

THE FEASIBILITY OF UTILIZING PRODUCED WATER TO IMPROVE DRINKING
WATER SUPPLY IN SOUTHEASTERN NEW MEXICO

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ABSTRACT

Southeastern New Mexico has experienced over a century of oil and gas drilling and years of fresh surface and groundwater shortages as freshwater aquifers and reservoirs are depleted. Demand for freshwater has increased due in part to production practices of the oil and gas industry. Various stakeholders are looking for opportunities to use alternative water sources, such as produced water, to offset freshwater use. Produced water, a byproduct of oil and gas drilling, is most often managed as a waste product. However, as technologic advances are made in water treatment and the demand for water grows, the use of produced water as an alternative water source in Southeast New Mexico continues to garner attention. Interest in this topic is not new to Southeast New Mexico. Previous work highlighted several knowledge gaps that needed to be filled. A better understanding of the spatial distribution of the produced water volumes and quality was necessary before efforts could focus on developing proof-of-concept case studies. Regulatory uncertainty and the ambiguity of how to legally proceed with potentially using produced water has also hampered progress. More information was needed from potential users of produced water such as agriculturalists, service companies, oil and gas companies, and mining companies before developing strategies around treatment technologies. The purpose of this project titled, “The Feasibility of Utilizing Produced Water to Improve Drinking Water Supply in Southeastern New Mexico,” is to address these concerns in a way that provides various stakeholders and decision-makers better information to address these gaps. An updated produced water database allows researchers to analyze some of the drivers of water chemistry variability. Resource maps have been produced and made available through an online web-mapping application that allows stakeholders and decision-makers easy access to the data. An analysis of the regulatory framework brought researchers together with the three agencies in New Mexico responsible for protecting and managing the state’s water resources, and resulted in a clearer path to navigate the regulations surrounding produced water. Researchers reached out to industry representatives and agriculturists to gain a better understanding of specific water quality and volume needs. This information was used as variables in a decision-support tool, which was run for three potential use case studies. For all of this work remain meaningful, three rounds of community meetings engaged community members and various stakeholders in the research process. The results of this work provide new information that will help decision makers in the process of utilizing produced water, thus extending freshwater supply.

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EXECUTIVE SUMMARY

The focus of this study is to provide decision makers and stakeholders in New Mexico new information that can potentially improve the sustainability of water supplies in Lea and Eddy Counties by describing the available volumes and quality of water produced during oil and gas exploration, commonly referred to as produced water. Lea and Eddy Counties are of particular interest for this type of research because of increasing population, increasing water demand, long-term drought conditions, long-term depletion of aquifers, and large volumes of produced water. This study includes an updated database with produced water quality data, a geochemical analysis of the produced water quality data, mapping produced water quality and volumes, a review of the regulatory framework surrounding produced water, an analysis of the available treatment technologies, and an assessment of potential beneficial uses. Three rounds of community meetings brought community members, stakeholders, and researchers together to iteratively discuss research questions and results throughout the project time period.

This study was sponsored by the New Mexico Environment Department's Drinking Water Bureau with funds from the Drinking Water State Revolving Loan Fund Set Aside Grant for the purposes of protecting sources of public drinking water supply. Produced water use fits into this framework because it is important to ensure that untreated produced water does not contaminate drinking water supplies; and because treated produced water that is substituted for fresh groundwater could potentially extend the life of drinking water sources. The report was completed by June 30, 2016 and is available online at: http://nmwrri.nmsu.edu/?page_id=4864

Produced water is extracted along with oil and gas at a ratio around 7:1 water to oil (NM OCD, 2015). Produced water volume data reported to the New Mexico Oil Conservation Division estimate over 776 million barrels (100,000 acre-feet) of water is produced annually from oil and gas wells in Lea and Eddy Counties (NM OCD, 2016). Typically, produced water is managed as a waste product and is either pumped into a deep salt-water injection well or stored in large evaporation ponds. It is also one of the largest costs in oil and gas production with disposal costs (electricity for pumping, transportation, and disposal fees) ranging between \$0.25 and \$2.00 per barrel of produced water (Boysen, 2002). Produced water volume at particular well changes throughout the life of the well with higher volumes as the well ages (Iggunu and

Chen, 2013). In Lea and Eddy Counties, produced water has high total dissolved solids which limits treatment options and increases treatment costs if the water were put to beneficial use

Population change and changes in land management correspond to changes in water use. In 2010 the population of Lea and Eddy Counties was 64,727 and 53,829, respectively. The population of Lea and Eddy Counties has increased by 16.6% and 4.2%, respectively, from 2000 to 2010 (U.S. Census Bureau, 2010). Between 1990 and 2010 there was an increase in water use in Lea County while a slight overall decrease in water use occurred in Eddy County (Figure ES-1).

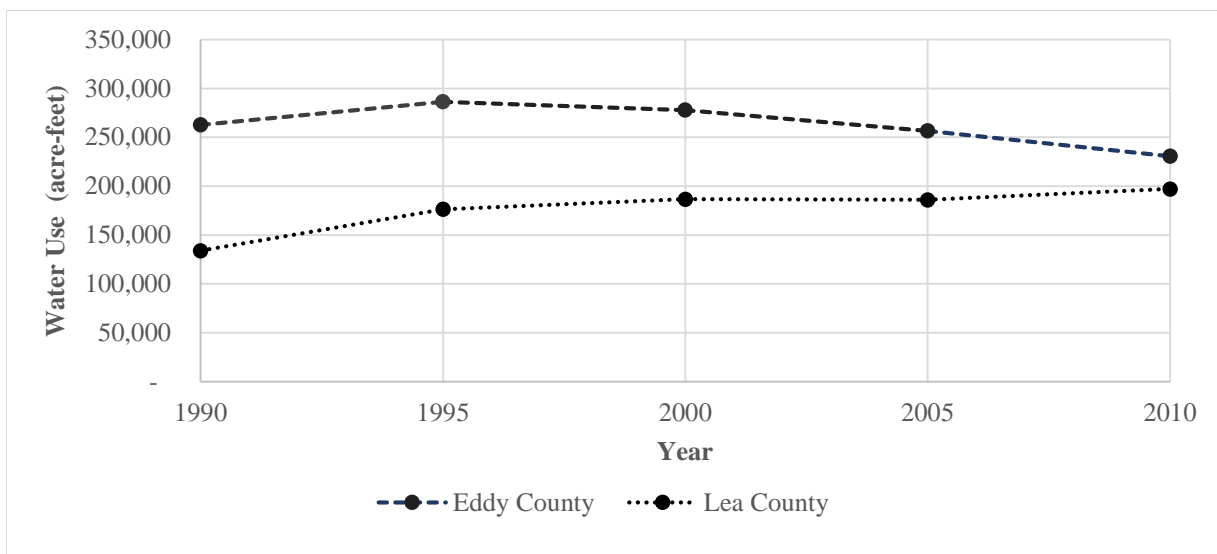


Figure ES-1 Water use in Eddy and Lea Counties 1990-2010 (NM OSE, 2016).

The decrease in water use in Eddy County can be attributed to the State of New Mexico purchasing and retiring approximately 27,300 acre-feet of water rights between 1991 and 2004 in order to remain in compliance with the Pecos River Compact delivery obligations (Blaine and Dixon, 2015). A majority of these water rights were categorized for use in irrigated agriculture and the effect is noted in the Office of the State Engineer reported water use by county (Table ES-1). In Lea County irrigated agriculture water use increased nearly 80,000 acre-feet. Public water supply use stayed relatively consistent between 1990 and 2010 even as the population increased, suggesting improved water conservation measures.

Table ES-1 Water Use by Category for Eddy and Lea Counties between 1990 and 2010 (acre-feet). Source: NM OSE Water use by categories reports.

Eddy County - Total Withdrawal	1990	1995	2000	2005	2010
Commercial (self-supplied)	238	752	1,265	2,230	504
Domestic (self-supplied)	161	448	243	160	203
Industrial (self-supplied)	464	665	881	1,256	2,109
Irrigated Agriculture	224,029	237,368	227,674	208,668	188,226
Livestock (self-supplied)	734	713	2,180	3,110	1,334
Mining (self-supplied)	13,730	11,184	6,229	6,343	9,303
Power (self-supplied)	-	-	-	-	-
Public Water Supply	14,667	15,410	16,117	14,398	15,465
Reservoir Evaporation	8,781	19,646	23,306	20,326	13,540
Total	262,804	286,186	277,895	256,491	230,684
Lea County - Total Withdrawal	1990	1995	2000	2005	2010
Commercial (self-supplied)	1,279	1,346	1,653	3,264	1,866
Domestic (self-supplied)	829	1,331	1,303	1,419	1,498
Industrial (self-supplied)	1,944	1,497	3,010	6,088	270
Irrigated Agriculture	92,049	131,163	129,792	135,371	172,297
Livestock (self-supplied)	793	1,497	2,797	3,737	2,186
Mining (self-supplied)	17,977	18,975	28,294	18,365	2,006
Power (self-supplied)	5,376	4,445	5,093	4,415	3,781
Public Water Supply	13,766	16,126	14,726	13,360	13,195
Reservoir Evaporation	-	-	-	-	-
Total	134,013	176,380	186,668	186,019	197,099

Between 2004 and 2014 oil production increased (Figure ES-2a) while natural gas production decreased (Figure ES-2b) in Eddy and Lea Counties. Many companies are now using horizontal hydraulic fracturing technologies and enhanced recovery methods for extracting oil and gas, which requires large volumes of water ranging between 40,000 to 60,000 bbls (approximately 5 to 8 acre-feet) of water needed for each well completion (LeBas et al, 2013). The water used to complete the wells is often times freshwater purchased by the oil and gas companies from local water right holders because it requires the least amount of pre-treatment prior to use, and thus cheaper. For water right holders, agriculturalists in particular, selling water to oil and gas companies can be more economically advantageous than growing crops. As a consequence, the freshwater is mixed with chemicals and becomes economically unrecoverable

as a freshwater source after use within the oil and gas industry. Another consequence of agricultural water being sold for oil and gas recovery is the reduction in application of irrigation waters to fields, which further exacerbates freshwater shortages by reducing recharge to groundwater aquifers.

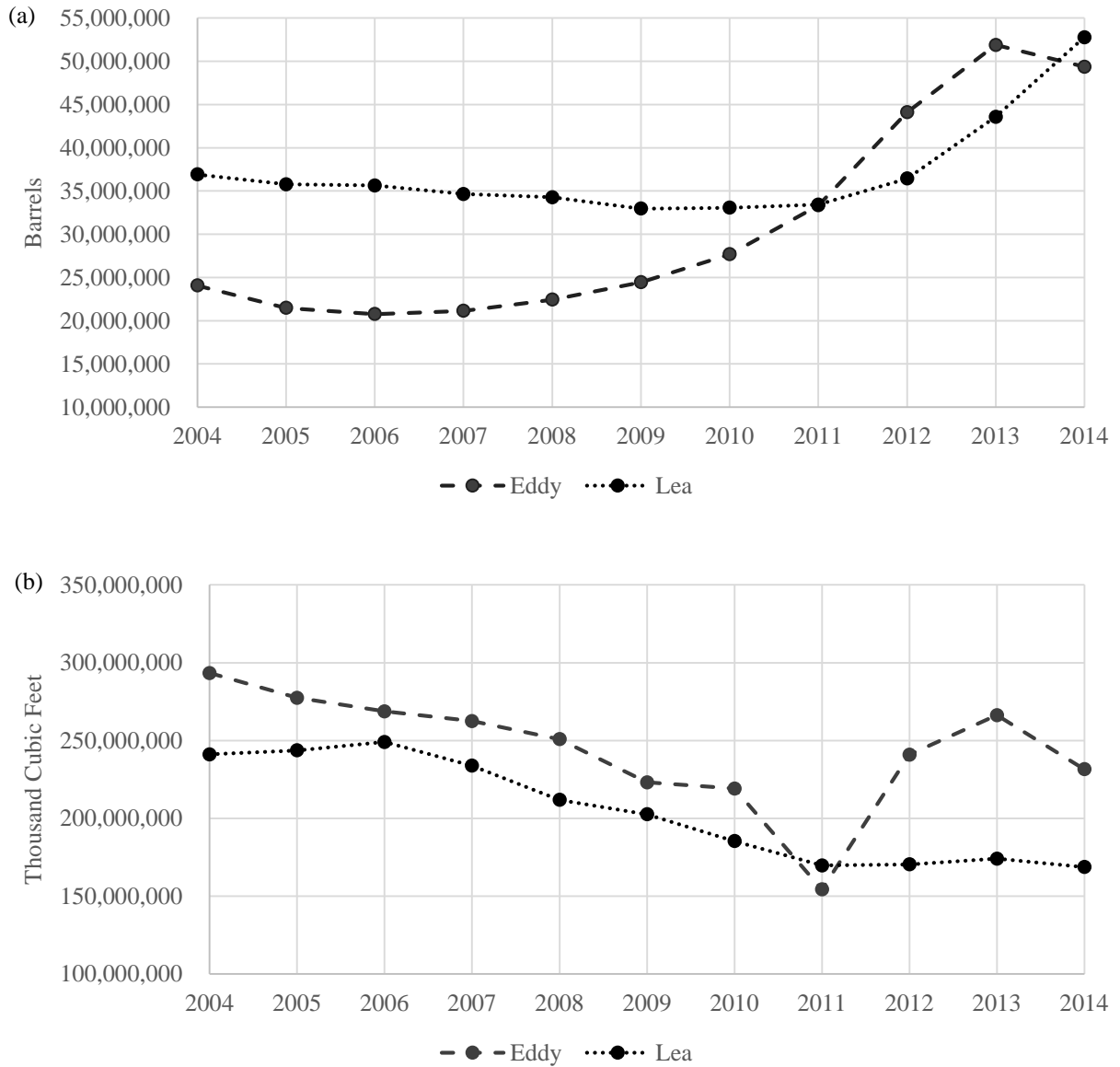


Figure ES-2 (a) Annual oil production; and, (b) annual gas production for Eddy and Lea Counties between 2004 and 2014.

The overall trend of annual precipitation in Eddy and Lea Counties is decreasing, as seen when examining the aggregated average annual PRISM data through 1985-2013 for Eddy and Lea Counties (Figure ES-3) (NM WRRI, 2016). Drought in Eddy and Lea Counties continues to be frequent and severe with most of the areas of the two counties being classified as abnormally dry to exceptional drought by the U.S. Drought Monitor for most of the period between 2000 to 2016 (Figure ES-4). Projected changes in climate are expected to greatly impact the U.S. Southwest with longer and hotter heat waves in the summer, hotter, more severe, and more frequent droughts, decreases in average precipitation, declines in river flow and soil moisture over the coming decades (Garfin et al., 2013).

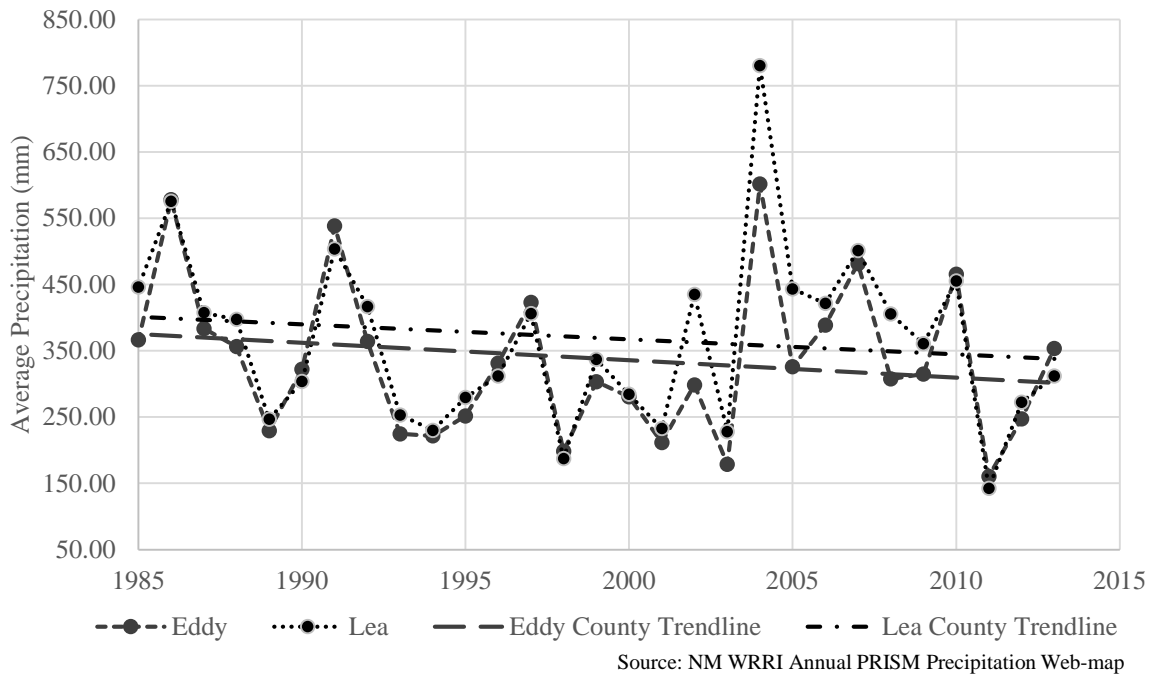


Figure ES-3 Annual average precipitation for Eddy and Lea Counties, 1985-2013.

