MODERATELY SALINE GROUNDWATER IN THE UINTA BASIN, UTAH

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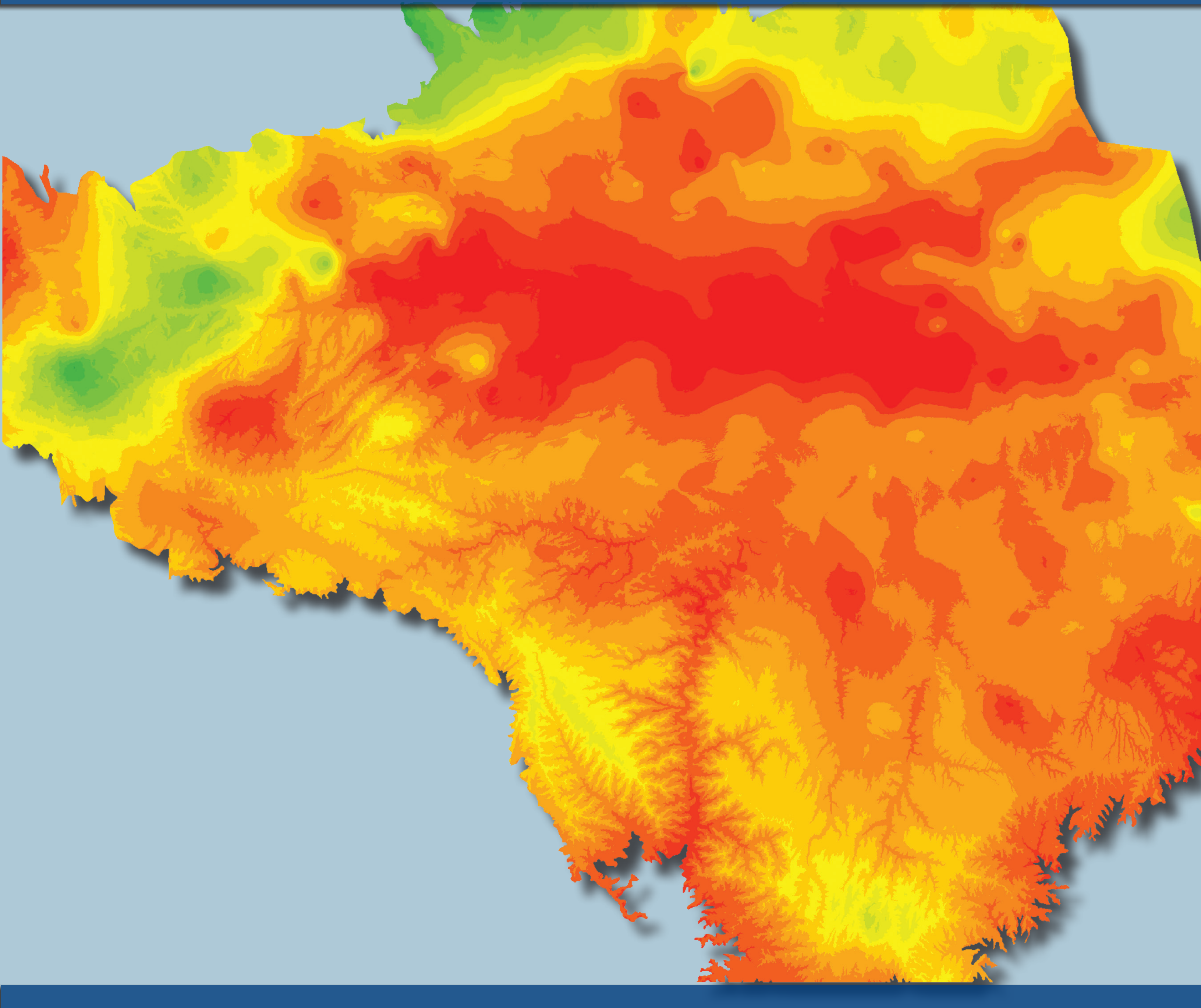

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CONTENTS

FIGURES

TABLES

PLATES

MODERATELY SALINE GROUNDWATER IN THE UINTA BASIN, UTAH

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ABSTRACT

The base of the moderately saline water (BMSW) in the Uinta Basin was first mapped in 1987 and re-mapped in this study using similar methods. Oil and gas operators in the Uinta Basin seeking underground disposal are generally required to inject waste production water below the BMSW or in waters greater than 10,000 mg/L total dissolved solids (TDS). Approximately 8000 new wells have been drilled in the basin since the 1987 study, providing significantly more data for refining the previous mapping. Water samples from primarily oil and gas activities through the basin's history were compiled into a database (2788 records) and used as an aid in mapping. In addition, interpreted oil and gas geophysical logs, in particular resistivity measurements (R_w), serve as an approximate proxy for the TDS of formation water. From the pool of new drilling, geophysical logs from 260 wells distributed throughout the basin were interpreted and used in mapping the BMSW. The Archie method, SP, and other resistivity methods were used in the interpretation of logs. Regional groundwater flow paths, saline minerals, structural shape of the basin, and faults and fractures strongly influence the distribution of TDS levels. Both older and new data points were used to create an elevation contour map of the position of the shallowest occurrence of the BMSW below the surface. Depth-correlated water analysis data were mapped and compared to the log-derived BMSW. Mapped water analysis data indicate the northern portion of the basin has numerous occurrences of water fresher than 10,000 mg/L below the BMSW, indicating a complex stratification of salinity coincident with the area of primary recharge, whereas shallow saline waters dominate the central portion of the basin. Data also demonstrate a poor correlation between TDS and the depth of the sample. Water samples from a few isolated areas show clear evidence of a change in TDS through time.

INTRODUCTION

Oil and gas production in the Uinta Basin produces waste water that requires proper disposal. Annual crude oil production in Uintah and Duchesne Counties (representing the majority of the basin's production) has increased 132% in the past 10 years to 17.5 million barrels, while natural gas has increased a remarkable 227% to 317 billion cubic feet (Utah Division of Oil, Gas, and Mining, 2011). Associated produced water increased 46% over the same period and totaled 75.8 million barrels in 2010. This equates to 7328 acre-feet of waste water or over 60% of the capacity of Pelican Lake, Uintah County. Water disposed through underground injection wells in the entire Uinta Basin for 2010 was 35.6 million barrels (Brad Hill, Utah Division of Oil, Gas, and Mining, personal communication, 2011). The upper 100 feet of water-saturated material in the Uinta Basin stores 31 million acre-feet of water (USWP, 1999). By way of comparison, the volume of disposed water for 2010 is 0.011% of this volume. Today's average cost of private disposal of oil and gas waste water is about $1.50/barrel, meaning last year's disposal of waste water in Uintah and Duchesne Counties cost the industry about $114 million. Without permitted water disposal options for operators, most production in the basin would cease.

Groundwater has been classified by the U.S. Environmental Protection Agency (EPA) as fresh if the TDS concentration is less than 1000 mg/L; slightly saline with TDS values from 1000 to 3000 mg/L; moderately saline between 3000 mg/L and 10,000 mg/L; and very saline to briny when greater than 10,000 mg/L TDS. Groundwater in this report is informally classified as "non-saline" when it has a TDS concentration less than 10,000 mg/L, while saline groundwater has a TDS greater than 10,000 mg/L.

Purpose and Scope

In the early 1980s, the Utah Division of Oil, Gas, and Mining (DOGM), faced with the task of implementing new EPA regulations for underground injection, engaged the U.S. Geological Survey to jointly study and publish a map of the base of moderately saline water in the Uinta Basin. This map (Howells and others, 1987, also referred to as Technical Publication 92 or TP-92) has guided state and federal regulatory agencies in evaluating new applications for underground disposal of oil and gas production waste water. Oil and gas operators use the map for siting new disposal wells. Since its publication, drilling in the Uinta Basin has continued, adding about 8000 new wells. These newer wells bring with them better geophysical logging techniques providing many potential additional data points to improve on the original mapping effort.

With new drilling/production comes increased need for water disposal wells. The objective of this project is to examine the geophysical logs from new drilling and pick the base of the moderately saline water in a subset of these new wells. These new data points were added to the previous study's data and used in creating a new updated series of contour maps of the base of the moderately saline aquifer (BMSW). Companion cross sections were added to this study to better illustrate the third dimension and the BMSW relationship to the stratigraphy and structure of the basin. Figure 1 shows the area of study.

Through the life of the Uinta Basin's exploration and development history, water quality data have been collected by operators, governmental agencies, and academia. This study represents the first attempt to compile basin-wide water quality data and use the database in mapping subsurface groundwater TDS. Available water quality data were used in the previous mapping efforts, but not formally compiled and published.

Water-bearing rocks or sediments with the EPA water quality attributes, discussed above, are often labeled aquifers, for example the "moderately saline aquifer." Howells and others (1987) carefully avoided attaching the term "aquifer" to their map. By definition (Bates and Jackson, 1987), an aquifer must "...yield economically significant quantities of water to wells..." Without testing, it is difficult to know what the yield would be from permeable beds encountered in the basin. Add to this the evaluation of current economics, determining what is an aquifer and what is not becomes a difficult task and beyond the scope of this project. However, state and federal regulations require saline waste waters be re-injected into saline "aquifers." State regulations allow for disposal of production waste water in other "non-saline" zones, but only with a special "aquifer exemption." BMSW (base of the moderately saline water) is the abbreviation used throughout the report and is specifically defined on subsequent pages. Mapping the BMSW will help all stakeholders in the basin achieve the goals of continued economic development of hydrocarbon resources while protecting future potential use of the basin's groundwater resources.

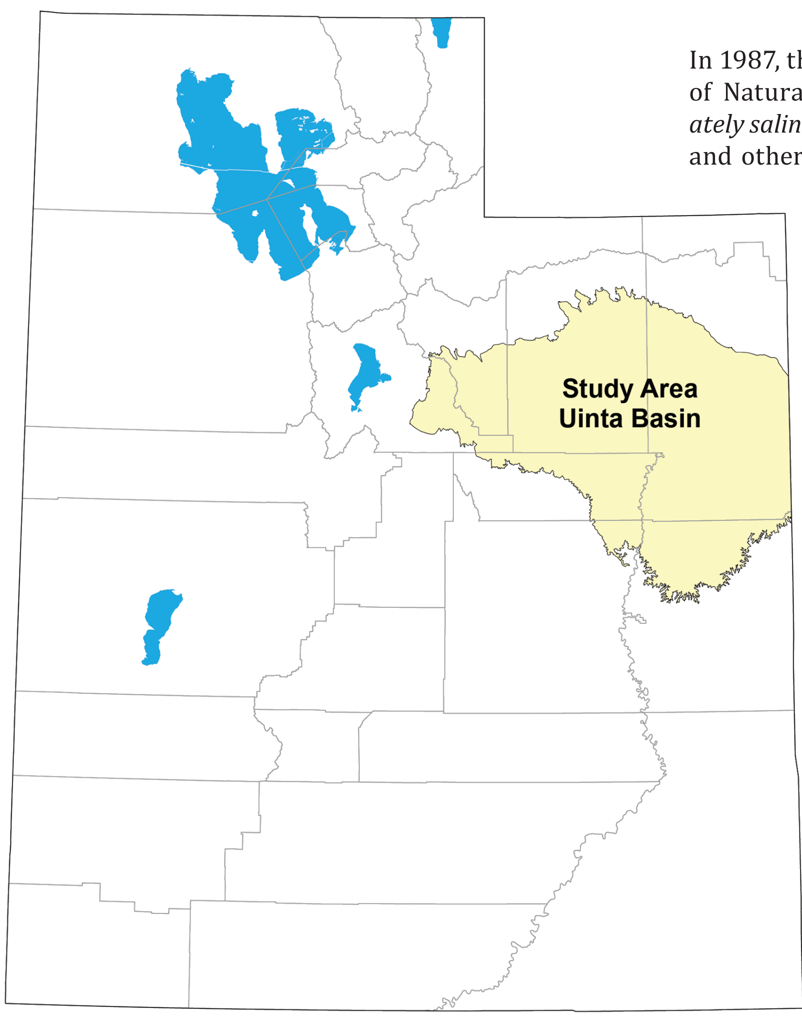

Figure 1. *Location of study area.*

Previous Studies

In 1987, the U.S. Geological Survey and Utah Department of Natural Resources jointly published *Base of moderately saline ground water in the Uinta Basin, Utah* (Howells and others, 1987). The publication provides a complete explanation of the various geophysical log interpretation techniques used to estimate groundwater TDS, along with a description of the geology of the Uinta Basin. Key recent papers related to Uinta Basin deep bedrock water quality include Gwynn (1992, 1995) and Zhang and others (2009). Steiger (2007) investigated water quality impacts related to underground injection in the Altamont-Bluebell field.

METHODS

Mapping groundwater TDS utilized two principle methods which produce results with a large range of accuracy. The primary method used geophysical log interpretation techniques. The second method used direct measurement of TDS from water samples taken primarily in oil and gas wells. Mixing of groundwater or connate water with anthropogenic sources from drilling and completing wells renders some of these samples questionable to unusable, but many samples were obtained from a production stream and are considered representative of in-situ conditions. Water quality data were not directly used to map the BMSW, but consulted during each log interpretation, when available. Additional details about the contouring methods for both the water quality and log-based estimates of the BMSW are discussed in the Results section.

Groundwater Samples

Groundwater samples from deep in the basin are an important contributor to a better understanding of the position of the "non-saline" water within the Uinta Basin. Representative samples of water from a particular horizon in a well create a firm point of reference for mapping and a calibration point for log interpretation methods. The addition of a groundwater database for use during log interpretation and final mapping of the BMSW improves the accuracy of the results. Figure 2 shows the locations of the 2788 water samples from 1520 different wells compiled for this study and the database can be found in appendix A.

Groundwater samples were compiled from a variety of sources. Sampling protocol is rarely available from these sources and likely ranges from poor to excellent. The user of these data should be aware of this important limitation. In addition, the thickness of the sampled interval is often several hundred to over 1000 feet, limiting the sample's usefulness.

Data Sources

The groundwater data source is identified in the database, with data gathered from prior publications, U.S. Geological Survey, contributions from operators in the basin, service companies, and a search of well files housed at DOGM. Many of the groundwater samples found in DOGM's files originate from permitted (present and past) disposal or injection wells. DOGM rules require operators to provide an analysis of injected water, which leads to analysis from surrounding producing oil and gas wells waste water stream, but filed under the disposal well's API number. This adds a great deal of information to the database, but makes it difficult to trace the source of the analysis back to an individual DOGM well file.

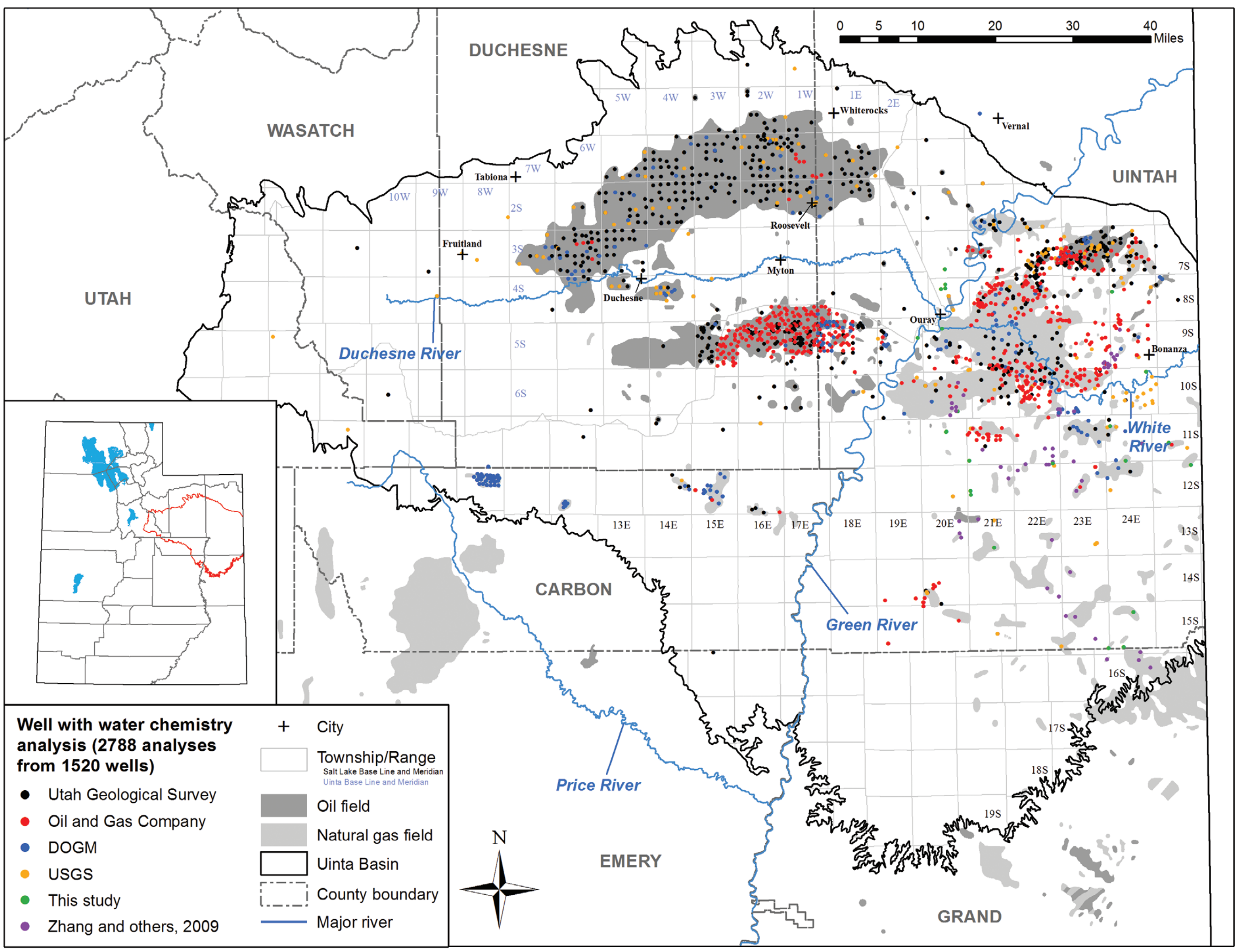

Figure 2. *Locations of water analyses compiled and found in appendix A.*

Table 1 provides a break-down of the sources of data for the water database. Due to this wide variety of sources, many of the fields of the database are incomplete and some fields are estimated. The "comment" field in the database describes various assumptions.

