A Summary of Salinities in Arizona's Deep Groundwater

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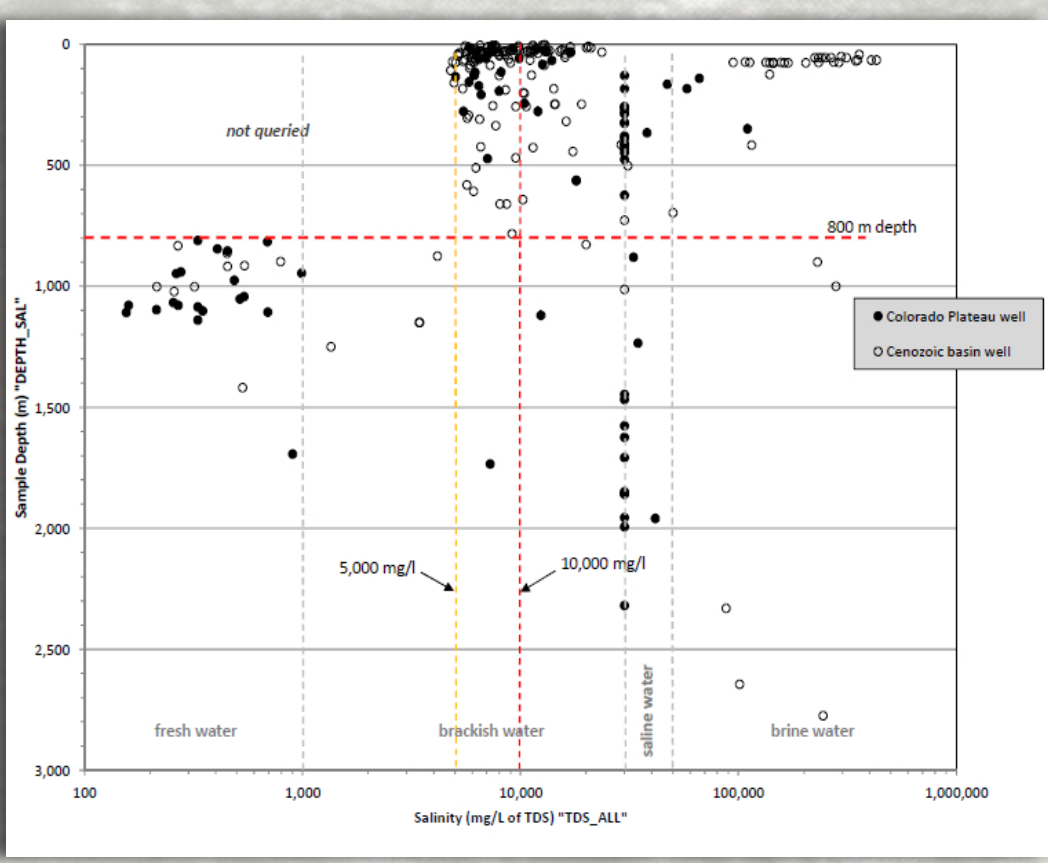
Arizona Geological Survey



Salinity vs. depth from wells in Arizona

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by

Brian F. Gootee, Michael K. Mahan and Diane S. Love

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1.0 Introduction

The Department of Energy (DOE), including its National Energy Technology Laboratory (NETL) and West Coast Regional Carbon Sequestration Partnership (WESTCARB), established national programs to evaluate the technical feasibility of long-term subsurface geologic storage of carbon dioxide (CO_2) produced by industrial activity. As part of a *WESTCARB Phase III – Arizona Geological Characterization* (contract No. 500-10-024), the Arizona Geological Survey (AZGS) is evaluating the potential for CO_2 sequestration in permeable geologic formations that are below 800 meters (m) (2,624 feet) depth below land surface (bls). Calculating basin volume below 800 m depth is important because CO_2 will only remain in a dense, near-liquid state at pressures corresponding to water overburden (hydrostatic pressure) at such depths. Successful sequestration requires both adequate permeability and porosity for large-volume CO_2 injection, and an impermeable cap rock that will prevent movement of CO_2 to shallower depths and potential escape to the atmosphere. Thus, research of storage potential is targeted at porous and permeable geologic formations with impermeable sealing strata in Cenozoic sedimentary basins in the Basin and Range province, and Paleozoic sedimentary formations in the Colorado Plateau province. Sediment volumes in the 88 Cenozoic basins in Arizona evaluated by Spencer (2011) total 42,247 cubic kilometers (km^3), with almost half of the sediment volume in the largest ten basins. The initial screening of Cenozoic sedimentary basins with significant volume and depths (below 800 m), resulted in ten candidate basins (Spencer 2011).