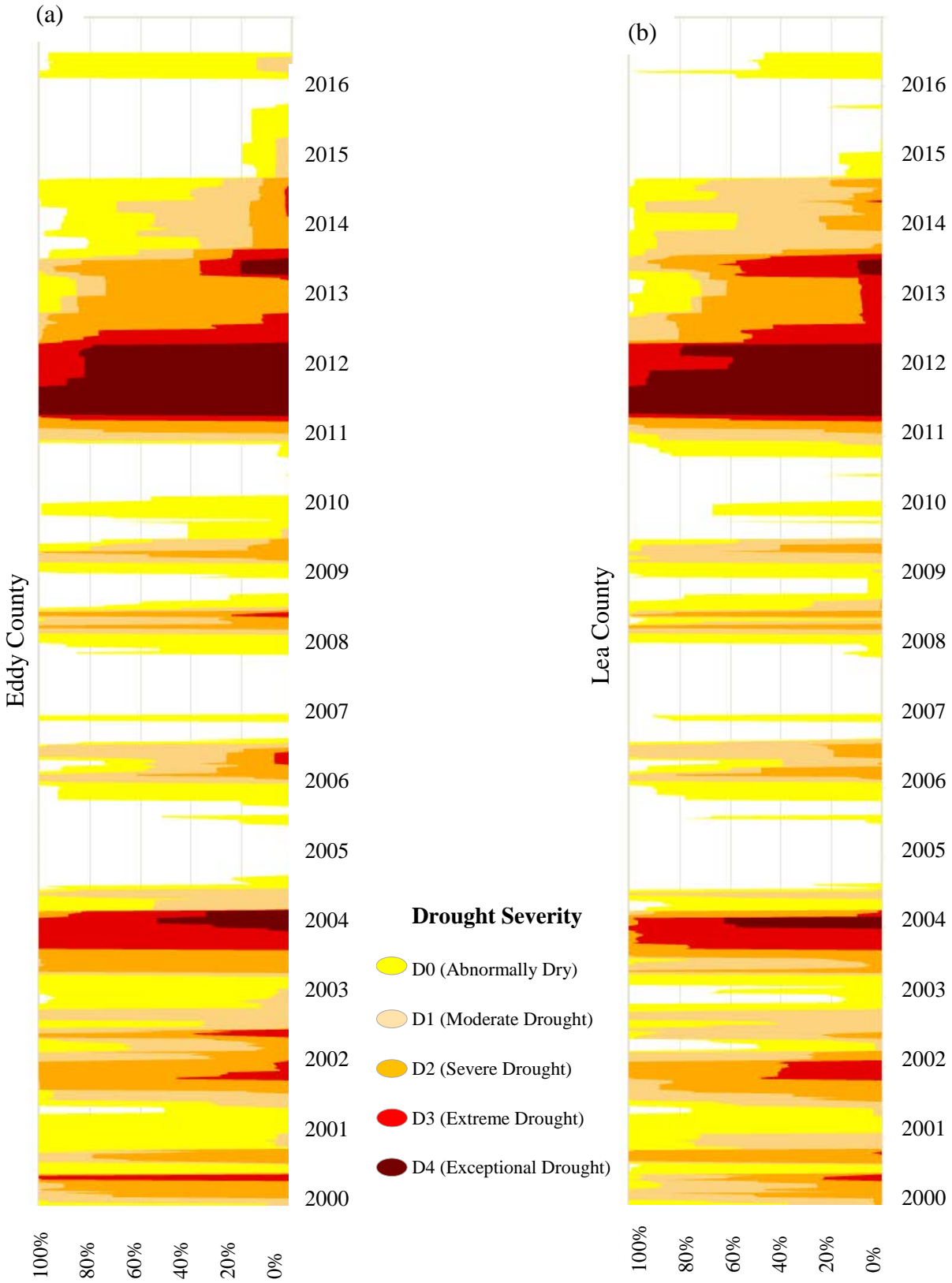


Figure ES-4 Percent of Eddy County (a) and Lea County (b) in drought conditions.

Source: <http://droughtmonitor.unl.edu/MapsAndData/Graph.aspx>

Lea and Eddy Counties of Southeast New Mexico are heavily reliant on water obtained from three aquifers, the Roswell Basin, the Pecos River Basin, and the High Plains Aquifer, with low to insignificant recharge rates (Figure ES-5). The Roswell Basin aquifer is an extensively used aquifer located between Vaughn, New Mexico and the New Mexico-Texas State line (Robson and Banta, 1995). The Roswell Basin aquifer consists of two aquifers, one composed of carbonate rocks and the other composed of alluvium. The total water annually diverted in the Roswell Basin has ranged between 280,213 and 440,946 acre-feet since 1967 (Thomas, 2013). Precipitation infiltration through permeable layers is the main source of recharge, but the basin also receives some recharge from water applied to irrigated agricultural fields. Natural recharge is estimated between 240,000 and 280,000 acre-feet annually (Robson and Banta, 1995). Aquifer water levels declined more than 40 feet in some areas and as much as 230 feet in other areas (Land and Newton, 2007).

The Pecos River Basin alluvial aquifer system extends from west central Texas into southern Eddy and Lea Counties. The alluvium ranges in thickness from 0 to 1,745 feet and contains an estimated 15 million acre-feet of freshwater and 85 million acre-feet of brackish groundwater (Meyer et al., 2012). The aquifer is recharged by precipitation, streamflow, return irrigation water, and subsurface flow from older formations (Robson and Banta, 1995).

The High Plains Aquifer, often referred to as the Ogallala Aquifer, underlies an area of approximately 174,000 square miles through Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (Robson and Banta, 1995). The area of the High Plains aquifer within New Mexico is recharged mostly from seepage from intermittent surface flow in streams or precipitation infiltration, with most of the recharge occurring from periods of snowfall when evapotranspiration rates are low. Infiltration of irrigation waters into agricultural lands is also a source of recharge. The aquifer naturally discharges from New Mexico into Oklahoma and Texas by subsurface flow. In 1980, the aquifer was supplying approximately 519,000 acre-feet of water to New Mexico and extraction has likely greatly exceeded recharge since the mid-1960s (Robson and Banta, 1995). Some parts of the High Plains Aquifer underlying New Mexico declined 150 feet since predevelopment (Gurdak et al., 2009).

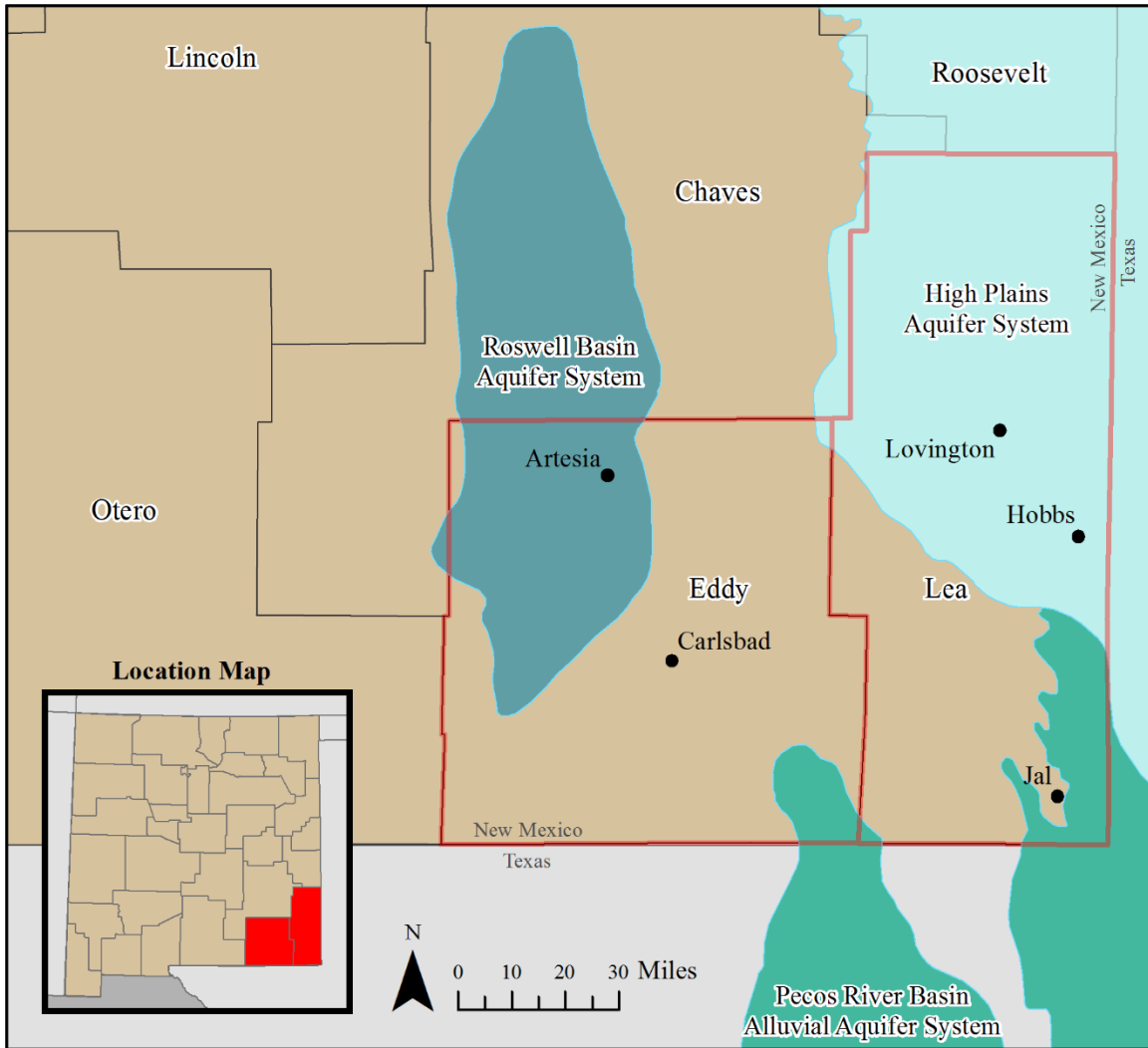


Figure ES-5 Aquifers underlying Eddy and Lea Counties.

The New Mexico Water Resources Research Institute collaborated with research professionals from the Petroleum Recovery Research Center at New Mexico Institute of Mining and Technology, Los Alamos National Laboratory, and New Mexico State University to address some of the remaining questions surrounding produced water. The remaining six chapters in this report provide details addressing specific research objectives.

Information on produced water quality with respect to location is necessary in order to fully understand the potential for beneficial use of produced water. Chapter 1 describes an updated produced water quality informational database and website. The database was previously online from 2004 until 2013 before it was deactivated due to security vulnerabilities

in the website code. This updated database provides produced water quality data recorded by industry at oil and gas wells around state and is foundational data for produced water research in New Mexico. Industry is not required to report water quality data and updates to the database are reliant on sharing from industry sources. During the course of this project nearly 4000 produced water quality samples in Southeast New Mexico were added to the database from industry sources. The addition filled in data gaps where new areas of oil and gas recovery have occurred since the first version of the database was released. This resource was used for the objectives described in Chapters 2, 3, 5, and 6, and is now publicly available through a searchable online resource at <http://octane.nmt.edu/waterquality/data/nmwaiidsSampleSearch.aspx> .

The geochemistry of produced water varies in formation and depth. Analysis of the spatial distribution and compositional variability advances the understanding of produced water quality in this region, which is critical for planning saltwater disposal and secondary recovery projects and for choosing proper treatment options for produced water. Chapter 2 provides an analysis of the spatial variability and geochemistry of produced water in Southeast New Mexico using data from the updated produced water quality database and a recently released USGS database. The analysis focuses on produced water quality in the western Permian Basin grouping waters by geologic formation. The analysis identifies areas where Total Dissolved Solids (TDS) are lower and might be considered for beneficial use.

Visualizing spatial produced water data can aid decision makers in recognizing spatial patterns and planning for potential beneficial reuse. Often these data are offered as static maps residing in reports and the derived information is limited to whatever can fit on a particular map. A more effective alternative is serving the data online through web-mapping applications that allow decision makers to ask and questions about the data interactively. Web-mapping applications developed from the updated produced water quality database and the New Mexico Oil Conservation Division are described in Chapter 3. The produced water quality web-map application features include: aggregated selected water quality constituents by township, option for searching by American Petroleum Institute (API) well identification number, and ability to estimate the average, minimum, and maximum values of selected water quality constituents within a user-defined area. The produced water volume web-map application utilizes produced water volume data for wells in Eddy and Lea Counties between 2004 and 2015. These data are

aggregated by township and an animation option illustrates the changes in volume over time. Tabular versions of both produced water quality and volume data can be directly downloaded from the web-mapping applications in .csv format. Additionally, spatial data can be downloaded as a file geodatabase and .kml files for use in Google Map applications.

Regulatory uncertainty has been one of the limitations in beneficial reuse of produced water in New Mexico. Three agencies are responsible for various aspects of water management in New Mexico; the Office of the State Engineer administers the state's water resources through supervision, measurement, appropriation, and distribution of the surface and groundwater; the New Mexico Environment Department is responsible for implementing federal water quality regulations; and, the Oil Conservation Division regulates all water within the oil and gas industry. While these agencies have clearly defined roles in the state's water management, a persistent ambiguity remained in the regulatory pathway for reuse of produced water outside the oil and gas industry. Chapter 4 addresses this ambiguity by providing an analysis of the regulatory framework surrounding produced water. This information was compiled in cooperation with the three agencies. The chapter offers example use case studies to illustrate the regulatory pathways for beneficial use of produced water.

Water treatment technologies continually improve, reducing costs and allowing treatment of water once only considered as waste. Many considerations are necessary to select appropriate treatment for produced water. Chapter 5 provides an overview of the current available treatment technologies and a table that summarizes removal efficiency, water recovery, waste creation, energy demand, and costs. The average TDS of produced water in Eddy and Lea Counties is approximately 90,000 mg/L based on information in the produced water database, and thus has high treatment costs. Information in Chapter 3 illustrates areas with lower average TDS where treated produced water might be economically viable given the current costs and treatment options. However, treatment plans for a specific well or group of wells will need individual analysis. Some of this analysis can be completed with a decision-support tool that considers multitude variables including water quality, treatment selection, beneficial use, and economics. The decision-support tool, a U.S. Department of Energy project, will be linked through the NM WRRRI website when completed in December 2016.

All of the information provided in Chapters 1-5 leads up to the ultimate goal of looking into the potential of utilizing produced water as an alternative water source. Each potential opportunity has unique water quality and volume requirements. Chapter 6 analyzes requirements for four of the potential uses identified in Eddy and Lea Counties with an emphasis on agriculture. Agriculture is a large contributor to New Mexico's economy and is also has the largest consumption of freshwater. A review of four major crops in Southeast New Mexico highlights the complexity using produced water for agriculture, specifically with considerations to unique soil chemistry and crop-tolerances. Mining, reuse within the oil and gas industry, and stream augmentation were also considered. Four potential use case studies were generated in Eddy and Lea using information from the produced water database, Geographic Information Systems, and decision-support tool. These case studies provide insight into the potential for use of produced water in Southeast New Mexico.

Several states including California, Texas, Colorado, and Wyoming have already identified opportunities, and implemented strategies, for reusing produced water for agriculture, stream flow enhancement, and aquifer storage and recovery. A review of case studies from these states provides insight into the similarities and differences in produced water reuse. Reuse of produced water within oil and gas industries is already occurring in New Mexico and is becoming more common since OCD changed 19.15.34.2 NMAC to encourage the recycling and reuse of produced water. At least one company is taking full advantage of the rule changes, reusing 3.5 million barrels of water in 2015 and completing 80% of well using recycled produced water in 2016.

Major accomplishments of this project were:

- Updated online produced water quality database
- Greater understanding of the geochemistry of produced water in three sub-basins of the Permian Basin.
- Decision-maker accessible web-map applications to explore produced water quality and volume data
- Reduction in the regulatory uncertainty through cooperative review of relevant regulations surrounding produced water.
- Review of the current treatment technologies and applicability to treating produced water in Eddy and Lea Counties.

- Review crop-tolerance levels and subsequent case studies of potential reuse of produced water in Eddy and Lea Counties.
- Three rounds of community meetings in Eddy and Lea Counties with high stakeholder engagement.

Although this project covered many topics, there are areas that need to be further addressed. First, available water quality data are only generally representative of the produced water quality and lack the detailed water quality parameters that are critical to selecting treatment processes and beneficial uses. It is also unclear from these data if and how produced water quality changes through time. Additional sampling with a scientific sampling design would fill this knowledge gap. Transportation and conveyance costs of produced water are high and need to be integrated in to the decision-support tool. Coupling a dynamic cost-distance tool to consider transportation costs through network analysis with the decision-support tool could assist in optimizing location of both treatment facilities and potential destinations of produced water. While caution was taken to best represent NM OCD produced water volume data, there was no clear method for separating produced water that was being used for waterflood or enhanced oil recovery within the provided database. This could lead to an over estimation in produced water volumes, for the Hobbs, New Mexico area in particular. Isolating produced water by disposed volume or by horizontal wells use could provide an additional disposal management tool. Lastly, although the report has outlined suggested regulatory pathways for produced water reuse outside of the oil and gas industry, there is a need for someone to champion a pilot study for agricultural reuse. This would clarify the permitting process and also provide feedback on crop-tolerances and potential contamination concerns.