Table 1. *Sources of water analyses in the project database.*

Source	Number of analyses
Utah Geological Survey (published)	1187
Oil and Gas company	833
Questar	*367*
Newfield	*194*
Anadarko	*185*
EOG	*22*
Bill Barrett	*20*
Halliburton	*16*
El Paso	*13*
XTO	*10*
Enduring Resources	*5*
Wind River Resources	*1*
DOGM well files	440
U.S. Geological Survey (published)	102
U.S. Geological Survey (unpublished)	87
This study	82
Zhang and others (2009)	57
Total	2788

Quality Control

The database contains many water analyses found in Gwynn (1995) that were collected from drill stem tests (DST). Contamination of these samples from drilling fluids or water cushions often occurs. Where possible, the recovery of each reported DST-sourced analysis was reviewed. If mud or water cushion was noted in the recovered fluids, the sample was rejected and not used in the mapping effort. When no information was available about the type of water sample, the date of the sample was used to check the well history files (DOGM website) in an attempt to understand the likely source. These endeavors were not always successful in producing a clear picture of the sample's validity and a qualitative judgment was required to accept or reject the sample.

Operator and DOGM file-sourced data presented other challenges. Often the depth interval of a sample was omitted. Other times, the sample date was not listed but an analysis date was available. In some cases, a complete anion-cation analysis was reported, but no TDS value was included. In these situations, the TDS was calculated and noted in the "comment" field of the database.

When a water sample was from an initial production test (IP), additional judgment was required. The amount of fluids recovered was reviewed and pre-testing stimulation considered as a source of formation water contamination. Water of condensation in very low water producing wells can dominate or contaminate water samples. Well 4304736731, SRU#8 in section 23, T. 13 S., R. 22 E., Salt Lake Base Line and Meridian (SLBLM), is an example. The well has a total depth (TD) of 10,134 feet and a production water sample from the separator recorded a TDS of 1799 mg/L. Production for the month was dominantly gas with 43 barrels of water. The following month only two barrels of water were produced. The well is perforated in the Dakota–Cedar Mountain Formations. The TDS value seemed anomalously low for this formation and depth, but few wells are sampled from this interval in the area. The logs on the well were examined and indicated saline water. The operator was contacted (Carl Kendall, Summit Resources, personal communication, 2010) and confirmed produced water from the well was typically "salty" but did not have a representative analysis. Mr. Kendall indicated that similarly low TDS waters have been found in other oil and gas wells with low water production and is believed to be mainly water of condensation formed during production.

Potassium was used as an indicator of contamination from drilling and completion activities. Potassium-chloride water is commonly introduced by various down-hole operations. Producing a well should "clean up" any introduced fluids from drilling and completion activities. Water analyses from production-type samples were queried from the database and should indicate the natural range of potassium found in the formation water. The query yielded 904 samples in the database sourced from "production" and sampled for potassium. Of these, 69 had a potassium concentration greater than 250 mg/L, with 47 sampled within one year of the completion date of the well. These data indicate that after one year of production about 97% of the produced water had a potassium concentration of less than 250 mg/L. Potassium concentration greater than 250 mg/L is a reasonably accurate indication of drilling and completion contamination of native reservoir fluids.

An example of mixed saline and "non-saline" waters within a 1500-foot zone in the Monument Butte field (southeastern Duchesne County) can be demonstrated using the Castle Peak 43-5 well (4301330858, section 5, T. 9 S., R. 16 E., SLBLM). The well was originally perforated from 4350 to 5756 feet in three zones and produced for three months with a cumulative water production of about 1600 barrels and then sampled with a TDS of 9260 mg/L. The well continued to produce. In April 1985, two new zones were added (net four additional feet) to the original gross interval, hydraulically fractured, and immediately sampled, resulting in a TDS of 28,877 mg/L and potassium ion concentration of 2600 mg/L. Two years later and after about an additional 200 barrels of produced water, the TDS was 19,931 mg/L. Assuming the first and last samples are representative of formation water, just four feet of new perforations in the middle of the original zone moved the entire section from above the BMSW to below it.

Since the water quality checks are a combination of quantitative and qualitative methods, some contaminated samples have been inappropriately included or rejected as the list of analyses was developed for water quality mapping. Where possible, the well files were checked to attempt to understand the context of operations at or around the time of the sample date.

Database

The water database for the project is found in appendix A. Table 2 provides a list of the fields in the database and a short explanation of the type of data in each field. Note the dual key fields in the table which use both the API number and TDS of the sample. This method allowed for multiple analyses per well. In just a couple of cases,

Table 2. *Water analysis database fields and explanation.*

Field name	Description
Number	Arbitrary identification number
API	(KEY FIELD) API number of well from which sample taken - no number indicates non-oil & gas type well
Sample Date	Date sample taken, sometimes is the analysis date. When format 1-Jan-year, only the year is know.
Well Name	Well name assigned by operator
Field Name	Oil and gas field name, blank if undesignated
County	
UTM E	Easting coordinate of well location, UTM using the NAD 83 projection
UTM N	Northing coordinate of well location, UTM using the NAD 83 projection
Elevation	Elevation in feet of the reference point in the field, Elevation Datum
Elevation Datum	GR = ground; DF = derrick floor; KB = Kelly bushing
Township	
Range	
Section	
Meridian	S = Salt Lake Base and Meridian; U = Uintah Base and Meridian
Data Source	Source of the entry, generally a publication, agency, or operator name
Sample Depth Top	Depth in feet to the top of the sampled interval
Sample Depth Base	Depth in feet to the bottom of the sampled interval
Formation	Formation of depth interval
Sampled by	Who took the sample, usually a company or agency
Type of Sample	Method, means, or location where sample taken
Analysis Method	Lab or field
Lab Name	Name of lab where analysis was performed
Raw R_w	Resistivity of the water in ohms-meters
Temp Raw R_w	Temperature of the water when Raw R_w was measured
TDS	(KEY FIELD) Total dissolved solids in mg/L – either measured or calculated
pH	pH of the sampled solution
Specific Gravity	Specific gravity of water sample
Ca	Calicum ionic concentration measured in mg/L
Na	Sodium ionic concentration measured in mg/L
K	Potassium ionic concentration measured in mg/L
Mg	Magnesium ionic concentration measured in mg/L
CO_3	Carbonate ionic concentration measured in mg/L
Cl	Chloride ionic concentration measured in mg/L
SO_4	Sulfate ionic concentration measured in mg/L
Bicarbonate	Bicarbonate ionic concentration measured in mg/L
Anion-Cation ratio	Anion-cation balance in percent difference
Used in Mapping BMSW	Yes or no – Quality of water analysis, was it used in BMSW mapping
Comments	

the TDS was altered by 1 mg/L to avoid a key violation. Where this occurred it is noted in the comment field. The field "Used in Mapping BMSW" contains an entry of "yes" or "no," answering the question of whether the sample should be used in mapping the BMSW. Of all the records in the database, 68% received a "yes" for use in the mapping. Rationale for a "yes" or "no" is based on the following: 1) Data are assumed valid without cause to doubt it. 2) If the potassium (K) is high, and an equal milli-equivalent amount of chloride could move the water's TDS over or under the 10,000 mg/L line when added or subtracted, then a sample gets a "no." 3) The anion-cation balance should be within about plus or minus 2% of 1.0 for dilute concentrations <1000 mg/L TDS (Hem, 1985), but for higher concentrations, like most in this study, tolerances are greater. A few of the laboratories did not analyze for TDS but noted the value was calculated from the sum of the anions and cations. In these few cases, the anion-cation balance must be considered in reaching a "yes" or "no" for the field. If the imbalance is sufficient to move the analysis over or under the 10,000 mg/L boundary (this is considered along with the high potassium values) then the sample received a "no." 4) Other reasons relating to inconsistencies in historic data or type of fluid recovered on DSTs could result in a "no." As mentioned above, most analyses of TDS use an evaporation method and the TDS concentration is not calculated from the anion-cation analysis. Most of the most recent samples for TDS fall into the analyzed group, and an anion-cation imbalance may be related to omission of reporting a major ion, whereas the TDS value is reliable within normal ranges.

Appendix A was constantly referenced during the log analysis part of the project. These data often aided in making better interpretations, but, unfortunately, only rarely did the sample interval fall within the same portion of the hole where the BMSW was believed to occur. This is because most of the water samples are associated with deeper producing intervals and the BMSW does not commonly fall within this depth interval in most of the Uinta Basin.

Total Dissolved Solids Estimated Using Borehole Geophysics

Most oil and gas wells run a suite of open-hole geophysical logs upon reaching total drilling depth. This has been the practice in the Uinta Basin with very few exceptions, and generally these unlogged holes were drilled in the earliest years of the basin's development history. This study, like its predecessor, used interpretation of the suite of geophysical logs run in selected wells as the primary means of mapping the BMSW. Several methods have been developed over the past 100 years of downhole geophysics, which provide an estimate of the TDS (salinity) of waters encountered in permeable strata and are discussed below.

Procedural Methods

Logs and software: Unfortunately, no project files from the original BMSW mapping effort from Howells and others (1987) could be located. DOGM did have some information in Mr. Gil Hunt's personal files relating chiefly to log interpretation methods. Howells and others (1987) elevation contour map of the BMSW is on two plates at a scale of 1:250,000 with all the data points plotted on these maps. The points represent Howells and others' estimated base of the moderately saline water picked using geophysical logs run in oil and gas wells. Using ArcGIS georeferencing techniques on a scanned version of Howells and others' original map, and plotting it along with well locations in DOGM's oil and gas well database, provides the means of linking each data point to an oil and gas well log or API number. Where the well spacing density near a data point was low, these picks are made with confidence. Where the well spacing density was high, possible error in tying the older data to a specific well may have occurred. Table 3 lists Howells and others' (1987) points with ambiguous or problematic well locations and appendix B lists all of the best ties of Howells' mapped points to specific wells, identified by API number.

LAS geophysical logs are digital, depth to logging parameter-type files that have been generated by service company logging equipment beginning in the late 1980s or have been digitized from older image log prints. All interpretation of geophysical logs for this study is LAS-based, enabling use of log interpretation software or direct calculation and presentation of derived curves on a digital suite of logs. Oil and gas operators generously donated hundreds of LAS logs for use in this project, while the Utah Geological Survey scanned or purchased the remaining needed LAS files.

Howells and others' (1987) evaluation did not include wells drilled after about 1985. For this study, all wells drilled after 1985 were plotted on a base map, along with Howells and others' data points and the elevation contours from their BMSW map. New wells were selected for evaluation based on locations that would "fill in" holes in Howells and others' (1987) data or help to better evaluate areas with steep BMSW elevation contours. Candidate wells with available LAS logs were selected. Many of these wells had to be subsequently rejected because the top of the logged depth was below the suspected (or previously mapped) BMSW boundary. This is a common problem in much of the Greater Natural Buttes area where operators regularly set the first string of casing between 3000 and 4000 feet in depth and rarely run open-hole logs before the casing is set. Well log suites needed to include a combination of both resistivity and porosity to be considered for picking the BMSW.

Table 3. *TP-92 problematic locations.*

API	Location Problem	BMSW Elevation	BMSW Depth	UTM E	UTM N	Elevation[1]	Twn	Rng	Sec	Mer.	Total Depth	Completion Date	Modifier[2]
		ft	ft	NAD 83	NAD 83	ft					ft		
4300711160	No nearby well	3456	2800	557135	4405405	6256 KB	12S	14E	3	S	4500	16-Jul-60	1
4301310496	No nearby well	3438	2317	583312	4473964	5755 GR	1S	1W	8	U	11482	22-Dec-63	1
4301330005	ambiguous	4002	1911	577913	4474860	5913 GR	1S	2W	2	U	10545	24-Aug-68	1
4301330039	ambiguous	3391	2686	577838	4476639	6077 GR	1N	2W	35	U	12030	11-Aug-70	4
4301330156	ambiguous	3048	2504	578344	4467432	5552 GR	1S	2W	35	U	13800	8-Feb-74	5
4301330346	ambiguous	3473	2245	575495	4468772	5718 GR	1S	2W	28	U	3500	11-Dec-74	1
4301330362	ambiguous	2619	4177	549974	4467467	6796 GR	1S	5W	35	U	4650	10-Apr-75	4
4301330371	ambiguous	3362	2772	554805	4457485	6134 GR	2S	4W	32	U	4000	17-Apr-75	1
4301330387	ambiguous	1707	4653	535307	4453498	6360 GR	3S	6W	8	U	11400	19-Jan-76	4
4301330388	ambiguous	3729	2046	545169	4452698	5775 GR	3S	5W	17	U	3710	2-Sep-75	1
4301330506	ambiguous	5142	288	582123	4431038	5430 GR	9S	17E	17	S	6200	27-Jan-83	1
4301330589	ambiguous	3711	2151	566157	4460634	5862 GR	2S	3W	21	U	12679	15-Jan-82	1
4301330630	ambiguous	3051	2645	576907	4432533	5696 GR	9S	16E	10	S	6085	15-May-82	1
4301330634	ambiguous	2885	2837	576139	4431715	5722 GR	9S	16E	15	S	5699	8-Apr-82	1
4301330704	ambiguous	3249	2966	565234	4466797	6215 GR	1S	3W	33	U	13845	25-Mar-83	1
4301330719	ambiguous	1083	5984	545977	4463249	7067 GR	2S	5W	9	U	14397	12-Jul-83	2
4301330762	ambiguous	5705	240	566241	4437033	5932 GR	5S	3W	4	U	6698	8-Aug-83	2
4301330842	ambiguous	5834	544	557600	4432579	6378 GR	5S	4W	15	U	6250	9-Jun-84	1
4301530022	No nearby well	-1743	8378	565649	4368651	6635 GR	16S	15E	3	S	8752	6-Oct-75	1
4301930240	ambiguous	4846	3597	652240	4367480	8443 GR	16S	24E	2	S	7600	13-Aug-75	1
4304710032	ambiguous	822	4776	663730	4438072	5598 GR	8S	25E	34	S	6610	5-Sep-65	1
4304710114	ambiguous	-439	5809	638961	4453478	5370 KB	7S	23E	7	S	3196	29-Oct-57	3
4304710870	ambiguous	1689	3428	633901	4456837	5117 GR	6S	22E	34	S	6600	10-Mar-64	1
4304715134	ambiguous	3183	1860	623012	4457281	5043 GR	6S	21E	33	S	7750	23-Jun-65	1
4304715300	ambiguous	-42	5542	641802	4448133	5500 KB	7S	23E	33	S	5592	22-Jul-64	1
4304720202	ambiguous	728	4552	607194	4463822	5280 GR	6S	19E	12	S	5894	1-Mar-68	1
4304720408	ambiguous	-1918	7118	627948	4474397	5200 GR	5S	22E	6	S	2349		3
4304720438	ambiguous	1085	3774	629050	4458950	4859 GR	6S	22E	30	S	8944	29-May-52	4
4304730066	ambiguous	982	4585	662509	4438875	5567 GR	8S	25E	34	S	14125	21-Jan-71	4
4304730103	ambiguous	2082	3330	633794	4449804	5412 GR	7S	22E	27	S	5888	18-Jun-71	1
4304730153	ambiguous	1261	3700	616316	4426432	4961 GR	10S	20E	2	S	11100	25-Jun-73	1
4304730156	No nearby well	2730	2471	646632	4431437	5201 GR	9S	23E	24	S	8500	20-Dec-73	1
4304730163	ambiguous	773	4748	660313	4446854	5521 GR	8S	25E	5	S	4561	10-Dec-73	3
4304730190	ambiguous	1468	3705	596262	4466115	5173 GR	2S	1E	3	U	12387	31-Mar-75	4
4304730298	ambiguous	4448	626	644473	4432500	5074 GR	9S	23E	15	S	9170	2-Dec-78	1
4304730341	ambiguous	309	5288	646222	4448618	5597 GR	7S	23E	25	S	5700	18-Oct-78	1
4304730369	ambiguous	1535	3800	640587	4423927	5335 GR	10S	23E	17	S	7085	13-May-78	1
4304730412	ambiguous	1922	3074	613399	4422688	4996 GR	10S	20E	16	S	8350	14-Nov-79	1
4304730458	ambiguous	1208	4167	634148	4450275	5375 GR	7S	22E	22	S	6801	16-Apr-81	1
4304730522	ambiguous	627	4907	644616	4449047	5534 GR	7S	23E	26	S	5700	20-Jun-79	1
4304730549	ambiguous	4531	226	626103	4432953	4757 GR	9S	21E	14	S	7000	23-May-79	2
4304730603	ambiguous	1627	3253	620413	4429787	4880 GR	9S	21E	30	S	6920	18-Mar-80	1
4304730647	ambiguous	4591	208	614277	4432304	4799 GR	9S	20E	15	S	5060	12-Nov-80	1
4304730732	ambiguous	203	4710	634269	4443586	4913 GR	8S	22E	10	S	6061	15-Jun-81	1
4304730826	ambiguous	2586	2381	597326	4424409	4967 GR	10S	18E	11	S	4818	24-Nov-82	1
4304730894	ambiguous	-205	5663	646122	4454597	5458 GR	7S	23E	12	S	5675	9-Jul-81	3
4304730959	ambiguous	4353	514	607752	4454941	4867 GR	7S	19E	1	S	4401	10-Aug-81	2
4304731018	ambiguous	4765	194	614912	4452286	4959 GR	7S	20E	15	S	7514	25-Jun-81	2
4304731128	ambiguous	4365	340	603067	4431718	4705 GR	9S	19E	16	S	7475	4-Feb-82	2
4304731200	ambiguous	4471	306	600566	4431637	4777 GR	9S	19E	18	S	5860	14-Jan-83	1
4304731300	No nearby well	-473	5747	634890	4453828	5274 GR	7S	22E	11	S	6186	26-May-83	1
4304731380	ambiguous	4758	295	587324	4436714	5053 GR	8S	17E	35	S	6200	27-Jan-84	2
4304731410	ambiguous	4544	295	596079	4436406	4839 GR	8S	18E	34	S	6237	7-Feb-84	2

