Sustainable River-Basin Salinity Management: Treatment Of Natural Brine Springs For Recovery Of Purified Sodium Chloride And Other Valuable Minerals

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SUSTAINABLE RIVER-BASIN SALINITY MANAGEMENT: TREATMENT OF NATURAL BRINE SPRINGS FOR RECOVERY OF PURIFIED SODIUM CHLORIDE AND OTHER VALUABLE MINERALS

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SUSTAINABLE RIVER-BASIN SALINITY MANAGEMENT: TREATMENT OF NATURAL BRINE SPRINGS FOR RECOVERY OF PURIFIED SODIUM CHLORIDE AND OTHER VALUABLE MINERALS

by

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THESIS

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Abstract

A treatment process was developed to extract sodium chloride salt, via evaporation, from high-salinity natural brine springs. The source of the brine studied in this project is watershed of the Salt Fork of the Brazos River in Texas. When evaporation is applied to the brine, various impurities precipitate along with the sodium chloride salt (halite). Therefore, a treatment was developed in order to produce a valuable, high-purity salt product. The treatment consists of pretreating the brine with sodium carbonate and hydrochloric acid to for softening and decarbonation. After evaporation, a brine wash post-treatment process was employed to increase the purity of the salt product. A salt purity of 99.3% was achieved, which could be marketed commercially. This purity was achieved by treating the brine with 0.1 molal sodium carbonate and 0.1073 molal of hydrochloric acid with 35% purity.
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1 Introduction

1.1 Background

As it flows easterly through Salt Creek, the Brazos River becomes naturally salt rich. A substantial amount of the salt load on the river can be attributed to Croton Creek and Salt Croton Creek (Figure 1.1), located in Kent County (southeast of Lubbock, Texas), which are characterized by underlain brine aquifers. The general area of interest is shown on Figure 1.1 in orange. Erosion of the floodplain, as well as seepage, has contributed to massive salt flats through which the Brazos River flows (2011 Brazos G Regional Water Plan, 2010). The brine consists of 96.3% sodium chloride (NaCl) in its aqueous form and 3.7% of impurities, of which sulfate (SO$_4^{2-}$) is the main contributor, as shown in Table 1.1. (A copy of the Ana-Lab report is provided in Appendix A.1.)

![Salt, Double Mountain, and Clear Forks of the Brazos River](image)

Source: Brazos River Authority

**Figure 1.1: Salt Fork of the Brazos River, TX (Brazos River Authority)**
Table 2.1: Brine Chemical Composition (Ana-Lab Corp, 2007)

<table>
<thead>
<tr>
<th>Ion</th>
<th>Concentration (mg/L)</th>
<th>Fraction of Sum of Ions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl⁻</td>
<td>177,000</td>
<td>64.1%</td>
</tr>
<tr>
<td>Na⁺</td>
<td>89,000</td>
<td>32.2%</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>6,510</td>
<td>2.4%</td>
</tr>
<tr>
<td>K⁺</td>
<td>1,520</td>
<td>0.6%</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>1,370</td>
<td>0.5%</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>775</td>
<td>0.3%</td>
</tr>
<tr>
<td>Alkalinity (as HCO₃⁻)</td>
<td>54</td>
<td>0.02%</td>
</tr>
<tr>
<td>Br⁻</td>
<td>26.3</td>
<td>0.01%</td>
</tr>
<tr>
<td>B</td>
<td>7.76</td>
<td>0.003%</td>
</tr>
<tr>
<td>Sr²⁺</td>
<td>2.89</td>
<td>0.001%</td>
</tr>
<tr>
<td>Fe²⁺</td>
<td>0.535</td>
<td>0.0002%</td>
</tr>
<tr>
<td>Sum of Ions</td>
<td>276,266</td>
<td>100%</td>
</tr>
</tbody>
</table>

Approximately 68% of salt consumption in the United States is attributed to the chemical industry, its largest consumer. Salt in this industry is mainly used for petroleum refining, petrochemistry, organic synthesis, and glass production, among other applications (Sedivy, 1996). The second largest salt user is used for water treatment at 12% (Maldon Crystal Salt Co., 2014). The annual world salt production is approximately 200 million tons (Sedivy, 1996). Domestic production of salt in the United States rose by approximately 9% in 2014 to 44.1 million tons, while its apparent consumption reached 54 million tons (USGS, 2014).

1.2 Goals and Objectives

The goal of this project is to evaluate the technical feasibility and economic viability of purifying sodium chloride from the brine spring water to produce a saleable salt product. The objectives of this project are to: (1) simulate precipitation of salts from the Salt Fork well brines; (2) demonstrate and measure several relatively economical treatment methods in the laboratory; and (3) demonstrate how to obtain high quality sodium chloride with high recovery of higher than 99% purity.
2 Methodology

2.1 Approach

The general research approach was to (1) simulate treatment with USGS PHREEQC modeling, (2) test treatment methods in the laboratory, and (3) refine and optimize treatment methods, as shown in Figure 3.1. The best case simulation scenarios were then performed in the laboratory to test their physical results. Additional methods including intermediate and post treatment, were also administered in order to increase the percentage purity of the salt. The method that rendered the highest purity was selected.

---

**Figure 2.1: Research Plan Flow Chart**
2.2 PHREEQC Simulation

Using the available water quality data provided by Ana-Lab Corp, the untreated brine as well as various treatment doses were modeled in an evaporation sequence using the US Geological Survey (USGS) PHREEQC code with the Pitzer activity option. The code uses a kilogram of water and runs an evaporation sequence until 100% of the water evaporates, while estimating the concentrations of the minerals and ions present throughout the evaporation sequence. The initial conditions of the brine are input in the model, as well as the ions and minerals to be calculated and displayed. Molality is used in this data because the aqueous solution changes density as it proceeds through the evaporation sequence. (USGS, 2015)

First, as a baseline for comparison, the PHREEQC model was used to simulate the precipitation and dissolution of ions during evaporation of the untreated brine. A copy of the PHREEQC code simulating the untreated brine evaporation is provided in Appendix A.2. In order to achieve a higher salt purity, it is necessary to remove the undesired minerals or ions present in the brine. These minerals include calcium, magnesium, carbonate, and sulfate salts. One of the anions that is particularly difficult to eliminate due to its high solubility is sulfate. Once the sulfate compounds precipitate, they are difficult and expensive to remove. The most common method for sulfate removal in solution is reverse osmosis which, in this project is not feasible (Crittenden, 2012). However, calcium and magnesium in their aqueous form are easier to significantly reduce their concentrations by treating the brine before precipitation (i.e. before evaporation). Using the results of the simulated evaporation, it was decided to pre-treat the brine with sodium carbonate (Na$_2$CO$_3$), also commonly known as soda ash. The addition of sodium carbonate reacts with calcium in the brine to form calcium carbonate which forms a solid-phase precipitate. The chemical reaction is shown in Equation 2.1.

\[ Ca^{2+}_{(aq)} + Na_2CO_3(S) \rightarrow 2Na^+_{(aq)} + CaCO_3(S) \] (2.1)

With a significant removal of calcium by the sodium carbonate addition, the problematic sulfate minerals were analyzed via modeling. Since sulfate has relatively high solubility with the remaining cations, as discussed earlier, it was decided to leave sulfate in solution and dispose with
the final small amount of reject. From the modeling results, an optimum evaporation percentage was determined by analyzing the range at which contaminants and precipitates were the lowest compared to sodium chloride salt concentrations. This was achieved by graphically locating the points of the evaporation sequence where the impurities were minimal.