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CHAPTER 1: IMPROVING AND UPDATING OF THE NM PRODUCED WATER QUALITY DATABASE: SUMMARY OF NEW MEXICO PRODUCED WATER DATABASE AND ANALYSIS OF DATA GAPS

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Introduction

The oil and gas industry in New Mexico generated almost 900,000 barrels of produced water in 2015, almost 116,000 acre-feet. This water is a byproduct of oil and gas production. It has been generally viewed as a liability in the industry for a number of reasons including lifting costs, separation and disposal costs, and issues surrounding corrosion and scale formation on infrastructure. As a result of concern over New Mexico's diminishing water resources, there is growing interest in the possibilities of reusing some of this water either within the industry or for other purposes. The resource is widely dispersed, and highly variable in quantity and quality. Knowledge of location, quality, and quantity is essential for evaluating any possible secondary use, and is also useful for the petroleum industry as an aid in reporting and compliance.

The current project objectives were to update and improve the existing produced water quality database created by the Petroleum Recovery Research Center (PRRC), a division of the New Mexico Institute of Mining and Technology (NMT), renew internet access to this database, provide GIS user-friendly functionality, and identify and attempt to fill in data gaps in newly active plays within the state, with an emphasis on southeastern New Mexico. The objectives support the work of other researchers on the overall project topic of using produced water to improve water supply sustainability in southeastern New Mexico. The following report is a description of work performed for that project.

Background

A number of years ago, the PRRC began to compile data on quality and quantity of produced water into the New Mexico Water and Infrastructure Data System (NM WAIDS) database as part of a project funded by the U.S. Department of Energy under DOE contract DE-FC26-02NT15134. This project entailed the design and creation of a water quality database, web-based interfaces to the data including a GIS map server, and integral tools to provide operators and regulators with necessary data and useful information to help them make

management and regulatory decisions regarding produced water. Detailed information about the project can be found in project annual and final reports (Cather et al., 2003, 2005)

Purposes of the original work relevant to the current project included assessments of the amount and quality of produced water to support the design of water treatment systems incorporating produced water, and also to aid producers in assessment of water quality issues such as corrosion and scale. The NM WAIDS database encompassed information on produced water quality/quantity in various producing regions of the state as well as some information on groundwater quality and depth in parts of southeastern New Mexico.

The NM WAIDS project was hosted on a large and complex website, GO-TECH, which was maintained by the Industry Service and Outreach Group at the PRRC. Work on the NM WAIDS database ceased over 10 years ago and the web-based interface and database were maintained as a static entity, with only one functional upgrade in 2007. In 2013 the entire GO-TECH site was taken offline at the request of NMT network administrators due to concerns about security of the site and its several underlying databases.

Priority in redesign and coding of GO-TECH was given to other sections of the site that had larger client bases. However, the need for the NM WAIDS data was underscored by many requests from both industry stakeholders and state agencies to redeploy the database, thus providing the incentive for the current project.

NM WAIDS Database Construction

A brief discussion of data collection, cleaning, and database construction processes that were used to build the original NM WAIDS database is provided here as reference documentation. Complete details can be found in the project final report (Cather, 2005). Creation of the database was one of the largest and most time-consuming tasks of the entire original effort. It was compiled from a large variety of source data. A number of regional oil and gas producers were solicited for water quality data, and many were very generous in sharing this information. Some of the data were provided in digital format, either as Microsoft Excel spreadsheets, Microsoft Access databases, or simple text files. Much data came from producers as paper forms supplied to them by the various companies employed to run the water analyses. Each data source had to be analyzed to determine what kind of information was available and in

what format (numeric, text, semi-quantitative), so the correct fields and data definitions could be built into the database structure. Examination of the thousands of paper forms and digital files revealed that data could be divided into four main categories: general information, general sample properties, anions, and cations. A number of tables and views were used in the database construction: primary tables were the general sample information (items such as sample name, location, formation, physical parameters), anion information (CO₃, SO₄, etc.), and cation information (Ca, Na, Mg, etc.). In addition to produced water quality, a large digital file of data on groundwater quality and depth in southeastern New Mexico was obtained from the Roswell office of the New Mexico State Engineer.

Researchers collected over 3000 water quality analysis forms for input into the database. There was an average of 30 fields on each form from which data had to be collected, and there were many types of forms, so the data types were not always the same from form to form. A web-based data entry system, designed to allow users to access the database remotely and securely for data entry was too time-consuming, requiring several minutes per form just to enter the data without any verification. Ultimately a process of scanning and using optical character recognition (OCR) technology was chosen. An additional advantage of the OCR process is that now a digital record of each image exists, so if there is a question about the data, the actual form image can be examined.

Many of the documents processed were poor copies of original forms that were difficult to read, and some were hand-written. Manual input was impractical for the amount of data to be entered and was also prone to significant typographical errors, but was the method used for many of the forms that could not be automatically converted to text. Figure 1.1 shows two typical water quality forms that could be processed automatically, with one being much easier to process than the other.

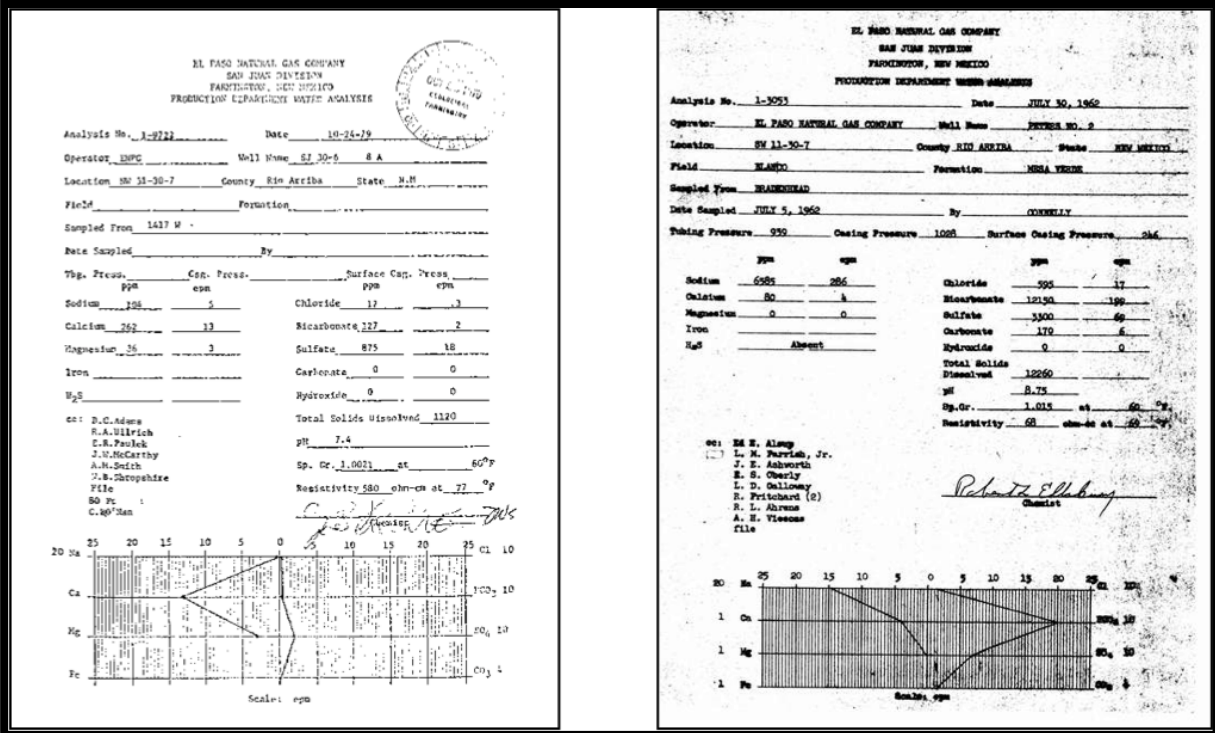


Figure 1.1 Example of two typical produced water quality data forms. These forms were both processed by OCR but the data on the left form was much easier to process. The smudges and fuzzy fonts on the right image produced more errors in processing. Data on left image was from a well drilled as part of a cathodic protection program, denoted by the “sampled from 1417 W” entry.

Once document processing was completed, a lengthy period of quality-checking ensued. Significant work in the original project went into developing automated routines for parsing and evaluating information. The original data were extremely non-standard in many respects, and two different types of data had to be evaluated: text-based data strings such as well names or miscellaneous notes, and numerical data that was written or typed on the forms. Given the large number of records, efforts were made to automate processes or use methods that could examine large amounts of data quickly.

One of the best ways to check data accuracy for the numerical water quality data was to examine the relationships in major element chemistry. Most water sample reports include data presented in two different units (Figure 1.1). This might be in parts per million (ppm), milligrams per liter (mg/l), milligram equivalents per liter (me/l) or equivalents per million (epm). Equivalents per million, a unit of measurement involving the number of ions, is often used in studies of chemistry of natural waters and in the interpretation of analyses. In waters of low

salinity, the unit epm is numerically the same as the unit milligram equivalents per liter (me/l). For practical purposes, they can be considered identical. Concentrations expressed in units of weight as parts per million (ppm) are sometimes desired for a particular purpose and are a very common reporting unit (Wilcox and Magistad, 1943). Conversion factors for some common anions and cations are included in Table 1.1. The equivalent weight of chloride is 35.5; thus 5 epm of chloride is the same as 177.5 ppm and 1 ppm chloride = 0.0282 epm.

Table 1.1 Conversion factors for common anions and cations

Cation	Equivalent weight	Conversion Factor (1/equivalent weight)	Anion	Equivalent Weight	Conversion Factor (1/equivalent weight)
Calcium (Ca)	20	0.05	Carbonate (CO ₃)	30	0.0333
Magnesium (Mg)	12.2	0.08197	Bicarbonate (HCO ₃)	61	0.0164
Sodium (Na)	23	0.0435	Sulfate (SO ₄)	48	0.0208
Potassium (K)	33.1	0.0302	Chloride (Cl)	35.5	0.0282
			Nitrate (NO ₃)	62	0.0161

To convert epm to ppm, multiply the concentration in epm by the equivalent weight. To convert ppm to epm, divide the concentration in ppm by the equivalent weight.

The linear relationship between epm and ppm was useful for checking accuracy of data where both measurements were reported. Figure 1.2 shows a graph of chloride reported in ppm vs. epm for some of the scanned data. In this figure it is seen that most reported data points lie on or very close to a line whose slope corresponds to the conversion values determined by ppm/epm. The human eye can quickly pick out several data points that vary greatly from expected, and also see that in general the data entry appeared to be good. A spreadsheet or programming method was also used. If the reported value was less than ½ or greater than two times the calculated value based on the conversion factor of 1ppm = 0.0282 epm for chloride, the data was considered suspect and values were checked against the scanned images of the data forms. In approximately half the cases, the error was found to be in the conversion of the image to text. The most common conversion error occurred in cases where the OCR program could not distinguish between a comma and a decimal point. In the other half of the cases checked, the OCR conversion was correct, and the problem lies in the actual data itself. A decision was made

to keep the data in the database and leave the decision to use the data to the individual database user. An error flag was used to indicate these records.

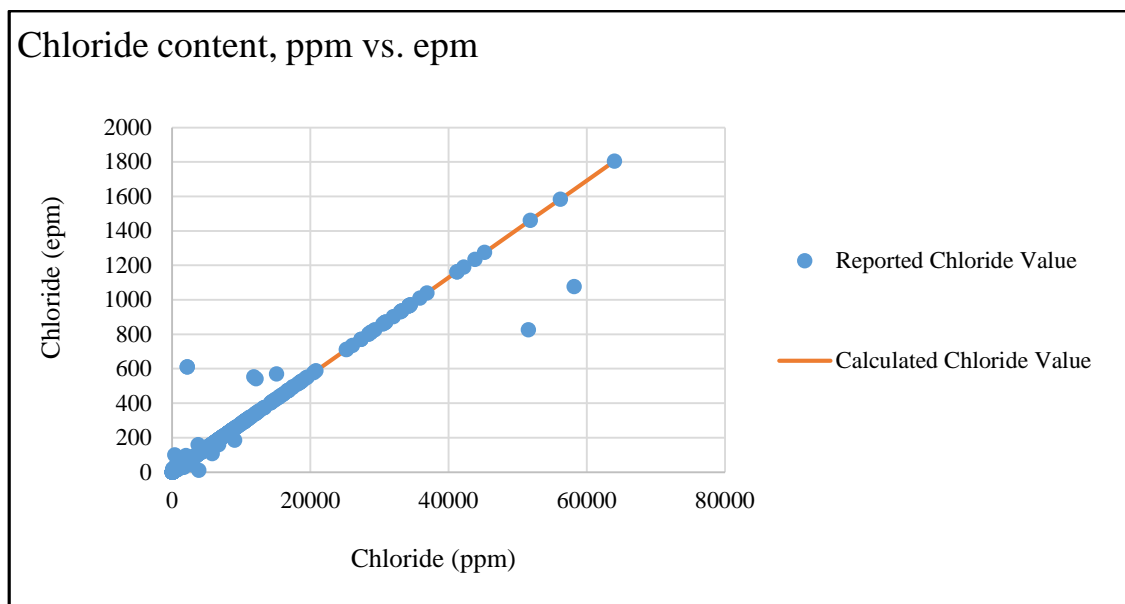


Figure 1.2 Reported and calculated values of chloride in ppm and epm units. Such comparisons were used for quality control of scanned and hand-entered data.

Apart from checking the quality of the numerical data, a tremendous amount of effort went into correctly identifying and locating wells (Wei et al., 2006). Once the database schema was constructed the various sets of digital or scanned and converted data were imported into the database. Elimination of duplicate data was a complex and iterative process (Wei et al., 2005) required after addition of each new data set. Later versions of the database were restructured to improve online performance but these changes did not include any changes or improvements to the content.

NM WAIDS Web Site

The original NM WAIDS web site was a useful tool for oil and gas operators and stakeholders in the state, and was also a valuable resource for researchers. The site provided access to a database comprised of two main datasets: Produced Water, with several thousand records of water quality from oil and gas wells throughout the state, and Groundwater, with very basic information but over 25,000 records, for southeast New Mexico only. There was an online manual of information concerning oilfield corrosion and scale identification, and a toolkit that

would allow users to calculate water compositions based on mixes of different types of waters and also probability and composition of any resulting precipitate (Figures 1.3-1.5). NM WAIDS received several hundred thousand visits a year at a time when the overall GO-TECH site was receiving a few million visits per year.

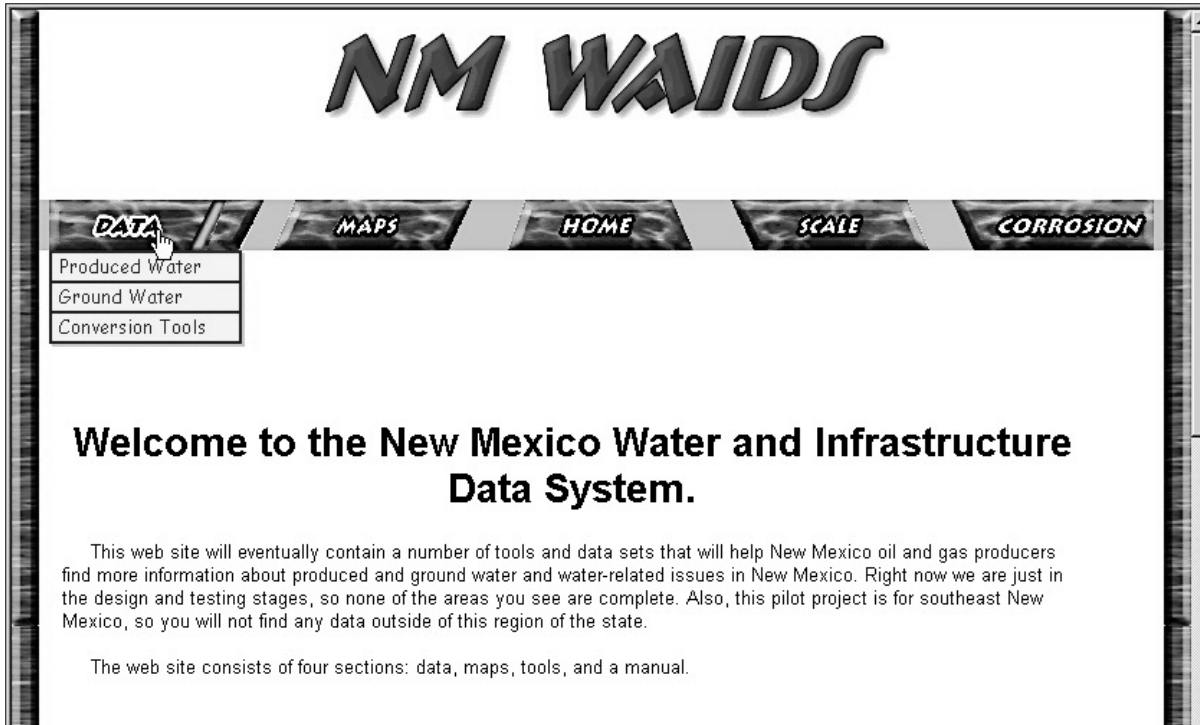


Figure 1.3 Home page for original NM WAIDS web site. Interface included links to produced water and groundwater databases and query pages, a GIS map server, various tools for predicting corrosion and scale, an online corrosion manual, and reference materials.