[1]GR = ground; KB = kelly bushing.
[2]1= picked point in well; 2= BMSW above this point in well; 3= BMSW is below this point in well; 4= picked point in well with "non-saline" water >500 ft below; 5= same as 2, but "non-saline" water at least 500 ft below

Wells meeting the criteria for selection for log analysis were then loaded into an LAS-capable viewer and saved. The software allowed for mathematical manipulations and display of any of the LAS parameters. *PfefferPro* software was used to analyze logs, as well as spreadsheet applications found in Asquith and Krygowski (2004).

Spatial distribution of data: Plate 1 posts all but one of Howells and others' (1987) estimated BMSW points, also referred to here as TP-92 data consisting of 400 points. One of the TP-92 points was not included because no oil or gas wells were found in the township where this point was plotted (T. 16 S., R. 19 E., SLBLM). New points from this study's estimated BMSW are also plotted on plate 1, but with a slightly different color, totaling 260 points. Examination of plate 1 shows the uneven distribution of points in the study, as wells are clustered within active oil and gas fields. The exception to this is in the Greater Natural Buttes area where the deep shallow-casing depth reduces the number of usable wells.

Geophysical Log Analysis

The resistivity of a solution can be precisely calculated using the composition of dissolved ions, their concentrations, and the temperature. TDS of formation water is the concentration of all dissolved ions in solution, regardless of composition, and is not dependent on temperature. Since the resistivity of a solution is composition dependent, and TDS is not, converting resistivity to TDS without knowing the concentration of ions requires some assumptions about the solutions composition. The simplifying assumption is: the bulk of the ions affecting resistivity are sodium and chloride. This is true for most, but not all, produced waters from the Uinta Basin.

Resistivity of rocks is measured by a variety of geophysical methods. The resistivity of a rock is dependent on two main properties: 1) the resistivity of the non-porous mineral matter, and 2) the resistivity of the fluids within the pores of the rock. The non-porous mineral matter resistivity is high and very close to a constant for a given lithology, whereas the pore-filling fluid resistivity can vary greatly. Therefore, changes in the measured resistivity of similar lithologies in the subsurface are due primarily to changes in the pore-filling fluids. Using the known relationships between resistivity of solutions and TDS, we can use measured resistivity from oil and gas well geophysical logs as a proxy or estimate for the TDS of the formation water.

Geophysical log analysis is the method used for picking the BMSW in wells in both this study and the prior study (Howells and other, 1987). Howells and others provide an excellent detailed discussion of all the geophysical log interpretation methods so only a brief review follows. Others have published on similar techniques (Peterson, 1991; Jorgensen, 1989, 1996). Log analysis methods provide an approximation of a variety of parameters needed in calculating an estimate of the TDS of a permeable bed's formation water. If all the variables involved in calculating an estimated TDS were know with certainty, the result would be quite accurate, but generally most of the variables are not precisely known. Table 4 provides an

Table 4. *Sensitivity of Archie method and other parameters in estimating TDS of formation water.*

Accuracy	**± 2 %**	**± 1 φ unit (0.01)**	**variable**		**±5%**	**±2°**	**up to 25%**	**TDS mg/L**	
Parameter	resistivity ohm-m	Density φ (2.68)	Sw %	R_{wa}	FT	MAST	non-saline ions	estimate	% change
True values	28	0.1	100	0.28	95°F	50°F	100% NaCl	18,000	na
S_w 50% (R_w .28@FT)	111	0.1	50	1.12	95°F	50°F	100% NaCl	4,000	-78%
S_w 75% (R_w .28@FT)	49.6	0.1	75	0.50	95°F	50°F	100% NaCl	9,500	-47%
Max + porosity error	28	0.11	100	0.34	95°F	50°F	100% NaCl	14,200	-21%
Max - porosity error	28	0.09	100	0.23	95°F	50°F	100% NaCl	23,000	28%
Max + log variables	28.6	0.11	100	0.35	95°F	50°F	100% NaCl	14,000	-22%
Max - log variables	27.4	0.09	100	0.22	95°F	50°F	100% NaCl	24,000	33%
Matrix density 2.65 g/cc	28	0.084*	100	0.20	95°F	50°F	100% NaCl	26,000	44%
89.5% NaCl (HCO3+SO4)	28	0.1	100	0.28	95°F	50°F	89.5% NaCl	18,940	5%
80% NaCl (HCO3+SO4)	28	0.1	100	0.28	95°F	50°F	80% NaCl	20,130	12%
Max both temperatures	28	0.1	100	0.28	99.5°F	52°F	100% NaCl	17,500	-3%
Min both temperatures	28	0.1	100	0.28	90.4°F	48°F	100% NaCl	18,500	3%

Based on hypothetical BHT of 138° F, TD of 6500 ft, depth of zone 3320 ft.
Assume a =1, m =2, n =2 (a=tortousity, m=cementation exponent, n=saturation exponent)
FT = formation temperature
MAST = mean annual surface temperature
R_{wa} = apparent water resistivity
φ = porosity
*hold raw density the same

overview of the accuracy of various petrophysical properties and the sensitivity of an Archie-based estimate of TDS (see discussion of Archie method below) on those parameters. Porosity and water/hydrocarbon saturation stand out as the most sensitive parameters related to the estimated TDS.

One of the difficulties with log analysis in the Uinta Basin is the common presence of hydrocarbons in the system. Resistivity measurements in a well are sensitive not only to the pore-filling fluid chemistry, but also to the amount of gas and more so of oil. Lipinski (2008) provides an excellent analysis of this effect in the Green River Formation, Monument Butte field, and how it can impact water saturation calculations and derived apparent water resistivity (Rwa). Montgomery and Morgan (1998) comment on the challenges stratified formation waters offer in the Bluebell field: "...apparent variability in formation water resistivities makes calculations of water saturation potentially suspect or unreliable."

Well logs were evaluated by combining two primary mechanisms, 1) using the *PfefferPro* software to evaluate a discrete bed or unit and, 2) using the mathematical manipulation capabilities of the LAS viewing software (*Strater*) to develop and display new derived curves. Initially an F-log (1/porosity squared) was created using the average density-neutron porosity, density porosity, or sonic porosity, usually in that order based on availability of the curves. Combined with the SP log, these curves help to grossly bracket the BMSW interval in the well. Using the *PfefferPro* approach, zones both above and below the bracketed BMSW were selected, based first on permeability and second on lithology (sandstone being preferred). Individual "units" were picked on the log and entered into the *PfefferPro* worksheet. With the units for evaluation selected, the LAS values were imported and each unit run through a series of evaluation techniques. A Pickett Plot was constructed for each unit and generally a cross-plot lithologic analysis was run, when the correct curves were available. The software provided a range of different techniques and the ability to experiment with differing parameters. With the best estimate for the apparent resistivity of the formation water (R_{wa}) for all units, the BMSW boundary could be further limited to a discrete footage range.

The second method used in log interpretation was the preparation of a hypothetical 10,000 mg/L pure Na-Cl water R_w curve adjusted for borehole temperature and plotted on the depth scale of each log. A second curve, representing a calculated R_{wa}, was plotted on the same depth scale. An added fill pattern allowed for a quick visual check on when the calculated estimate was over or under the 10,000 mg/L curve. This method allowed for a check on the first method and a quick view of the deeper portion of the borehole, below the picked BMSW.

Archie method: This method is based on the equation:

$$R_o = F(R_w) \quad (1)$$

where:

R_o = the resistivity of water-filled formation.
F = the formation factor = a/φ^m, a = tortuosity factor, φ = porosity, and m = cementation factor.
R_w = the resistivity of the water in the pore space (Archie, 1942).

The Archie equation is rearranged to solve for R_w. Howells and others (1987), Asquith and Krygowski (2004), and Ellis and Singer (2008) provide a more detailed discussion of use of the Archie method. Without core petrophysics and water analyses from a particular zone, all of the parameters in the Archie equation are assumed or estimated from field studies, geophysical logging techniques, or operator trial and error. The results are as good as the combination of assumptions and estimates of Archie parameters. The beginning approach was to assume a =1 and m = 2.0, which is supported by work from Cluff and others (2008) and from unpublished company reports (Jim Kinser, Bill Barrett, personal communication, 2010). Based on work in the Uinta Basin by Cluff and others (2008), m was determined using their constructed curve relating the best choice of m for a given porosity. Their work showed that the m factor was reduced when porosity dropped below 10%. Cluff and others (2008) also demonstrated that the m value was affected by the salinity of the formation waters. Their experiment looked at varying the salinity from 20,000 mg/L to 200,000 mg/L. Within this range, m decreased with decreasing salinity. Inappropriate use of a value of 2.0 for m causes an overestimation of the salinity, which could occur when the porosity is below 10% or in zones with moderately saline formation waters. In table 4, when the porosity dropped below 10%, and no such adjustment was made, the resulting estimated TDS error increased.

SP method: The SP (self-potential) method is based on the electrical potential developed between the borehole and the permeable beds or zones encountered. Howells and others (1987) and Ellis and Singer (2008) provide more detailed explanations of the method. An advantage of this method is that it does not require knowing the porosity of the zone of interest. Like many other log analysis methods, there are many things that can cause incorrect results. Thin beds, shale, and hydrocarbon content suppress the SP and negatively affect the accuracy of the calculated R_w. Since shale and hydrocarbons are both commonly associated with a large part of the stratigraphic section of the Uinta Basin, these limitations must always be considered when applying the method.

Resistivity method: This method is used when no porosity log is available. In the current study, a well was eliminated from the selection list if it did not have a porosity log and so the method was not used. Additional information about the method is found in Howells and others (1987), Jorgensen (1996), and Asquith and Krygowski (2004).

Input Factors

Log calculations involve various input factors which profoundly affect the resultant estimate of the TDS concentration. Table 4 helps to illustrate the effects of the parameters discussed below.

Temperature: The resistivity of a solution is dependent on the temperature. Determining the temperature of the borehole and/or near borehole temperature involves several assumptions. The first of these is estimating the mean annual surface temperature (MAST) of the location of the well. With very few temperature measurement sites in the Uinta Basin, constructed maps are created using known temperature averages and topography. The map used (Thornton and others, 1996) bracketed the temperature in five degree Fahrenheit increments and used a small scale. The map was overlain on the project base map. An estimate of the temperature within this five degrees was then based on the elevation of the well.

The bottom hole temperature (BHT) was determined using a combination of the reported BHT from the log header information and an adjustment based on the Horner technique, as modified by Chapman and Keho (1982) and Chapman and others (1984), which uses the difference between the recorded BHT with elapsed time. The objective of the analysis is projecting the temperatures to an equilibrium bottom hole temperature (EBHT). Data points were gathered from wells where two temperature measurements were taken over some known period of time (Chapman and Keho, 1982). Chapman and others (1984) used 97 such data points from the Uinta Basin to develop a curve relating elapsed time since drilling stopped and recorded BHT to EBHT, shown in figure 3. The greater the elapsed time, the lower the percent adjustment to BHT. All R_{wa} calculations were made at formation temperature and then converted to a temperature of 68°F using the equation:

$$R_{w2} = R_{w1}(T_1 + 6.77/T_2 + 6.77) \quad (2)$$

where:

R_{w2} = resistivity at 68°F.
R_{w1} = resistivity at formation temperature.
T_1 = formation temperature.
T_2 = 68°F.

Water chemistry: The composition of dissolved solids in the water will change its resistivity. All industry chart books are based on a pure sodium-chloride solution. The resistivity of a 10,000 mg/L solution of pure sodium-chloride at 68°F is 0.65 ohm-m (Schlumberger, 1984; Baker-Hughes, 1995). As other constituents are substituted for sodium and chloride, the resistivity of the resultant solution, of similar concentration, increases. Most industry chart books provide a page devoted to estimating the resistivity of a complex solution containing more than sodium and chloride ions. Within the Uinta Basin,

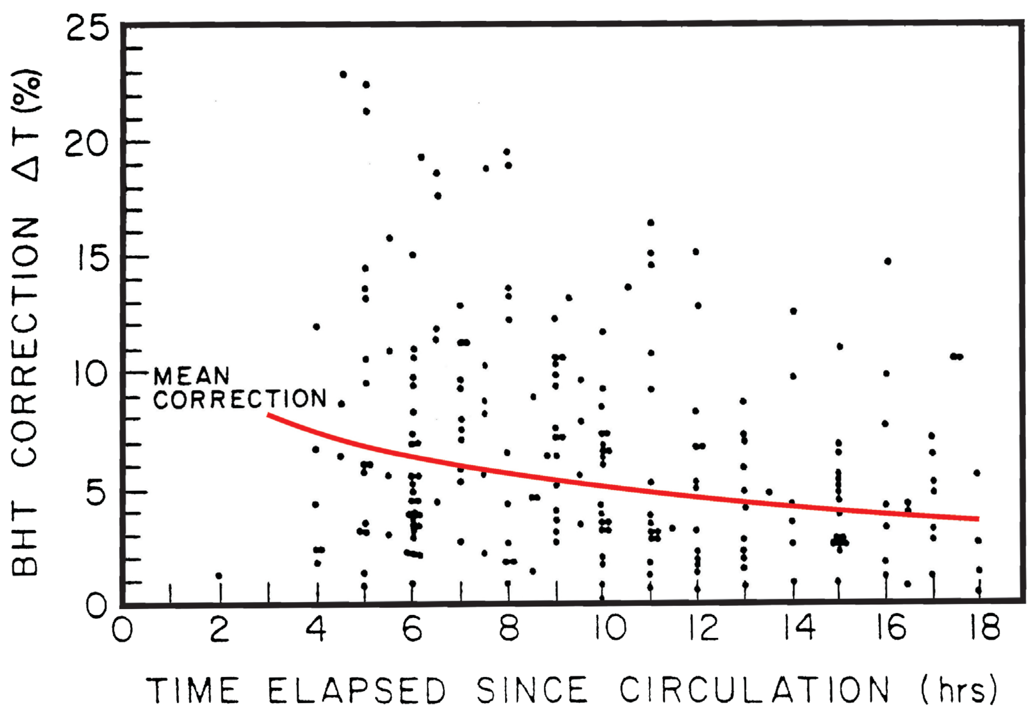

Figure 3. *Magnitude of bottom-hole correction, expressed as a percentage of the observed value in °C as a function of elapsed time after circulation, for 97 wells with BHT values recorded (after Chapman and Keho, 1982).*

a strongly calcium-bicarbonate or sulfate-dominated 10,000 mg/L solution can yield an R_w of up to 0.82 ohm-m. Sodium-chloride dominated waters are most common within the deeper portions of the basin (Zhang and others, 2009). Unfortunately it was uncommon to find a water analysis from the depth interval near the BMSW in wells. Most water samples are from deeper producing zones, so calibrations of the expected R_w from water samples in units near the BMSW in a well were rarely performed. Typically, a pure sodium-chloride solution was used in construction of the expected R_w curve unless available water data indicated otherwise.