2.3 Laboratory Procedures

2.3.1 Sample Preparation

Brine samples were collected in 100 mL volumetric flasks and then transferred to large petri dishes for weighing. The density of the brine was calculated using the mass and volume and the specific gravity of the dissolved solids was obtained by dividing the density of the brine with the density of the water (1 kg/L). To calculate the mass of the water in the brine, equation 2.2 was used where the mass fraction is estimated at 20% (Haynes, 2006). This equation determines the water mass contained in the sample before evaporation is applied. The mass of sodium carbonate based on the PHREEQC model of 0.1, 0.15, and 0.2 mol/kg sodium carbonate was then calculated using Equation 2.3.

\[
M_{WB} = M_S(1 - \omega_{TDS}) \quad (2.2)
\]

\[
M_{Na_2CO_3} = M_{WB} \times m_{Na_2CO_3} \times MW_{Na_2CO_3} \quad (2.3)
\]

\(M_{WB}\) = water mass before treatment (kg)

\(M_S\) = mass of solution (kg)

\(\omega_{TDS}\) = mass fraction of total dissolved solids

\(m_{Na_2CO_3}\) = sodium carbonate dosing from PHREEQC analysis (moles/kg water)

\(M_{Na_2CO_3}\) = mass of sodium carbonate (kg)

\(MW_{Na_2CO_3}\) = molecular weight
2.3.2 Pre-treatment addition method

After determining the mass of the sodium carbonate to be added, each 100 mL sample was transferred to a beaker for easier mixing. The sodium carbonate dose, in the form of anhydrous salt, was weighed and administered to the brine. In order to determine if mixing, unmixing, and settling time would render better results, samples 1 to 6 shown on Table 3.1 were applied different combinations of administration. If vigorously mixing was applied to the sample, the mixing was stopped after the solution showed signs of homogeneity which consisted of a cloudy white mixture, usually less than five minutes. The samples were left settling in the beakers with a plastic cover to prevent evaporation.

Table 3.1: Sodium carbonate addition method

<table>
<thead>
<tr>
<th>Sample No</th>
<th>Mixed</th>
<th>Unmixed</th>
<th>Settling time (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>X</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>X</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>X</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>X</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>X</td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>6</td>
<td>X</td>
<td></td>
<td>24</td>
</tr>
</tbody>
</table>

2.3.3 Precipitant Filtration & Evaporation Monitoring

After the settling time concluded, separation of the precipitate (product from the sodium carbonate mixture) from the supernatant was performed using gravity filtration with a 5 μm filter placed in a Büchner funnel (Figure 2.2). At this point, the treated brine was weighted again and Equation 2.4 was applied to determine the mass of the water after the treatment. Equation 2.5 was then applied in order to determine the mass of the evaporate.
Figure 2.2: Brine sample filtration apparatus

\[ M_{Wa} = M_S (1 - \omega_{TDS}) \]  \hspace{1cm} (2.4)

\[ M_e = M_{Wa} - M_{W\%} \]  \hspace{1cm} (2.5)

\( M_e \) = evaporate mass

\( M_{Wa} \) = water mass after treatment

\( M_{W\%} \) = mass of water at % evaporation

The supernatant was transferred to large petri dishes and placed in the fume hood for evaporation at air temperature. The samples’ weights were checked hourly until the desired mass was reached.

2.3.4 Post-evaporation precipitate purification

After the desired mass was reached, the remaining liquid in the salt crystal slurry was separated from the solids by filtering through a 5 \( \mu \)m filter. Further removal of sulfates from the salt precipitates was performed by physically removing the impurity with a brine wash. The brine wash was prepared similarly to the brine salt treatment. The resulting salt crystals were dissolved in deionized (DI) water. Figure 2.3 displays a schematic of the process where (a) is the preparation
of the brine wash where the crystals were dissolved in DI water and (b) shows the preparation of the brine with the brine wash at the end.

![Diagram of the process schematic of (a) brine wash and (b) brine evaporation treatment](image)

**Figure 2.3: Process Schematic of (a) brine wash and (b) brine evaporation treatment**

For better results by lowering the sulfate concentrations from using the brine wash, an additional DI wash was added to the post-evaporation treatment. The DI wash was implemented on the preparation of the brine wash as well as the brine crystal treatment. The wash was administered by pipetting it on the filtered crystals after the brine wash. Separation of the excess liquid and the salt slurry was also performed using a 5 μm filter. Table 2.4 shows the samples with their respective treatments. Visual representation of the process is displayed in Figure 2.4.
Table 2.4: Post-Evaporation Treatment Variations

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Na$_2$CO$_3$ Dosing (m)</th>
<th>Brine Wash</th>
<th>DI Wash</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.2</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.2</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.2</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>10</td>
<td>0.2</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>11</td>
<td>0.1</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.1</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>0.1</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>14</td>
<td>0.1</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>15</td>
<td>0.15</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>0.15</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>0.15</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>18</td>
<td>0.15</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
An additional pre-treatment step was tested to increase the salt purity by removing carbonate prior to evaporation. The brine treated with sodium carbonate was dosed with hydrochloric acid to convert the carbonate to carbon dioxide gas, as shown in Equations 2.6 and 2.7. This step was performed after the brine was filtered from the calcium carbonate precipitate. Hydrochloric acid (35%) was added until the sample’s pH was below 4.3, which readily decarbonates the solution (Walton, 2008), as shown in Figure 2.5. After the evaporation, the salt was washed with the brine wash and DI water. Figure 2.6 shows the schematic for this treatment configuration, which was administered to samples 27 to 32.
\[ \text{CO}_3^{2-} (\text{aq}) + 2\text{HCl} (\text{aq}) \rightarrow \text{H}_2\text{CO}_3 (\text{aq}) + 2\text{Cl}^- (\text{aq}) \]  