Part of the evaluation process is to assess CO_2 storage potential and includes identifying geologic formations below 800 m depth, where groundwater salinity concentrations exceed 10,000 milligrams per liter (mg/L) of total dissolved solids (TDS). This concentration represents the threshold above which water is considered non-potable and unsuitable as drinking water (United States Environmental Protection Agency (US EPA), (US EPA 2012). This report presents the results of salinity-data collection throughout Arizona, the data sources and methods used, and a brief discussion of the results, especially with regard to areas in Arizona identified as having CO_2 storage potential.

2.0 Background and Salinity Criteria

Salinity generally represents the total of dissolved salt constituents or dissolved "solids", referred to as TDS present in an aqueous water sample. The US EPA has established National Secondary Drinking Water Regulations that set non-mandatory water quality standards for aesthetic considerations, such as taste, color and odor. The US EPA has established a water quality secondary contaminant level for TDS of 500 mg/L as the upper limit with noticeable effects for hardness, deposits, and salty taste. Water quality exceeding this limit is considered nonpotable (US EPA, 2011).

Salinity based on dissolved solids in water is generally divided into range of concentrations as "fresh", "brackish", "saline" and "brine". Brackish water is defined as having a salinity level between fresh water and seawater—seawater contains TDS concentrations of approximately 35,000 mg/L. Saline water is a general term for water that contains a significant concentration of dissolved salts. Salt solutions ranging from the typical concentration of seawater up to a typical saturated solution, depending on temperature, are considered brines.

Water Salinity Based on Dissolved Salts

Water Classification	TDS level (mg/L)
Fresh	0 to 1,000
Brackish	1,000 to 30,000
(Seawater)	(typically 35,000)
Saline	30,000 to 50,000
Brine	> 50,000

A saline formation assessed for CO_2 storage is defined as a porous and permeable body of rock containing water with TDS greater than 10,000 mg/L (NETL, 2010).

For the purposes of this investigation, the AZGS reported TDS in mg/L and specific conductance (conductivity) in micro Siemens per centimeter (µS/cm). Specific conductance is used as a proxy for a salinity concentration where TDS data were not available. Because of the scarcity of available water-quality records for wells with depths below 800 m, we also reported salinity data for wells with depths shallower than 800 m where salinity is greater than 5000 mg/L (Table 1).

Salinity data between 5,000 and 10,000 mg/L TDS were included in the screening process, taking into consideration that elevated groundwater salinity concentrations may relate to general geologic conditions or geographic regions with elevated TDS above 10,000 mg/L. The groundwater salinity data were formatted in accordance with the National Carbon Sequestration Database and Geographic

Information System (NATCARB), a GIS-based tool developed by the NETL to provide a view of carbon capture and storage potential (available online at http://www.natcarbviewer.com/) (NETL 2012).

Criteria used to screen salinity data was based on project objectives and existing water-quality well data as follows:

- Salinity data collection concentrated on 10 identified Cenozoic sedimentary basins with significant volumes and depths below 800 m;
- Salinity greater than 10,000 mg/L or equivalent for groundwater in deep formations below 800 m depth; and
- Salinity greater than 5,000 mg/L or equivalent for groundwater in shallow formations above 800 m depth.

3.0 Data Sources

Salinity data were collected from the following sources: Arizona Department of Environmental Quality (ADEQ), J.C. Witcher (from Witcher, 1995), Arizona Department of Water Resources - Groundwater Site Inventory (ADWR-GWSI) database, United States Geological Survey - National Water Information System (USGS-NWIS), and Arizona Oil and Gas Conservation Commission (AZ OGCC) well archives. Each source of salinity data required slightly different methodology for collecting, screening and data analysis, discussed separately below. All data records are listed in Table 1 and plotted in Figure 1.

