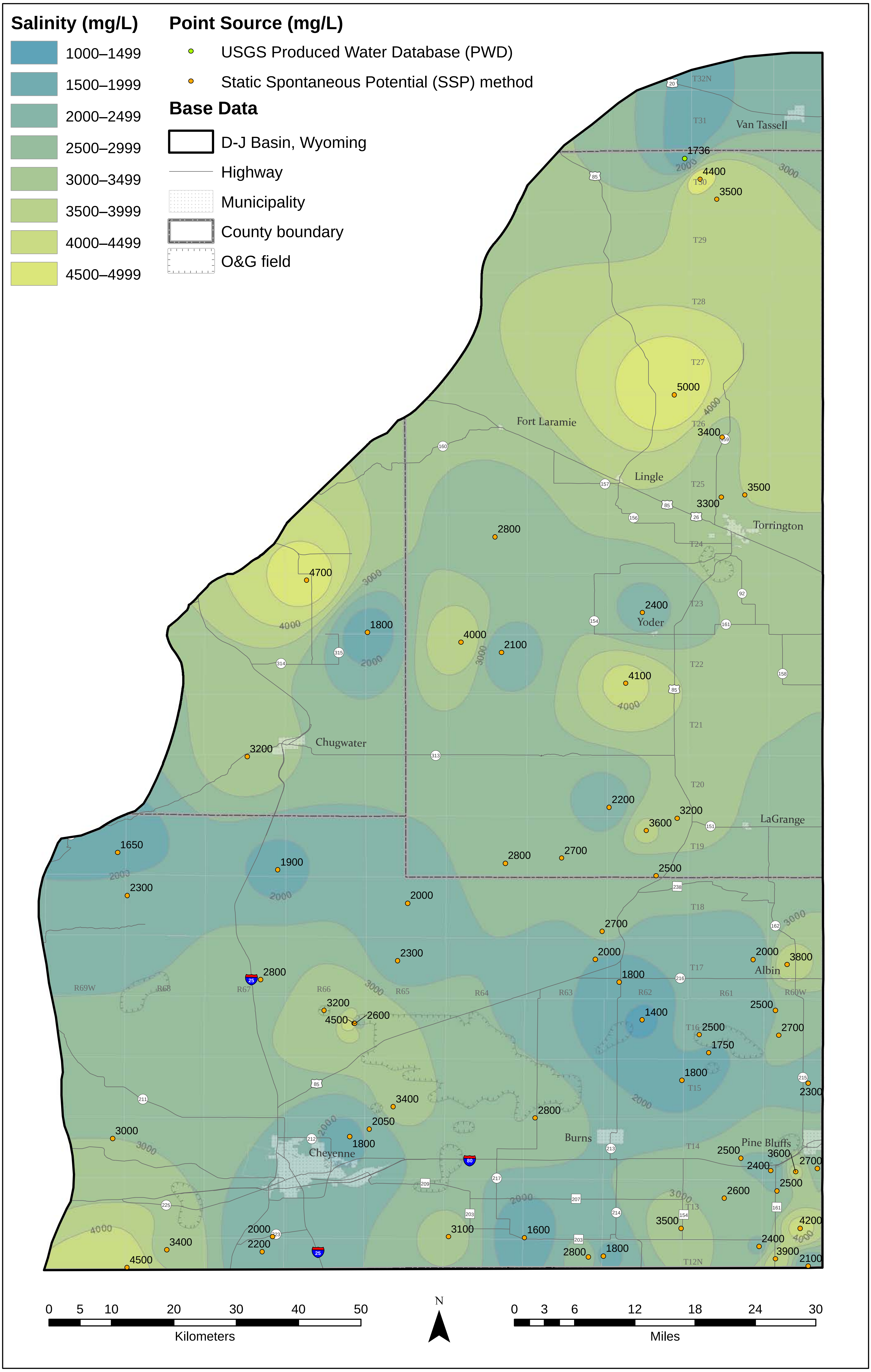
A-3. Salinity (mg/L) values at 1,500–1,999’ below ground surface (bgs).