(2.6)

\[ \text{H}_2\text{CO}_3 (\text{aq}) \rightarrow \text{CO}_2 (\text{g}) + \text{H}_2\text{O} (\text{l}) \]  

(2.7)

Figure 2.5: Hydrochloric acid (HCl) addition with pH meter monitoring
2.3.6 Chemical analysis

After the salt samples were dried at ambient temperature, they were dissolved in DI water to near the conductivity limit of the ion chromatography (IC) system of about 1100 μS/cm which was checked using a conductivity meter. The dissolved salt samples were analyzed for major anion and cation composition (Ca$^{2+}$, Mg$^{2+}$, Na$^+$, K$^+$, Cl$^-$, and SO$_4^{2-}$) with a simultaneous DIONEX ICS-
2100 and ICS-1100 system. Alkalinity was measured separately via titration with 0.04 N sulfuric acid.

To determine NaCl salt purity, Equation 2.8 was used for calculation.

\[
NaCl \text{ Purity} = \frac{C_{Na} + C_{Cl}}{\Sigma C_T} \times 100\% \tag{2.8}
\]

\(C_{Na}\) = sodium concentration (mg/L)

\(C_{Cl}\) = chloride concentration (mg/L)

\(\Sigma C_T\) = total ion concentration in the sample (mg/L)
3 Results & Observations

3.1 PHREEQC Simulations

3.1.1 Evaporation Simulation of Untreated Brine

The PHREEQC modeling revealed the precipitation and dissolution of different ions when the untreated brine was evaporated. Figure 4.1(a) illustrates the aqueous concentrations in molality of ions present during the water evaporation process of the raw brine. Sodium and chloride in aqueous concentrations follow a steady trend until about 90% evaporation where sodium shows slight precipitation and chloride increases in concentration. Aqueous concentrations of magnesium (Mg), sulfate (SO₄) and potassium (K) increase with higher percent evaporation. Calcium (Ca), however, begins precipitating steeply at 90%. The untreated brine, as seen in Figure 3.1(b) below predicted glauberite, celestite, and calcite as well as other impurities’ precipitation. The names of the compounds or ions with their respective molecular formulas are shown in Table 3.1. Between 70 and 100% evaporation, the code shows a formation of impurities as precipitates. These impurities include: glauberite (Na₂Ca(SO₄)₂), polyhalite (K₂MgCa₂(SO₄)₄), and bloedite (MgNa₂(SO₄)₂)-compounds containing sulfate-precipitate which is what needs to be avoided. Figure 3.1(b) shows a steep spike in halite (NaCl) solid formation at around 30% evaporation. The modeled evaporation sequence of the brine indicated that carbonate and sulfate minerals would precipitate along with the sodium chloride leading to a mixed salt with a purity near 96% at the end of the evaporation without any treatment shown on Figure 3.1 (c).

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Molecular Formula</th>
<th>Mineral</th>
<th>Molecular Formula</th>
<th>Mineral</th>
<th>Molecular Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anhydrite</td>
<td>CaSO₄</td>
<td>Glaserite</td>
<td>NaK₅(SO₄)₂</td>
<td>Pirssonite</td>
<td>Na₂Ca(CO₃)₂</td>
</tr>
<tr>
<td>Bloedite</td>
<td>MgNa₂(SO₄)₂</td>
<td>Glauberite</td>
<td>Na₂Ca(SO₄)₂</td>
<td>Polyhalite</td>
<td>K₂MgCa₂(SO₄)₄</td>
</tr>
<tr>
<td>Burkeite</td>
<td>Na₆CO₃(SO₄)₂</td>
<td>Halite</td>
<td>NaCl</td>
<td>Sylbite</td>
<td>KCl</td>
</tr>
<tr>
<td>Calcite</td>
<td>CaCO₃</td>
<td>Hexahydrate</td>
<td>MgSO₄</td>
<td>Sygnetite</td>
<td>K₂Ca(SO₄)₂</td>
</tr>
<tr>
<td>Celestite</td>
<td>SrSO₄</td>
<td>Natron</td>
<td>Na₂CO₃</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 3.1: PHREEQC results for (a) aqueous concentrations, (b) solids amounts, and (c) sodium chloride purity of evaporation of untreated brine
3.1.1 Evaporation simulation after sodium carbonate pre-treatment

Simulated sodium carbonate treatment with various doses shown in Figure 3.2 (a), (b), and (c) demonstrates sulfate concentrations increasing throughout the evaporation sequence; however sulfate minerals do not begin precipitating until late stages. The ions in aqueous concentrations on the different sodium carbonate dosages (Figure 3.2) predicted a similar trend with the majority of the ionic concentrations in the brine. Calcium ion concentrations were very low demonstrating that adding sodium carbonate greatly diminishes this impurity.

The solids concentrations on the other hand are significantly different on the 0.1 m sodium carbonate dosing (Figure 3.3 (c)) than those shown on Figure 3.3(b) and Figure 3.3(c). The code predicts that the 0.1 mol/kg sodium carbonate addition will render less solids concentrations than the other two treatment doses. Experimenting with higher and lower sodium carbonate dosing, the code was used to pinpoint the amounts of the treatment that offered the best results. The calcite (CaCO₄) concentrations on the solids concentrations graphs should be disregarded in this case since this precipitate was removed in the laboratory experiments via filtration. As shown in Figure 3.4, the highest purity achieved at 0.1 mol/kg, 0.15 mol/kg, and 0.2 mol/kg Na₂CO₃ dosing occurred at approximately 95%, 80% and 60% of water evaporation, respectively.
Figure 3.2: PHREEQC Simulation Aqueous Concentrations with (a) 0.1 mol/kg Na$_2$CO$_3$ dosing, (b) 0.15 mol/kg Na$_2$CO$_3$ dosing, (c) 0.2 mol/kg Na$_2$CO$_3$ dosing
Figure 3.3: PHREEQC Simulation Solids Amounts with (a) 0.1 mol/kg Na$_2$CO$_3$ dosing, (b) 0.15 mol/kg Na$_2$CO$_3$ dosing, (c) 0.2 mol/kg Na$_2$CO$_3$ dosing
3.2 Pre-Treatment Methods (Chemical Treatment)