ADEQ, 2011

Water-quality data were requested from the ADEQ office in Phoenix, Arizona, during the fall of 2011. The data were provided in multiple datasets and were parsed into four statewide quadrants - A, B, C, and D. The datasets were combined, sorted and copied to the salinity database (Table 1). Data are included from groundwater wells that did not penetrate the target depth of 800 m-bls, but for which groundwater exceeded 5,000 mg/L TDS.

Witcher, J.C., 1995

James Witcher's Geothermal Resource Data Base (1995) for thermal water in Arizona includes thermal wells and spring-salinity data collected directly or compiled by the author from various data sources. These data were used to update the Geo-Heat Center State Geothermal Database for Arizona (updated November, 2003) (Geo-Heat Center, 2002). The chemistry data in the dataset were limited to wells and springs in southeastern Arizona.

The data were sorted, screened based on our criteria, and added to the salinity database. All groundwater quality records from Witcher's database and included in this investigation are from wells completed shallower than the target depth of 800 m-bls, but which exceeded TDS and conductivity criteria of 5,000 mg/L TDS.

ADWR-GWSI, 2011

The ADWR-GWSI database was provided to AZGS by ADWR during the fall of 2011. The dataset was provided in two worksheets; one that contained the groundwater water-quality records and the second that contained the well-site location. The water-quality records were combined with the site-location data, sorted, screened, and added to the salinity database. All of the ADWR-GWSI water-quality records are from wells with total depth less than 800 m.

USGS-NWIS, 2011

The USGS-NWSI data were captured from the NWIS database accessible online (USGS-NWIS, 2010). Both reported TDS and conductivity were derived from multiple groundwater parameters (Table 1, 'Remarks' field) pertaining to TDS and conductivity (. For wells with time-series data (data measured

at successive time instants spaced at uniform time intervals), multiple water-quality records were collected.. The records were combined, sorted, screened, and added to the salinity database. Groundwater salinity in only one well below the target depth of 800 m exceeded 10,000 mg/L TDS.

AZ Oil and Gas Wells, 2012

The AZGS Oil and Gas Conservation Commission (AZ OGCC) oil and gas well files (archived with AZGS) were searched for wells located in the Colorado Plateau and from each of the ten Cenozoic basins in Arizona identified as having CO_2 storage potential. Thus, this data set did not include all OG wells in Arizona. Each well file was reviewed for reports, driller logs, geophysical logs, and mud-logs and reported salinity data were extracted. The AZ OGCC records were compiled, sorted, and added to the salinity database. We identified a total of 22 wells below 800 m depth with measured TDS exceeding 10,000 mg/L. An additional 12 OGCC wells lacking measured TDS or conductivity, indicated salty groundwater from drill-stem tests (DST) below the 800 m depth.

4.0 Methods and Analysis

All water-quality data were extracted from records that met the search screening criteria outlined above and are provided in Table 1. A total of 270 wells returned salinity records that met the groundwater salinity reporting criteria described in Section 2.0. In several cases multiple measurements were recorded on different dates from the same well. . If there were multiple records for a single well, the most recent salinity measurement was used. For wells with one screened interval (section of the well casing that is perforated or consists of a screen that allows groundwater to enter the well casing), the middle of the screened interval was selected to represent the depth of the water (”Depth_Sal” field in Table 1). If salinity records were reported from a well with multiple well-screen intervals, but the discrete intervals were not known, then the highest elevation screened interval is reported. For AZ OGCC wells, with only a qualitative term “salt water” reported for groundwater salinity, a minimum arbitrary value of 30,000 mg/L indicating saline water was used for analytical purposes.

For well records with only conductivity values reported, which are more commonly measured in the field, conductivity values were converted to equivalent TDS values based on the following equation:

$$TDS\ (mg/L) = k * EC\ (\mu S/cm)$$

Where “k” is the conversion factor and EC is electrical conductivity. For wells which had both TDS and conductivity measurements, the conversion factor between TDS to conductivity ranged between 0.349 and 0.850, from a total of 10 paired values. The average was 0.642, and was chosen as the conversion factor for determining the minimum value for conductivity of approximately 7,800 µS/cm (equivalent to 5,000 mg/L TDS). For comparison, previous work by Witcher (1982) used a conversion factor in the Willcox basin of 0.6 based on field data. Conductivity values below 7,800 µS/cm and shallower than the target depth of 800 m-bls were not included.