Hydrocarbons: Hydrocarbons are abundant within the stratigraphic section of the Uinta Basin, causing one, if not the most, difficult factor in log interpretation. Hydrocarbons increase the resistivity of a permeable zone and resistivity is a proxy for TDS. Unrecognized hydrocarbon saturation in permeable beds drives the interpreter towards concluding the R_w of the formation water is fresher than reality. Lipinski (2008) provides an excellent discussion of this problem in the Monument Butte field. From sidewall core analysis in the well 4304733662 (DOGM web files, accessed 11/30/11), the middle Green River Formation contains oil saturations from 5 to 58%.

Typical methods for gas detection were used including density-neutron crossover, lithology cross plotting, and SP deflection in contrast to the polarity of the resistivity curve separation. Access to a mud log during salinity interpretation is very helpful in attempting to adjust the R_{wa} for the effects of hydrocarbon saturation. Unfortunately, mud logs are not available for most wells in the basin. Pickett plots with water saturation (S_w) curves of 100 and 60 percent were helpful in adjusting Rwa for some assumed hydrocarbon saturation. Interpretive license was applied to this problem and when such license impacted the interpreted R_{wa} for a zone, it was so noted. Correction for hydrocarbons was probably on the conservative side (R_{wa}'s too high). This approach errs on the side of aquifer protection, but points to the need for collection of good formation water samples in the regulatory process for future disposal wells.

Lithology: Lithologic interpretation makes a considerable difference in the assumed porosity for a unit. Most logs in the basin are run using a density of 2.68 g/cc and a sand matrix for the neutron log. Sandstone is the dominant reservoir in the basin, but occasionally a lime-dominated zone was evaluated and the porosity values appropriately changed. Data from core indicate 2.65 g/cc may be the best representation of Mesaverde Group sandstone reservoirs (Brynes and others, 2007; Jim Kinser, Bill Barrett Corporation, personal communication, 2009). A change in density from 2.68 g/cc to 2.65 g/cc will change the porosity of the unit downward about 1.5%. Table 4 shows how this change in porosity affects the R_{wa} and estimated TDS. As with hydrocarbons, available mud logs would aid in lithologic determination, but are not commonly available.

Time: This fourth dimension was not directly studied but is worthy of a few comments. From Howells and others' (1987) mapping, no profound changes are implied by the new data that can be related to time. In reviewing the more recent drilling, caution was used in areas where water injection is, or has been, part of the operating history. Several water analyses were rejected for use in mapping the BMSW based on nearby injection history and anomalous water quality. Future changes in basin water quality are inevitable, but the small amount of injected water relative to basin capacity would require more detailed study to document these changes.

HYDROGEOLOGY

The Uinta Basin's hydrogeology is very complex. About 80% of the basin's recharge occurs in the north from the Uinta Mountains, with elevations in excess of 13,000 feet (Hood and Fields, 1978; Zhang and others, 2009). The southern edge of the basin (as defined in this study, Plate 1) includes part of the Book Cliffs, a relatively high (8000 to 9000 ft) escarpment that contributes minor recharge from the south. To date, no basin-wide computer-based groundwater-flow model with a water budget has been developed for the Uinta Basin. A water budget was developed prior to the use of computer models and summarized by Holmes (1985) to be 630,000 acre feet. Waste production water disposed by injection for 2010 represents 0.5% of this volume. Bredehoeft and others (1994) modeled the basin, but with an objective of explaining high pressure encountered at depth in the Altamont-Bluebell field. The reader is referred to Howells and others (1987) for a more detailed summary of the basin's hydrogeology. Smaller portions of the basin have been studied since 1987 and are briefly reviewed below, based on where they occur in the stratigraphic section.

Stratigraphy

Figure 4 is a diagrammatic stratigraphic column of Uinta and Piceance Basin stratigraphy. The applicable stratigraphy for the Uinta Basin is on the left side of the diagram. Howells and others (1987) provide a brief hydrogeologic description of each of the formations in the Uinta Basin, while several other authors have addressed the natural gas (Morgan, 1993; Chidsey, 1993a, 1993b) and crude oil (Morgan, 2009a, 2009b) resources of the basin. Relevant new hydrogeologic studies or discussion follow below.

Duchesne River–Uinta Formations

The Duchesne River and Uinta Formations are the youngest sedimentary rocks in the basin and only crop out in the north. Underground injection and disposal wells are sited in these formations. Glover (1996) combines these two formations into one aquifer, with most of its recharge from the Uinta Mountains and discharge to local streams. The thickness of this combined unit is about 8000 feet and Glover models a confining unit below the aquifer consisting of the Parachute Creek Member of the Green River Formation, which separates it from the underlying Douglas Creek aquifer. The Duchesne River–Uinta aquifer coarsens towards the Uinta Mountains, with the Uinta Formation being the finer-grained of the two units. Glover reports an area of confined conditions in the center of the model area.

Freethey (1992) studied an area in the Altamont-Bluebell field, mainly in eastern Duchesne County, looking for evidence of upward leakage from existing water disposal wells into shallow domestic groundwater wells. Most of the shallow disposal wells were completed in the lowermost section of the Duchesne River Formation, from 2000 to 3500 feet deep, where the BMSW is relatively shallow. Groundwater flow in this part of the basin appears to be from northwest to southeast. Freethey (1992) found no direct evidence of upward leakage, but suggests several approaches to a more detailed study of the issue. Naftz (1996) describes rock-water interactions from recharge to discharge areas in this aquifer. The lower Uinta Formation and upper Green River Formation in the Cedar Rim field contain trona and likely other evaporites, affecting the salinity of the formation fluids (Jim Kinser, Bill Barrett Corporation, written communication, 2012).

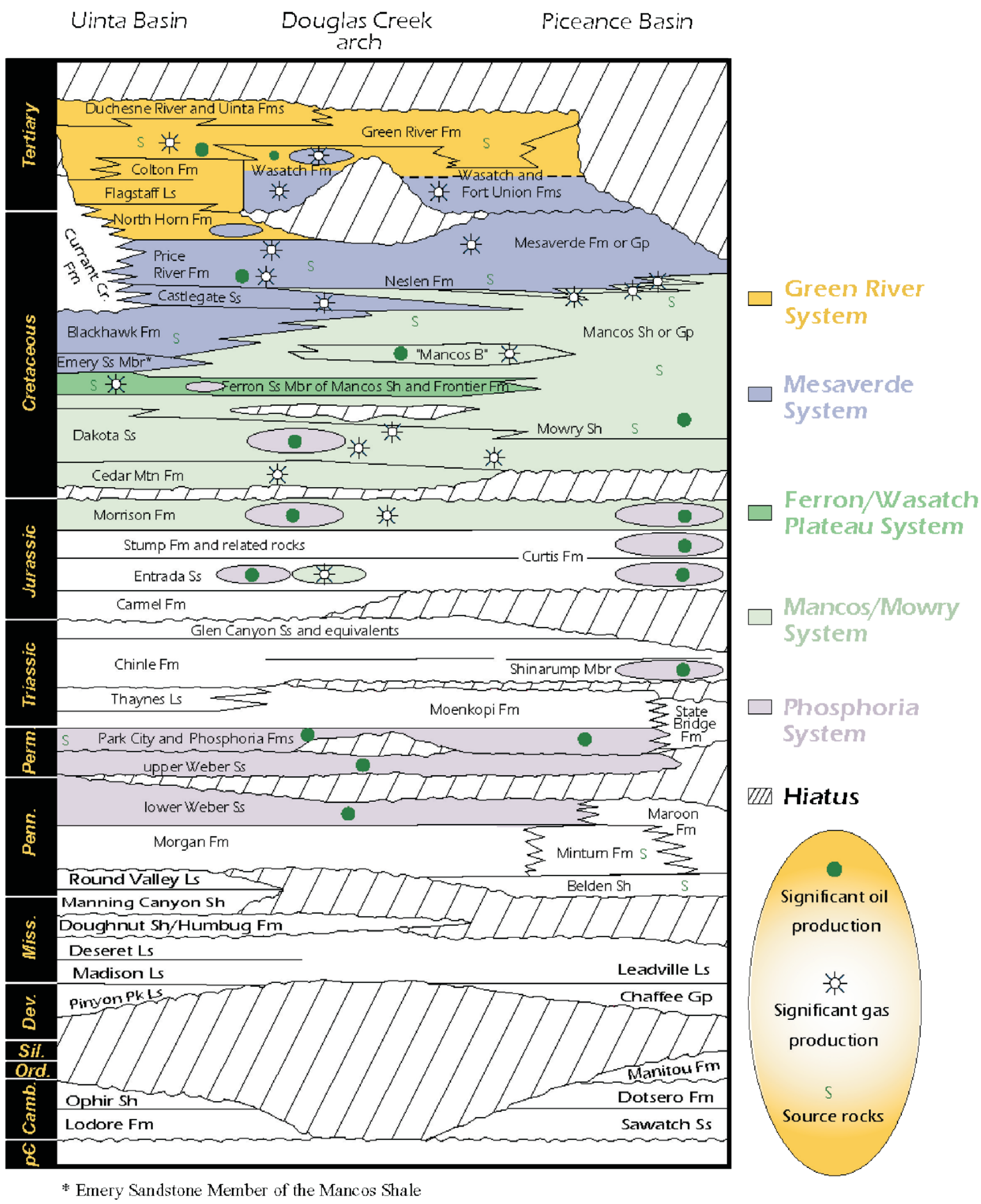

Figure 4. *Stratigraphic column of the Uinta and Piceance Basins, Utah and Colorado (from U.S. Geological Survey, 2003).*

Green River Formation

The Green River Formation is found throughout most of the subsurface of the basin except for a band about 3 to 10 miles wide along the southern limit of the study area. The formation is an important source and reservoir for oil and gas. The upper portion of the formation in the eastern part of the basin contains the Birds Nest aquifer, a potential large-scale saline water disposal zone (Vanden Berg and others, 2011). Holmes and Kimball (1987) studied the Green River Formation in the eastern portion of the basin, near the potential oil shale development areas. Stratigraphically, the study looked at the formation from the Birds Nest aquifer (upper Green River Formation) to the intertonguing Renegade Member of the Wasatch Formation. The section studied had a strong east-west anisotropy based on flow modeling, believed to be tied to a similarly oriented fracture pattern, which parallels the region's gilsonite veins. The authors provide a detailed analysis of the geochemical evolution of waters as they move through these aquifers. Wanty and others (1991) discuss groundwater geochemistry of the Green River and Wasatch Formations along flow paths in the basin.

Kelso and Ehrenzeller (2008) provide a good summary of oil and gas activity in the western Greater Monument Butte area, which includes core data from several holes and lithologic descriptions from the middle portion of the Green River Formation. Lipinski (2008) discusses the log responses from the Green River Formation in the central Uinta Basin noting: 1) the complexities of varying R_w, lithologic variations, and the almost ubiquitous partial saturation of solid hydrocarbons, 2) the value of applying shale models in log interpretation are not particularly helpful given the inability to accurately predict shale volume, 3) calculating R_w from Archie's equation almost always yields a value too high (too fresh) because the residual oil found in the rocks causes anomalously high resistivity, and 4) porosity of greater than 20% is an indication of relatively fresh water because these higher porosity rocks are the result of dissolution of carbonate cement by non-saline water.

Wasatch Formation

The Wasatch Formation lies below, but interfingers with the lower portion of the Green River Formation. Many of the recent studies mentioned above for the Green River Formation also address the Wasatch Formation. Zhang and others (2009) cover this formation in their basin-wide paper on hydrogeochemistry. Pitman and others (1986) offer updated studies on the geology and hydrocarbon potential of the formation.

Estes-Jackson and others (2008) share their experience in the Hanging Rock field (T. 12 S., R. 23 E., SLBLM) with Wasatch production. Four sidewall core samples yielded an average grain density of 2.64 g/cc, water samples from the reservoir indicate an R_w = 0.058 at 68°F, and the sandstone reservoir rocks are chert arenites with a shale content of about 10% and gamma-ray cutoff of 75 API units.

Stancel and others (2008) studied the Love field (T. 11 S., R. 21 E., SLBLM) and give a range of TDS values for waters from the Wasatch and Mesaverde of the Greater Natural Buttes field, which range from 20,000 to 30,000 mg/L and 45,000 to 50,000 mg/L respectively. Co-mingled waters have a TDS range of 31,000 to 44,000 mg/L. The authors provided water analyses from 17 wells within the Love field for this study (see appendix A). From 409 core samples, the average grain density was 2.68 g/cc. Stancel and others (2008) noted the following relating to vertical movement of water in the basin:

> Faults with 50 to 150 ft of throw are recognized in the western part of the GNB [Greater Natural Buttes] Fairway where they cut the top of the Uteland Butte Limestone . . . Limited 2-D seismic coverage coupled with interpretation from aeromagnetic data indicate that these faults overlie and may be in continuity with the major west-northwest-trending fault system that defines the southern extent of the GNB Fairway. Some "plumbing" associated with deeper seated faults is supported by the observation that several wells drilled in proximity to the Uteland Butte faults have recovered anomalously high water cuts that may be coming from a deeper source.

Mesaverde Group

The Mesaverde Group has been an expanding frontier for new drilling in the Uinta Basin in the past 20+ years. Where most of this drilling has occurred, the formation has produced mostly saline water. Water freshens with shallower depths and toward its outcrop on the south side of the basin (Zhang and others, 2009). Stancel and others (2008) characterized the produced water TDS from the Mesaverde in the Greater Natural Buttes field as ranging from 45,000 to 50,000 mg/L; from 564 core samples in the Love field the average density was 2.67 g/cc. However, the Mesaverde section drilled in the West Tavaputs area had a matrix density of 2.65 g/cc (Jim Kinser, Bill Barrett Corporation, personal communication, 2009).

Sub-Mesaverde Group

In the past, most drilling below the Mesaverde Group was limited to the southern part of the basin (mainly to the Dakota Formation) where drilling depths were shallower. Improved drilling and completion techniques along with higher petroleum prices have increased interest in reservoirs such as the Mancos Shale, along with plays in Jurassic and older rocks. These factors have driven drilling ever deeper and farther north into the basin for these objectives. In the deeper part of the basin, water in these formations is generally saline.

Structure

Plate 1 shows the structural axis of the basin. South of this line, rocks dip to the north, and north of this line, beds dip steeply south or are overturned. For additional structural information on the Uinta Basin see references such as: Johnson, 1986; Stone, 1993; U.S. Geological Survey Assessment Team, 2003; Anderson, 2005; Sprinkel, 2007, 2009; and Morgan, 2009a. Plate 1 also shows faults taken from the digital geologic map of Utah (Hintze and others, 2000). The basin has two dominant fracture patterns which follow the faulting, east-west (Duchesne fault zone) and northwest-southeast (gilsonite dike trend). Local areas may have fractures that vary from these regional trends.

RESULTS

The results of the mapping the BMSW are presented on plate 1, which shows the elevation of the BMSW surface. Both the old (TP-92) data and new points added in this study are used in the contouring (Table 5). Some of the old TP-92 points were re-evaluated and changed (15 points). These altered points are shown on Plate 1 with a red dot in the center of the map symbol. TP-92 and new data points are divided by symbol color (TP-92 = dark blue, new points = light blue) with five different conditions of data points for both old and new. The data conditions are: 1) BMSW is picked within the logged interval; 2) the BMSW was not found in the logged interval and the water appears to be saline in the shallowest part of the well log, and generally the top of the logged interval is also the depth/elevation assigned to the point, thus the BMSW is "less than" the depth posted (greater than when converted to elevation); 3) the well logs indicate "non-saline" water to the total logged depth, and the total depth of the logged interval is the depth of the point, thus this is "deeper than" the point depth posted (less than when converted to elevation); 4) BMSW picked within the logged interval, but the logs also indicate "non-saline" water more than 500 feet below the mapped BMSW; 5) same as condition 2 above, but "non-saline" water is observed at depth in the well at least 500 feet below the picked BMSW.