Several modes of pre-treatment applications were investigated in order to identify the methods that produce the highest purity. In order to assess the performance of the mode of the chemical treatment implementation, the samples were treated with the same amount of sodium carbonate for easier comparison (0.2 mol/kg). Only half evaporation was performed since at this point the main purpose was to determine which implementation method will render higher purity. The laboratory experiment results shown on Table 3.2 display that if the sample at 50% evaporation, in this case 1 and 2 are treated without any stirring of the sodium carbonate, purity is lower compared to the samples that were stirred. Ultimately, samples 3 and 4, which were left less than a day of reaction time, possessed a higher purity by approximately 1% compared to the samples 5 and 6 which were left reacting for 24 hours. This led to conclude that the treatment’s performance was higher with a five hour reaction time versus one day. Figure 3.4 shows the overall purities for the three methods.
Table 3.2: Salt purity after 50% evaporation with 0.2 mol/kg Na$_2$CO$_3$

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Sample No.</th>
<th>Ca$^{2+}$</th>
<th>K$^+$</th>
<th>Mg$^{2+}$</th>
<th>Na$^+$</th>
<th>Cl$^-$</th>
<th>SO$_4^{2-}$</th>
<th>HCO$_3^-$</th>
<th>NaCl Purity</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>0.000</td>
<td>0.533</td>
<td>0.000</td>
<td>152</td>
<td>224</td>
<td>6.73</td>
<td>12.7</td>
<td>95.0%</td>
<td>Unstirred 5 hour reaction time</td>
</tr>
<tr>
<td>2</td>
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<td>0.000</td>
<td>0.504</td>
<td>0.000</td>
<td>153</td>
<td>224</td>
<td>6.72</td>
<td>12.7</td>
<td>95.0%</td>
<td>5 hour reaction time</td>
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<td>3</td>
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<td>0.000</td>
<td>0.096</td>
<td>0.000</td>
<td>179</td>
<td>274</td>
<td>1.03</td>
<td>15.9</td>
<td>96.4%</td>
<td>5 hour reaction time</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.000</td>
<td>0.132</td>
<td>0.000</td>
<td>179</td>
<td>275</td>
<td>1.04</td>
<td>15.9</td>
<td>96.4%</td>
<td>24 hour reaction time</td>
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<tr>
<td>5</td>
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<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>180</td>
<td>274</td>
<td>1.32</td>
<td>20.7</td>
<td>95.4%</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>0.000</td>
<td>0.166</td>
<td>0.000</td>
<td>180</td>
<td>276</td>
<td>1.32</td>
<td>20.5</td>
<td>95.4%</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.4: Pre-treatment Method Purities

3.3 Post-evaporation Treatment Methods (Crystal Washing)

When 0.2 mol/kg of sodium carbonate was added to the sample, PHREEQC showed 0.132 m of sulfates present according to graph Figure 3.1 (b), at around 50% of evaporation. In order to minimize sulfate concentrations, a brine wash was prepared to remove this impurity physically. Theoretically, this solution will rinse off more of the sulfates from the crystal by supersaturating them with concentrated cleaner salt water. Since the sulfates are concentrated in the aqueous solution and not in the crystals, the left over water was decanted. Furthermore, rinsing the crystals with the salt water (with less sulfate concentrations) resulted in lower sulfates present.
From the graphs provided by the code, it was estimated that 80% evaporation was an optimal point on the three doses that will render a high purity. Table 3.3 shows the purities of the different dosing with the brine and DI wash at 80% of evaporation with a five hour reaction time which corresponded to the highest purities on Table 3.2. The dosing with higher purity, as predicted by the PHREEQC code, corresponded to 0.1 mol/kg sodium carbonate with brine and deionized water wash corresponding to samples 13 and 14.

**Table 3.3: Salt purity after 80% evaporation with different Na₂CO₃ dosing**

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Concentrations (mg/L)</th>
<th>% Purity</th>
<th>Notes</th>
</tr>
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<td></td>
<td>Ca²⁺</td>
<td>K⁺</td>
<td>Mg²⁺</td>
</tr>
<tr>
<td>7</td>
<td>0.000</td>
<td>0.424</td>
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<tr>
<td>8</td>
<td>0.000</td>
<td>0.341</td>
<td>0.073</td>
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<tr>
<td>9</td>
<td>0.000</td>
<td>0.321</td>
<td>0.126</td>
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<tr>
<td>10</td>
<td>0.000</td>
<td>0.359</td>
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<td>13</td>
<td>0.000</td>
<td>0.169</td>
<td>0.000</td>
</tr>
<tr>
<td>14</td>
<td>0.000</td>
<td>0.222</td>
<td>0.115</td>
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<tr>
<td>15</td>
<td>0.000</td>
<td>0.103</td>
<td>0.546</td>
</tr>
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<td>16</td>
<td>0.000</td>
<td>0.105</td>
<td>0.474</td>
</tr>
<tr>
<td>17</td>
<td>0.000</td>
<td>0.253</td>
<td>0.408</td>
</tr>
<tr>
<td>18</td>
<td>0.000</td>
<td>0.239</td>
<td>0.352</td>
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Figure 3.5 shows graphically the purities rendered by the different treatment methods. The blue color shows the brine wash method while the purple colored bars show the brine and DI wash post-treatment method. It was noticed that at this evaporation, carbonate was greatly increased due to less water remaining in which at this point it was decided to implement the tertiary treatment of hydrochloric acid.
4.4 Pre-evaporation Treatment Methods

The different doses of sodium carbonate treatment yielded different alkalinity measured as carbonate concentrations, which the PHREEQC code did not predict accurately. Therefore different amounts of hydrochloric acid doses were administered in order to eliminate it. This treatment should be applied before the brine wash. The addition of hydrochloric acid (HCl) treatment is mentioned after the post-treatment because the alkalinity concentrations were discovered in this manner. These concentrations are shown in Table 3.4.

Table 3.4: Hydrochloric acid dosage required for decarbonation

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>pH Initial</th>
<th>pH Final</th>
<th>Alkalinity (mg/L as CO₃⁻)</th>
<th>HCl Dosage (μl/100 mL brine)</th>
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<tbody>
<tr>
<td>19</td>
<td>8.74</td>
<td>3.39</td>
<td>12</td>
<td>400</td>
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<tr>
<td>20</td>
<td>9.05</td>
<td>3.41</td>
<td>19</td>
<td>830</td>
</tr>
<tr>
<td>21</td>
<td>8.91</td>
<td>3.35</td>
<td>15</td>
<td>600</td>
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</table>
4.5 Overall Results

Table 4.5 and Figure 4.6 show the highest purity achieved was that of 99.3% corresponding to soda ash treatment with a dosing of 0.1 molal, post treatment of brine and DI wash and the HCl addition (samples 22 and 23).