The resulting TDS calculated from conductivity using the conversion factor of 0.642 were combined with measured TDS values. Where water quality records reported both TDS and conductivity values, the reported TDS value was retained over the calculated TDS value from conductivity. This method resulted in one TDS (mg/L) value per well, plotted in Figure 1.

The salinity data, presented in Table 1, were plotted verses the well depth in order to identify any salinity depth trends in the Colorado Plateau and Basin and Range provinces. Chart 1 shows all salinity data grouped by the Colorado Plateau and Cenozoic basins in the Basin and Range province, and is discussed in the following section. Chart 2 shows all salinity data for only the Cenozoic basins, including the WESTCARB priority basins.

5.0 Results and Discussion

A total of 270 water-quality well records were retrieved based on the salinity criteria used in this study, and are listed in Table 1. Descriptions of GIS data fields used in Table 1 are listed in Table 2. The search identified a total of 22 wells with salinity greater than 10,000 mg/L TDS below 800 m depth, 34 wells with salinity less than 10,000 mg/L TDS below 800 m depth, and 214 wells with salinity greater than 5,000 mg/L TDS above 800 m depth.

From data plotted in Figure 1 some general observations of salinity distribution and concentration can be made. On the Colorado Plateau, wells yielding saline groundwater are unevenly distributed. Sixteen (16) of the 22 wells deeper than 800 m with >10,000 mg/L TDS are on the Colorado Plateau; however, many Plateau wells >800 m depth yield fresh drinking water. The Colorado Plateau appears to have fresher groundwater below 800 m depth than the Cenozoic basins. Several areas with no salinity data below 800 m depth have brackish groundwater with elevated salinity above 800 m depth, which may suggest elevated salinity below 800 m. However, groundwater salinity above and below an aquitard may be much different, and it is possible for deeper water below an aquitard to be less saline. For example, on the Colorado Plateau, perched groundwater in the Coconino aquifer (C-aquifer) receiving ephemeral or epigenic water is disconnected from deeper, endogenic groundwater in the Redwall (R-) aquifer (a significant aquifer within the Plateau). A good example of an aquitard within the Colorado Plateau is seen at the confluence of the Colorado and Little Colorado rivers in Grand Canyon, where salt precipitates from groundwater seeping out of the Cambrian Tapeats Sandstone. Overlying the Tapeats is the Cambrian Bright Angle Shale, which acts as an aquitard separating saline groundwater in the Tapeats from overlying fresh water in the R-aquifer. In the Holbrook area saline groundwater is perched in shallow alluvium and in the C-aquifer (Figure 1).

While salinity data below 800 m on the Colorado Plateau are sparse, aquitard conditions likely separate saline and fresh groundwater. For most of the deep salinity data between Flagstaff and northeastern Arizona within the Colorado Plateau, known aquitards separate overlying fresh groundwater (blue triangles in Figure 1, mostly in Permian and Mississippian aquifer units) from underlying saline groundwater (red triangles, mostly Devonian and Cambrian aquifer units).

In the Basin and Range Province, salinity data for well water from below 800 m are scarce, but available data indicates that both saline and fresh groundwater are present below the 800 m depth in the largest Cenozoic basins. Although these data are scarce in the largest basins, deep salinities are elevated and may indicate saline conditions are present at greater depths and over a broad extent. Well data indicates fresh groundwater below 800 m in the Tucson and Willcox basins; however, there are too few data to exclude the possibility of deep saline groundwater elsewhere in the basins, considering that the wells are not located in the basin center or axis where connate saline groundwater would be more likely. Perhaps the most significant and obvious aspect of elevated salinity above 800 m depth is the TDS concentration along river corridors in southern Arizona. Most of these elevated salinity conditions are the result of concentrated salts derived from continuous agricultural recharge. The Gila River in the Safford basin represents a well-known example of this phenomenon (Towne, 2009).