Water analyses from wells help constrain the BMSW picks from geophysical logs. Figure 5 summarizes all of the water analyses from the database (appendix A) that received a "yes" for mapping the BMSW. From the figure, TDS and depth show some increase in the bottom end of the data cloud, but the highest TDS values are associated with depths less than 6000 feet. This is likely related to the saline zones in the shallow Green River Formation (Birds Nest aquifer). Clearly depth and TDS are poorly correlated when all of the basin's aquifers are lumped together; however, as mentioned earlier, some individual

Table 5. *Well logs interpreted and BMSW picked for this study. (Excel file included on CD.)*

API	Well Name	BMSW Elevation	BMSW Depth	Mapped[1]	Twn	Rng	Sec	Mer.	Well Type[2]	Total Depth	Completion Date
		ft	ft							ft	
4304737831	UTE 2-17A1E	3371	2190		1S	1E	17	U	OW	11226	13-Sep-08
4304730830	UTE TRIBAL 1-25A1E	327	5000	NO	1S	1E	25	U	D	14054	14-Nov-83
4304731112	BOLTON 2-29A1E	41	5394	NO	1S	1E	29	U	OW	13100	10-Feb-82
4304739467	FLYING J FEE 2-12A1	3317	2400		1S	1W	12	U	OW	10854	28-May-08
4301330011	VICTOR C BROWN 1-4A2	5095	863		1S	2W	4	U	OW	11434	9-Apr-69
4301332202	BOWMAN 5-5A2	2655	3485	NO	1S	2W	5	U	OW	16015	25-Jun-01
4301330737	FISHER 1-16A4	2111	5420		1S	4W	16	U	OW	17593	10-Sep-83
4301330196	STEVENSON HEIRS 1-36A5	2734	3966		1S	5W	36	U	OW	15700	14-Oct-86
4304730931	1-2B1E	1486	3710		2S	1E	2	U	OW	12600	5-Nov-83
4304732409	HORROCKS 2-5B1E	2923	2448		2S	1E	5	U	OW	12672	27-May-93
4304734080	THOMAS 4-10B1	2410	2706		2S	1W	10	U	OW	12900	8-Mar-02
4304732744	RICH 2-13B1	2112	3000		2S	1W	13	U	OW	12500	1-Oct-96
4304731981	COOK 1-26B1	2494	2530		2S	1W	26	U	OW	15500	5-Nov-91
4301331056	EVANS-UTE 2-17B3	3511	2530		2S	3W	17	U	OW	13200	27-May-85
4301331298	WEIKART 2-29B4	-293	6500	NO	2S	4W	29	U	OW	12900	18-Mar-92
4301330316	S. BROADHEAD 1-9C5	4718	1300		3S	5W	9	U	OW	11516	9-Nov-74
4301332112	OWL 3-17C5	1618	4214		3S	5W	17	U	OW	9897	12-Jan-99
4301331612	UTE 2-5C6	2576	4389		3S	6W	5	U	OW	12600	6-Sep-98
4301334276	9-11-36 BTR	3305	2990		3S	6W	11	U	OW	11280	12-Apr-10
4301330243	CEDAR RIM 6	2889	3202		3S	6W	21	U	OW	10005	29-Mar-74

Table 5. *continued*

API	Well Name	BMSW Elevation	BMSW Depth	Mapped[1]	Twn	Rng	Sec	Mer.	Well Type[2]	Total Depth	Completion Date
		ft	ft							ft	
4301330298	UTE TRIBAL G-1 (1-24C6)	5355	500		3S	6W	24	U	OW	10230	8-Nov-74
4301333638	12-36-36 BTR	5003	990		3S	6W	36	U	GW	10146	20-Oct-07
4301331038	SMITH 1-20C7	-1205	7902		3S	7W	20	U	OW	10800	28-Feb-85
4301331634	SMITH 2X-23C7	2333	4318		3S	7W	23	U	D	5250	25-Jun-96
4305130010	MA SMITH OIL INVEST. 1	1980	5317		3S	9W	16	U	D	13260	28-Jul-81
4304751046	UTE TRIBAL 11-2-4-1E	4601	630		4S	1E	2	U	OW	7900	20-Sep-10
4304733541	UTE TRIBAL 4-25	4292	789		4S	1E	25	U	OW	6720	1-Mar-01
4301333944	UTE TRIBAL 12-22-4-1	3686	1452		4S	1W	22	U	OW	6975	14-Oct-08
4304734527	UTE TRIBAL 31-31	4682	338		4S	2E	31	U	D	14614	30-Sep-02
4304734158	LELAND BENCH 35-22	4605	100		4S	2E	35	U	D	14400	21-Aug-02
4301333634	UTE TRIBAL 8-30-4-2	5100	430		4S	2W	30	U	D	285	20-Oct-07
4304733017	UTE TRIBAL 29-13 D3E	4171	540	NO	4S	3E	29	U	GW	8062	21-Jan-98
4301331938	UTE TRIBAL 33-16-D3	4128	1750	NO	4S	3W	33	U	WI	6529	24-Dec-97
4301331012	COYOTE UTE TR 4-9D4	4862	888		4S	4W	9	U	OW	8500	19-Oct-85
4301331212	UTE TRIBAL 2-18D	4460	1490		4S	4W	18	U	OW	7990	28-Sep-88
4301331818	FEE 28-02D4W (WSW)	4408	1552		4S	4W	28	U	WS	3027	13-Nov-98
4301333565	7-7-46BTR	5022	912		4S	6W	7	U	GW	8731	1-Nov-07
4301333657	7-20-46 DLB	5111	1017		4S	6W	20	U	OW	7406	21-Mar-08
4301333576	LC TRIBAL 8-28-46	5671	1618		4S	6W	28	U	OW	6250	28-Feb-08
4304738400	HUBER FED 26-24	2746	2600		5S	19E	26	S	OW	14529	24-Sep-07
4301331858	UTE TRIBAL 07-15	4994	1080		5S	3W	7	U	WI	6208	30-May-97
4301331475	UTE TRIBAL 29-10	5079	1463		5S	3W	29	U	WI	5962	16-Dec-95
4301332568	UTE TRIBAL 11-13-54	5590	685		5S	4W	13	U	OW	6475	12-Oct-04
4301333300	UTE TRIBAL 10-18-54	4808	1777		5S	4W	18	U	OW	6190	5-Feb-07
4301332891	UTE TRIBAL 13-26-54	4903	1868		5S	4W	26	U	OW	6180	15-Apr-06
4301332896	UTE TRIBAL 4-32-54	5170	1740		5S	4W	32	U	OW	5981	6-Sep-06
4301332720	UTE TRIBAL 11-8-55	3120	4050		5S	5W	8	U	D	6226	23-Oct-05
4301332841	UTE TRIBAL 13-20-55	6244	1308		5S	5W	20	U	OW	6108	30-Dec-05
4301332759	UTE TRIBAL 16-25-55	6237	845		5S	5W	25	U	OW	6075	29-Jul-05
4301333363	UTE TRIBAL 3-32D-55	4765	1652		5S	5W	32	U	OW	6120	20-Apr-07
4301333577	LC TRIBAL 7-3-56	5841	1540		5S	6W	3	U	OW	6150	3-Nov-07
4301333541	LC TRIBAL 3-17-56	5972	1893		5S	6W	17	U	OW	6040	1-Dec-07
4301332993	UTE TRIBAL 3-25-56	5899	1908		5S	6W	25	U	OW	6292	15-Dec-06
4304737558	FEDERAL 6-11-6-20	3001	1916		6S	20E	11	S	OW	8270	30-Mar-07
4304739078	FEDERAL 14-24-6-20	2383	2388		6S	20E	24	S	OW	7700	24-Nov-08
4304737559	FEDERAL 5-19-6-21	2384	2366		6S	21E	19	S	OW	7671	27-Jan-07
4304733871	HORSESHOE BEND 26-2	2266	2700		6S	21E	26	S	GW	3750	19-Jul-01
4304734682	HSB 4-28	3035	1787		6S	21E	28	S	GW	3869	17-Dec-02
4304731698	ANNA BELLE 31-2-J	2704	2000	NO	6S	21E	31	S	OW	7150	28-Mar-86
4304731672	CROQUET FEDERAL 2	3250	1540		6S	21E	35	S	GW	3530	4-Nov-85
4304730878	W WALKER ST 2-32	3295	1667		6S	22E	32	S	D	3565	22-Jul-85
4304737399	N WALK HOLL 2-32-6-23	392	4542		6S	23E	32	S	GW	10732	29-Sep-07
4304732444	WILLOW CREEK 1-8	2544	2581		6S	24E	8	S	D	7500	30-Oct-93
4301333449	FEDERAL 8-1-64	5751	685		6S	4W	1	U	OW	5620	9-Nov-07
4301333448	FEDERAL 5-3-64	5910	1128		6S	4W	3	U	OW	5985	29-Jun-07
4301332699	FEDERAL 6-1-65	6383	977		6S	5W	1	U	OW	5920	15-Nov-06
4301333491	FEDERAL 6-11-65	4575	3106		6S	5W	11	U	OW	5985	19-Oct-07
4301330538	INDIAN CANYON U 2	3172	4084		6S	7W	14	U	GW	18003	30-Sep-81
4304930014	HALLS FED 1-13-3C	6298	1452		7S	05E	13	S	D	12061	24-Mar-85
4304736668	WALL 13-17	3941	890		7S	20E	17	S	GW	14761	21-Dec-06
4304731381	PELICAN FED 3-35	2044	2803		7S	20E	35	S	D	6857	24-Nov-83
4304735408	BBE 15G-16-7-21	2776	2018		7S	21E	16	S	OW	7111	10-Feb-06
4304736516	BBW 11G-20-7-21	1239	3710		7S	21E	20	S	OW	7330	30-Mar-06

Table 5. continued

API	Well Name	BMSW Elevation	BMSW Depth	Mapped[1]	Twn	Rng	Sec	Mer.	Well Type[2]	Total Depth	Completion Date
		ft	ft							ft	
4304734837	SU BW 6M-7-7-22	3494	1574		7S	22E	7	S	GW	14250	6-Jul-04
4304733765	RW 22-13A	3881	1540		7S	22E	13	S	OW	6175	18-Oct-01
4304734403	SU BRENNAN 15W-18-7-22	4202	944		7S	22E	18	S	GW	9200	19-Jun-02
4304735670	RWU 32-27AG	2647	2796		7S	22E	27	S	OW	6030	15-Feb-05
4304735608	WHU 84	28	5380		7S	23E	1	S	OW	5504	30-Sep-04
4304733497	RW 13-19B	508	4908		7S	23E	19	S	WI	8594	24-Jul-00
4304737946	RW 12-32BG	803	4545		7S	23E	32	S	GW	7588	3-Apr-07
4304735238	RW 32G-16C	112	5700		7S	24E	16	S	GW	5765	19-Mar-04
4304735239	RW 12G-20C	111	5540		7S	24E	20	S	GW	5613	30-Mar-04
4304735098	RW 34-22C	47	5700		7S	24E	22	S	GW	9990	11-Dec-03
4301332374	SAND WASH 11-19-8-17	4962	400		8S	17E	19	S	WI	6590	5-Dec-05
4304734475	IGNACIO 33-221	4195	470		8S	20E	33	S	GW	7855	28-Apr-02
4304733648	WV 9W-2-8-21	2045	3000		8S	21E	2	S	GW	8225	8-Jan-01
4304735412	SU 11MU-9-8-21	3811	1000	NO	8S	21E	9	S	GW	10130	24-Jun-04
4304735372	WVX 8MU-19-8-21	3808	902		8S	21E	19	S	GW	10100	8-Sep-04
4304732458	GH 12	1206	3500	NO	8S	21E	19	S	WI	5420	6-Apr-95
4304734340	WV 8W-24-8-21	3194	1605		8S	21E	24	S	GW	7585	18-Mar-03
4304734105	NDC 109-27	1469	3314		8S	21E	27	S	D	6867	4-Sep-03
4304734507	TRIBAL 36-148	3645	1065		8S	21E	36	S	GW	12104	8-Feb-04
4304735457	GB 3MU-3-8-22	448	4795		8S	22E	3	S	GW	9992	21-Apr-05
4304734762	OU GB 12W-4-8-22	1911	3295		8S	22E	4	S	GW	8300	8-Mar-03
4304735381	SG 2MU-11-8-22	638	4500		8S	22E	11	S	GW	9600	27-May-05
4304734646	OU WIH 13W-21-8-22	2739	2195		8S	22E	21	S	GW	7475	4-Apr-03
4304735388	WRU EIH 4MU-25-8-22	908	3998		8S	22E	25	S	GW	8520	10-Jan-05
4304735331	EIHX 11MU-25-8-22	675	4270		8S	22E	25	S	GW	8335	14-Mar-05
4304733583	N CHAPITA 111-32	3330	1400	NO	8S	22E	32	S	D	6737	7-Aug-00
4304736061	WKRP 823-34A	2794	2300		8S	23E	34	S	GW	9150	19-May-06
4304732538	RW 41-4F	1683	3920		8S	24E	4	S	GW	10055	1-Feb-95
4304737671	BZ 10D-16-8-24	2200	3018		8S	24E	16	S	GW	13694	30-Aug-07
4304738498	SAND RIDGE 1-28	1863	3316		8S	24E	28	S	GW	8300	10-Nov-08
4304737276	CWD 12ML-32-8-24	2900	2210		8S	24E	32	S	D	8000	21-Jun-06
4304737884	E COYOTE 10-2-8-25	-281	5962		8S	25E	2	S	D	7200	25-Jan-07
4304732253	COYOTE FEDERAL 12-5	1978	3636		8S	25E	5	S	OW	4674	25-Aug-92
4304732255	COYOTE FEDERAL 13-7	2331	3198		8S	25E	7	S	OW	4500	10-Oct-92
4304737114	HK 12ML-30-8-25	2909	2374		8S	25E	30	S	D	7376	2-Oct-06
4304731129	FEDERAL 7-14R-9-17	3981	1180		9S	17E	14	S	OW	6011	18-Jun-82
4301332274	BELUGA U 4-18-9-17	4197	1260		9S	17E	18	S	WI	5875	25-Aug-04
4304735594	FEDERAL 10-4-9-18	4622	350		9S	18E	4	S	OW	6020	20-Jun-06
4304731199	DRIETTE BENCH 34-5	4507	270		9S	19E	5	S	OW	5700	29-Sep-82
4304737755	NBU 920-20I	1987	2800	NO	9S	20E	20	S	GW	10700	9-Aug-08
4304737011	FEDERAL 920-26M	2143	2720		9S	20E	26	S	GW	7600	18-Apr-07
4304733869	JENKS 5-153	4215	470		9S	21E	5	S	GW	7315	24-Aug-01
4304733009	NBU 260	3233	1721		9S	21E	28	S	GW	8418	2-Mar-00
4304730234	CWU 33-16	3179	1600		9S	22E	16	S	GW	6620	30-Mar-77
4304739371	NBU 922-18G	2139	2677	NO	9S	22E	18	S	GW	9530	1-May-08
4304735547	CWU 651-6	3467	1442		9S	23E	6	S	GW	8063	8-Nov-04
4304738875	NBE 12SWD-10-9-23	3324	1650		9S	23E	10	S	WD	2070	29-Nov-07
4304736353	NBE 5ML-10-9-23	2891	2080	NO	9S	23E	10	S	GW	9100	1-Jun-06
4304736098	NBE 4ML-10-9-23	2714	2272	NO	9S	23E	10	S	GW	9175	22-Nov-06
4304733806	BONANZA 4B-12	2644	2404		9S	23E	12	S	D	8529	18-Mar-05
4304735278	CWU 859-29	3200	2045		9S	23E	29	S	GW	8948	3-Jan-06
4304737667	CWU 868-33X(RIGSKID)	2064	3272		9S	23E	33	S	GW	8575	14-Aug-06
4304735362	SOUTHMAN 9-23-22-36	2222	3160		9S	23E	36	S	WD	8552	15-Apr-04