Table 4.5: Salt purity with Na₂CO₃ and HCl treatment after 80% evaporation

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Ca²⁺</th>
<th>K⁺</th>
<th>Mg²⁺</th>
<th>Na⁺</th>
<th>Cl⁻</th>
<th>SO₄²⁻</th>
<th>HCO₃⁻</th>
<th>% Purity</th>
<th>Notes</th>
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<td>22</td>
<td>0.000</td>
<td>0.362</td>
<td>0.217</td>
<td>203</td>
<td>314</td>
<td>3.23</td>
<td>0.000</td>
<td>99.3%</td>
<td>0.1 m Na₂CO₃</td>
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<td>23</td>
<td>0.000</td>
<td>0.354</td>
<td>0.208</td>
<td>203</td>
<td>314</td>
<td>3.25</td>
<td>0.000</td>
<td>99.3%</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>0.000</td>
<td>0.412</td>
<td>0.091</td>
<td>201</td>
<td>312</td>
<td>3.83</td>
<td>0.000</td>
<td>99.2%</td>
<td>0.15 m Na₂CO₃</td>
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<tr>
<td>25</td>
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<td>0.397</td>
<td>0.102</td>
<td>202</td>
<td>312</td>
<td>3.85</td>
<td>0.000</td>
<td>99.2%</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>0.000</td>
<td>0.572</td>
<td>0.373</td>
<td>195</td>
<td>299</td>
<td>6.95</td>
<td>0.000</td>
<td>98.4%</td>
<td>0.2 m Na₂CO₃</td>
</tr>
<tr>
<td>27</td>
<td>0.000</td>
<td>0.571</td>
<td>0.386</td>
<td>195</td>
<td>299</td>
<td>6.94</td>
<td>0.000</td>
<td>98.4%</td>
<td></td>
</tr>
</tbody>
</table>

Note: Samples 23, 25 and 27 are duplicates of 22, 24 and 26

Figure 4.6: Salt Purity with Brine & DI wash post-treatment and HCl dosing
4.6 Cost Analysis

A cost analysis was performed based on the treatment that rendered the best results pertaining to samples 22 and 23. Soda ash prices are based upon regional market values based on El Paso, TX as of August 2015.

\[
Soda\ Ash\ Cost = \frac{0.1 \text{ mole } \text{Na}_2\text{CO}_3}{\text{kg brine water}} \times \frac{106 \text{ g } \text{Na}_2\text{CO}_3}{\text{mole } \text{Na}_2\text{CO}_3} \times \frac{\text{kg brine water}}{360 \text{ g } \text{NaCl}} = \frac{0.029 \text{ g } \text{Na}_2\text{CO}_3}{\text{g NaCl}}
\]

\[
= 0.029 \text{ ton } \frac{\text{Na}_2\text{CO}_3}{\text{ton NaCl}} \times \frac{\$771.61}{\text{ton } \text{Na}_2\text{CO}_3} = \frac{\$22.37}{\text{ton NaCl}}
\]

Hydrochloric acid cost estimate was approximately $992 per ton at industrial grade of 35%.

The estimate per ton of halite production is shown below.

\[
HCl\ Cost = \frac{0.004 \text{ L } \text{HCl}}{\text{kg brine water}} \times \frac{1.49 \text{ kg}}{\text{L}} \times \frac{\text{kg brine water}}{0.360 \text{ kg } \text{NaCl}} = \frac{0.0165 \text{ ton } \text{HCl}}{\text{ton } \text{NaCl}} \times \frac{\$992.08}{\text{ton } \text{HCl}}
\]

\[
= \frac{\$16.37}{\text{ton NaCl}}
\]

\[
Total\ Profit = \frac{\$44.25}{\text{ton NaCl}}
\]

The selling price for the product was determined by the USGS Mineral Commodity Statistics and Information for salt for the year of 2014 under the Solar salt average bulk price (USGS, 2015). Solar salt has a purity ranging from 99-99.7% (Sedivy, 1996) which falls within the purity acquired by the soda ash-hydrochloric acid treatment. For the year 2014, solar salt was estimated at $83/ton which translates into a profit of about $44 per ton of halite production at a purity of 99.3%.
4 Conclusions

4.1 General conclusions

The results show that the technical feasibility and economic viability of purifying sodium chloride from the brine was achieved. Simulation of the evaporation enabled to better estimate the pre-treatment dosing. The highest purity is produced by mixing 0.1 mol/kg and brine solution vigorously for 5 minutes followed by 5 hours of sedimentation. Then, the solution is gravity filtered and dosed with 400 μL/100 mL of hydrochloric acid at 34-37% purity. Once it is evaporated to 80%, the salt crystals are washed with the brine to diminish sulfate concentrations and the excess solution is drained. After the brine wash, the slurry is rinsed with DI water for better purity. This method produces a sodium chloride salt with approximately 99.3% purity. The experiments have shown that this procedure will render a high purity that is economically feasible as well with a profit of $44 per ton of sodium chloride. The method does not however reach the desired purity of 99.5%. As mentioned earlier, the amounts used to yield the best case scenario for this brine might not have the same results for others. Therefore the dosing of the chemicals for the treatment will have to be adjusted.

4.2 Recommendations

We recommend that the large scale implementation be composed of a continuous mixed tank reactor where the soda (Na\(_2\)CO\(_3\)) and brine is combined for a certain amount of time. This is followed by a sedimentation basin to allow the settling of the precipitants to take place. Then the precipitate is extracted at the bottom of the sedimentation basin where it is directed to a belt press. The belt press extracts more brine from the precipitate and is redirected to the product tank. Then the filtered brine will be further treated with HCl. Simultaneously, the treated brine from the sedimentation overflow is transferred to the product tank for evaporation. The best option for this tank is a baffled channel which allows for greater surface area for faster evaporation. After reaching 80% evaporation, the salt is then drained from the excess water by using a mesh screen. The salt is washed with the concentrated brine wash as discussed earlier in an adjacent tank and
drained again with another mesh screen. If an increase of percent purity is desired, it is suggested to wash the crystals with distilled or deionized water.
References

2011 brazos G regional water plan (September 2010). (Governmental No. HDR-00044-00100499-10)(9448 Region G Plan, draft 3-201, salinity control, IPP section 4819)


Brazos River Authority. What is the brazos river? http://waterschool.brazos.org/category/Brazos-River.aspx


doi:http://dx.doi.org/10.1016/j.desal.2009.09.141


doi:http://dx.doi.org/10.1016/j.watres.2010.07.070


doi:http://dx.doi.org/10.1016/j.desal.2013.12.038

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Appendix

A.1 Ana-Lab Corp Chemical Analysis

Ana-Lab Corp. P.O. Box 9000 Kilgore, TX 75663
Phone 903/984-0551 FAX 903/984-5914 e-Mail corp@ana-lab.com
NELAP-accredited #02008

