Spatial Variability and Geochemistry of Produced Water in Southeastern New Mexico, USA

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ABSTRACT

Growth in unconventional oil and gas has spurred concerns on environmental impact and interest in beneficial uses of produced water, especially in arid regions such as the Permian Basin, the largest U.S. tight-oil producer. Information on spatial variability of salinity and inorganic constituents of produced water in western Permian Basin is lacking despite an increased stream of wastewater generated from oil and gas production. Variability and geochemistry of produced water by geologic formation from Guadalupian (Late Permian) to Ordovician ages were investigated in western half of the Permian Basin (Delaware Basin, Central Basin Platform and Northwest Shelf). The total dissolved solids (TDS) of produced water increased with depth in the Delaware Basin and Central Basin Platform to Delaware and Wolfcamp formations with maximum average TDS of 225 g/L and 154 g/L respectively, and then decreased with further increases in depth. In contrast, the salinity of produced water decreased with depth below Guadalupian age formations in the Northwest Shelf with a maximum average TDS of 205 g/L in Artesia formation. Kriged contour maps of TDS and major ions showed a wide variability both in space and depth across three sub-basins. Furthermore, occurrence of meteoric waters in the upper and deeper formations across three sub-basins were attributed to uplifting and tilting effects and water flooding. The compositional data analysis illustrated that the salinity of the produced water was mainly from dissolution of Na-Ca-Cl minerals and sea water evaporation. These results have advanced our understanding of the produced water compositional variability, which supports effective management and beneficial use of produced water in the study area.

Keywords: Formation, Geochemistry, Permian, Produced Water, TDS
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INTRODUCTION

Limitation of fresh water due to long-term drought and increasing demands is increasing the interest and potential viability for use of nontraditional waters such as industrial wastewater derived from oil and gas operations [1]. Produced water is an incidental byproduct from drilling and production of oil and gas. The water quality in the Permian Basin area, the most productive tight oil play in the United States, is typically considered very poor, which limits the feasibility for beneficial use of produced water in this region [2-8]. The average ratio of produced water to oil (v/v) is approximately 7:1 in the U.S., and in Lea and Eddy counties of New Mexico, more than 70 million barrels of produced water is generated annually [9,10]. The produced water, thus, is the largest waste stream from oil and gas production. Oil and gas industries have developed horizontal drilling and hydraulic fracturing technique to increase unconventional hydrocarbon production from low permeability reservoirs [11-14]. This has likely increased the volume and variability of produced water within the Permian Basin by increasing the number and types of formations that are in production.

Permian Basin produced water quality and chemical composition is known to be extremely variable [5]. Understanding the sources and chemistry of produced water is critical in oil-field management and petroleum exploration for many reasons such as planning for saltwater disposal and secondary recovery projects, proper treatment of production fluids to prevent corrosion and enhance phase separation. Also, predicting and locating variations in produced water quality supports evaluating potential beneficial uses and treatment needs. Despite prior work, there is still vast uncertainty in the composition of produced water within the various formations and sub-basins of the Permian Basin.

Different approaches have been used in previous studies to classify produced water chemical composition and water quality. The geochemistry of produced water has been explored using isotopic data and conservative elements [15]. Meteoric water has been described as water of lower salinity and of higher quality as well as derived from precipitation. The salinity of meteoric water increases as the water migrates through the soils and adjacent rocks [15,16]. Some studies have explained the occurrence of meteoric water in deep reservoirs due to high hydraulic gradients and conductivity of rock deposits [17]. For example, water that has a shorter residence time also has
less time to dissolve minerals. Generally, increases in total dissolved solids (TDS) correspond with increases in subsurface residence time and age of water.

Understanding the geochemistry is important to interpret the produced water quality and is often accomplished using compositional data analysis. The compositional data analysis method overcomes the limitations of conventional data analysis because spurious relationship occurs while analyzing compositions especially the geochemistry of water. The compositional data in this method are interpreted employing isometric log-ratio (ilr) transformation coordinates and the data plotted using these coordinates follow the standard Euclidean geometry [18].

Diminishing water quality and supply in water stressed areas like Lea and Eddy counties in New Mexico exacerbates the need for information on produced water quality. This information can be used by various stakeholders such as water resources management authorities, farmers, industries and water utilities to address water security. Therefore, the analysis and interpretation of produced water is necessary to understand reuse/recyclable feasibility of wastewater for possible beneficial uses. For instance, various stakeholders might be interested in using the produced water with/without treatment. In addition, the interpreted water quality data will be useful for stakeholders who want to plan and design water treatment technologies.