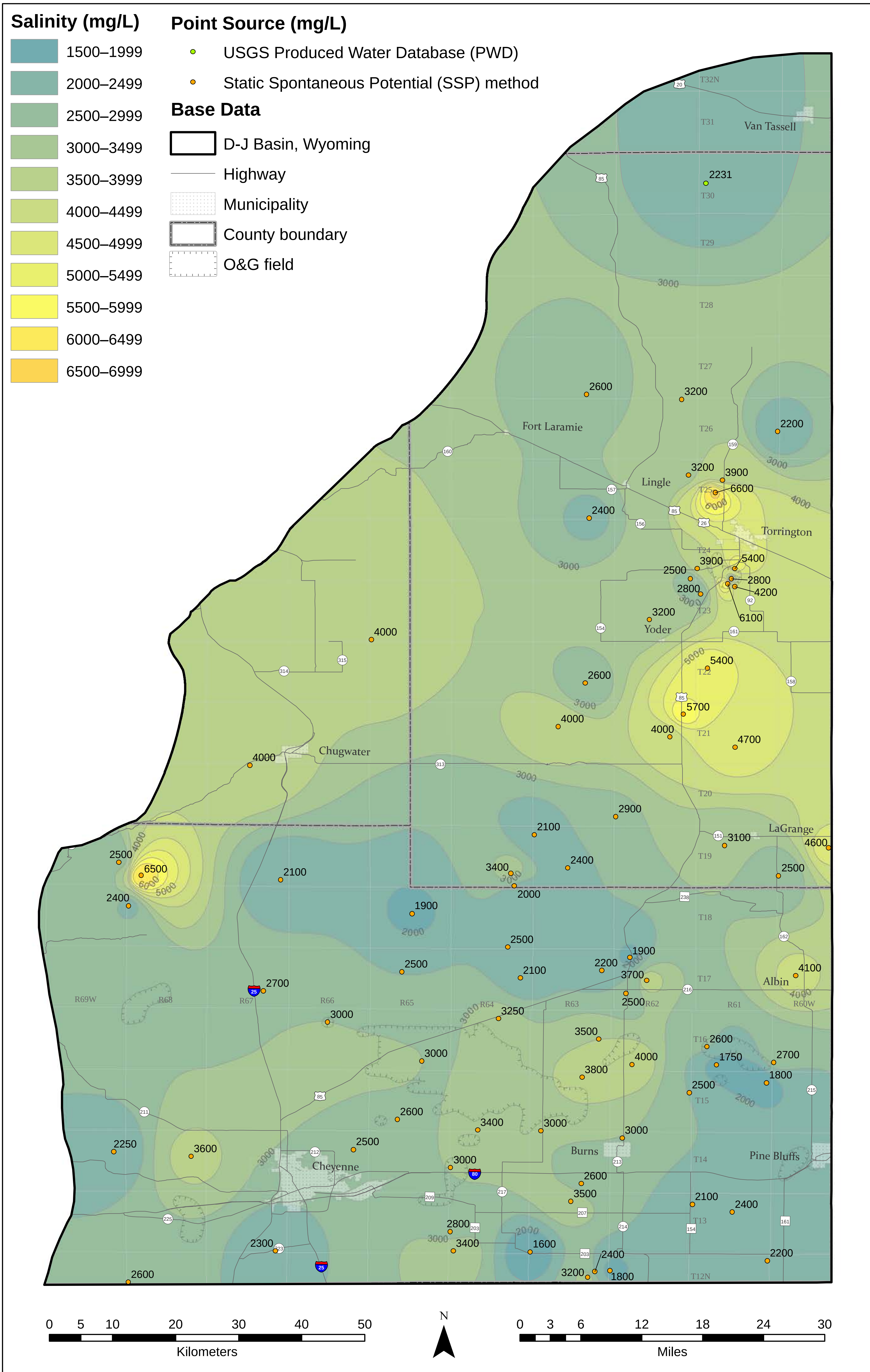
A-4. Salinity (mg/L) values at 2,000–2,499’ below ground surface (bgs).