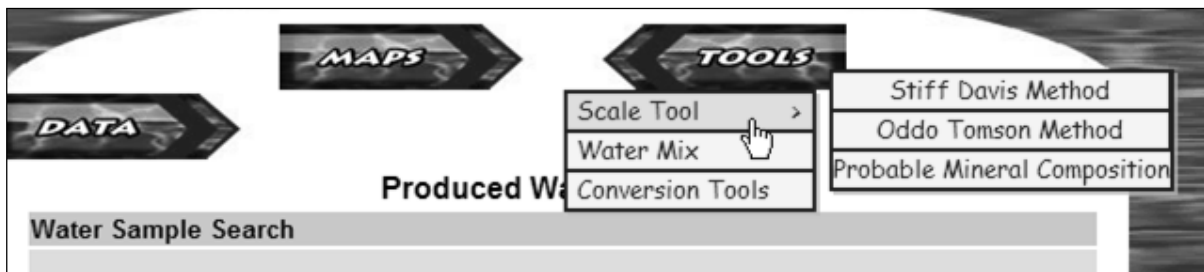


Figure 1.4 Tools included two scale calculation tools, a mineral composition tool, one to determine the composition of mixing of two waters, and unit conversion calculators.

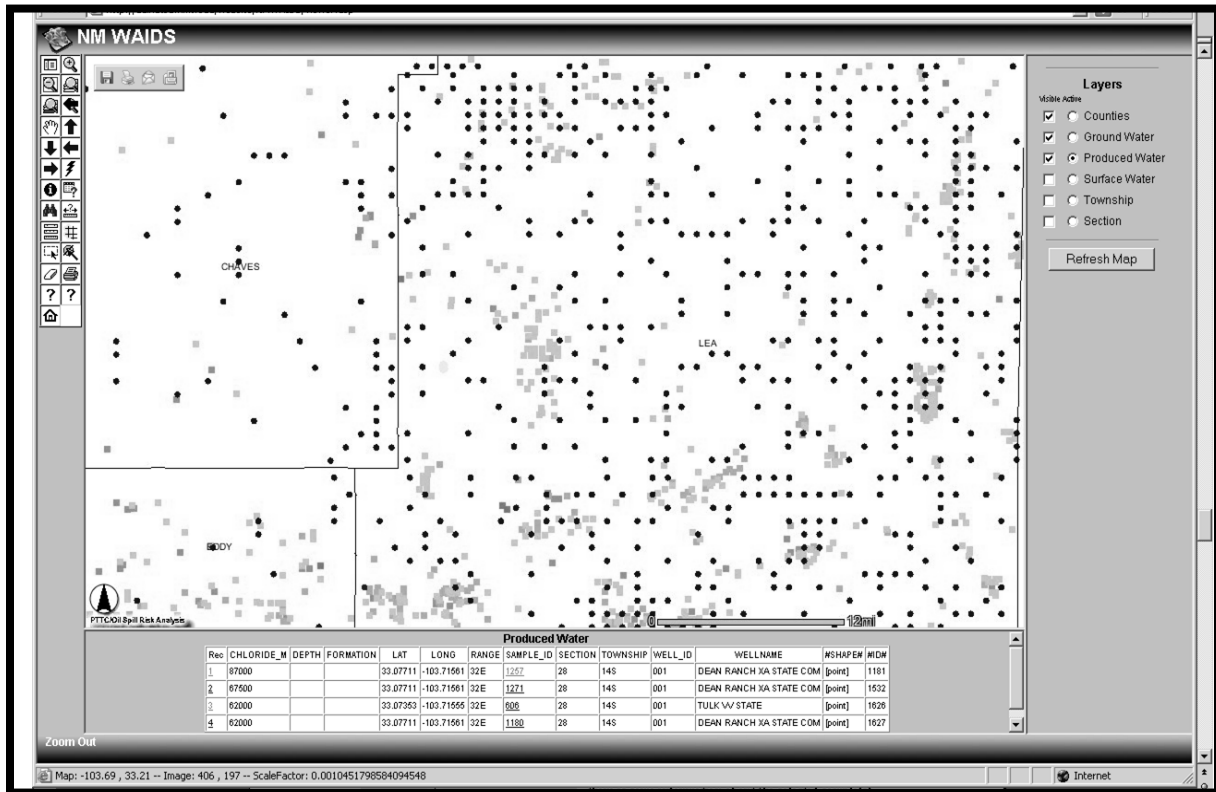


Figure 1.5 Original NM WAIDS online GIS map server interface zoomed to Lea County. Produced and Groundwater data shown as darker and lighter gray, with darker colors having higher chloride content.

In the years elapsed since the database was first put online, cyber security has become an increasingly important consideration. The last functional upgrade to the NM WAIDS web site was completed in 2006-2007. With passing time this interface and the coding behind it had become vulnerable to hacking. In 2013, the GO-TECH server (octane.nmt.edu) was identified as compromised and deemed a security risk by federal agencies so the server was taken out of service by NMT. As a result of this, the entire GO-TECH website, including NM WAIDS, was subjected to a series of web application tests to identify vulnerabilities with the site. Testing was conducted by CAaNES LLC (now RiskSense, Inc.), a company devoted to Internet threat and vulnerability management. Testing identified and validated 1028 security vulnerabilities that were classified by risk posed by each vulnerability to the organization. Out of the total 1028 vulnerabilities, 439 belonged to a high threat class, 23 belonged to a medium threat class and 566 were of low threat. The vast majority of threats were due to either cross-site scripting or injection. Cross-site scripting can allow malicious content to be delivered to a web application

user, while injection (in particular SQL injection) can allow malicious content or code to infect the server database system.

All of the hardware and software components of the system required updating; and much of the old code simply would not work well with the updated programs and systems. This upgrade was labor intensive and required significant resources; thus it was prioritized as to relative importance to our client base. Two parts of GO-TECH were deemed highest priority: the section containing New Mexico Production Data access pages, and the section devoted to access to NM State Land Office data. Because of the scarcity of funding and other resources, and the perceived lower priority given the water databases, upgrades to NM WAIDS of any type would have been very unlikely without the additional project funding provided by WRRI.

Methodology

Database Inspection, Cleaning, and Expansion

As a first step in the current project the existing NM WAIDS database was evaluated for structure and content. There were multiple tables that contained the same information – careful examination allowed deletion of four related tables. The remaining information was reorganized into tables containing location information, sample information, water quality data, and water injection and production volumes. See [Appendix A](#) for more information on database tables. During this process it became apparent that some of the information was still suspect; in particular duplicate data still existed because of the difficulties in well identification during the initial data collection period. Some wells still lacked proper identification or location information, and some numerical data was obviously wrong as compared with its overall data cohort.

Data Coverage

The existing data were also examined for gaps that might be filled in the course of the project. Data were plotted using ArcGIS to determine where there might be gaps in the spatial distribution of data in the original database. As expected, the major gap was the age of the data – much dated from the 1950s to 1999, and little new data was entered after original database deployment in 2004. The other significant gap was a lack of data that sampled wells drilled during the recent increase in horizontal drilling of oil wells in the Delaware Basin. Figure 1.6

shows some of the general geologic provinces of the Permian Basin and distribution of some recently active oil-producing formations. Other oil and gas plays have been more important in past decades and this is reflected in the data. Figures 1.7 and 1.8 show stratigraphic charts depicting the major producing oil and gas plays of the Permian Basin in New Mexico. While there were samples from the Bone Spring, various formations comprising the Delaware Mountain Group, and the Wolfcamp, these units were greatly underrepresented compared with current interest and drilling activity.

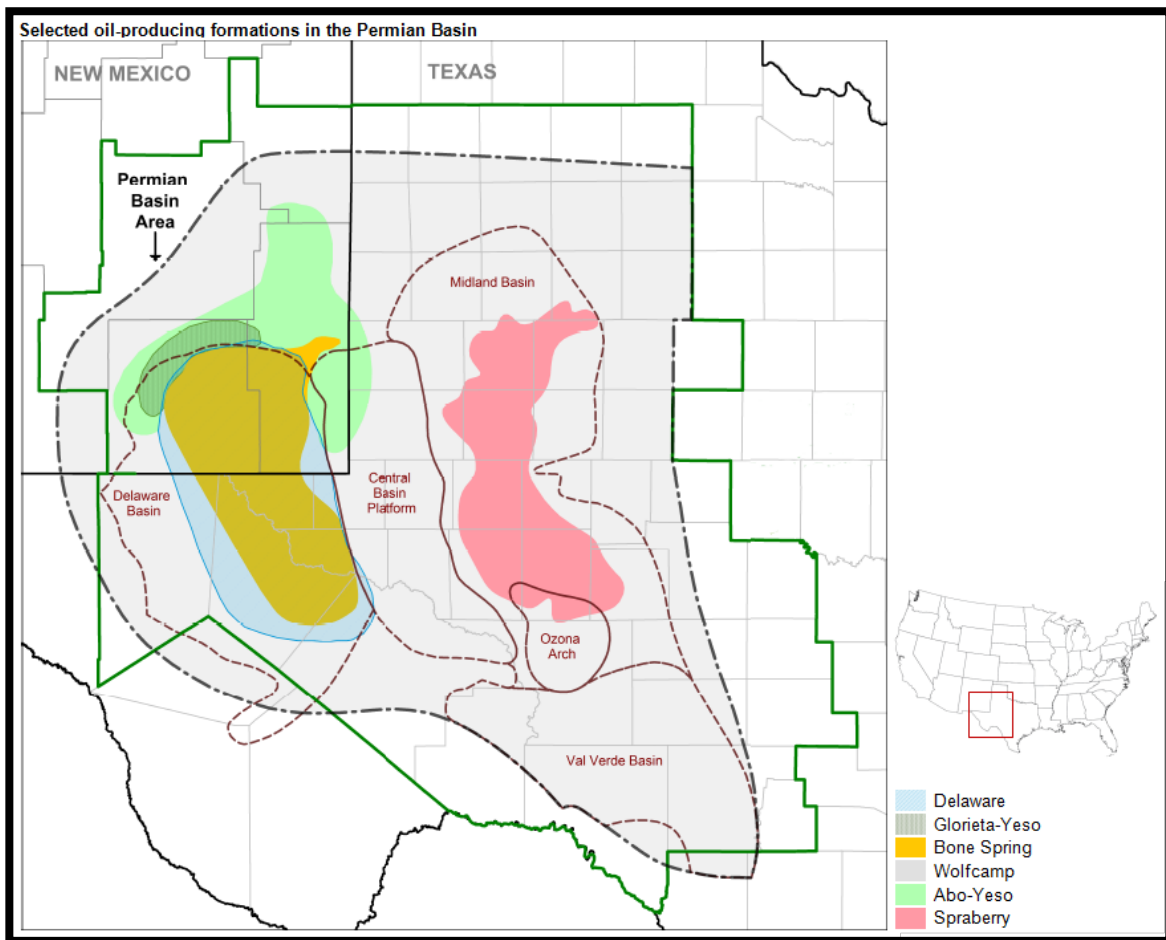


Figure 1.6 Geologic provinces and significant oil producing formations in the Permian Basin (from EIA, 2014)

Northwest Shelf, Central Basin Platform Oil and Gas Plays				
Age	Strata		Oil or Gas Play	
Triassic	Chinle			
	Santa Rosa			
Permian	Ochoan	Dewey Lake Rustler Salado		
		Guadalupian	Artesia Group	Tansill
	Yates			
	Seven Rivers			
	Queen			
	Grayburg		Upper San Andres and Grayburg Plays	
		San Andres		Northwest Shelf Platform (120) Central Basin Platform (124) Artesia Vacuum Trend (125)
	Leonardian	Yeso	Glorieta	
			Paddock	Leonard Restricted Platform Carbonate (117)
			Blinebry	
Tubb				
Drinkard				
Wolfcampian	Abo		Abo Platform Carbonate (116)	
	Hueco (Wolfcamp)		Wolfcamp Platform Carbonate (114)	
Pennsylvanian	Virgilian	Cisco	Northwest Shelf Upper Pennsylvanian Carbonate (110)	
	Missourian	Canyon		
	Des Moinesian	Strawn	Northwest Shelf Strawn Patch Reef (109)	
	Atokan	Atoka	Atoka-Morrow Gas Play (202)	
	Morrowan	Morrow	Morrow Gas Play (203)	
Miss.	Mississippian Undivided		Mississippian Gas Play (208)	
Devonian	Upper	Woodford	Woodford Shale	
	Middle			
	Lower	Thirtyone	Devonian Thirtyone Deep Chert (106)	
Silurian	Upper	Wristen	Wristen Buildups and Platform Carbonates (105)	
	Middle			
	Lower	Fusselman	Fusselman Platform Carbonates (104)	
Ordovician	Upper	Montoya		
	Middle	Simpson	Simpson Cratonic Sandstone (103)	
	Lower	Ellenburger	Ellenburger karst-modified ramp carbonate (102)	
Cambrian	Bliss			
Precambrian	Igneous, metamorphic, volcanic rocks			

Figure 1.7 Oil and Gas plays of the Northwest Shelf and Central Basin Platform (after Broadhead, 2004). Plays that are present on the Northwest Shelf and Central Basin Platform are listed next to their appropriate stratigraphic units. Numbers in parentheses represent the play identification number as defined in Broadhead, 2004.

Delaware Basin Oil and Gas Plays					
Age		Strata		Oil or Gas Play	
Triassic		Chinle			
		Santa Rosa			
Permian	Ochoan	Dewey Lake			
		Rustler			
		Salado			
		Castile			
		Guadalupian	Delaware Mountain Group	Bell Canyon	Delaware Mountain Group Basinal Sandstone (130)
				Cherry Canyon	
	Leonardian	Brushy Canyon		Bone Spring Basinal Sandstone and Carbonate (118)	
	Bone Spring				
Wolfcampian	Hueco (Wolfcamp)		Wolfcamp Slope/Basin Play (115)		
Pennsylvanian	Virgilian	Cisco			
	Missourian	Canyon			
	Des Moinesian	Strawn			
	Atokan	Atoka		Atoka-Morrow Gas Play (202)	
	Morrowan	Morrow		Morrow Gas Play (203)	
Miss.		Mississippian Undivided		Mississippian Gas Play (208)	
Devonian	Upper	Woodford		Woodford Shale (207)	
	Middle				
	Lower	Thirtyone		Devonian Thirtyone Deep Chert (106)	
Silurian	Upper	Wristen		Wristen Buildups and Platform Carbonates (105)	
	Middle				
	Lower	Fusselman			
Ordovician	Upper	Montoya			
	Middle	Simpson			
	Lower	Ellenburger			
Cambrian		Bilss			
Precambrian		Igneous, metamorphic, volcanic rocks			

Figure 1.8 Oil and Gas plays of the Delaware Basin (after Broadhead, 2004). Plays that are present on the Northwest Shelf and Central Basin Platform are listed next to their appropriate stratigraphic units. Numbers in parentheses represent the play identification number as defined in Broadhead, 2004.

One of our industry partners in the current project was instrumental in providing more recent data that helped fill some of the data gaps in the Permian Basin. Additional data were also obtained from old sources including previously unscanned forms of USGS water quality data which did not appear to already exist within their own database (personal communication, Nathan Myers, 2015), and data obtained from other producers that had been acquired after the initial database was created that had been too difficult to identify at the time it was received. The NM WAIDS database contained a large amount of data from all over the state including the San Juan Basin, another major hydrocarbon province. Project emphasis on southeastern New Mexico and the short performance period precluded attempts at acquiring more current data from other areas. Should additional funding be made available efforts should be made to gather more recent data from the Mancos and Gallup plays in the San Juan Basin, as well as sample data from coalbed methane produced waters in the Raton Basin.

Data Cleaning

In the course of evaluating the content of the NM WAIDS database several areas of work were identified. These included correcting wrong and incomplete well identification and location information, eliminating data transcription errors, and duplicate data, and standardization of field and formation names. Although the processes for correcting these problems will not be related in detail, a brief discussion is in order. Duplicate records were identified by the process of looking not only at well names and APIs, but by comparing actual data values. Values for commonly-populated fields such as total dissolved solids (TDS), chloride, pH, and specific gravity were commonly used in combination as unique identifiers to search for duplicates. This step was performed after all new data were added ensuring the process only need be repeated once.

Following duplicate elimination, crosschecks of remaining data were made with the current well database maintained by the NM Oil Conservation Division (NM OCD). If well name and API was consistent between sources no further action was necessary, but several hundred wells had inconsistencies that required more research. In the great majority of cases, well names and/or ID numbers were changed from the name given in the original information. However, a few hundred wells had problems with names, API numbers, and locations, including correct identification of county and state.