The objective of this study was to characterize the spatial distribution and variability of produced water quality in the Delaware Basin, Central Basin Platform and Northwest Shelf sections of the Permian Basin. This report also compares the geochemistry of the produced water in three sub-basins. The produced water quality databases (USGS and New Mexico WAIDS) have been used to describe the variability of salinity and water constituents in the study area. Classical statistical and geostatistical tools were used to analyze and interpret spatial variability and the geochemistry of produced water was analyzed using a compositional data analysis technique.

**METHODOLOGY**

**STUDY AREA**

The Permian Basin consists of several sub-basins: The Central Basin Platform separates Midland Basin in Texas and the Delaware Basin in Southeast New Mexico and Southwest Texas; the Northwest Shelf lies to the north of the Delaware Basin covering majority of New Mexico area.
Four counties of New Mexico and seventeen counties of Texas cover the entire study area of the Permian Basin. The Northwest Shelf is located in an area of Lea, Eddy, Chaves, and Roosevelt counties of New Mexico and Cochran, Culberson, Lubbock, Yoakum, Terry, and Hockley counties of Texas. Similarly, Lea, Eddy, Pecos, Culberson, Reeves, Winkler, Ward, and Loving counties cover an area of the Delaware Basin. The Central Basin Platform is located mainly in Texas counties except in Lea county of New Mexico. Figure 1 shows location of produced water sample points, Permian Basin, and counties in study area.

Figure 1: Maps showing a) location of wells in the Delaware Basin, Central Basin Platform and Northwest Shelf sections of Permian Basin and b) site maps of counties (blue), Permian Basin (yellow), Lea and Eddy counties (green) of study area. [18].

GEOLOGICAL INFORMATION

The Permian Basin is a structural basin containing various formations of sedimentary rocks. In the study area, the Guadalupian and Ordovician are the youngest and oldest formations respectively as shown in Table 1 [19]. Because of larger number of samples in Guadalupian age, the formations were divided into subgroups: Artesia (youngest) and Delaware (oldest). Furthermore, the samples of different formations in each age/group were combined together for comparative study. Different formations have different types of rocks and minerals because they have formed in different
ages/periods. Carbonate is dominant in San Andres formation which has higher hydraulic conductivity than formations in Leonardian group. Lower hydraulic conductivities of Leonardian group formations are due to presence of redbed minerals. The existence of lenticular shale layers in Pennsylvanian group contributes to the lower hydraulic conductivity although the groups also contain carbonate minerals. The Devonian group consists of fractured carbonate layers leading to higher hydraulic conductivity. Three formations of Ordovician age are McKee, Simpson,

Table 1: Stratigraphic column of geological formations in the three sub-basins (modified from Dutton et al. [21].

<table>
<thead>
<tr>
<th>Geologic Age (group)</th>
<th>Delaware Basin</th>
<th>Central Basin Platform</th>
<th>Northwest Shelf</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Guadalupian</strong></td>
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<tr>
<td>(Artesia)</td>
<td>Tansill</td>
<td>Yates</td>
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<td></td>
<td>Yates</td>
<td>Seven Rivers</td>
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<tr>
<td><strong>Guadalupian</strong></td>
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<td>(San Andres)</td>
<td>San Andres</td>
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<td>San Andres</td>
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<td>Bell Canyon</td>
<td>Cherry Canyon</td>
<td>Delaware</td>
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<td>Brushy Canyon</td>
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<td></td>
<td>Cherry Canyon</td>
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<td></td>
<td>Delaware</td>
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<td>Glorieta</td>
<td>Glorieta</td>
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<td>Avalon Shale</td>
<td>Blinebry</td>
<td>Paddock</td>
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<td></td>
<td>Bone Spring</td>
<td>Clear Fork</td>
<td>Blinebry</td>
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<td></td>
<td>Yeso</td>
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<td>Clear Fork</td>
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<td>Drinkard</td>
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<td>Abo</td>
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<td><strong>(Wolfcamp)</strong></td>
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<td>Cisco</td>
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<td>Morrow</td>
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<td><strong>Pennsylvanian</strong></td>
<td>Devonian</td>
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<td>Fusselman</td>
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<td><strong>Devonian</strong></td>
<td>McKee</td>
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<td></td>
<td>Simpson</td>
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<tr>
<td><strong>Ordovician</strong></td>
<td>Ellenburger</td>
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and Ellenburger in which Ellenburger is the oldest formation. The Ellenburger formation contains a thick layer of carbonate rocks and the thickness varies from 150 to 330 m. Similarly, Simpson formation (80-500 m thick) located above Ellenburger constitutes interbedded sandstone, shale, and limestone. The Montoya formation consists of carbonate limestone-dolomite rocks with an average thickness of 75 m. Due to similarity between Devonian and Silurian age formations, the samples of these formations were combined in one group.