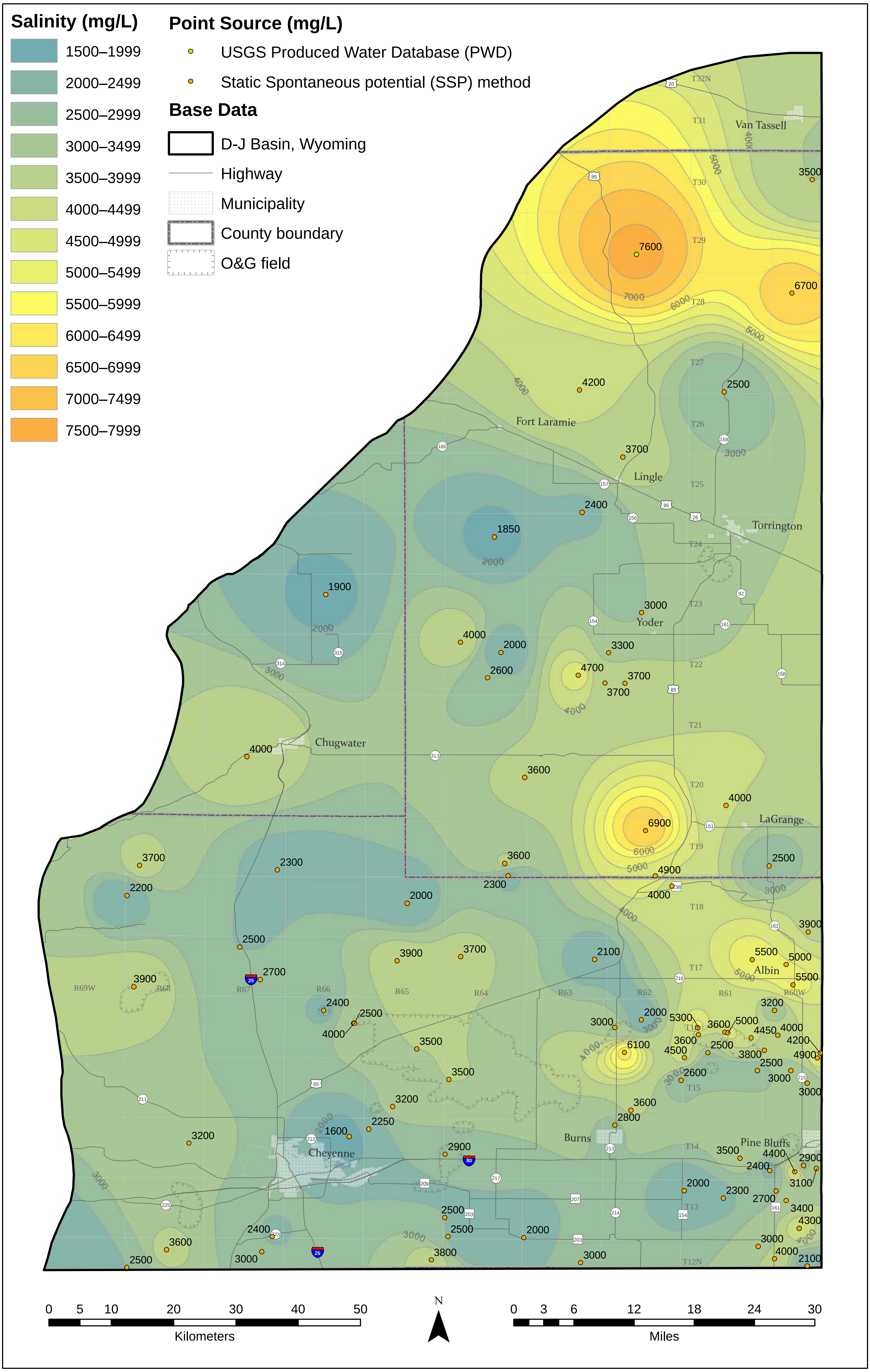
A-5. Salinity (mg/L) values at 2,500–2,999' below ground surface (bgs).