In order to identify any potential vertical trends of salinity in groundwater, salinity was plotted versus depth at which the formation groundwater was sampled (see section 4.0 for methods applied). Chart 1 illustrates salinity as TDS versus sample depth in the Colorado Plateau and Basin and Range provinces. At depths below 800 m, groundwater salinity ranges from fresh to brine. Assuming most agricultural wells are less than 610 m (2,000 feet) depth, elevated salinity from agricultural recharge can be discounted (e.g., . Higley and Safford basins). Based on this assumption a crude trend of increasing salinity with increasing depth may be present, but data are insufficient regionally or basinwide, and well spacing and depths with reported salinity data are unequally represented both laterally and vertically, thus making correlations between salinity and depth uncertain. The maximum depth for fresh-water salinity of 1,000 mg/L TDS or less appears to be approximately 1,500 m (4,900 feet); however, this may not be an accurate assessment where local data are absent.

A second chart was made to analyze any potential trends in salinity within individual WESTCARB Cenozoic basins (Figure 1 and Chart 2). Overall, no regional or local-basinwide trends are apparent. Individual basins, however, appear to have salinity concentrations distinctly different from adjacent basins (e.g., Tucson and Picacho basins; Willcox and Safford basins). Both fresh and brine groundwater can be found below the target depth of 800 m. Picacho and Luke basins may exhibit a trend of increasing salinity with increasing depth below 800 m (Chart 2). Potential geologic factors such as basin-volume or basins proximal to each other do not appear to reveal any trends in salinity (Chart 2). Elevated salinity concentrations at shallow depths from agricultural recharge are readily apparent in Higley and Safford basins.

It is important to note that several factors can affect TDS, including sampling methods, depth, borehole-screened intervals and drilling fluids at the time of sampling. Numerous geologic factors related to structure, stratigraphy, porosity, permeability, rock chemistry, basin geometry, faults, impermeable seals, geothermal gradients, and salt domes (Ex. Luke basin) can affect salinity concentration and spatial variation within aquifers. Additionally, the extent to which agricultural development has impacted salinity in groundwater with increasing depth is not clear. For example, elevated salinity in the Safford basin was identified as being derived from a combination of agricultural recharge and artesian leakage from underlying basin-fill sediments with elevated connate saline groundwater (Harris, 1999; Towne, 2009). Thus, local factors and geologic conditions emphasize the need for basin-specific evaluation of saline aquifers.

6.0 Conclusions

AZGS has compiled well-water salinity data for Arizona as part of the evaluation process to assess CO_2 storage potential below an 800-m threshold depth in saline aquifers. A total of 270 wells with reported salinity data were retrieved from multiple databases. Only 22 wells were retrieved with reported salinity exceeding 10,000 mg/L TDS from depths below the threshold depth of 800 m bls. The remaining 248 salinity values, the majority from shallower wells, were useful in identifying existing salinity conditions of the Colorado Plateau and Basin and Range provinces where elevated salinity does and does not exist. From the available salinity data, the following aspects of elevated salinity were deduced:

- Fresh, brackish, saline, and brine water exist below 800 m depth in the Colorado Plateau and Cenozoic basins.
- A large number of brackish, saline and brine groundwater samples appear to be closely related to shallow, downward-percolating groundwater recharged from irrigation; however, the extent to which this has impacted deeper, underlying groundwater is not clear.
- Correlations between salinity and depth are difficult to discern regionally or basinwide.
- Brackish and saline conditions are present in both provinces below 2,000 m (6,500 feet) depth. At shallower depths, a wide range of salinity concentration is present.
- A salinity concentration of 1,000 mg/L TDS or less appears to be limited to depths less than approximately 1,500 m (4,900 feet).
- A trend between Cenozoic basin volume and salinity is not apparent.
- The Colorado Plateau appears to have less saline groundwater below 800 m depth than do Cenozoic basins.
- Several areas with no salinity data from below 800 m depth have elevated brackish groundwater above 800 m depth, which may indicate elevated salinity at depths below 800 m.

Groundwater sampling and geologic factors contributing to elevated salinity in groundwater are numerous and should be considered as part of any local assessment of a saline aquifer. Records reporting deep salinity in Arizona are sparse. In order to adequately assess the lateral extent of saline aquifers with depths greater than 800m and greater than 10,000 mg/L TDS, additional deep-well data, and likely deep exploration wells, would be needed to obtain water samples for analysis.

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