**ANALYSIS AND INTERPRETATION OF PRODUCED WATER QUALITY**

The United States Geological Survey (USGS) has created the database of produced water in oil and gas producing zones throughout the U.S. to monitor and archive produced water quality data. To analyze the produced water quality in study area, the current version of produced water database (v2.2) developed by the USGS was used [20]. Within the study area, the database contains 4115 samples that have unique formation names and TDS values with sampling period from 1930 to 1994. These data were supplemented by 772 samples obtained from the New Mexico produced water database (http://octane.nmt.edu/gotech/) with data collected from 2007 to 2015. Relevant information used from the database included location, identification number, geographic coordinates, sampling date, and concentration data (Na, Cl, Ca, Mg, SO₄, HCO₃, K, Br). Figure 2 shows a schematic flow-chart for the data analysis methodology used in this study. The samples that did not have total dissolved solids (TDS) and formation names were not included in this evaluation. Additionally, duplicate samples were removed based on locations, TDS, and formation names. To describe and interpret the salinity and chemical constituents of the produced water, three techniques were used: geostatistical, compositional data analysis, and generic classifications.

A classical statistic was used to evaluate mean, quartile, geometric mean, and histograms for TDS and water constituents. Formations were divided into eight groups according to the geological time and depth (Table 1), and analyzed separately for three sub-basins. Kriged contour maps were produced for spatial variability of TDS and water constituents using Kriging interpolation in ArcGIS. Kriging is a technique used in geostatistics to determine spatial statistics and evaluate variability [21].
Due to the large variability of water content in high salinity waters, previous reports have shown that relationships plotted between ions can exist spurious correlations rather than actual interactions [22,23]. To avoid such problems, application of compositional data analysis is an increasingly used method for analysis of geochemical data, especially brines. In this case, subcompositions of multivariate concentration data were converted into ilr transformation coordinates before plotting the data. The number of interested constituents were first converted into non-overlapping groups known as a sequential binary partition to maximize geochemical interpretation [24]. The corresponding ilr coordinates \( z_i \) were calculated using the sequential binary partition as follows [18]:

\[
z_i = \frac{r_is_i}{\sqrt{r_i + s_i}} \ln \left( \frac{x_j^{r_i}}{x_l^{s_i}} \right)
\]

where, \( r_i \) and \( s_i \) are the number of constituents with +1 and -1 respectively and \( x_j \) and \( x_l \) are the constituents coded with +1 and -1, respectively. The benefit of using compositional data analysis technique is direct application of conventional techniques to interpret the plot because the data follow the standard Euclidean geometry once they are transformed into ilr coordinates [25].

For classification of produced water, major ions were used to show the gross overview of types of water present in the study area. In addition to major cations and anions, available bromide data was also used to identify possible sources of water constituents. The produced water was classified into meteoric, brines, and mix types (i.e., mixture of meteoric and brine types). The meteoric water comprised of TDS values less than 75 g/L and Cl/SO\(_4\) ratio below 50, the brine constituted TDS values above 125 g/L and Cl/SO\(_4\) ratio greater than 50 and the mix water had TDS values in the ranges 75-125 g/L with Cl/SO\(_4\) ratio below 50 [26].
RESULTS AND DISCUSSION