Fortunately, both the NM OCD and the Colorado Oil and Gas Conservation Commission (COGCC) now have extensive online resources including images of well files, hearing cases, administrative order documents and searchable databases of well information. By using these resources and the ability of Google to search millions of documents for specific words almost every single well was correctly identified. Only three wells out of over 5500 remain unidentified. For all other wells, the API number, well name and well ID number were corrected to reflect the most current information. The publicly available NM OCD database (called ONGARD) does not include well names for those wells that were out of production prior to the advent of the ONGARD database. Wells plugged prior to about 1992 are simply listed as “PreOngard Well” both in the database and on the various web pages that access ONGARD and or other NM OCD databases. Fortunately, the PRRC has maintained a copy of the NM OCD data for many years and one feature of our own database is that we do include the last known well name and could supply that information for those wells. It was also discovered that a number of wells that were not correctly identified in the NM WAIDS database were actually wells in southwestern Colorado; corrected information was added for these wells.

Although a significant amount of quality control had been done on the numerical water quality data when the database was first deployed in 2004, we revisited data in the course of review for the new iteration of the database. One issue was found with resistivity data – some was reported in ohm×m and some in ohm×cm on the original forms, and sometimes the unit listed on the original form was not correct, as was obvious from the magnitude of the reported value. All data in the current database were standardized to ohm×cm and unusual values checked against original data where available. Values of other data were checked in some cases where they stood out because of unusually high or low values, and generally were found to be consistent with what was originally reported on the form.

One interesting finding was made when old forms were reviewed. Over 100 samples from the San Juan Basin included some variation of the abbreviation CPS, often followed by a numeric designation, in the “sampled from” blank on the form or simply written at the top of the form, or an entry such as seen in Figure 1.1, where there was a number followed by the letter “W”. A search of OCD online image files enabled us to determine that these samples were not actually from water produced by an oil or gas well, but were samples of water taken from deep

groundbed cathodic protection wells that were drilled by operators to prevent electrolytic corrosion of subsurface infrastructure associated with the oil and gas wells in the area. While the water quality information is therefore less useful for evaluating produced water, it is still helpful information concerning water quality and depth in that region and was retained in the database with the notation that the data was from CPS wells and should be considered groundwater data.

One other important question was raised when examining the data; this concerns the actual samples themselves. It was not always clear whether the analyzed samples were actually water from the producing formation, samples from the fluid in the well from a mix of formations, or even from tank batteries from more than one well. Reported depth might often be the total depth of the well so was not a reliable indicator. Finally, sample quality might have been poor to begin with – sample dates and analysis dates reveal time gaps that could alter water chemistry due to atmospheric exposure (Patzke, 1989). Some samples were collected during major waterflood activities and likely reflect significantly altered water chemistry, while others were collected because the producer was having a problem with scaling or corrosion. In most cases, particularly in older wells, water quality was not evaluated routinely so the information may be skewed towards more problematic water quality (Hiss et al, 1969). None of these issues were controllable in our work, but are worth mentioning so users are aware of potential problems with data.

Data Standardization

Standardization of field name and formation data improves the ability of a user to search the database by a pool or a formation, and this type of information is often requested by operators in the area. Field name and formation data entered in the earliest version of the NM WAIDS database was derived directly from the forms or operator records and resulted in considerable variability. Both field and formation were described using a variety of abbreviations and names. Subsequent work on unrelated projects has provided us with a standardized list of pool names, formation names, and a GIS layer of pool boundaries for New Mexico. Figure 1.9 is an example of this work, showing the pools that comprise the Leonardian play in the Central Basin Platform (CBP) and Northwest Shelf (NWS). Pools are categorized by producing formation, and play boundaries by potential for further development. Standardized field and formation names were incorporated into the newest version of the database. In addition to

formation, samples were also grouped into plays following the work of Broadhead et al (2004), Engler and Cather (2014), and Engler et al (2015).

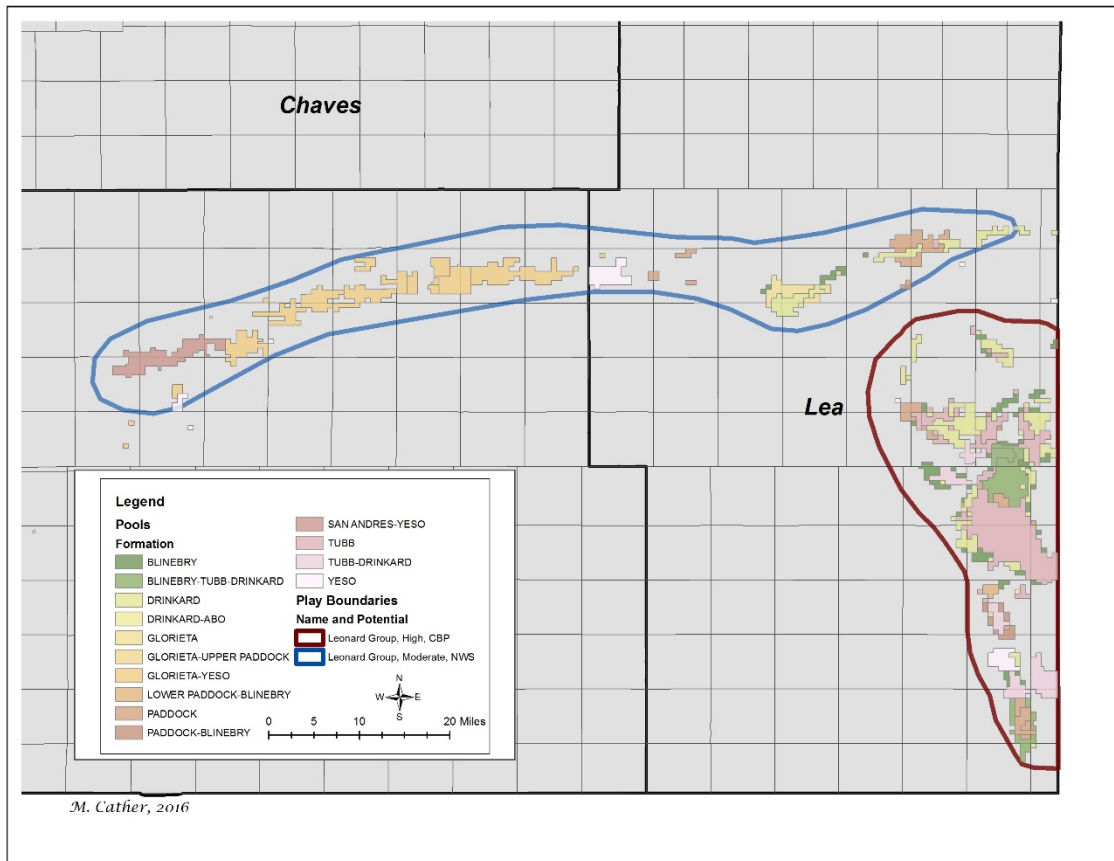


Figure 1.9 Pool and play boundaries for the two major Leonardian plays in southeastern NM.

Website Redevelopment

The original NM WAIDS project was created using the Integrated Development Environment (IDE) Microsoft Visual Studios, using C# as a programming language. The project utilized ASPX pages for the user interface. Much of the old code had security flaws that could be exploited to hack servers, change data, or even infect client computers with malware. Improvements to the graphical user interface were necessary in order to be integrated with the new look developed for the GO-TECH main site.

Several steps were necessary to achieve the objective of getting the Produced Water Quality Database and NM WAIDS web site back online. These steps included:

- Review all existing code that pertained to the NM WAIDS web site, including client and server side as well as any database procedures that would be relevant
- Document functionality of all code
- Identify security issues, poor coding practice, inconsistencies, and broken links or procedures, and determine appropriate fixes
- Identify an optimum IDE and programming language
- Convert all code and procedures to updated platforms and languages
- Configure server to handle different operating environments that are needed by various components of the web site including a legacy system requested by one of our state agency clients
- Run security testing on web site
- Beta-test revised web site and make needed changes
- Publish new version of web site

Results and Discussion

Data Analysis and Identification of Data Gaps

Data from at least four sources were combined to create the newest version of the NM Produced Water Quality Database (NM PWQD). The bulk of the data were from the older NM WAIDS database. However; over 2700 new samples were added. These come primarily from operator-contributed databases, with minor amounts of data obtained from previously unknown sources found warehoused either in physical or online repositories. Figure 1.10 shows a map comparing the areal distribution of newly added data as compared with what was previously in the database in the Permian Basin. Many of the additions covered the central part of the Delaware Basin, where the majority of new completions in the New Mexico part of Permian Basin have been in the past 5-6 years.

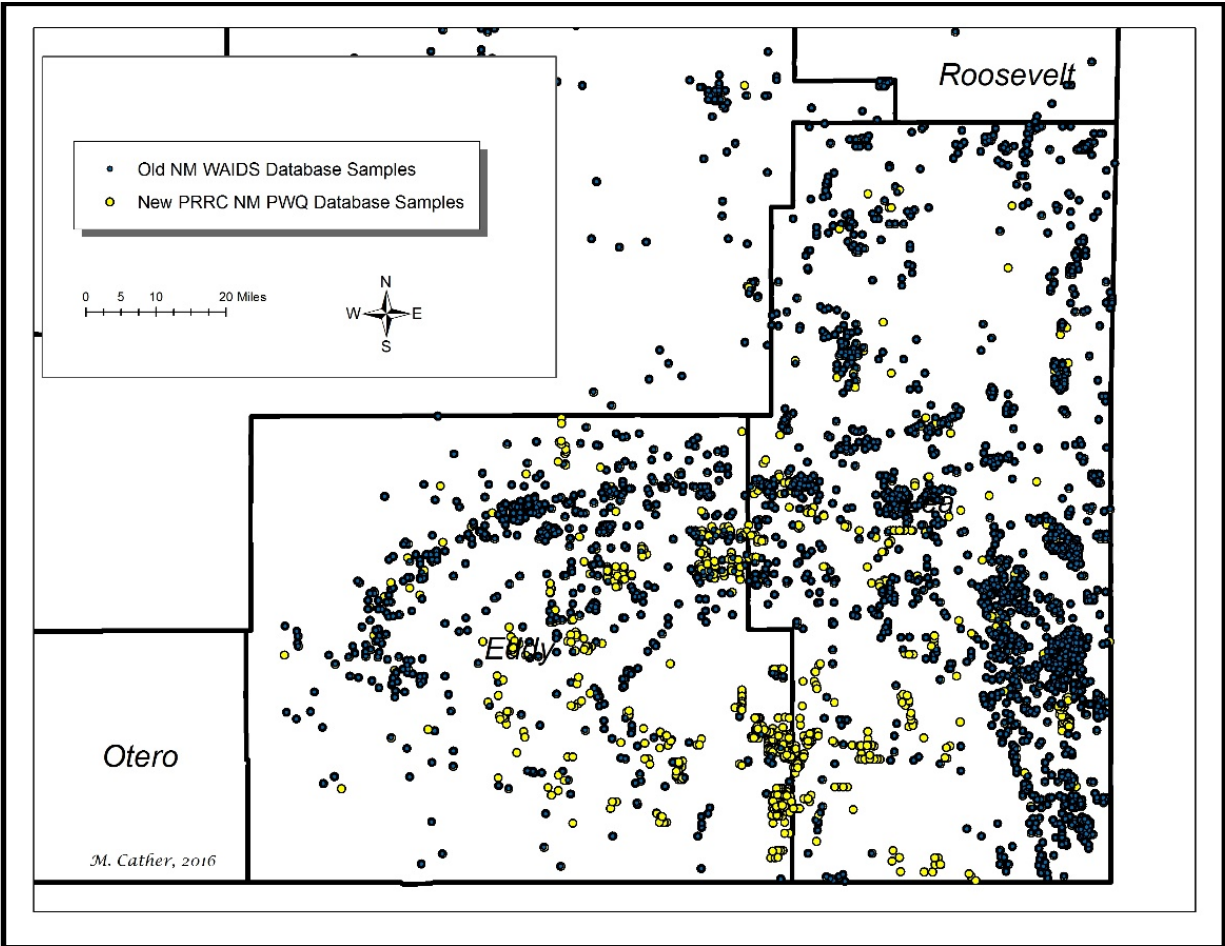


Figure 1.10 Comparison of locations of old data vs. newly acquired data.

Sample Vintage

Samples show a wide spread in age of the data. Table 1.2 and Figure 1.11 show distribution of samples by vintage of data using the year the sample was taken or analyzed as a criterion. Although much of the data is older, it is still relevant. About 60% of the 6353 samples in the database from Eddy, Lea, and Chaves counties, are from wells that are still not listed as plugged by the NM OCD.

Table 1.2 Sample vintage

Vintage	NM WAIDS	NM PWQD
2010-2016		1532
2000-2009	502	803
1990-1999	904	1088
1980-1989	150	833
1970-1979	641	918
1960-1969	533	677
1950-1959	778	552
<1950	46	37
Unknown	3161	3053
	6715	9493

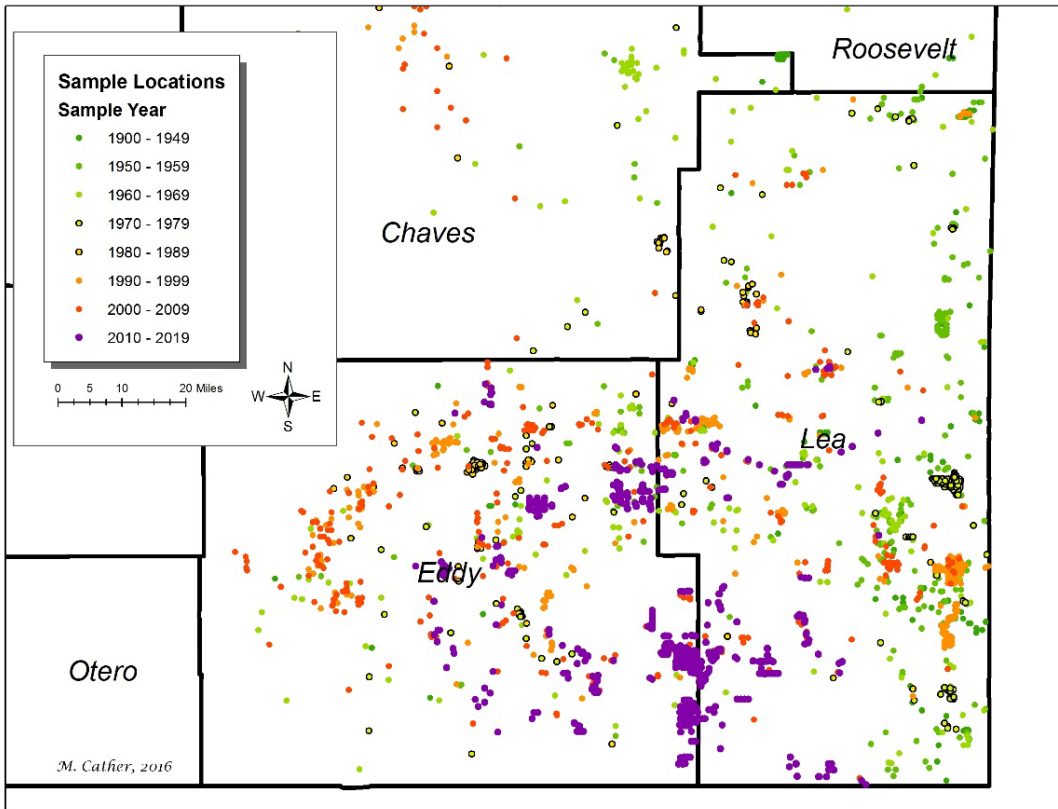


Figure 1.11 Distribution of samples with respect to date sample was taken or analyzed.

Areal Distribution

Approximately 67% of the total 9493 samples in the database are in the Permian Basin of New Mexico. Visual assessment of areal distribution of the data (Figure 1.12) illustrates that sample locations are fairly dispersed and widespread, consistent with distribution of oil and gas wells. A comparison of this with actual well locations shows coverage that reflects the general distribution of wells, particularly with respect to more recent well activity (Figure 1.13). Aggregating sample location by township does show some areas are over-represented, with very few wells but each well having more than one sample, or under-represented with no samples. Out of 490 townships in southeastern New Mexico, 406 had at least one sample, but 317 of those townships had a sample rate of 5% or less. Figure 1.14 shows sample rates by township in the area, recent well activity, and indicates regions that, based on low sample numbers and high activity, would benefit by additional sampling.