Printed: 05/03/2007 Page 1 of 3

Report To

R W Rodgers
1831 Mayweaver Lane
Richmond, TX 77469

Project 353449

Results for Client KWRI

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SM 212068, 200th Ed.
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Gulf Coast Region: 21004 Kings Row St. H Beaumont TX 77708

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www.ana-lab.com

Form rpt/JOELES Created 10/13/2004 v1.2
A.2 PHREEQC code for evaporation sequence of untreated brine: aqueous concentrations

```
TITLE   Evaporation of Salt Fork Brine
SOLUTION 1 Salt Fork Water Well No. 2
    units   mg/L
    density 1.2135
    pH      7.0 #estimated
    Ca      775
    Mg      1370
    Na      89000
    K       1520
    S(6)    6510 #SO4
    Cl      177000 charge
    Br      26.3
    B       7.76
    Fe      0.535
    Alkalinity 54.9 as HCO3
    C 1 CO2(g) -3.5

EQUILIBRIUM_PHASES
#carbonates
    CO2(g) -3.5 10
    Calcite 0 0
    Natron 0 0
    Nahcolite 0 0
    Trona 0 0
    Gaylussite 0 0
    Pirssonite 0 0
#hydroxides
    Brucite 0 0
#sulfates
    Gypsum 0 0
    Anhydrite 0 0
    Glauberite 0 0
    Bloedite 0 0
    Syngenite 0 0
    Kieserite 0 0
    Hexahydrite 0 0
    Polyhalite 0 0
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    Burkeite 0 0
    Celestite 0 0
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#chlorides
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    Sylvite 0 0

USER_GRAPH       Simulation D
    headings  H2O  Na  K  Mg  Ca  Cl  SO4  HCO3
    axis_scale x_axis  0  1  0.1  0.01
    axis_scale y_axis -5  2  1.0  0.5
    axis_titles  "Fraction Evaporated" "Log(Molality)"
    chart_title  "Untreated Brine Aqueous Concentrations"
    start
        10 graph_x 1 - TOT("water")
```
A.3 PHREEQC code for evaporation sequence of untreated brine: solids concentrations

TITLE   Evaporation of Salt Fork Brine
SOLUTION 1 Salt Fork Water Well No. 2
units    mg/L
        density 1.2135
pH      7.0 #estimated
Ca      775
Mg      1370
Na      89000
K       1520
S(6)    6510  #SO4
Cl      177000  charge
Br      26.3
Sr      2.89
B       7.76
Fe      0.535
Alkalinity  54.9 as HCO3
C   1   CO2(g)    -3.5
EQUILIBRIUM_PHASES
#carbonates
  CO2(g)        -3.5  10
  Calcite       0  0
  Natron        0  0
  Nahcolite     0  0
  Trona         0  0
  Gaylussite    0  0
  Pirssonite    0  0
#hydroxides
  Brucite       0  0
#sulfates
  Gypsum        0  0
  Anhydrite     0  0
  Glauberite    0  0
  Bloedite      0  0
  Syngenite     0  0
  Kieserite     0  0
  Hexahydrite   0  0
  Polyhalite    0  0
  Arcanite      0  0
  Burkeite      0  0
  Celestite     0  0
A.4 Evaporation sequence of aqueous solution concentrations on 0.1 m Na₂CO₃ brine

SOLUTION 1 Salt Fork Water Well No. 2
units mg/L
density 1.2135
pH 7.0 # estimated
Ca 775  
Mg 1370  
Na 89000 charge  
K 1520  
S(6) 6510  
Cl 177000  
Br 26.3  
Sr 2.89  
B 7.76  

C \text{ l CO}_2(g) -3.5

EQUILIBRIUM PHASES
#carbonates
CO_2(g) \text{-3.5 10}
Calcite 0 0
Natron 0 0.1
Nahcolite 0 0
Trona 0 0
Gaylussite 0 0
Pirssonite 0 0

#hydroxides
Brucite 0 0

#sulfates
Gypsum 0 0
Anhydrite 0 0
Glauberite 0 0
Bloedite 0 0
Syngenite 0 0
Kieserite 0 0
Hexahydrite 0 0
Polyhalite 0 0
Arcanite 0 0
Burkeite 0 0
Celestite 0 0
Glaserite 0 0

#chlorides
Halite 0 0
Bischofite 0 0
Sylvite 0 0

USER_GRAPH Simulation D
-headings H2O Na K Mg Ca Cl SO4 HCO3
-axis_scale x_axis 0 1 0.1 0.01
-axis_scale y_axis -5 2 1.0 0.5
-axis_titles "Fraction Evaporated" "Log(Molality)"
-chart_title "0.1 m Na2CO3 Treatment Aqueous Concentrations"
-start
10 graph_x 1 - TOT("water")
20 graph_y log10(tot("Na")), log10(tot("K")), log10(tot("Mg")), log10(tot("Ca")), log10(tot("Cl")), log10(tot("S")),
log10(tot("HCO3"))
85 if STEP_NO > 20 THEN PRINT "x", "Na", "K", "Mg", "Ca", "Cl", "S"
90 if STEP_NO > 20 THEN PRINT 1 / tot("water"), (tot("Na")), (tot("K")), (tot("Mg")), (tot("Ca")), (tot("Cl")), (tot("S"))
-end

REACTION 2
H2O \text{-1.0}
56 moles in 50 steps
A.5 Evaporation sequence of solids concentrations on 0.1 m Na₂CO₃ brine

SOLUTION 1 Salt Fork Water Well No. 2
units mg/L
density 1.2135
pH 7.0 # estimated
Ca 775
Mg 1370
Na 89000 charge
K 1520
S(6) 6510
Cl 177000
Br 26.3
Sr 2.89
B 7.76
C 1 CO₂(g) -3.5

EQUILIBRMIUM_PHASES
#carbonates
  CO₂(g)  -3.5  10
  Calcite 0 0
  Natron 0 0.1
  Nahcolite 0 0
  Trona 0 0
  Gaylussite 0 0
  Pirssonite 0 0
#hydroxides
  Brucite 0 0
#sulfates
  Gypsum 0 0
  Anhydrite 0 0
  Glauberite 0 0
  Bloedite 0 0
  Syngenite 0 0
  Kieserite 0 0
  Hexahydrite 0 0
  Polyhalite 0 0
  Arcanite 0 0
  Burkeite 0 0
  Celestite 0 0
  Glaserite 0 0
#chlorides
  Halite 0 0
  Bischofite 0 0
  Sylvite 0 0