Table 5. *continued*

API	Well Name	BMSW Elevation	BMSW Depth	Mapped[1]	Twn	Rng	Sec	Mer.	Well Type[2]	Total Depth	Completion Date
		ft	ft							ft	
4304735695	WK 9ML-2-9-24	2494	2747	NO	9S	24E	2	S	GW	7050	10-Oct-05
4304735966	BONANZA 9-24-21-8	2735	2200		9S	24E	8	S	GW	7855	17-Nov-06
4304735694	BONANZA 2B-16	2384	2855		9S	24E	16	S	D	7823	16-Jun-04
4304735693	BONANZA 9-24-31-27	2667	2892		9S	24E	27	S	GW	6882	17-Aug-04
4304735861	BONANZA 9-24-11-36	3102	2398		9S	24E	36	S	GW	6566	11-Feb-06
4304734814	LITTLE JOE 9-25-41-7	3378	2102		9S	25E	7	S	GW	6450	3-Jun-04
4304734756	HOSS 9-25-34-20	1899	3908		9S	25E	20	S	GW	6300	31-Dec-02
4304736422	SOUTHAM CYN 9-25-22-32	3307	2218		9S	25E	32	S	D	5447	5-Nov-05
4305130002	GREMO HILL FEE 1	1433	6200		10S	08E	16	S	D	6200	13-Jan-70
4301332242	FUZZY CLOUD 1-12	3449	2940		10S	15E	12	S	D	12935	24-May-02
4301333168	BIG SPRING 3-36 GR	3508	3265		10S	15E	36	S	OW	4980	9-Oct-07
4301333485	BIG WASH 61-16GR	3329	3170		10S	16E	16	S	OW	5650	7-Aug-07
4301333202	PETES WASH U 14-24 GR	3363	2956		10S	16E	24	S	OW	5440	31-Oct-07
4304732155	DESERT SPRINGS 24-C-11	2509	3054		10S	17E	24	S	D	7500	9-Jan-92
4304735932	RB DS FED 1G-7-10-18	1940	3393		10S	18E	7	S	OW	5346	1-Apr-05
4304735798	MANATEE FED 1	1922	3172		10S	18E	9	S	OW	5027	1-Jan-06
4304733244	FEDERAL 7-19-10-18	2315	3110		10S	18E	19	S	WS	4933	8-Sep-03
4304731882	WH FED 2-26	1942	3426		10S	19E	26	S	GW	6500	23-Feb-90
4304736666	KINGS CANYON 1-32E	2293	2994		10S	19E	32	S	GW	9668	27-Jan-06
4304731704	ISLAND UNIT 28	1423	3460		10S	20E	6	S	GW	6750	30-Jul-86
4304735549	RBU 1-14F	1623	3532		10S	20E	14	S	GW	8597	1-Jan-07
4304734986	RBU 2-20F	1880	3280		10S	20E	20	S	GW	8517	30-Sep-04
4304732988	NBU 391-5E	2452	3476	NO	10S	21E	5	S	GW	6600	29-Jul-98
4304738109	NBU 1021-10P	1895	3250		10S	21E	10	S	GW	9410	3-Nov-07
4304739098	STATE 1021-28M	2361	2956		10S	21E	28	S	GW	9155	25-Feb-08
4304738849	STATE 1021-36K	2316	3142		10S	21E	36	S	GW	8714	6-Jul-07
4304739482	NBU 1022-13M1S	1618	3688		10S	22E	13	S	GW	8100	9-May-08
4304737546	NBU 1022-17J	1961	3296		10S	22E	17	S	GW	8705	23-Jan-08
4304736407	ROCK HOUSE 10-22-21-36	2566	3052		10S	22E	36	S	GW	8212	5-Mar-06
4304737214	BONANZA 1023-6F	1999	3140		10S	23E	6	S	GW	8380	20-Oct-06
4304738299	BONANZA 1023-14C	2595	2970		10S	23E	14	S	GW	7800	19-Mar-08
4304736306	ROCK HOUSE 7-32-10-23	2839	2402		10S	23E	32	S	GW	7500	19-Aug-05
4304732560	FEDERAL 21-27	347	5058		10S	24E	27	S	GW	6490	28-Mar-95
4304736238	SOUTHMAN 10-24-13-30	2554	2512		10S	24E	30	S	GW	6575	23-Apr-08
4304736933	SOUTHAM CYN 10-25-11-6	3306	2060		10S	25E	6	S	GW	5630	3-Nov-06
4304739595	WEAVER CYN 26-2	2995	2782		10S	25E	26	S	GW	4520	27-Oct-08
4304736421	SOUTHAM 10-25-21-32	1452	4356		10S	25E	32	S	GW	4900	11-Dec-05
4304930003	SKYLINE GOVT 1	3196	5002		11S	07E	10	S	D	11750	16-Jan-70
4301332308	CASTLEGATE 1-35-12-10	2560	4705		11S	10E	35	S	WD	6400	13-Jun-02
4301333005	BADLANDS 1-01	3528	4224		11S	14E	1	S	D	12900	28-Dec-06
4301332475	GATE CYN 41-20-11-15	3653	2934		11S	15E	20	S	GW	9565	2-May-05
4301332611	GATE CYN 41-19-11-16	3330	3068		11S	16E	19	S	GW	11925	5-Apr-05
4301331949	SEGO RESOURCES 4	3551	2978		11S	16E	31	S	D	6992	15-Jan-98
4301331996	TWIN KNOLLS 5-9 J	4296	2276		11S	17E	9	S	D	7998	1-Feb-98
4304731824	ALGER DSS 1	1450	4000	NO	11S	19E	2	S	GW	9375	19-Oct-88
4304736907	ALGER DSS 8-17	2192	3538		11S	19E	17	S	GW	10860	1-Nov-06
4304736165	LCU 2-1H	2181	3212		11S	20E	1	S	GW	9116	6-Nov-05
4304731818	WILLOW CREEK UNIT 2	2237	3260		11S	20E	5	S	GW	9105	19-Jun-88
4304736939	BIG DCK U 3-27H	3330	2280		11S	20E	27	S	GW	9503	17-Oct-08
4304736674	LOVE 1121-15H	2714	3042		11S	21E	15	S	GW	8650	12-Sep-06
4304736728	BIG DCK 11-21-11-28	2867	3030		11S	21E	28	S	GW	8624	2-Aug-06
4304736996	BITTER CREEK 1122-2B	2648	3048		11S	22E	2	S	GW	8080	9-Jun-07
4304734774	BITTER CREEK 4-2	2520	3088		11S	22E	4	S	GW	8110	9-Jun-03

Table 5. *continued*

API	Well Name	BMSW Elevation	BMSW Depth	Mapped[1]	Twn	Rng	Sec	Mer.	Well Type[2]	Total Depth	Completion Date
		ft	ft							ft	
4304736045	LIZZARD 1122-21O	2563	3430		11S	22E	21	S	GW	8144	8-Mar-05
4304737836	BUCK CAMP 11-22-14-36	2816	2595		11S	22E	36	S	WD	6690	11-Aug-06
4304736152	ROCK HOUSE 11-23-44-2	2670	3360		11S	23E	2	S	GW	7510	26-Nov-06
4304733026	ATCHEE 1	2982	2930		11S	23E	15	S	WD	5160	28-Apr-98
4304736314	STUMPJUMP 11-23-23-33	2921	3518		11S	23E	33	S	GW	7700	15-Oct-06
4304738281	HANG ROCK 11-23-41-36	2739	3240		11S	23E	36	S	D	4550	3-Sep-07
4304736184	RAINBOW 11-24-31-16	3130	2366		11S	24E	16	S	GW	6330	15-Dec-06
4304737460	RAINBOW 11-24-23-20	3217	2695		11S	24E	20	S	D	6400	17-Mar-07
4304734118	QUEST 11-25-24-10	1933	4113		11S	25E	10	S	D	4538	8-Jul-09
4304731803	HELLS HOLE 9110	3357	3500	NO	11S	25E	12	S	GW	7460	11-Dec-87
4304731896	EVACUATION CR UNIT 1	1587	4292		11S	25E	25	S	D	8543	11-Sep-90
4300730141	MATTS SUMMIT ST A-1	4163	3836		12S	09E	14	S	GW	5202	22-Aug-92
4300730140	HUBER-FED 6-8	3321	4072		12S	10E	8	S	GW	6030	28-Oct-93
4300731450	P5	6467	2102		12S	11E	31	S	GW	2654	17-Nov-08
4300730158	SLEMAKER A-1	2702	4780		12S	12E	5	S	GW	7000	13-Feb-93
4300730209	BRYNER A-1X (RIG SKID)	3199	3895		12S	12E	11	S	GW	6415	16-Dec-93
4300730851	SOLDIER CREEK 4-28	3342	4000		12S	12E	28	S	GW	3990	9-Nov-02
4300731008	PRIC. PEAR 5-13-12-14	4987	2612		12S	14E	13	S	GW	7485	29-Jun-06
4300731193	PRIC. PEAR 15-18-12-15	4739	2798		12S	15E	18	S	GW	7280	19-Oct-06
4300730954	PRICKLY PEAR U FED 7-25	4386	2668		12S	15E	25	S	GW	7400	27-Jan-06
4300731196	PRIC. PEAR 10-27-12-15	4555	2746		12S	15E	27	S	GW	7375	19-Jan-07
4300731318	PPU FED 16-27-12-16	4191	3021		12S	16E	27	S	GW	7571	9-Oct-07
4300730460	JACK CANYON UNIT 8-32	4279	2674		12S	16E	32	S	GW	9406	7-Feb-04
4304735970	UTE TRIBAL 3-9-1219	2599	2966		12S	19E	9	S	D	6505	3-Feb-06
4304736555	BIG DCK U 41-3	2792	3197		12S	20E	3	S	GW	8553	7-Oct-08
4304733243	FEDERAL Q 33-4	2879	3100		12S	21E	4	S	D	6500	8-May-99
4304736133	COTTONWD 12-21-14-10	2836	3256		12S	21E	10	S	D	7945	16-May-06
4304736424	AGENCY DR 12-21-31-36	3021	3052		12S	21E	36	S	GW	7050	10-May-06
4304732839	ROSEWOOD FED 4-6	3024	3230		12S	22E	4	S	D	6201	15-Aug-98
4304738055	HR 10MU-2-12-23	2873	3092		12S	23E	2	S	GW	4862	4-Jan-07
4304733484	DWR 12-23-31-21	3382	2610		12S	23E	21	S	GW	4500	22-Dec-08
4304732674	E BITTER CREEK 23-24	2995	3298		12S	23E	24	S	D	5800	6-Aug-95
4304733343	DWR 12-23-12-28	3804	1822		12S	23E	28	S	GW	5989	21-Oct-99
4304735084	HANGING ROCK FED 7-2	1933	4225		12S	24E	7	S	GW	4364	5-Jan-04
4304735927	ATCHEE RIDGE 16-19 #1	3346	3428		12S	25E	19	S	GW	4510	19-Oct-07
4304732587	DRAGON CYN 27-12-25 1	2456	3870		12S	25E	27	S	D	5421	24-Jun-96
4300730804	TD-3	6387	2000	NO	13S	13E	19	S	GW	2002	26-Oct-01
4300730982	PETERS PT 11-6-13-17	4177	2565		13S	17E	6	S	GW	9125	13-Sep-05
4304736931	UTE TRIBAL 1-20-1319	3265	3234		13S	19E	20	S	GW	13250	2-Apr-07
4304736598	UTE TRIBAL 1-33-1319	3455	3316		13S	19E	33	S	GW	5356	24-Jun-05
4304737291	MUSTANG 1320-10I	2773	3494		13S	20E	10	S	GW	8658	22-Jun-06
4304737289	MUSTANG 1320-13D	2791	3296		13S	20E	13	S	GW	8300	3-Aug-06
4304736383	MUSTANG 1321-6C	2785	3028		13S	21E	6	S	GW	7600	2-Jan-06
4304736374	UTAH OIL SHALE 1321-8A	3053	2914		13S	21E	8	S	GW	7444	9-Mar-06
4304733448	CHIMNEY ROCK 32-14	3532	3068		13S	21E	32	S	GW	11644	5-Oct-00
4304736731	SRU #8	3955	2730		13S	22E	23	S	GW	10465	23-Mar-06
4304738771	ATCHEE FED 32-4-13-25	3950	3250		13S	25E	4	S	GW	3851	23-Oct-07
4304732659	ATCHEE RIDGE 15-13-25 1	4462	3000		13S	25E	15	S	D	6860	26-Jul-96
4304732602	ATCHEE RIDGE 24-13-25 1	5188	2647		13S	25E	24	S	D	5805	26-Jul-96
4304736910	NHC 1-25-14-19	3946	3304		14S	20E	30	S	GW	4717	3-Nov-06
4304731096	PINE SPRINGS 9-12-14-21	3202	2755		14S	21E	12	S	GW	6225	21-Feb-82
4304736911	NHC 15-31-14-21	4082	2998		14S	21E	31	S	GW	10121	14-May-07
4304736962	PINE SPRINGS 15-36-14-22	3863	3310		14S	22E	36	S	GW	6050	12-Jul-06

Table 5. *continued*

API	Well Name	BMSW Elevation	BMSW Depth	Mapped[1]	Twn	Rng	Sec	Mer.	Well Type[2]	Total Depth	Completion Date
		ft	ft							ft	
4304730325	RAT HOLE CYN 1 7-8-14-25	4859	1864		14S	25E	8	S	D	4950	17-Nov-77
4304732705	RAT HOLE CYN 23-14-25 1	5131	2125		14S	25E	23	S	D	4600	6-Jun-96
4301931388	DIVIDE 2	4747	3500		15.5S	24E	32	S	GW	3600	10-Oct-01
4304737541	WF 14C-29-15-19	2845	5290		15S	19E	29	S	GW	13910	30-Aug-06
4304734955	N HILL CREEK 2-14-15-20	2678	4473		15S	20E	14	S	GW	11700	21-Jan-05
4304739499	NHC 12-33-15-20	3900	3640		15S	20E	33	S	GW	12149	15-Feb-08
4304738968	V CYN 20-1	4024	3242		15S	21E	20	S	GW	11309	20-Nov-07
4304737705	MAIN CYN FED 23-7-15-23	4980	2050		15S	23E	7	S	GW	10370	20-Feb-07
4304735685	HORSE POINT ST 43-32	4550	3106		15S	23E	32	S	GW	8425	10-Sep-04
4304732592	BLACK HORSE 9-15-24 1	3875	3725		15S	24E	9	S	GW	6192	6-Jun-96
4304731012	TP SPRINGS 14-18-15-25	4774	3097		15S	25E	18	S	D	8492	29-Oct-82
4301530022	NELSON UNIT 1	2347	4300		16S	15E	3	S	GW	8752	6-Oct-75
4301931405	MOON CYN # 2	2787	4610		16S	21E	9	S	GW	10300	2-Jun-05
4301931398	MOON CANYON 1	3456	4748		16S	21E	32	S	GW	10220	10-Dec-03
4301931458	KELLY CYN 10-8-16-22	2947	4392		16S	22E	8	S	GW	10962	21-Feb-06
4301931448	CEDAR CAMP 3-5-16-23	3895	3748		16S	23E	5	S	D	10369	27-Apr-05
4301930788	THREE PINES ST 32-10	4384	2092		16S	23E	32	S	D	7153	9-Aug-81
4301931454	WESTWATER ST 22-32	4539	2802		16S	24E	32	S	GW	7555	17-Jul-06
4301930646	FED 13-3-16-25	5213	3266		16S	25E	3	S	GW	7475	3-Jan-81
4301930460	FEDERAL 1-20	4370	2926		16S	25E	20	S	D	6479	9-Jul-79
4301911165	DIAMOND RIDGE UNIT 3	3837	2580		17S	22E	25	S	D	7633	24-May-60
4301930398	STATE 411 2	132	5270		18S	20E	23	S	D	10786	24-Jan-79
4301930727	BOGART CANYON 35-4	5351	3817	NO	18S	20E	35	S	D	8932	29-Aug-81
4301930770	DIAMOND CYN II U 15-15	3403	2674		18S	22E	15	S	GW	6334	7-Sep-81
4301930809	RATTLESNAKE CYN 2-12	4075	3498		19S	19E	2	S	GW	8174	10-Dec-81
4301930804	RATTLESNAKE CYN 16-4	4084	2565		19S	19E	16	S	D	7670	26-Aug-81
4301930734	STATE 14-4	4819	3820		19S	20E	14	S	D	8175	21-Dec-81
4301930086	FEDERAL 418-1	947	6028		19S	21E	23	S	D	6713	31-May-72

[1]If the column is blank the BMSW value was mapped, if "NO," the well was not used for mapping.
[2]GW = gas well; OW = oil well; WI = injection well; WD = water disposal; WS = water source well; D = dry hole

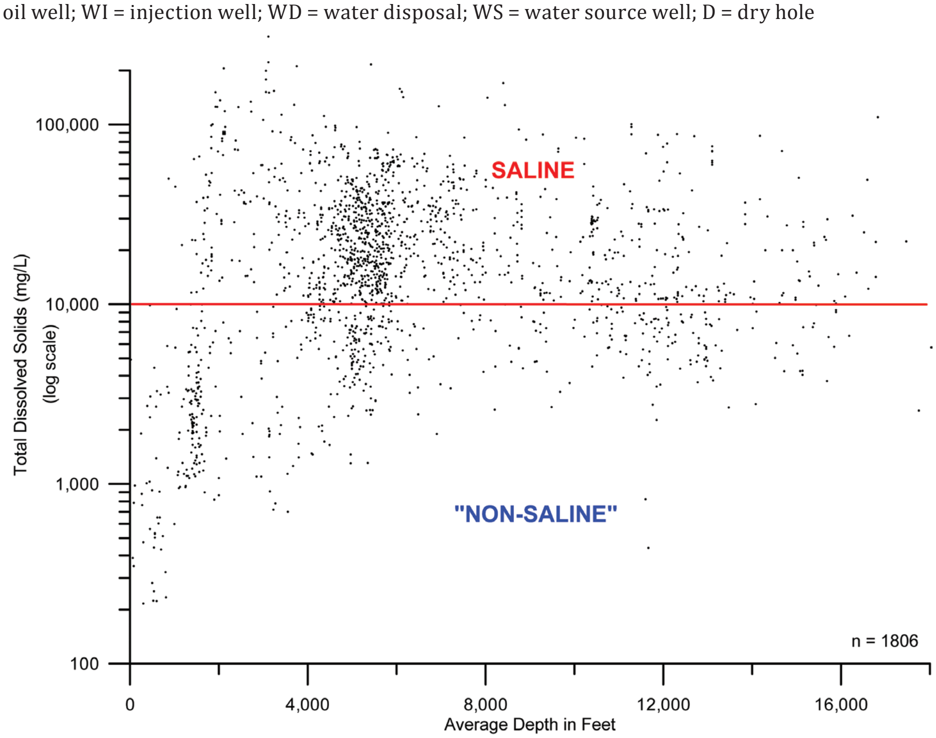

Figure 5 . *Total dissolved solids verses average depth of sample for all water analyses used in mapping.*

aquifers may show increasing salinity with depth (e.g., Mesaverde). The BMSW should be expected at a large range of depths.