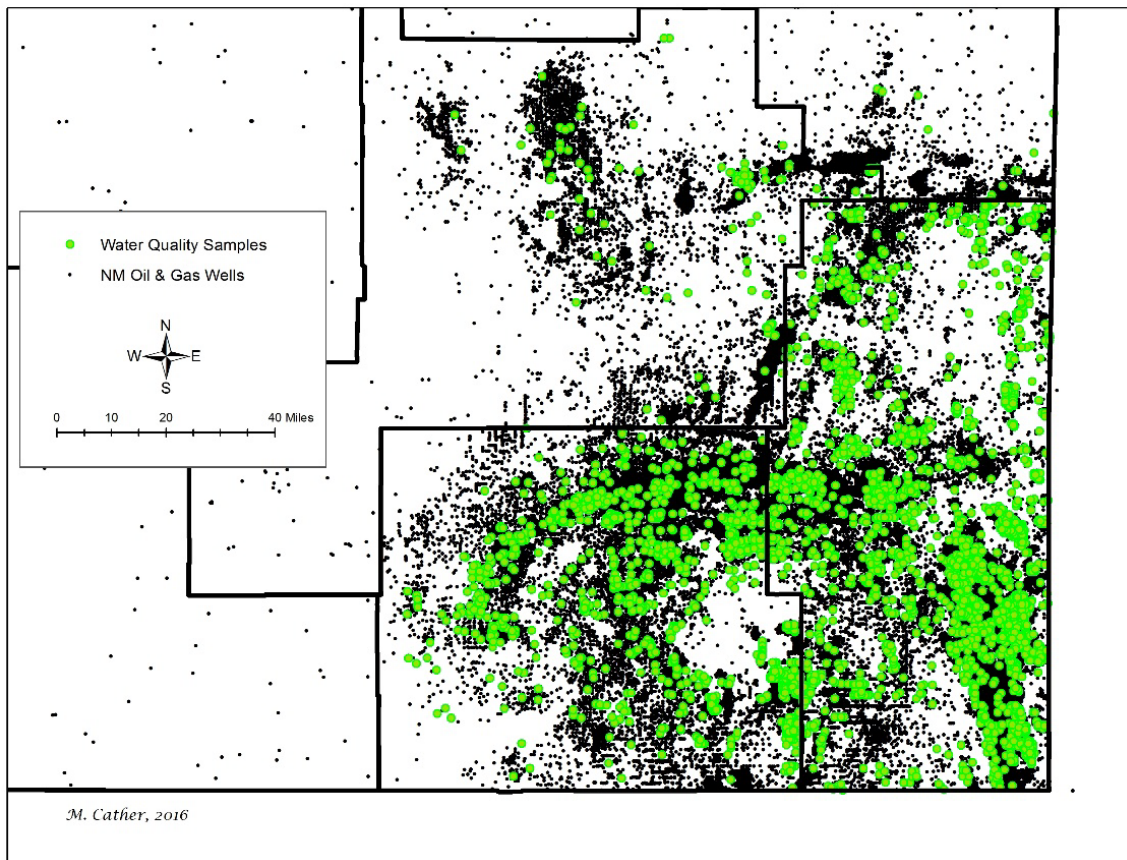


Figure 1.12 Distribution of samples as compared with overall distribution of oil and gas wells in southeastern New Mexico.

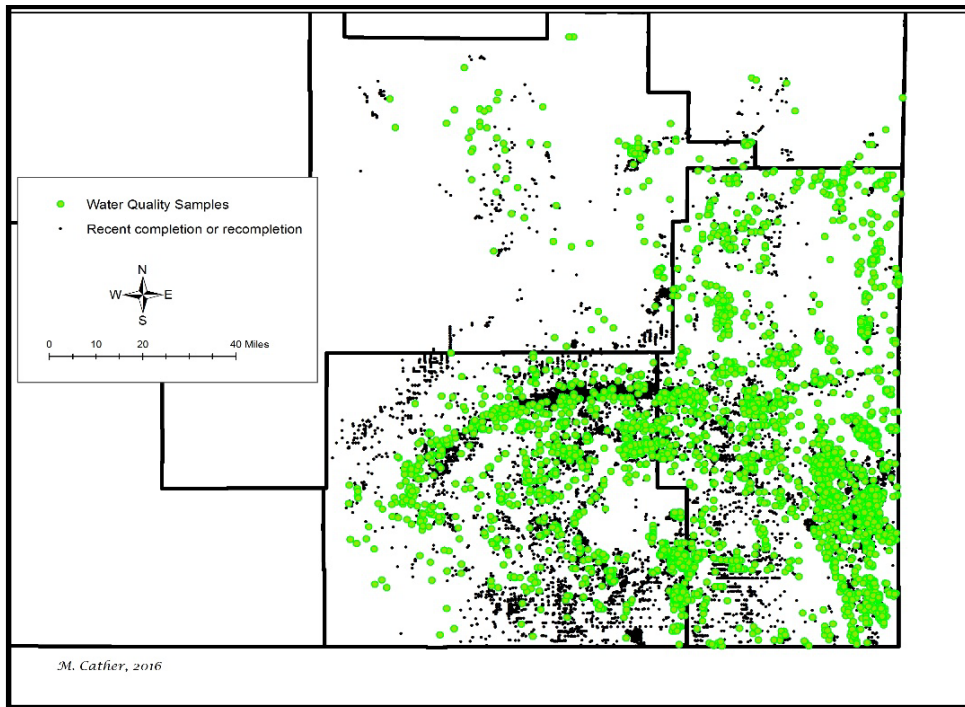


Figure 1.13 Distribution of samples as compared with recent well activity (completion or recompletion after 2010) in southeastern New Mexico.

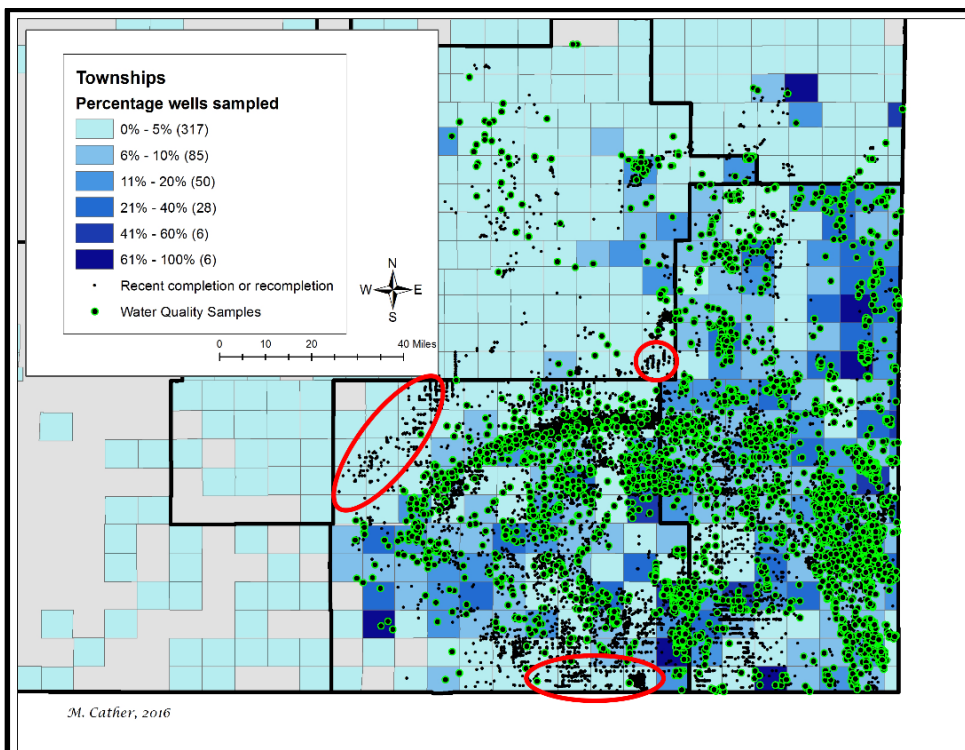


Figure 1.14 Map comparing relative density of sampling by township with current activity and with all sample locations. Darker colored townships indicate a higher percentage of total wells in the township have been sampled. Red ellipses are areas that would benefit from additional sampling efforts.

Distribution by Play

Figure 1.15 shows the sample set classified by the plays identified in southeastern New Mexico and Figure 1.16 shows a similar map with recent well activity, noted as completions or recompletions since January 2011. It is clear from this that the Bone Spring and Delaware Mountain Group Basinal sandstones, primarily the Brushy Canyon sandstone, are still under-represented with respect to their importance to producers. Likewise, wells producing from Artesia platform sandstones have probably more data than necessary. These wells were heavily sampled during the 1950s and 1960s when the play was active in both primary and waterflood-enhanced production. Many of these wells are still operational although at a reduced production level.

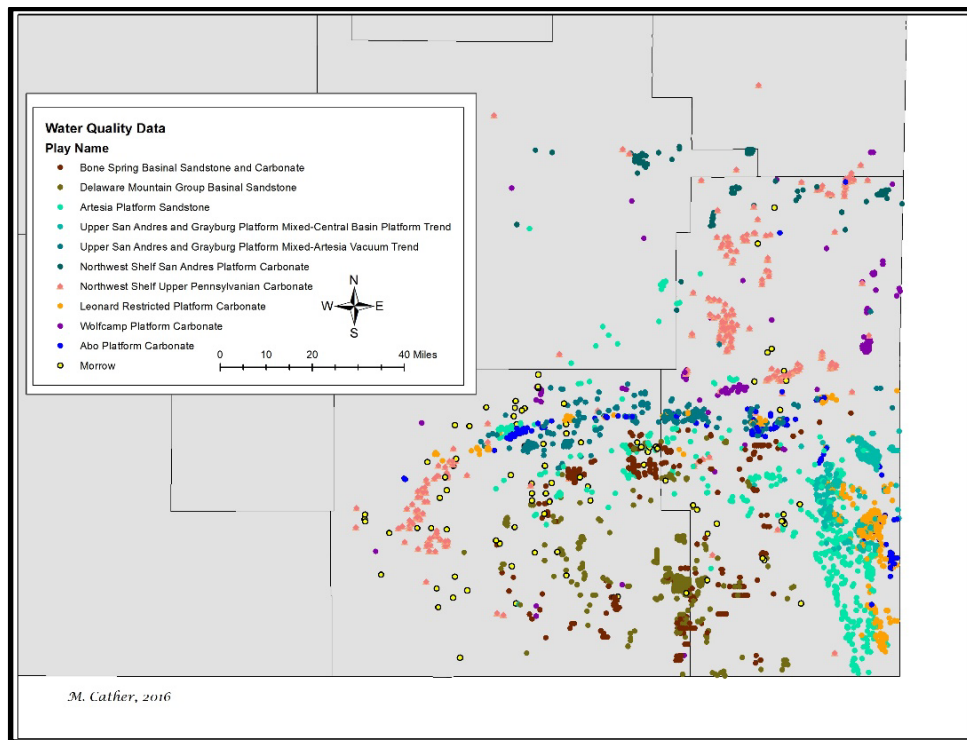


Figure 1.15 Water quality data by play. Not all samples have enough information to assign to a play.

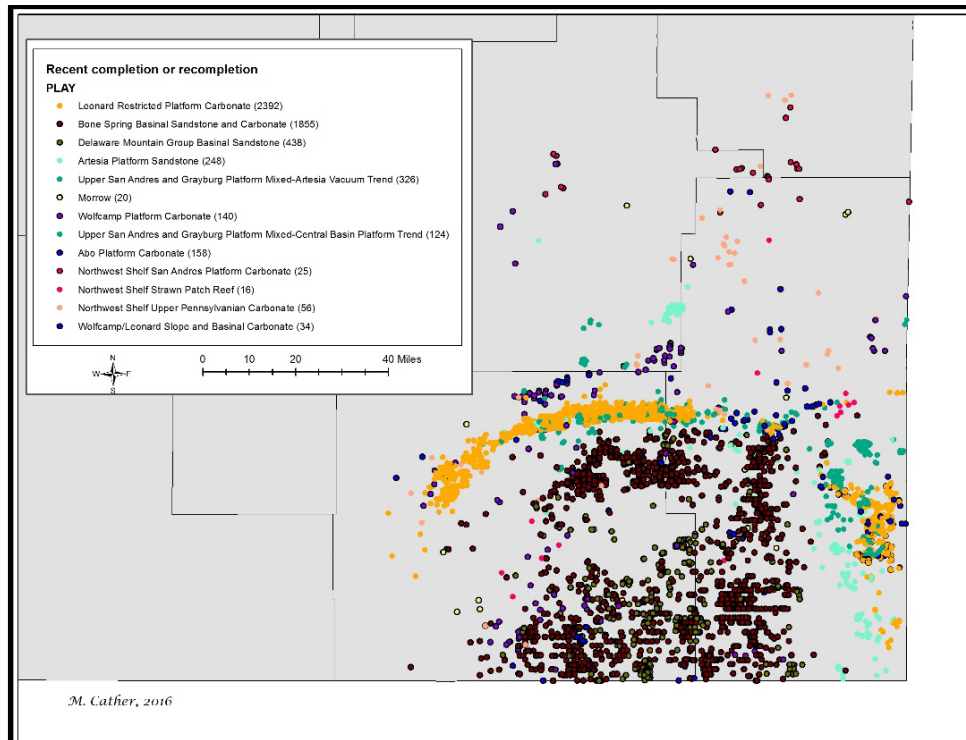


Figure 1.16 Map showing recent drilling activity in southeastern New Mexico, defined as completion or recompletion recorded since 1/1/2011, wells grouped by play.

Water Volume Analysis

In addition to understanding variation in water quality, it is important to know where water is being produced. Any type of reuse scenario would probably have to consider locating in an area where a significant volume of water of “acceptable for need” quality is currently being produced. Producers report volumes of oil, gas, and water production to the NM OCD on a monthly basis. The information is entered into the ONGARD database, and monthly updates to the public are provided via ftp server as an enterprise-scale database. PRRC has been automatically downloading, processing, and archiving that data in our own production database since 1996. The water volume data reported by operators, particularly in years prior to about 2000 were considered somewhat unreliable (Jane Prouty, personal communication, 2005), but are the best data available. For wells in some areas, water is both injected and produced as part of pressure maintenance and waterflood operations, so not all the volume of produced water is necessarily available for reuse. Reported production volumes may not accurately reflect what the reservoir would produce without those operations. Data concerning recycling of this nature are difficult to obtain in the public databases.

Production data can be looked at on a per-well basis, or aggregated by township. All liquid production is reported in barrels (42 gallons). One acre-foot of water is about 7758 barrels. Figure 1.17 depicts cumulative production from individual wells that have reported water production in the past three years. For simplification of the figure, wells that produced under about 400,000 barrels of water, or about 50 acre feet, for their lifetime of production were omitted. There are relatively few wells that produce a very large volume of water and it would be worth investigating these wells further.

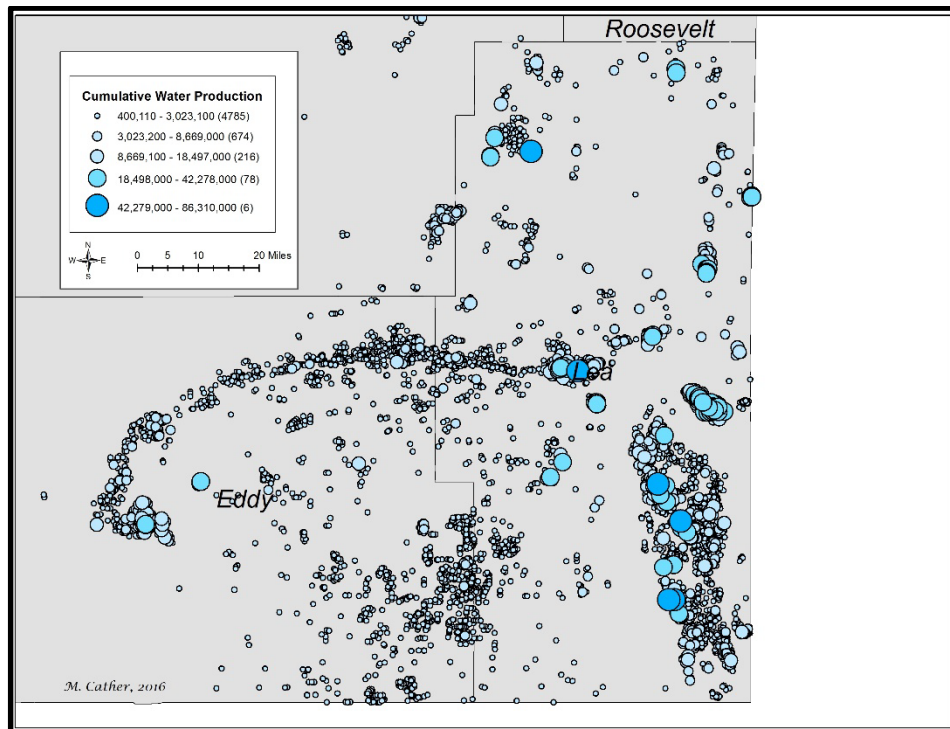


Figure 1.17 Cumulative production of water for wells producing over 60 acre-feet of water cumulatively. All wells in this figure reported water production in 2014 or 2015. 1 barrel of water is about 42 gallons; 1 acre-foot is equivalent to 7758 barrels.

Figures 1.18 and 1.19 provide an aggregated view of water production in southeastern New Mexico, looking first at total water production and second only at annual production for 2015. It can be seen that although a similar pattern of production exists in the two maps, there is an increase in water production in recent time in the deeper parts of the Delaware Basin towards the southern border of the state. Unfortunately, this water is often found to be highly saline and would be costly to use for any purpose that required relatively low salinity water. Figure 1.20 does highlight one area in eastern Lea County that has both low TDS waters reported, and high production volumes. This area might be a target for further investigation into water reuse.