USER_GRAPH Simulation D
  -headings H₂O Anhydrite Bloedite Burkeite Calcite Celestite
  Dolomite Glauberite Glauberite Halite Hexahydrite Magnesite
  Natron Pirssonite Polyhalite Sylvite Syngenite Trona
  -axis_scale x_axis 0 1 0.1 0.01
  -axis_scale y_axis -5 2 1.0 0.5
  -axis_titles "Fraction Evaporated" "Log(Moles of Solid)"
  -chart_title "0.1 m Na₂CO₃ Treatment Solids Concentrations"
A.6 Evaporation sequence of aqueous solution concentrations on 0.15 m Na₂CO₃ brine

SOLUTION 1 Salt Fork Water Well No. 2
units mg/L
density 1.2135
pH 7.0 # estimated
Ca 775
Mg 1370
Na 89000 charge
K 1520
S(6) 6510
Cl 177000
Br 26.3
Sr 2.89
B 7.76
C 1 CO₂(g) -3.5
EQUILIBRIUM_PHASES
  #carbonates
  CO2(g)  -3.5  10
  Calcite  0  0
  Natron   0  0.15
  Nahcolite  0  0
  Trona    0  0
  Gaylussite  0  0
  Pirssonite  0  0
  #hydroxides
  Brucite  0  0
  #sulfates
  Gypsum   0  0
  Anhydrite  0  0
  Glauberite  0  0
  Bloedite  0  0
  Syngenite  0  0
  Kieserite  0  0
  Hexahydrite  0  0
  Polyhalite  0  0
  Arcanite  0  0
  Burkeite  0  0
  Celestite  0  0
  Glaserite  0  0
  #chlorides
  Halite    0  0
  Bischofite  0  0
  Sylvite   0  0
USER_GRAPH  Simulation D
- headings  H2O  Na  K  Mg  Ca  Cl  SO4  HCO3
- axis_scale x_axis 0 1 0.1 0.01
- axis_scale y_axis -5 2 1.0 0.5
- axis_titles  "Fraction Evaporated" "Log(Molality)"
- chart_title  "0.15 m Na2CO3 Treatment Aqueous Concentrations"
- start
  10  graph_x 1 - TOT("water")
  20  graph_y log10(tot("Na")), log10(tot("K")),
      log10(tot("Mg")), log10(tot("Ca")), log10(tot("Cl")), log10(tot("S")),
      log10(tot("HCO3"))
  85 if STEP_NO > 20 THEN PRINT "x", "Na", "K", "Mg", "Ca", "Cl", "S"
  90 if STEP_NO > 20 THEN PRINT 1 / tot("water"), (tot("Na")),
      (tot("K")), (tot("Mg")), (tot("Ca")), (tot("Cl")), (tot("S"))
- end
REACTION 2
  H2O  -1.0
  56 moles in 50 steps
INCREMENTAL_REACTIONS true
END

A.7 Evaporation sequence of solids concentrations on 0.15 m Na2CO3 brine
SOLUTION 1 Salt Fork Water Well No. 2
units mg/L
density 1.2135
pH 7.0 # estimated
Ca 775
Mg 1370
Na 89000 charge
K 1520
S(6) 6510
C1 177000
Br 26.3
Sr 2.89
B 7.76
Cl 177000
Br 26.3
Sr 2.89
B 7.76

C 1 CO2(g) -3.5

EQUILIBRIUM PHASES
#carbonates
CO2(g) -3.5 10
Calcite 0 0
Natron 0 0.15
Nahcolite 0 0
Trona 0 0
Gaylussite 0 0
Pirssonite 0 0

#hydroxides
Brucite 0 0

#sulfates
Gypsum 0 0
Anhydrite 0 0
Glauberite 0 0
Bloedite 0 0
Syngenite 0 0
Kieserite 0 0
Hexahydrite 0 0
Polyhalite 0 0
Arcanite 0 0
Burkeite 0 0
Celestite 0 0
Glaserite 0 0

#chlorides
Halite 0 0
Bischofite 0 0
Sylvite 0 0

USER_GRAPH Simulation D
-hearings H2O Anhydrite Bloedite Burkeite Calcite Celestite
Dolomite Glaserite Glauberite Halite Hexahydrite Magnesite Natron Pirssonite Polyhalite Sylvite Syngenite Trona
-axis_scale x_axis 0 1 0.1 0.01
-axis_scale y_axis -5 2 1.0 0.5
-axis_titles "Fraction Evaporated" "Log(Moles of Solid)"
-chart_title "0.15 m Na2CO3 Treatment Solids Concentrations"
-start
 10 graph_x 1 - TOT("water")
 30 if equi("Anhydrite") > 1e-5 then graph_y
    log10(equi("Anhydrite")) else graph_y -5
 35 if equi("Bloedite") > 1e-5 then graph_y
    log10(equi("Bloedite")) else graph_y -5
 40 if equi("Burkeite") > 1e-5 then graph_y
    log10(equi("Burkeite")) else graph_y -5
 50 if equi("Calcite") > 1e-5 then graph_y log10(equi("Calcite"))
else graph_y -5
60 if equi("Celestite") > 1e-5 then graph_y log10(equi("Celestite")) else graph_y -5
73 if equi("Dolomite") > 1e-5 then graph_y log10(equi("Dolomite")) else graph_y -5
75 if equi("Glaserite") > 1e-5 then graph_y log10(equi("Glaserite")) else graph_y -5
76 if equi("Glauberite") > 1e-5 then graph_y log10(equi("Glauberite")) else graph_y -5
77 if equi("Halite") > 1e-5 then graph_y log10(equi("Halite")) else graph_y -5
78 if equi("Hexahydrite") > 1e-5 then graph_y log10(equi("Hexahydrite")) else graph_y -5
79 if equi("Magnesite") > 1e-5 then graph_y log10(equi("Magnesite")) else graph_y -5
80 if equi("Natron") > 1e-5 then graph_y log10(equi("Natron")) else graph_y -5
81 if equi("Pirssonite") > 1e-5 then graph_y log10(equi("Pirssonite")) else graph_y -5
82 if equi("Sylvite") > 1e-5 then graph_y log10(equi("Sylvite")) else graph_y -5
83 if equi("Syngenite") > 1e-5 then graph_y log10(equi("Syngenite")) else graph_y -5
84 if equi("Trona") > 1e-5 then graph_y log10(equi("Trona")) else graph_y -5
end