Rules for Mapping the BMSW Boundary

The BMSW boundary is identified in a well log by the shallowest natural occurrence of the first 500-foot gross interval or “window” containing a net thickness of saline permeable beds greater than 50%. Other “non-saline” permeable beds may be present in the 500-foot “window” but must represent less than 50% of the total net permeable beds. The BMSW boundary is placed at the base of the first “non-saline” permeable bed above the gross 500-foot saline “window.” Figure 6 shows several hypothetical wells, “windows,” and the BMSW to help illustrate the mapping rule.

The mapping rule is slightly different than the one used by Howells and others (1987) in TP-92. In the prior study, the 500-foot window was used but could contain no “non-saline” permeable bed greater than 30-feet thick. The new mapping rule has its greatest effect where the basal Mesaverde Group and Mancos Shale/Dakota Formations are penetrated in a well and the Mesaverde is “non-saline” and Dakota saline. In these cases, TP-92 authors placed the BMSW at the top of the first saline permeable bed, typically at or near the Dakota. This put the entire Mancos Shale above the BMSW. The Mancos Shale is known for its high salt content (Tuttle and others, 2005, 2007) and low permeability (Schamel, 2006). Therefore, it is more reasonable to place the BMSW boundary at the base of the Mesaverde; the last “non-saline” permeable zone. In the eastern Uinta Basin, the clastic tongues of the Mancos (Emery and Ferron Members) rarely exhibit much permeability or are unrecognizable. However, if the Emery and Ferron were present and saline, the BMSW would still fall at the base of the Mesaverde, assuming it is “non-saline.” TP-92 data points in the southern portion of the study area were reviewed and modified using the new mapping rules.

Base of the Moderately Saline Water

Plate 1 is a contour map of the elevation of the BMSW. The contours were developed using algorithms to organize the “scattered” data points into regular gridded data. The output grid was generated for square grids of 100 meters. Information about the gridding parameters is provided in appendix C. The TP-92 data and new points generated by this study were combined for gridding/mapping, but all points from both data sets were not used in the contouring of the BMSW surface. Points of the type described above as 2, 3, or 5 were reviewed when plotted spatially to eliminate points that would inappropriately limit the contours. For example, if two nearby points were both type-2 points (or type 2 and 5), where the BMSW was shallower than the depth listed for each point, and one had an elevation of 3000 feet and the other an elevation of 4000 feet, the first point was dropped from the scattered data input file. The same procedure was used to drop inappropriately shallow type-3 wells. The points on plate 1 with posted elevation values were used in making the contoured surface of the BMSW. A point without an elevation label was dropped from the gridded scattered data file for the above reasons. Three additional wells were dropped from the TP-92 data set based on new well log analysis and water analyses in the area (see Area Specific Anomalies section, T. 3 S., R. 6 W., Uinta Base Line and Meridian [UBLM])

Plates 2 and 3 compare the surface generated in plate 1 with two additional surfaces generated from the water quality database. Plate 2 is the result of mapping the elevation of the top interval of saline water (>10,000 mg/L TDS) based on water analyses in appendix A. The method involves a similar procedure of gridding the saline water quality sample’s top interval in the well, converted to elevation on a 100 meter grid. The saline water elevation grid could then be subtracted from the BMSW grid to find areas where the top of the saline water surface is above the BMSW surface. The gridded surfaces of the saline and “non-saline” waters were generated using a Kriging algorithm.

The color-filled contours on plates 2 and 3 are based on the amount of difference in the elevation between the top elevation of the water chemistry-sourced grids and the BMSW elevation grid (the greater the difference in elevation the cooler the colors). The red-filled contour represents a difference of 1000 feet or less, which, considering the accuracy of the log-based calculations, may be insignificant. The cause of these anomalies in plate 2 is either the log calculation-based mapping is inaccurate or thin isolated beds of saline water are present above the BMSW, which are tolerated based on the mapping rule. The water samples are from a discreet depth interval (sometimes rather large) and generally do not afford application of the mapping rules; therefore, the BMSW shown in plate 1 has not been altered based on the saline areas shown in plate 2. Red-filled areas on plate 2 represent areas where the BMSW may be more ambiguous or reflect an inaccuracy with the log interpretation methods, lack geophysical log coverage in the shallow section of wells, and these are areas where more care and study are required to define safe disposal zones. Overall, plate 2 demonstrates that the methods used to map the BMSW are generally consistent with water chemistry above the BMSW.

Plate 3 is generated using similar methods to those described above for plate 2, but displays those areas where gridded values of “non-saline” water elevation,

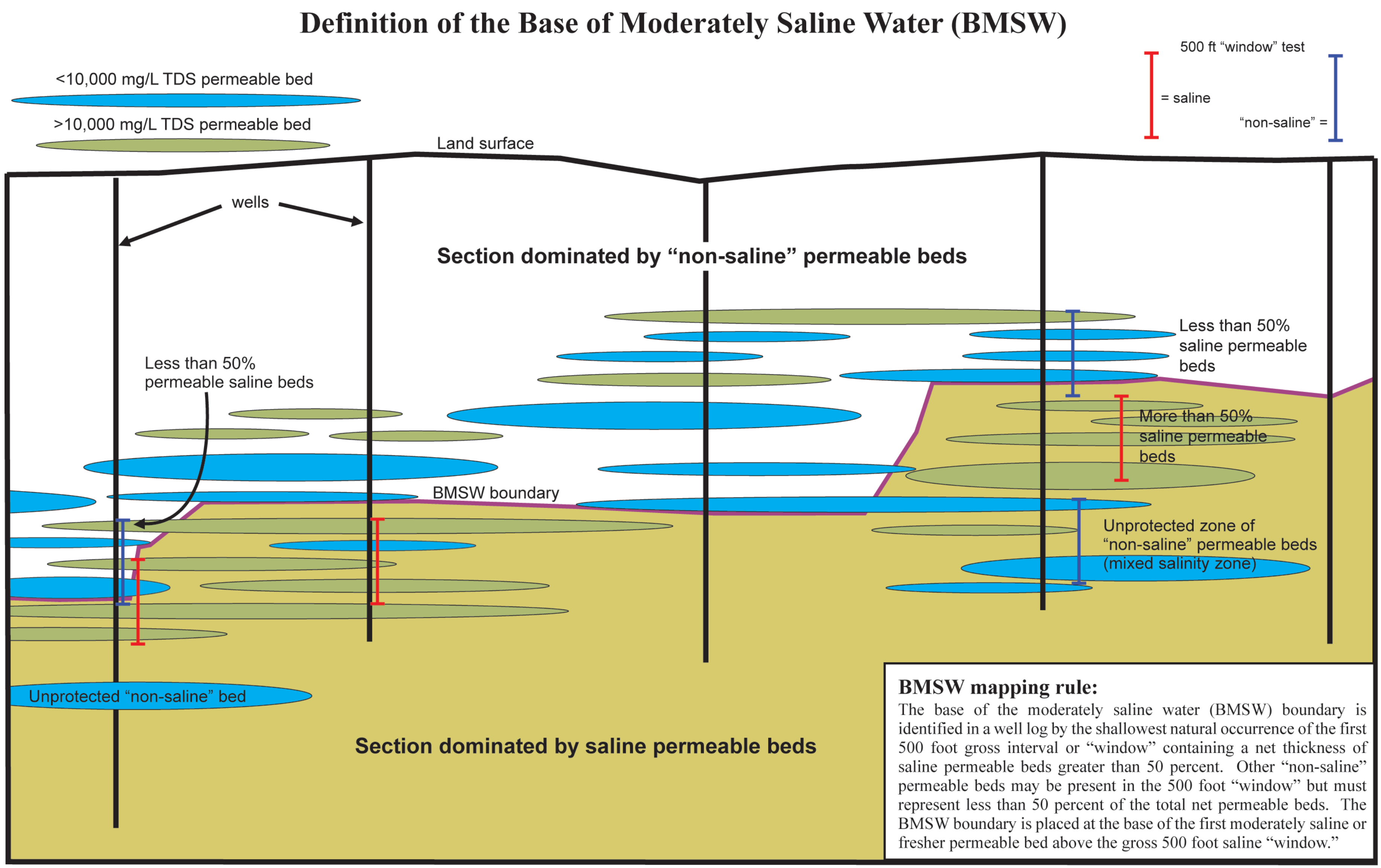

Figure 6. *Diagrammatic section illustrating the rule used in mapping the BMSW. The red bars are hypothetical "windows" or vertical intervals used when applying the BMSW mapping rule.*

based on water analysis, lie below the BMSW shown in plate 1. The grid generated for the "non-saline" water elevation is based on a kriging algorithm. The contoured area on plate 3 represents the area that lies within a search radius of 6400 meters (about 4 miles). This limited the influence of a water sample to the search radius. The difference in the elevation of the two gridded surfaces is contoured with color fill. Warm colors (red-yellow) represent the smallest difference and cooler colors (blue-purple) represent the largest differences. The warm-colors represent minor differences that may be related to methods, similar to areas on plate 2, but with opposite deviation from the BMSW. Areas of significant differences (>1000 feet, cool colors) are areas where a shallow moderately saline zone is underlain by one or more moderately deep to very deep "non-saline" zone(s), implying that more than one "BMSW" occur in these areas.

The colored-filled areas of plate 3 represent one method of identifying areas where the "non-saline"/saline waters are complexly stratified. Howells and others (1987) identified this same complex vertical stratification of varying TDS levels when they called out wells in which "... one or more intervals of fresh to moderately saline water is known (from chemical analysis) or believed (from analysis of logs) to occur more than 500 feet below the base of moderately saline water shown." These types of points are identified as conditions 2 and 5. The colored areas identified on plate 3 are based solely on data from water analyses. Note that many type-2 or type-5 log-based interpretation points lie outside any color-filled contours on plate 3, indicating these deeper "non-saline" water areas are larger than the water analysis mapped areas of plate 3.

A section of "non-saline" water underlying a shallower saline section is illustrated by well 4304730174 located in section 1, T. 2 S., R. 1 W., UBLM. The well was first completed in 1976 from 11,035 to 12,752 feet in the Wasatch Formation and produced for about a year at a few hundred barrels of water a day with a TDS of 7750 mg/L. In late 1977, the well was plugged back and perforated in the lower Green River Formation from 8770 to 8906 feet. A water analysis taken in October of 1978 contained a TDS of 20,900 mg/L. Clearly "non-saline" water is present in the deeper Wasatch. Plate 1 shows the BMSW deepening in the area and wells to the west one mile and south two miles indicate deeper "non-saline" water. The southern of these wells, 4304732744, is completed from 9518 to 10,936 feet and a water sample from this interval had a TDS of 6604 mg/L. Other evidence for complex stratification of TDS comes from operator experience. Jack Watson (Enduring Resources, personal communication, 2009) identified an area southeast of the Oil Springs field (T. 12 S., R. 24 E., SLBLM) and shown on plate 3, where "non-saline" water is encountered in the top of the Mesaverde Group, well below the mapped BMSW. Similarly, Smouse (1992) lists Rw values for Altamont-Bluebell field ranging from 1.0 to 1.2 for the Green River Formation and from 0.97 to 4.12 for the deeper Wasatch Formation.

Plate 4 is a contour map of the depth to the BMSW surface mapped in plate 1. This map was constructed using the U.S. Geological Survey 30-meter digital elevation model (DEM) grid and subtracting the same grid used to contour the BMSW. The map should aid in planning future disposal well locations. Cross section lines A through E are labeled on plates 1 through 4 and numbered in subsequent order, plates 5 through 9. The BMSW and formation boundaries are shown on these structural sections.

Old Versus New Mapping

Figure 7 compares BMSW mapping from TP-92 with mapping done for this study. The TP-92 data, minus some select wells (TP-92 edited data), as previously described, were used in this figure, but to better preserve the character of the earlier work, the TP-92 points that were altered (red dot on symbol, plate 1) were changed back to their original value. Using these TP-92 points, a grid on 100-meter centers was prepared. BMSW points generated by this study, and appropriate "less than" and "greater than" points edited out, were used for creating the second grid of similar size. The "new" grid was subtracted from the TP-92 grid to produce a difference grid, which was then contoured. The grid was cropped in the north portion of the basin because no new points were available in this area. Positive depths values represent areas where the newly mapped BMSW is shallower than that on the TP-92 map, whereas negative value areas are where the newly mapped BMSW is deeper than TP-92 data.

In the northwestern portion of the basin, in Wasatch County, two shallower anomalies are caused by two new points surrounded by numerous deeper TP-92 points. Few post-TP-92 wells were available in the area, giving the new shallower points greater influence than perhaps deserved. Additionally, the deeper anomaly (blue) along the Wasatch-Duchesne County boundary is an area with no new points but is an old shallow anomaly from TP-92 mapping that persists (section B–B', plate 6). The TP-92 point at well 4305110747 (see plates 1-3) at the center of the anomaly was reviewed. "Non-saline" beds likely occur at depth, so the anomaly is related to a shallow perched zone of saline water. This anomaly appears to be large on figure 7, but is the result of no new data points near the shallow TP-92 point at the center of the anomaly, and many deeper new points surrounding the TP-92 point. This anomaly may prove to be much smaller or disappear with additional drilling and analysis.

The anomaly south of the town of Tabiona, on the northern edge of the mapped area, is related to data density. At the center of the anomaly is the relatively shallow

TP-92 data point. The anomaly lies along the edge of the available new data, all with deeper picks. Southeast of Whiterocks is a shallow anomaly involving two wells and trending grossly north-south. Recall the map for TP-92 points is using the original values. These two points were reviewed and changed to much shallower depths, reflected on plate 1. This is an area with a shallow saline zone (perhaps perched) over a deeper "non-saline" section.

Between Ouray and Bonanza (T. 8 S., R. 21 E., SLBLM) is a deeper anomaly with new points running 1000 to greater than 2000 feet deeper than the TP-92 data. Old and new points number the same within the colored contours, but two of the new points were not used in mapping (because they tend to pull down the contours) while all of the TP-92 points were used (plate 1). The TP-92 points had six wells that were "less than the top of the logged interval," condition 2 points and two actual picked depths, while the new data had only one "less than" point and all the others were picked points (plate 1). The southern third of the anomaly lies within the Greater Natural Buttes field where it is difficult to find new drilling with logs run over the upper 3000 feet of the hole. The newer data found deeper "non-saline" water. Since the newer data is in an area where the start of the logged interval is deeper, it is possible the new points are mapping a second BMSW and the TP-92 data is principally mapping in a shallow saline zone.

The southeasternmost deeper anomaly (T. 14 S., R. 25 E., SLBLM) has its center near the Utah border at TP-92 well 4304730597 (plate 1), which indicates a very shallow BMSW. Nearby wells indicate gas saturation in the shallow section, making a pick difficult and suspect. This well has no logs posted on the DOGM website (accessed 11/30/10) so no check of the pick is possible. As a substitute, logs for 4304731894 to the south were examined from 800 to 7800 feet. The BMSW appears to be near the base of the Mesaverde Group or the top of the Mancos Shale. This corroborates the new data point and 4304732705 is partly responsible for the anomaly. Perhaps there is a very shallow thin zone of saline water, but the logs in the area start too deep to confirm this.

Figure 7 indicates a broad area of shallower BMSW at the very southern end of the project area. This is caused by the change in the mapping rules between the two studies. The BMSW is now mapped at the base of the moderately saline Mesaverde, much shallower than the saline Dakota-Morrison Formations mapped by original TP-92 data.

Regional Trends

A prominent deep trend in the BMSW wraps around the northern end of the entire basin (plates 1, 5, and 8). Howells and others (1987) suggest this is related to recharge from the Uinta Mountains immediately to the north. Other authors concur with Howells and others (1987) and suggest this same regional flow path to account for the thick section of "non-saline" groundwater (Freethey, 1992; Glover, 1996; Zhang and others, 2009). Howells and others (1987) suggest a possible deep regional discharge to the southwest, but offer no particular evidence to support the idea. Deep upward flow in the center of the basin and discharge to surface streams is referenced by Zhang and others (2009) as a regional sink for groundwater flow. Desolation Canyon of the Green River at Three Fords Rapid is the deepest incision in the project area's topography, with an elevation of 4260 feet. The BMSW's deepest elevation is just under -5000 feet (plate 1), or 9260 vertical feet below this potential discharge point.