VARIATION OF SALINITY BY BASINS AND FORMATIONS

Variability of TDS and water constituents of the produced water was evaluated in space and depth of three sub-basins. Of the 4887 samples in three sub-basins, 32% of samples were from Delaware Basin, second largest sub-basin in Permian Basin; the Central Basin Platform comprised of 39% of total samples, and the remaining samples were from the Northwest Shelf. The average TDS of the Northwest Shelf was similar to that of the other sub-basins. The average TDS values of the Delaware Basin and Central Basin Platform were 136 g/L and 95 g/L which were 120% and 83% of the average TDS of three sub-basins, respectively.
In addition to Basin wide comparison of the TDS, the TDS values were also analyzed within each sub-basin by depth. The formations shown in Table 1 were classified into three groups based on similar TDS in the histograms shown in Figure 3: the group 1 comprised of Artesia and San Andres formations; the group 2 comprised of Delaware and Leonardian formations, and the group 3 comprised of Wolfcamp, Pennsylvanian, Devonian and Ordovician formations. The average TDS values of the group 1 formations in the Delaware Basin and Central Basin Platform were similar, and were in the ranges 55 – 75 % of the average TDS of the three sub-basins while the average TDS values in this group of the Northwest Shelf were 175% of the average TDS of the three sub-basins. The lower salinity in these groups of the Delaware Basin and Central Basin Platform could be due to dissolution of evaporite minerals into meteoric water and higher salinity in the Northwest Shelf might be expected from high energy deposits, low permeability and poor hydraulic connectivity with adjacent formations [15,27,28]. In the group 2 formations, the average TDS in the Delaware Basin was 167% of the average TDS of the three sub-basins, and the groups from the Northwest Shelf had similar average TDS to that of the three sub-basins. Similarly, the group 3 formations in all three sub-basins had similar average TDS except in lower and upper formations of this group and were in the ranges 60-80% of the average TDS of the three sub-basins. The highest occurrence of average TDS in the Central Basin Platform was found in group 3 formations, especially in Wolfcamp, which was 135% of the average TDS of the three sub-basins.
Figure 3: Histograms of TDS from Guadalupian (Permian) to Ordovician age formations in three sub-basins.
Other relevant statistical parameters such as minimum, Q1 (25%-percentile), Q3 (75%-percentile), and maximum were used to observe and compare the trends with respect to the median TDS (Figure 4). For instance, the minimum values in Delaware Basin were similar in all formations irrespective of the depth while the Q1 were consistent with the trends of the average TDS values. Interestingly, similar Q1 of TDS were observed in lower formations (Pennsylvanian – Ordovician) in all three sub-basins. Moreover, the maximum TDS values linearly decreased with depth up to Wolfcamp formations and then increased linearly with further increase in depth. However, the Q3 of TDS decreased continuously with depth in the Northwest Shelf except in Ordovician formations.

Figure 4: Relative distribution of the statistical parameters of the TDS in the three sub-basins.
Figure 5 shows the contour maps of TDS of three groups in three sub-basins. The majority of areas in the group 1 had TDS values higher than 100 g/L in the Northwest Shelf with 50% of areas with TDS greater than 200 g/L. On contrary, 50% of areas in the Delaware Basin and Central Basin Platform had TDS values below 70 g/L. Similarly, larger (~75%) areas in group 3 formations had TDS values below 70 g/L similar to group 1 formation in all three sub-basins with the remaining areas having TDS in the ranges of 100-200 g/L. The TDS values in group 2 formations were above 100 g/L throughout the sub-basins with approximately 25% of areas in the Delaware Basin having TDS in the ranges of 200-400 g/L. Thus, the variability of salinity existed not only by depth but also in space throughout the sub-basins.

Besides interactions of water with rocks or minerals in different formations, hydraulic connectivity among formations could also be a reason for the large variation of the salinity in lateral and vertical directions. High hydraulic connectivity and thereby shorter residence time in group 1 formations of the Delaware Basin and Central Basin Platform might have resulted in relatively less saline water while the opposite characteristic of group 2 formations in all three sub-basins might lead to an elevated salinity.
The statistical and spatial analysis of major cations (Na, Ca and Mg) and anions (Cl, SO\textsubscript{4} and HCO\textsubscript{3}) were also performed to compare variability of the salinity. Figure 6 indicates relative distribution of Ca, Na and Cl by formations in the three sub-basins. The graphs of ions were prepared by normalizing geometric means of each constituent to 100 in each sub-basin. The
distribution trends of Ca, Na, Cl and Mg along the depth were consistent with the salinity. On the contrary, relative abundances of bicarbonate and sulfate differed with the salinity and were higher in upper formations in comparison to lower formations (Figure 6). Therefore, the analyses revealed high quality water, water having various water constituents, in upper formations. The cause of such a high quality water could be due to infiltration of meteoric water and the interactions with rocks or minerals constituting these ions. Moreover, the contour maps of Na, Cl, Ca and SO₄ show the relative concentrations throughout the sub-basins (Figure 7). The dominant ions, which have larger contribution on the salinity of the water, had similar extent of concentrations in all three sub-basins which reflected that the possible rocks or minerals contributing the salinity in the produced water was the Na-Cl-Ca type rocks or minerals. The difference in relative abundances of Ca and SO₄ ions in a contour maps across three sub-basins show that the decrease in sulfate concentration might be due to sulfate reduction, dolomitization or ion exchange reactions.