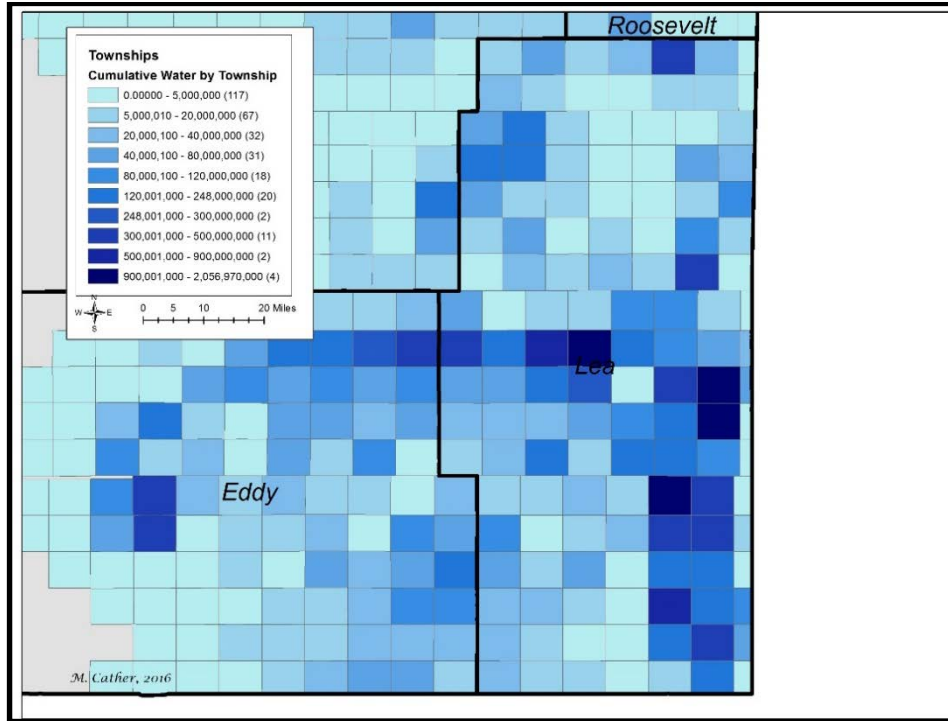


Figure 1.18 Cumulative water production by township, reported in barrels (bbls).

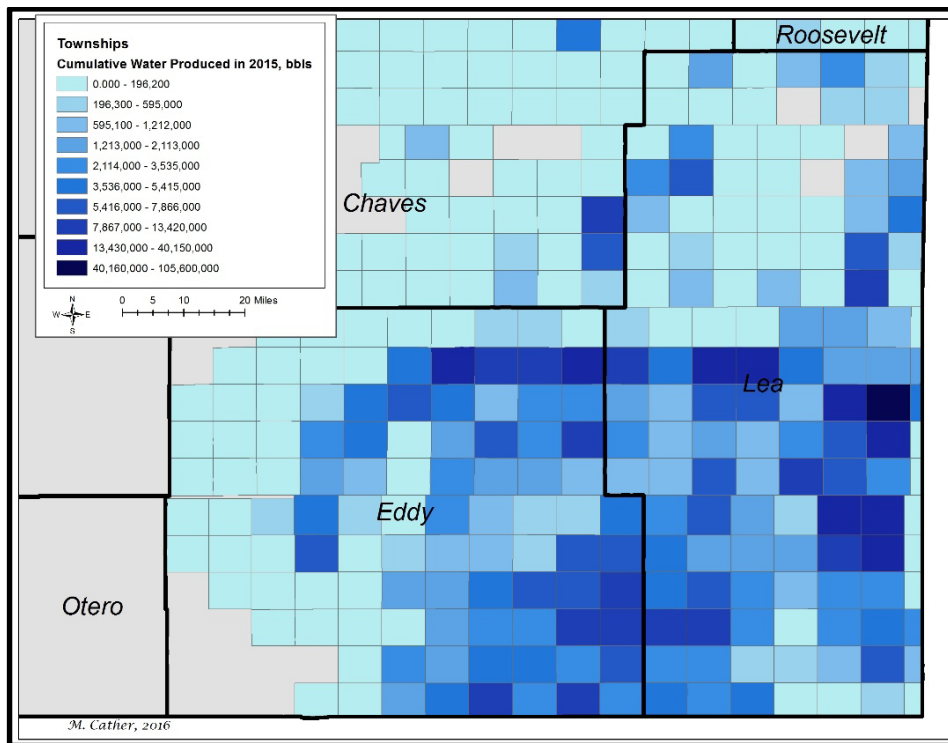


Figure 1.19 Production of water by township in 2015.

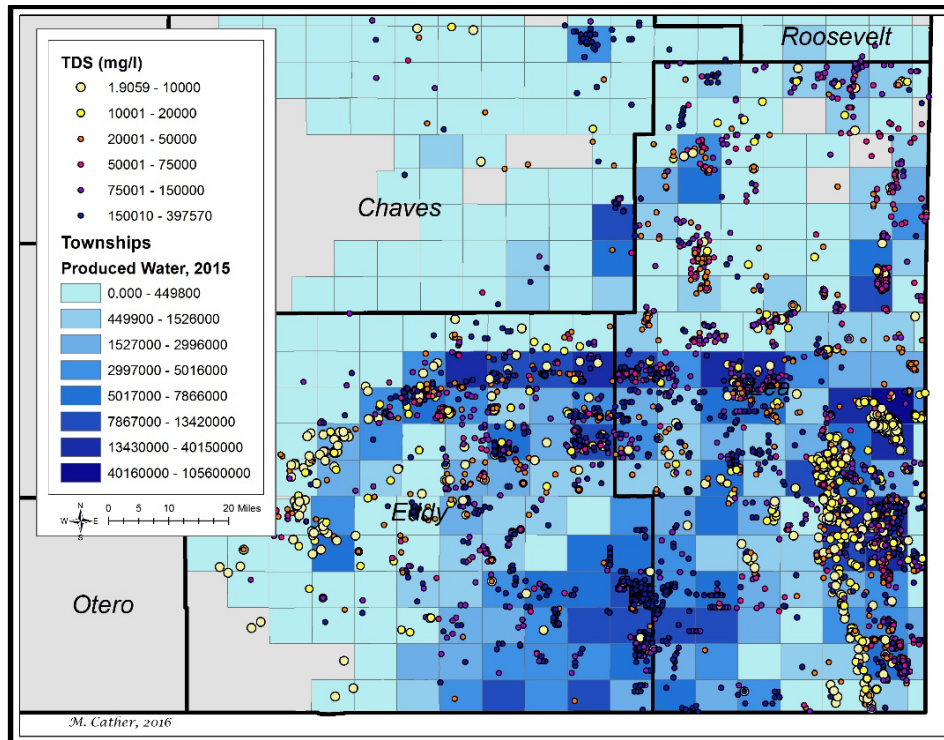


Figure 1.20 Water production in 2015 compared with TDS of samples. Samples with lower TDS values (yellow circles) show clusters in eastern Lea County where there is also relatively high water production.

Data Deployment

Several challenges arose during the process of redesigning and recoding the NM WAIDS. NM WAIDS was part of a larger web site (GO-TECH) that has provided access to a variety of data since 1996, and we wanted to create an entire site that, with the exception of the NM State Land Office data pages, all had the same theme, look and feel. This was made difficult for a variety of reasons. Each section of the old web site used different programming languages and Internet Development Environments (IDE). The underlying database servers resided on several machines with different vintages of operating systems and database servers. In order to comply with NMT security requirements, all components of all sections of the website had to be upgraded to the most recent versions available. Each component was subjected to a variety of security tests prior to publication. Finally, we were requested to put the new web site on a virtual machine that would be operated by the campus computer services department and this introduced another layer of complexity and the largest time delays of all.

The following has been completed to date: PRRC has moved all database services to a single machine, created a new project based on a different IDE and language, structured the project to have a Model View Controller (MVC) layout, converted ASPX files to Thymeleaf .html files, recycled and reformatted old Javascript code, and connected and tested the various database connections with more secure coding. Most of the web tools, with the exception of the GIS mapping capabilities, have been recoded. Data download functions have been recoded and enabled. The revised design layout for the entire site, including NM WAIDS is complete at this point. Internal beta testing is underway. The Produced Water Quality Database has been updated on our server, so that any query accesses the most recent version of the database.

Because of delays in deployment of the new website we have added water quality database search functionality to our existing GO-TECH website, which was also recoded and has undergone extensive security testing. The search is available from the URL <http://octane.nmt.edu/gotech/water/producedwater.aspx> and will be easily found from links in the menus at the left or top of any page (Figure 1.21). Figure 1.22 is a screen shot showing the results of a search on the well name “State J”. Searches use a “like” configuration so the user does not have to know an entire name. Searches can use a combination of location criteria (township, range, section), or can use a specific API. Experience has shown that these are the most common sorts of searches the typical user will use. The result panel is simple, showing the well identification, location, and TDS and chloride data. Each column is sortable, and the results can be paged through if there are more than 10 results. The user is also advised that more data is available and they can create and download Excel spreadsheet by pressing the appropriate button. This spreadsheet (Figure 1.23) contains the full set of data available for the results, and includes water quality information, field and formation, and latitude and longitude.

octane.nmt.edu/gotech/Water/producedwater.aspx

~ Home
~ Production Data ▶
~ Well Data ▶
~ Water Data ▶
~ NM Priceshet
~ Projects ▶
~ Software ▶
~ Other Links ▶
~ Help ▶

North American Oil and Gas News
Net Energy Trends
Recent data show divergent trends for rail shipments of crude oil, ethanol, and biodiesel
Oil, Gas and Mining: How rising FX volatility impacts finance, accounting and treasury professionals
Canada's National Energy Board says Mackenzie Gas Project still in public interest

NYMEX LS Crude 49
Waha Hub Gas 2.369
Henry Hub 2.409
Updated : 6/2/2016

State Land Office Data Access
OCD well/log image files
PRRC NM-TECH NM-BGMR

Source: Oil Voice

~ Home>>~ Water Data>>Produced Water Data

Home
Production Data
Other Searches
Older Data
Production Summaries
Well Data
Well Activity
First Production
Water Data
Produced Water Data
NM Priceshet
Projects
SLO
Software
C-115 Filing
Decline Curve Plotting
Other Links
NM O and G Links
Other States
Help
Land Unit Description
Acknowledgements

PRODUCED WATER DATA SEARCH

Data in the New Mexico Produced Water Quality Database v.2 was updated in 2016 for the first time in many years. Data should be used for general informational purposes only. The uncertainties in data collection procedures, analysis quality and specific sample sources make it unsuitable as basis for any significant business or policy decisions. Data was gathered from many sources and about 5400 distinct wells in NM are represented. More data exists for most samples than is provided by the results screen; the downloadable spreadsheet contains more information including field, formation, sample source (where available), and latitude/longitude.

Funding for the database was provided by the U.S. DOE, various New Mexico State agencies, NMT, and WRRI.

SEARCH PANEL

API NUMBER Example: 3004511439

WELL NAME TOWNSHIP RANGE

SECTION

Too many or not enough results? Change your search criteria and press the **Submit** button to improve results.

RESULT PANEL

PETROLEUM RECOVERY RESEARCH CENTER, SOCORRO, NM-87801

Figure 1.21 Screen shot of Produced Water Database search page. Links on left-hand and top menus both provide access from the GO-TECH home page <http://octane.nmt.edu/gotech/>

PRODUCED WATER DATA SEARCH

Data in the New Mexico Produced Water Quality Database v.2 was updated in 2016 for the first time in many years. Data should be used for general informational purposes only. The uncertainties in data collection procedures, analysis quality and specific sample sources make it unsuitable as basis for any significant business or policy decisions. Data was gathered from many sources and about 5400 distinct wells in NM are represented. More data exists for most samples than is provided by the results screen; the downloadable spreadsheet contains more information including field, formation, sample source (where available), and latitude/longitude.

Funding for the database was provided by the U.S. DOE, various New Mexico State agencies, NMT, and WRRI.

SEARCH PANEL

API NUMBER Example: 3004511439

WELL NAME TOWNSHIP RANGE SECTION

Too many or not enough results? Change your search criteria and press the **Submit** button to improve results. There may be more information for these samples. For all available data including lat/long location, press **EXPORT to EXCEL** to create a downloadable file.

RESULT PANEL

WELLNAME	API	TOWNSHIP	RANGE	SECTION	Tds(Mg/L)	Chloride(Mg/L)
STATE J #004	3002501147	14S	33E	23	36121.8	18249.8
STATE J #006	3002501149	14S	33E	23	36098.3	19649.3
STATE J #007	3002501150	14S	33E	23	35595.2	17163.5
STATE JO #001	3002500354	15S	32E	33	117536	71040
STATE J 2 #008	3002508747	22S	36E	02	7810	3073
STATE J 2 #012	3002508750	22S	36E	02	5988	2628
STATE J #006	3002501149	14S	33E	23	28553	13600
STATE J #006	3002501149	14S	33E	23	64000	35800
STATE J #006	3002501149	14S	33E	23	45720	24600
STATE J #007	3002501150	14S	33E	23	50100	24200

Figure 1.22 Screen shot of the main search and result panel for the NM PWQD on the GO-TECH web site at <http://octane.nmt.edu/gotech/water/producedwater.aspx>.

wellname	api	latitude	longitude	section	township	range	unit	ftgns	ftgww	county	state	company	field	formation	depth
STATE J #004	3002501147	33.0919037	-103.59155	23	14S	33E	E	1980N	660W	LEA	NM	GILLESPIE OI	SAUNDERS	PERMO-PENNSYLVANIAN	
STATE J #006	3002501149	33.0882759	-103.58724	23	14S	33E	K	1980S	1980W	LEA	NM	GILLESPIE OI	SAUNDERS	PERMO-PENNSYLVANIAN	
STATE J #007	3002501150	33.0955276	-103.58724	23	14S	33E	C	660N	1980W	LEA	NM	GILLESPIE OI	SAUNDERS	PERMO-PENNSYLVANIAN	
STATE JO #001	3002500354	32.9688644	-103.72061	33	15S	32E	O	990S	1980E	LEA	NM				
STATE J 2 #008	3002508747	32.4226341	-103.23706	2	22S	36E	F	1980N	2310W	LEA	NM		ARROWHEAT	GRAYBURG	
STATE J 2 #012	3002508750	32.4262543	-103.24136	2	22S	36E	D	660N	990W	LEA	NM		EUMONT	ARTESIA	
STATE J #006	3002501149	33.0882759	-103.58724	23	14S	33E	K	1980S	1980W	LEA	NM		SAUNDERS	PERMO-PENNSYLVANIAN	
STATE J #006	3002501149	33.0882759	-103.58724	23	14S	33E	K	1980S	1980W	LEA	NM		SAUNDERS	PERMO-PENNSYLVANIAN	
STATE J #006	3002501149	33.0882759	-103.58724	23	14S	33E	K	1980S	1980W	LEA	NM		SAUNDERS	PERMO-PENNSYLVANIAN	
STATE J #007	3002501150	33.0955276	-103.58724	23	14S	33E	C	660N	1980W	LEA	NM		SAUNDERS	PERMO-PENNSYLVANIAN	
STATE J #007	3002501150	33.0955276	-103.58724	23	14S	33E	C	660N	1980W	LEA	NM		SAUNDERS	PERMO-PENNSYLVANIAN	
STATE J D COM. #001	3002524153	32.541378	-103.37865	29	20S	36E	K	1650S	1980W	LEA	NM				
STATE J #001	3002505619	32.6620979	-103.28004	17	19S	37E	E	1980N	660W	LEA	NM		EUNICE MON	GRAYBURG/SAN ANDRES	
STATE J #002	3002505620	32.6657257	-103.28004	17	19S	37E	D	660N	660W	LEA	NM		EUNICE MON	GRAYBURG/SAN ANDRES	
STATE J #004	3002505622	32.6657181	-103.27575	17	19S	37E	C	660N	1980W	LEA	NM		EUMONT	ARTESIA	
STATE J #004	3002505622	32.6657181	-103.27575	17	19S	37E	C	660N	1980W	LEA	NM		EUMONT	ARTESIA	

Figure 1.23 Screen shot of a portion of the downloaded spreadsheet obtained for the wells returned in the search request depicted in Figure 1.20.

Redeployment of the online GIS mapping service to both oil and gas production wells and produced water sample data was explored. Initial work using one particular software solution

did not work well on the large production well dataset, so efforts were focused on using Google Maps as a programming interface. A beta product was created but would require significant modification before it can be useful to a general audience. This effort was considered of lower priority; geospatial data will be provided to WRRI for inclusion in the general GIS web service that they are compiling for this study. As mentioned previously, latitude and longitude information will be provided as part of the downloaded spreadsheet from the GO-TECH. This will enable users to create their own maps, which in our experience is often the most requested type of service.

Recommendations for Additional Work

While this project provides access to an upgraded and expanded version of the produced waters database for Lea and Eddy Counties, there are still a few areas that require additional efforts:

1) Web site testing, maintenance, and upgrades: Although the preliminary web site is complete, it is expected that the early weeks of use will bring requests and comments from users. Responding to some of these will certainly improve functionality; what our developers find to be best for information display and download may not correspond to what the client audience prefers.

2) Database updates and enhancements: The water quality database is relatively static. Although a significant amount of data was added in this latest version, we have not investigated the updated versions of public datasets such as those compiled by the USGS and other agencies that should be incorporated into the database (USGS, 2016). Because of challenges involved in duplicate record elimination and the short time frame for the current project, we chose not to add these resources at this time. In particular, other available datasets should be analyzed to see if they contain different and newer data from the areas identified in this study as under-represented.

3) Inclusion of reference materials developed for and derived from previous NM WAIDS work. An online manual of corrosion information was developed for the NM WAIDS project, and at least two student theses were written based on the water data collected for the produced and groundwater databases (Davidson, 2003, Haley, 2004). This information, particularly the

Davidson thesis still has value, particularly for southeastern New Mexico and should be included as a resource in the redesigned web site.