Lucas and Drexler (1975), Bredehoeft and others (1994), and McPherson and Bredehoeft (2001) mapped an area of over-pressured rocks in the Uinta Basin which approximately matches the area of deep "non-saline" water shown in plate 1. Bredehoeft and others (1994) show evidence for hydrocarbon generation and believe it is the cause of the over-pressured zone. Bartberger and Pasternack (2009) called on expulsion of water from clays in the over-pressured deep eastern Greater Green River Basin, Wyoming, to explain a freshening of formation water at depth. This may contribute to "non-saline" water found in the deep Green River Formation along the northern edge of the Uinta Basin. It is hard to envision a present day groundwater flow path from the Uinta Mountains into this "over-pressured vessel." However, "non-saline" water is found both in the deep over-pressured area and above it, indicating that perhaps both earlier freshwater recharge from the Uinta Mountains and later water expulsion from clays at depth may explain the TDS pattern.

A long east-west trend of shallow BMSW parallels the Duchesne fault zone north of T. 5 S. (UBLM) or T. 10 S. (SLBLM) (plate 1). This trend also corresponds with the center of the basin during Green River Formation deposition. The upper Green River Formation was deposited by a retreating and sometimes saline lake whose center migrated through time to the west (Franczyk and others, 1992). Dyni and others (1985) mapped an area of bedded salts in the upper Green River Formation (saline facies) centered on T. 3 S., R. 5 W., UBLM. The combination of available salts in the upper Green River Formation, an east-west fault and fracture system, which may enable vertical mobility of fluids in the rock column, and the topographic low (see plate 8, D–D') of the Uinta Basin all likely contribute to shallow saline groundwater along this trend. Disruption and widening of the trend to the east is likely related to a fracture orientation change to northwest-southeast (similar to the gilsonite veins) and groundwater in-flow from the Douglas Creek arch along

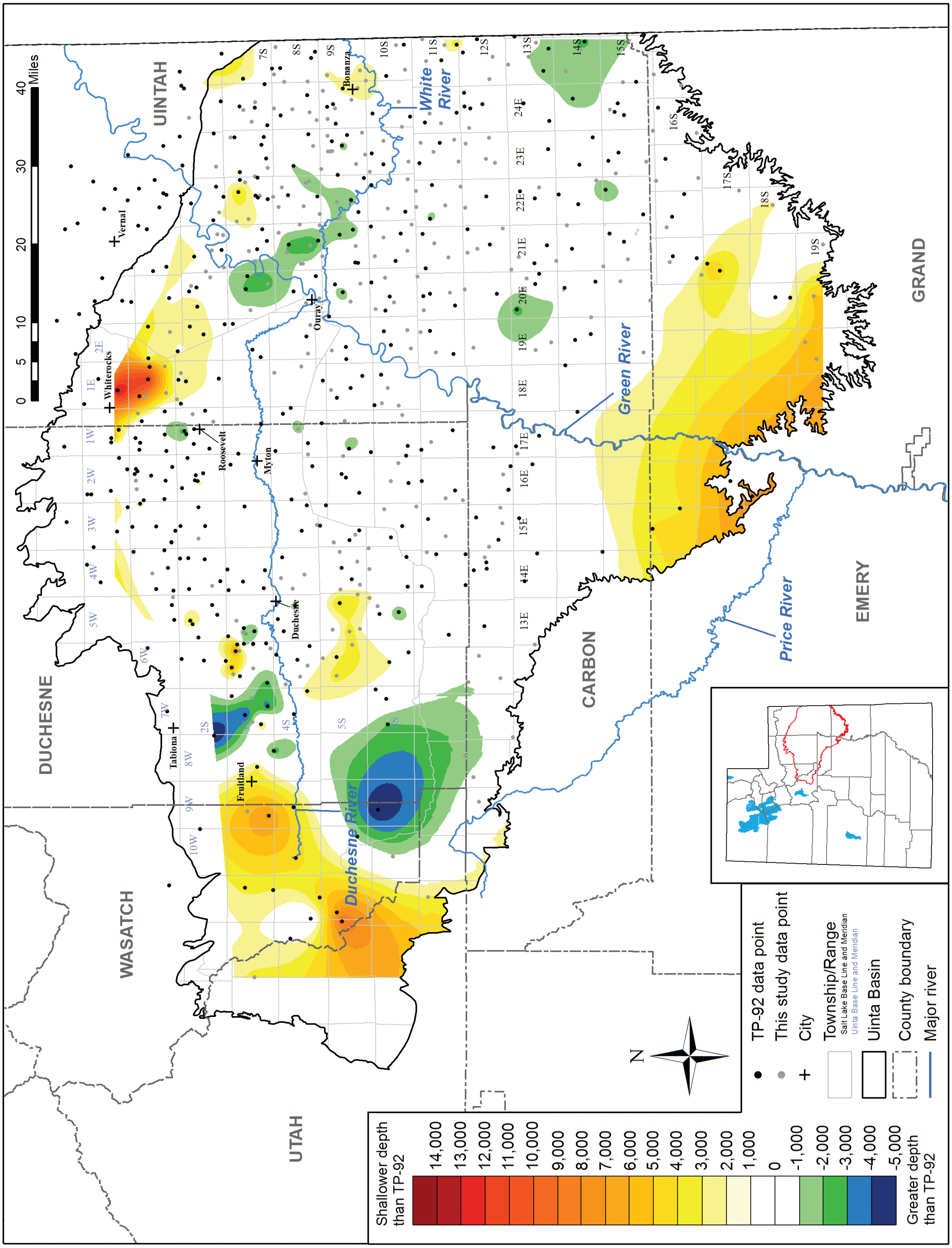

Figure 7. *Contour map of the depth difference in feet of the BMSW between new values from this study and select TP-92 values.*

the Utah-Colorado state line (Zhang and others, 2009).

A similar, but less prominent trend of shallow saline water is found in the south-central portion of the basin and parallels the structural trend of faults shown on plate 1. This trend begins on the West Tavaputs Plateau (T. 13-14 S., R. 15 E., SLBLM) and continues southeast toward T. 15 S., R. 22-23 E, SLBLM. The trend is sub-parallel to the Garmesa fault zone (Stone, 1977) and the northeastern edge of the Uncompahgre uplift. The saline facies of the Green River Formation thins to the south and is a less important factor than in the northern trend, perhaps a reason the trend is less prominent than its northern neighbor. The southwest side of this trend is defined by a subtle "low," which is based on very few data points.

Area Specific Anomalies in the BMSW

T. 1 N., R. 1 W., UBLM: The BMSW elevation difference between the two TP-92 BMSW points 4301330707 and 4301330942 is 8095 feet in less than one mile. The well with the deeper BMSW (11,037 feet deep), 4301330707, has resistivity/SP log (R_{mf} 3.0 at 83°F) from 2353 feet to TD (17,419 feet) and density-neutron log coverage from 8500 feet to TD. The SP character confirms the BMSW pick, but deeper in the well, the SP indicates a return to less saline conditions. Additional review found Howells and others' (1987) original pick reasonable. Well 4301330942 has a resistivity/SP (R_{mf} 1.03 at 50°F) log from 24 feet to TD (17,264 feet), and density-neutron log coverage from 5000 feet to TD. Based on the SP log, Howells and others' (1987) pick is on the top saline bed with 140 feet of impermeable beds above. Mapping rules used in this study would move the BMSW up to the base of the overlying permeable bed at 2720 feet, increasing the BMSW's difference between the two studies. This abrupt change of the BMSW is likely the edge of a perched layer of saline groundwater (to the south and east) overlying deeper "non-saline" groundwater. Plate 1 data points to the south and east indicate this tongue of shallower saline water has "non-saline" water below.

T. 3 S., R. 6 W., UBLM: In the northeast portion of this township is a minor "hole" in an otherwise fairly consistent shallow BMSW. On first pass the feature had considerable relief defined mainly by three TP-92 points, which have subsequently been dropped from inclusion in the scattered data set. These three dropped points all have red dots on the TP-92 well symbology (plate 1). The TP-92 wells were dropped based on three factors.

First, new water analyses from well 4301334276 (section 11, T. 3 S., R. 6 W., UBLM) have a TDS of 11,609 mg/L from a large interval from 8565 to 10,705 feet in the hole. A second well, 4301334277 (section 10, T. 3 S., R. 6 W., UBLM), sampled from 8102 to 10,740 feet yielded a TDS of 10,970 mg/L, and both wells indicated the water at depth is very near the 10,000 mg/L boundary, but above it. In section 9, T. 3 S., R. 6 W., UBLM, the well 4301350646 sampled formation water from 7676 to 7812 feet in the well and reported a TDS of 14,073 mg/L. Finally, well 4301330056 (section 14, T. 3 S., R. 6 W., UBLM), a disposal well, took two samples from the interval 2857 to 3373 feet, reporting a TDS of over 200,000 mg/L for both. The water analysis data indicate formation water is going from shallow very saline to deeper and freshening water. Most of the sampled water has high sulfate and bicarbonate, which will increase the resistivity of the water for 10,000 mg/L water. It is best to use a resistivity near 0.74 at 68°F for the 10,000 mg/L boundary.

Second, all of the dropped TP-92 logs were examined along with several newly drilled wells in the area and all logs give ambiguous indications of water salinity. One new well in section 11 was added to the newly interpreted well collection with the BMSW likely above the shallow casing. The water analyses from the area provided a bias for the well interpretation. Difficulty in log interpretation has been noted by others for the Altamont-Bluebell area (Morgan, 2009a).

Third, recent drilling and analysis by Bill Barrett Corporation has indicated saline minerals in the lower Uinta Formation and upper Green River Formation in this area (Jim Kinser, Bill Barrett Corporation, written communication, 2012). These saline minerals are likely related to the shallow-depth, high salinities in the area. The anomaly, defined by the 2000 foot elevation contour on plate 1, is surrounded by a BMSW encountered at higher elevations (shallower depths). As drilling and water sampling continues with step out and in-fill drilling, evidence may support a much shallower BMSW in the area of the present anomaly.

T. 3 S., R. 7 W., UBLM: From east to west across the township is a steep drop in the BMSW. Westward the BMSW stays deep (plate 5), but the well density drops in this area. In well 4301310754, at the apex of the low, a water sample was obtained via production from 10,055-11,670 feet with a TDS of 10,800 mg/L. The top of the sample depth is just a few hundred feet higher in the hole than the log-estimated BMSW (10,687 ft), indicating reasonable agreement between water quality and log analysis. However, like the anomaly described in the township to the east, more water samples may prove the BMSW lies at shallower depths.

T. 5 S., R. 5 W., UBLM: The logs were examined for the anomalous TP-92 well 4301330541 and the BMSW pick of 493 feet in elevation was confirmed. However, the top of the logs are at a depth of 1250 feet (5156 feet elevation) and many surrounding wells have higher elevations for their BMSW picks. It is probable that the first BMSW is shallower but was not detected because of no log coverage in the shallow part of the well. Assuming an undetected shallower BMSW, this would be a good example of multiple intervals of moderately saline water separated by saline waters.

Birds Nest aquifer: The area of the Birds Nest aquifer, which contains large nodules of nahcolite ($NaHCO_3$), is shown on plate 1 and centers around T. 9 S., R. 21 E., SLBLM (Vanden Berg and others, 2011). A dashed line within this area on plate 1 delineates the approximate change in the Birds Nest aquifer from saline to the north to “non-saline” in the south. As shown on plate 1, this boundary corresponds with a northward shallowing of the BMSW related to high-salt content in the Birds Nest likely, related to active dissolution of nahcolite.

T. 7 S., R. 25 E., SLBLM, and Red Wash field: TP-92 well 4304710078 creates a closed low near the Utah-Colorado border. Logs for this well are not publicly available (DOGM website, accessed 2011). The well lies outside the Uinta Basin bounding fault and on the east side of Raven Ridge (Sprinkel, 2007). This low is connected to a trough extending to the west into the Red Wash field (T. 7 S., R. 23 E., SLBLM) where complexly stratified TDS water is common (see plate 3). The Red Wash low, or trough, can be also seen in cross section on plate 5. The drop in elevation of the BMSW on the section line is near the mapped edge of the Birds Nest aquifer shown on plate 1. The low may be related to recharge from the Douglas Creek arch along the Utah-Colorado state line and the eastern edge of the saline facies in the upper Green River Formation. However, if the reduction of saline water in the shallow portion of the Red Wash field is related to the reduction of salines in the upper Green River Formation, the tongue of shallow saline water to the north of the Red Wash low must have another source. This saline tongue crosses the basin axis (Roberts, 2003) and bounding fault into a structurally complex area north of the Section Ridge anticline (Sprinkel, 2007).

T. 14 S., R. 25 E., SLBLM: This high on the southeast flank of the basin is partly related to a topographic high in the same area. The high extends southwest toward T. 15 S., R. 22 E., SLBLM. From cross section C–C' (plate 7), on the south part of the high, the BMSW rises along with the land surface. On the cross section, the BMSW approximately parallels the top of the Mesaverde Group. At the center of the anomaly in T. 14 S., R. 25 E., SLBLM, the BMSW lies in the Green River Formation to Mesaverde Group, with depths ranging from 433 to 3250 feet (see plate 4). This edge of the basin is different from the most southern part (plate 1), where the BMSW becomes deeper near the basin edge (plate 9, E–E'), but in cross section E–E', the surface drainage divide is crossed near well 4304731448 and both the topography and the BMSW generally descend southward from this well.

The Fourth Dimension—Time

The groundwater flow system in the Uinta Basin is dynamic and changes with time. Numerous examples of a well’s changing produced water chemistry are found in the data (for example, 430130130, 4301330149, 4301330202, 4301330105, 4301330143, 4301330106, appendix A). Some of these examples may be related to “cleaning up” after the well begins to produce, but many of the examples span significant periods of time and produce large volumes of water, clearly indicating real changes over time in the chemistry of the formation water.

Another element effecting changes in produced water quality with time is injection into the subsurface either by disposal wells or injection wells. To evaluate a possible change in water quality due to injection, TDS data from the water quality database in the Monument Butte field were queried for all analyses from wells in the field completed before and after January 1, 1996 (the approximate date when injection began), and with a “yes” in the “used in mapping the BMSW” column (appendix A). Injection water used in the field is “non-saline,” generally taken from shallow water wells, so water injection in the field should freshen produced natural formation waters. Table 6 summarizes the findings. A very minor drop in the TDS has occurred in water samples from the field which post-date the on-set of injection. Red Wash field has been using water injection to enhance production since about 1950. A query of analyses for Red Wash field yielded no water samples taken before water injection began, so a similar comparison was not possible.

Table 6. *Changes in produced water TDS before and after water injection in the Monument Butte field, Utah.*

Condition	Number of Analyses	Avg.	Max.	Min.	Std. Dev.
Pre-injection	64	24,459 mg/L	73,000 mg/L	3800 mg/L	14,004 mg/L
Post-injection	114	21,245 mg/L	73,497 mg/L	5139 mg/L	12,043 mg/L

CONCLUSIONS

The BMSW in the Uinta Basin is complex and influenced by the interaction of recharging fresh groundwater, saline stratigraphy, and groundwater flow paths. In many parts of the basin, multiple stratified intervals of saline and “non-saline” groundwater are present in the vertical section to depths over 15,000 feet, implying more than a single moderately saline zone. Compiled and depth-correlated water analyses from various sources provide a calibration for geophysical-log interpretation of the elevation of the BMSW, although most of the water samples are recovered from producing intervals, which are rarely coincident with the BMSW. The TDS concentration of depth-correlated water quality samples clearly shows a poor correlation to depth taken as a whole, but individual formations may show some correlation of quality and depth. Spatial distribution of geophysical log-derived estimates of TDS and formation water sample analyses are not equally distributed, both spatially and vertically in the basin, impacting the local accuracy of the mapping. Prior mapping and new mapping are similar, with some exceptions, and new mapping has better defined the BMSW surface. Injection and disposal effects on the groundwater quality in the basin from the mid-1980s to the present can be demonstrated, but only in a few specific wells and fields. The volume of disposed water is relatively small compared to the storage space available within the basin, and therefore is not expected to affect large areas. The BMSW surface is influenced by the stratigraphy and structure of the basin, with the surface commonly crossing formation boundaries. In the northern portion of the basin, water analyses and log-picked salinity both indicate a broad zone of deep "non-saline" water, often complexly stratified with saline water. Because log-based calculations used to estimate TDS in a well are sometimes uncertain, a need for a definitive characterization of formation water of a specific bed or zone for regulatory purposes should always rely on a laboratory analysis of a valid water sample.

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