Figure 6: Relative abundances of major ions (geometric mean values for each constituent were normalized to 100%) in three sub-basins.
Figure 7: Kriged contour maps of major ions in the three sub-basins.

CLASSIFICATION OF PRODUCED WATER

Figure 8 shows the distribution of different types of water and their locations in space and depth. The produced water was classified into different types at lower confidence because only TDS and Cl/SO₄ were used in the criteria for classifications. A total of 1017, 1515, and 1010 samples were employed for the classifications in the Delaware Basin, Central Basin Platform, and Northwest Shelf, respectively. The fraction of each water type was determined by summing all types of water in each sub-basin. The fractions of meteoric water were the highest in the Northwest Shelf and Central Basin Platform in comparison to the mix and brines waters, while the Delaware Basin had
similar number of brines and meteoric samples. Each type of water was further divided into three groups representing three groups of formations with depth as used in the interpretation of salinity (Figure 8).

Figure 8: Fractional distribution of various water types and their locations in the three sub-basins. G1: group 1 formations; G2: group 2 formations and G3: group 3 formations.

Large number of meteoric samples were spatially distributed in group 3 formations whereas the group 1 formations had the majority of meteoric samples located along the ridges of the three sub-basins except in the Northwest Shelf. Likewise, brine water in group 1 and 3 of the Northwest
Shelf and Central Basin Platform were spatially distributed throughout these sub-basins except in the group 2, which were mainly in the Delaware Basin. Furthermore, mix waters were also spatially distributed across the three sub-basins in all three groups of formations although the number of mix waters was less than that of meteoric and brines waters.

In addition to spatial distribution of water types, the fractions of water types from Guadalupian-Ordovician ages formations in the three sub-basins are shown in Figure 9. Approximately 80% of the samples in Artesia and San Andres group formations were of meteoric type in the Delaware Basin and Central Basin Platform whereas brine comprised of close to 80% in these formations of the Northwest Shelf (Figure 9). Occurrence of meteoric waters in the Central Basin Platform were comparable to that of brine except in the Wolfcamp formations where the highest average TDS was observed. In the Delaware Basin and Northwest Shelf, a large number of samples were of meteoric type in the group 3 formations except in the oldest formation.
Figure 9: Distribution of samples by water types from Guadalupian to Ordovician age formations in three sub-basins. Percentage of samples by water type was calculated considering total number of samples to 100% in each formation.

ORGINS OF PRODUCTED WATER

For a gross overview of the data, major ions were used for discrimination of produced water originated from different formations analogous to Stueber et al. [29]. The correlation between TDS and major ions were obtained from the direct plot of concentration data in all three sub-basins. The decreasing trends of correlation coefficients were found in the sequence of Cl<Na<Ca<SO₄ which was consistent with the percentages of ions in the data sets. Since the correlation coefficients of Cl
and Na were not same, the presence of chloride ions in water was not from dissolution of halite alone.

Table 2: Correlation coefficients between major ions by formations in three sub-basins.

<table>
<thead>
<tr>
<th>Geologic Age(group)</th>
<th>Delaware Basin</th>
<th>Central Basin Platform</th>
<th>Northwest Shelf</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Na vs Cl</td>
<td>Ca vs Cl</td>
<td>Ca vs SO4</td>
</tr>
<tr>
<td>Artesia</td>
<td>0.9668</td>
<td>0.4029</td>
<td>0.0560</td>
</tr>
<tr>
<td>San Andres</td>
<td>0.9299</td>
<td>0.6549</td>
<td>0.4296</td>
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<td>Wolfcamp</td>
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</tr>
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</tbody>
</table>

Although the correlation coefficient of Ca vs TDS was not as high as that of Na and Cl, relatively higher occurrence of Ca compared to other cations could be due to ion-exchange reactions, dolomitization, or contribution from Ca-Cl type rocks. Moreover, negative correlation was found for SO4 with TDS. Besides the relationships between TDS and ions, the possible minerals such as halite, anhydrite were assessed from the correlation between ions along the depths of three sub-basins (Table 2). The correlation coefficients between Na and Cl were higher than 0.90 in the majority of formations expect in Delaware formation of the Delaware Basin. In the Northwest Shelf and Central Basin Platform, higher correlation coefficients (>0.90) were only obtained in the formations where higher TDS values were observed. Relatively lower correlation coefficients between Na and Cl and higher correlation coefficients between Ca and Cl in the same formations also reveal that the decrease in Na concentration with respect to Cl could be due to aqueous replacement of Ca by Na associated with the ion exchange sites of the rocks or minerals.