REACTION 2
H2O -1.0
56 moles in 50 steps
INCREMENTAL_REACTIONS true
END

A.8 Evaporation sequence of aqueous solution concentrations on 0.2 m Na₂CO₃ brine

SOLUTION 1 Salt Fork Water Well No. 2
units mg/L
density 1.2135
pH 7.0 # estimated
Ca 775
Mg 1370
Na 89000 charge
K 1520
S 6510
Cl 177000
Br 26.3
Sr 2.89
B 7.76
C 1 CO2(g) -3.5
EQUILIBRIUM_PHASES
#carbonates
CO2(g) -3.5 10
Calcite 0 0
Natron 0 0.2
Nahcolite 0 0
Trona 0 0
Gaylussite 0 0
Pirssonite 0 0
#hydroxides
A.9 Evaporation sequence of solids concentrations on 0.2 m Na2CO3 brine

SOLUTION 1 Salt Fork Water Well No. 2
units mg/L
density 1.2135
pH 7.0 # estimated
Ca 775
Mg 1370
Na 89000 charge
K 1520
S(6) 6510
Cl 177000
Br 26.3
Sr 2.89
B 7.76

user_graph Simulation D
-headings H2O Na K Mg Ca Cl SO4 HCO3
-axis_scale x_axis 0 1 0.1 0.01
-axis_scale y_axis -5 2 1.0 0.5
-axis_titles "Fraction Evaporated" "Log(Molality)"
-chart_title "0.2 m Na2CO3 Treatment Aqueous Concentrations"
-start
10 graph x 1 - TOT("water")
20 graph_y log10(tot("Na")), log10(tot("K")), log10(tot("Mg")), log10(tot("Ca")), log10(tot("Cl")), log10(tot("S")), log10(tot("HCO3"))
85 if STEP_NO > 20 THEN PRINT "x", "Na", "K", "Mg", "Ca", "Cl", "S"
90 if STEP_NO > 20 THEN PRINT 1 / tot("water"), (tot("Na")), (tot("K")), (tot("Mg")), (tot("Ca")), (tot("Cl")), (tot("S"))
-end
REACTION 2
H2O 1.0
56 moles in 50 steps
INCREMENTAL_REACTIONS true
END
C 1 CO2(g) -3.5
EQUILIBRIUM_PHASES
#carbonates
   CO2(g)  -3.5   10
  Calcite  0   0
  Natron  0   0.2
  Nahcolite  0   0
  Trona  0   0
  Gaylussite  0   0
  Pirssonite  0   0
#hydroxides
   Brucite  0   0
#sulfates
   Gypsum  0   0
   Anhydrite  0   0
   Bloedite  0   0
   Syngenite  0   0
   Kieserite  0   0
   Hexahydrite  0   0
   Polyhalite  0   0
   Arcanite  0   0
   Burkeite  0   0
   Celestite  0   0
   Glaserite  0   0
#chlorides
   Halite  0   0
   Bischofite  0   0
   Sylvite  0   0

USER_GRAPH Simulation D
- headings H2O Anhydrite Bloedite Burkeite Calcite Celestite
   Dolomite Glaserite Glauberite Halite Hexahydrite Magnesite
   Natron Pirssonite Polyhalite Sylvite Syngenite Trona
- axis_scale x_axis 0 1 0.1 0.01
- axis_scale y_axis -5 2 1.0 0.5
- axis_titles "Fraction Evaporated" "Log(Moles of Solid)"
- chart_title "0.2 m Na2CO3 Treatment Solids Concentrations"
- start
  10 graph_x 1 - TOT("water")
  30 if equi("Anhydrite") > 1e-5 then graph_y log10(equi("Anhydrite")) else graph_y -5
  35 if equi("Bloedite") > 1e-5 then graph_y log10(equi("Bloedite")) else graph_y -5
  40 if equi("Burkeite") > 1e-5 then graph_y log10(equi("Burkeite")) else graph_y -5
  50 if equi("Calcite") > 1e-5 then graph_y log10(equi("Calcite")) else graph_y -5
  60 if equi("Celestite") > 1e-5 then graph_y log10(equi("Celestite")) else graph_y -5
  73 if equi("Dolomite") > 1e-5 then graph_y log10(equi("Dolomite")) else graph_y -5
  75 if equi("Glaserite") > 1e-5 then graph_y log10(equi("Glaserite")) else graph_y -5
  76 if equi("Glauberite") > 1e-5 then graph_y log10(equi("Glauberite")) else graph_y -5
  77 if equi("Halite") > 1e-5 then graph_y log10(equi("Halite")) else graph_y -5

78 if equi("Hexahydrite") > 1e-5 then graph_y
log10(equi("Hexahydrite")) else graph_y -5
79 if equi("Magnesite") > 1e-5 then graph_y
log10(equi("Magnesite")) else graph_y -5
80 if equi("Natron") > 1e-5 then graph_y log10(equi("Natron"))
else graph_y -5
81 if equi("Pirssonite") > 1e-5 then graph_y
log10(equi("Pirssonite")) else graph_y -5
82 if equi("Sylvite") > 1e-5 then graph_y log10(equi("Sylvite"))
else graph_y -5
83 if equi("Syngenite") > 1e-5 then graph_y
log10(equi("Syngenite")) else graph_y -5
84 if equi("Trona") > 1e-5 then graph_y log10(equi("Trona")) else
graph_y -5
-end
REACTION 2
  H2O -1.0
  56 moles in 50 steps
INCREMENTAL_REACTIONS true
END
Vita

Priscilla Sandoval is currently seeking her Master’s degree in Environmental Engineering. She acquired her Bachelors of Science in Civil Engineering at UTEP in May 2013. During her undergraduate studies, she received an award for Best Overall Design in her senior project titled “Far Eastside Bus Transit Terminal.” Additionally, she was awarded with the Academic Achievement Award in 2013 and graduated Cum Laude. She acquired her Engineer-In-Training certificate in May of 2013.

Her experience includes working as a teaching assistant for the Hydraulic engineering laboratory where she taught approximately 30 students for two semesters. She also worked as a research assistant for three semesters while developing an economically feasible chemical and physical treatment on brine to acquire 99.3% extract. In the duration of these three semesters, she also worked with applying a Low Impact Development (LID) technique applicable in the arid and semiarid regions. She also interned for four months at the International Boundary & Water Commission (USIBWC). During her internship, she provided conditions of the reservoirs and gaging stations throughout the Rio Grande which flows from Colorado and Texas. She also developed the historical data in a newly acquired software named AQUARIUS.


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This thesis/dissertation was typed by Priscilla L Sandoval.