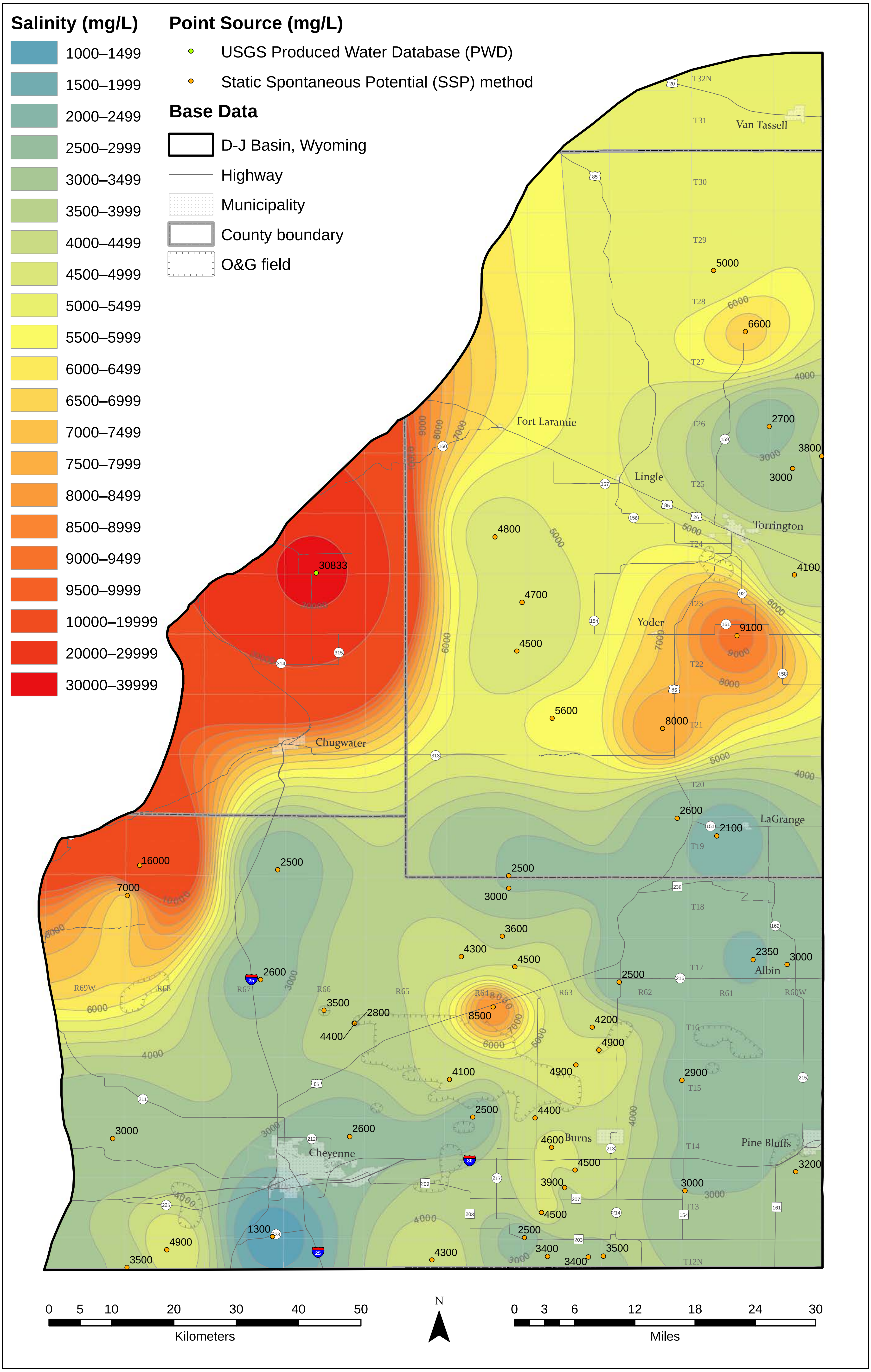
A-6. Salinity (mg/L) values at 3,000–3,499' below ground surface (bgs).



A-7. Salinity (mg/L) values at 3,500–3,999' below ground surface (bgs).



A-8. Salinity (mg/L) values at 4,000–4,499' below ground surface (bgs).



A-9. Salinity (mg/L) values at 4,500–5,000' below ground surface (bgs).