In addition to direct plot of major ions, compositional data analysis was used to evaluate origin of water constituents in the produced water in three sub-basins. Scatter plots prepared using ilr
transformation coordinates in all formations of three sub-basins showed clustering of water samples at the zone where Ca-Cl and Na-Cl types rocks or minerals had contributed the water constituents (Figure 10). The sample points along the dash vertical line of horizontal axis at the value of zero indicate the contribution of halite whereas the data points away from the vertical line and leaning towards left implies the contribution of water constituents mainly from Ca-Cl type rocks or minerals [18]. Few points in deeper formations (Pennsylvanian-Ordovician ages) had more Na than Cl. Furthermore, available bromide data, a conservative tracer, were also used to illustrate origin of water constituents of the produced water. Of 161 samples in three sub-basins, about 60 % of samples had a molar Br/Cl ratio above 0.001, a typical Br/Cl ratio of seawater, which indicated that there might be some sources of bromide within the formations [30,31]. More than 20% of samples were from Delaware- and Pennsylvanian-age formations with the highest occurrence of Br/Cl ratio of 0.006 in Pennsylvanian-age formations. These incremental ratios of Br/Cl might be due to precipitation of halite in which Br has less affinity for halite lattice [32].
Figure 10: Scatter plot of isometric log ratios for sub-compositions (Na, Cl, Ca and SO$_4$) in three sub-basins.

From direct scatter plots of Na/Br vs Cl/Br and Na vs Cl in three sub-basins, it was found that the majority of samples were along the halite dissolution lines in Na/Br vs Cl/Br plots although the correlation coefficients between Na and Cl in Na vs Cl plots were not equal or close to 1 (Figure
These results also confirmed dilution effect with meteoric water as reported in a previous study [22]. The ilr transformation coordinates were also used to explore further for possible sources of Br in the produced water. Figure 12 shows zones in ilr scatter plots where different water constituents might have been originated [22]. From the plot, it is clear that the salinity in Delaware formation of the Delaware Basin was due to seawater evaporation as dominant samples trend coincided in the seawater evaporation lines, and the salinity in the Leonardian formation of the Northwest Shelf was derived from different processes as shown in Figure 12.

Figure 11: Scatter plots of a.) molar ratios of Na/Br vs. Cl/Br and b.) molar concentrations of Na and Cl in the three sub-basins.
Figure 12: Scatter plots of isometric log ratio transformation of Na, Cl and Br in the three sub-basins.
CONCLUSIONS
Produced water may be available as a potential source of water supply. However, the poor water quality suggests that some treatment may be required before most beneficial use options are feasible. In addition, the extreme variability in water composition challenge re-use feasibility. This study characterized the spatial distribution and variability of produced water quality in the Delaware Basin, Central Basin Platform and Northwest Shelf sections of the Permian Basin to support beneficial use feasibility assessment. The major factors controlling geochemistry and variability of produced water were examined with sedimentary rock layers formed during different geological time periods, which was inferred from the analysis of more than 4000 samples in the Delaware Basin, Central Basin Platform and Northwest Shelf of the Permian Basin. Upper formations (Guadalupian-age) had lower TDS compared to the Delaware- and Leonardian-age formations in the Delaware Basin and Central Basin Platform. The TDS of deep formations (Pennsylvanian-Ordovician ages) in these Basins were similar to Guadalupian-age formations. On the contrary, average TDS of Northwest Shelf decreased with increase in depth (Guadalupian – Ordovician ages). The results showed that the meteoric waters (with lower salinity) existed even in deep formations which could be due to water flooding or tilting and uplifting effects. Moreover, the hydraulic conductivity of different formations might have significant effects on variability of salinity and water constituents in space and depth. In addition, the variation in geochemistry of produced water was due to Na-Cl-Ca type rocks primarily of Na-Cl type in deep brines. The spatial variability of water constituents was consistent with the trends of salinity in the study area. Thus, the changes in salinity within the study area were consistent with the geological formation, and reported produced water quality in the USGS database. The statistical characterization of TDS has quantified the water quality variability. The results of this investigation have identified areas and depths of decreased TDS, which may be considered for various beneficial use feasibility analyses.

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