4) Closer integration of the water quality database with produced water volume information. The GO-TECH web site has production and injection volumes for oil and gas wells in New Mexico as reported by the NM Oil Conservation Division, and users can easily find the information. This information is all updated every month on our web site. A static version of some of the water volume data has been included in the latest copy of the NM PWQD database. This includes water production and injection volumes for 2014 and 2015, as well as cumulative total volumes. An improvement would be integration of volume and quality information so no additional search from the user is needed, and keeping this information up-to-date.

Summary

Work completed during the past two years has completely upgraded and revised the New Mexico Produced Water Quality database and web site. These data and the web site, originally compiled as part of a DOE-funded project that terminated in 2005, were taken offline because of cybersecurity vulnerabilities identified in 2013, and since that time there was no public access to the thousands of water quality records for produced and groundwater data that were contained in the databases. The new web site has much of the functionality of the old site.

Work undertaken primarily in support of the project focus on Lea and Eddy Counties has included improvement, augmentation, and analysis of data in southeastern New Mexico. Over 2700 new records have been added, and all data have undergone a significant amount of verification and correction. Analysis of data by geographic distribution, vintage, and producing plays shows the database is fairly consistent with production trends in the area, where there is more emphasis now on oil plays and in plays that are producing from the Bone Spring and Delaware Mountain Group formations. Volumetric analysis highlights certain areas in eastern Lea County that produce a great volume of water. Some of these areas have water that appears to be of relatively low salinity and TDS and these locations may warrant further investigation as targets for water reuse.

Data Disclaimer

Data in the New Mexico Produced Water Quality Database should be used for general informational purposes only. The uncertainties in data collection procedures, analysis quality and specific sample sources make it unsuitable as basis for any significant business or policy decisions.

References

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CHAPTER 2: SPATIAL VARIABILITY AND GEOCHEMISTRY OF PRODUCED WATER IN SOUTHEASTERN NEW MEXICO, USA

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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 (Jester, 2013). 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 (Galley, 1958; Veil et al., 2004; Jacobs et al., 1992; Khan et al., 2016; EPA, 2015; Benko et al., 2008; NM EMNRD, 2015). 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 (Lee et al., 2002; OCD, 2015). 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 (Maguire-Boyle et al., 2014; Van Voast, 2003; Alley et al., 2011; Orem et al., 2014). 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 (Khan et al., 2016). 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 (Barnaby et al., 2004). 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 (Barnaby et al., 2004; McFarlane et al., 2002). Some studies have explained the occurrence of meteoric water in deep reservoirs due to high hydraulic gradients and conductivity of rock deposits (Davidson, 2003). 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 (Engle et al., 2016).

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 2.1 shows location of produced water sample points, Permian Basin, and counties in study area.

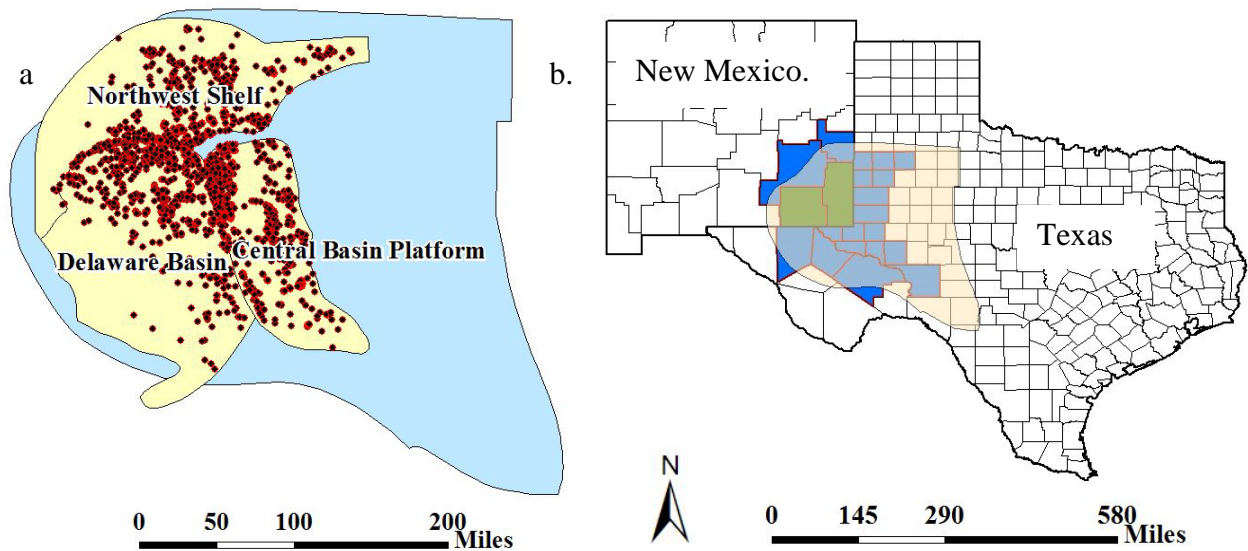


Figure 2.1 Maps showing a) location of wells in the Delaware Basin, Central Basin Platform and Northwest Shelf sections of Permian Basin and b) site maps of counties (blue), Permian Basin (yellow), Lea and Eddy counties (green) of study area (Engle et al., 2016).

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 2.1 (Dutton et al., 2004). 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 2.1 Stratigraphic column of geological formations in the three sub-basins (modified from Dutton et al. (David, 1977)).

Geologic Age (group)	Delaware Basin	Central Basin Platform	Northwest Shelf
<i>Guadalupian (Artesia)</i>	Tansill		
	Yates	Yates	Yates
	Seven Rivers	Seven Rivers	Seven Rivers
	Queen	Queen	Penrose
	Penrose	Penrose	Queen
	Grayburg	Grayburg	Grayburg
<i>Guadalupian (San Andres)</i>	San Andres	San Andres	San Andres
<i>Guadalupian (Delaware)</i>	Bell Canyon		
	Brushy Canyon	Cherry Canyon	
	Cherry Canyon		Delaware
	Delaware		
<i>Leonardian (Wolfcamp)</i>	Glorieta	Glorieta	Glorieta
	Avalon Shale	Blinebry	Paddock
	Bone Spring	Clear Fork	Blinebry
	Yeso	Yeso	Clear Fork
		Drinkard	Tubb
		Abo	Yeso
			Drinkard
		Abo	
	Wolfcamp	Wolfcamp	Wolfcamp
<i>Pennsylvanian</i>	Cisco		Cisco
	Canyon	Cisco	Canyon
	Strawn	Canyon	Strawn
	Atoka	Strawn	Atoka
	Morrow		Morrow
<i>Devonian</i>	Devonian	Devonian	Devonian
	Fusselman	Fusselman	Fusselman
<i>Ordovician</i>		Mckee	
		Simpson	
	Ellenburger	Ellenburger	Ellenburger

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 (Blondes et al., 2016). 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, and Br). Figure 2.2 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.

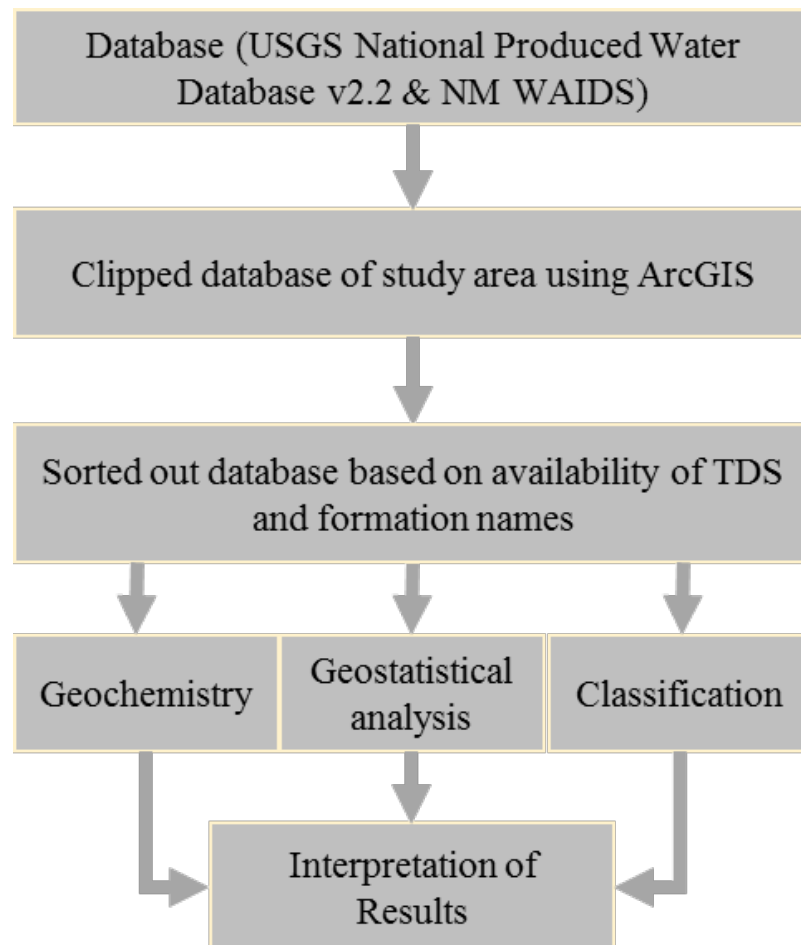


Figure 2.2 Schematic flow-chart of the methodology for produced water quality analysis.

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 2.1), 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 (David, 1977).

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 (Engle and Rowan, 2013; Egozcue et al., 2003). 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 (Egozcue, and Pawlowsky-Glahn, 2005). The corresponding ilr coordinates (z_i) were calculated using the sequential binary partition as follows (Engle et al., 2016):

$$z_i = \sqrt{\frac{r_i s_i}{r_i + s_i}} \ln \frac{(x_j)^{\frac{1}{r_i}}}{(x_l)^{\frac{1}{s_i}}}$$

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 (Blondes et al., 2015).

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/SO₄ ratio below 50, the brine constituted TDS values above 125 g/L and Cl/SO₄ ratio greater than 50 and the mix water had TDS values in the ranges 75-125 g/L with Cl/SO₄ ratio below 50 (Stueber et al., 1998).

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 2.1 were classified into three groups based on similar TDS in the histograms shown in Figure 2.3: 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 (Barnaby et al., 2004; Siegel and Anderholm, 1994; Merrill et al., 2015). 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.

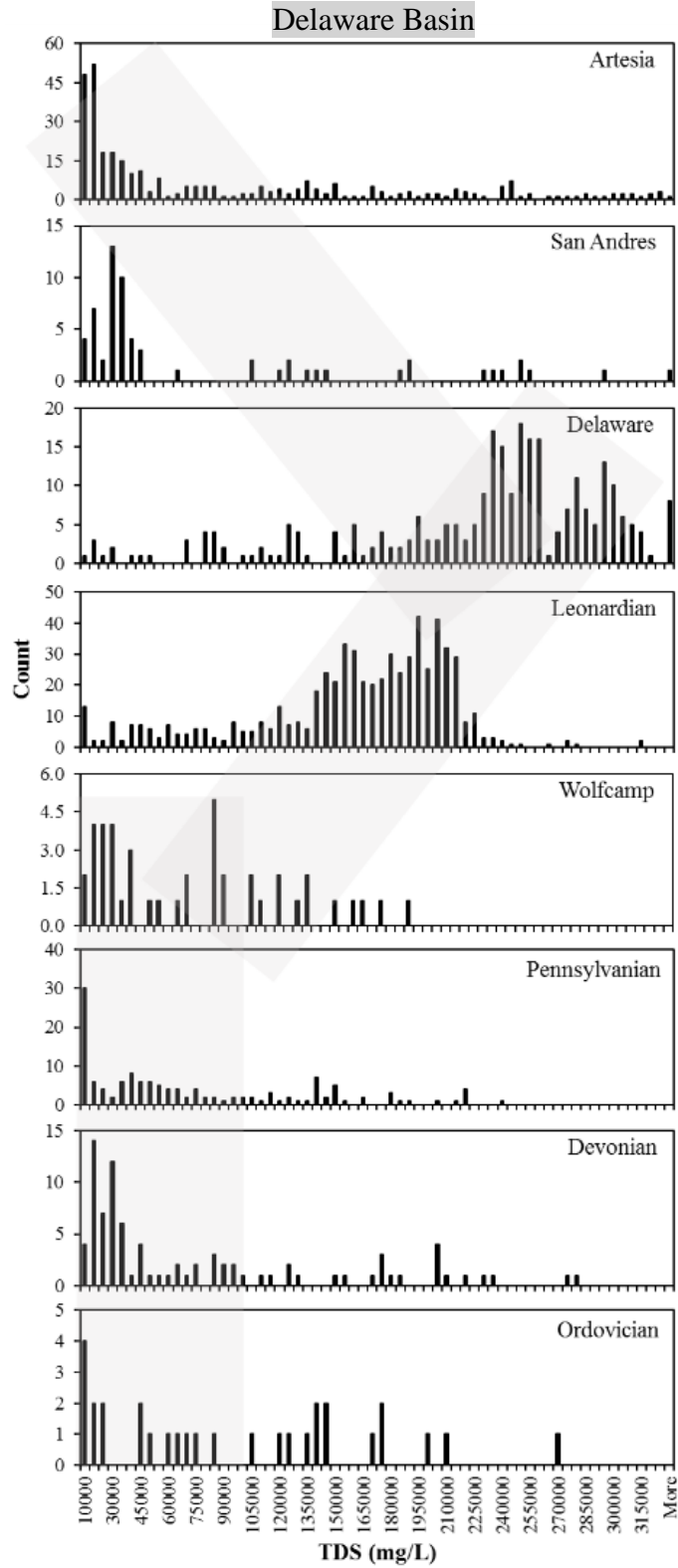


Figure 2.3 Histograms of TDS from Guadalupian (Permian) to Ordovician age formations in three sub-basins. (Continued)

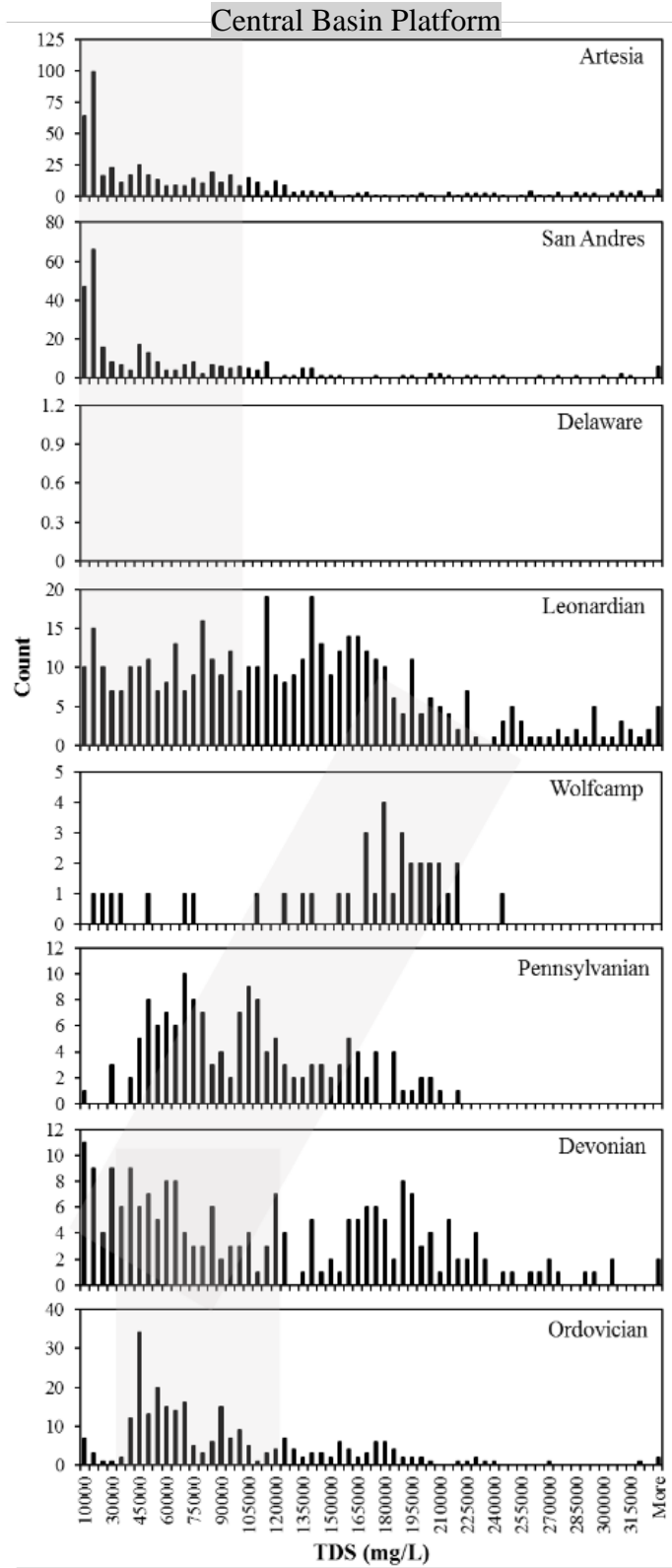


Figure 2.3 Histograms of TDS from Guadalupian (Permian) to Ordovician age formations in three sub-basins. (continued)

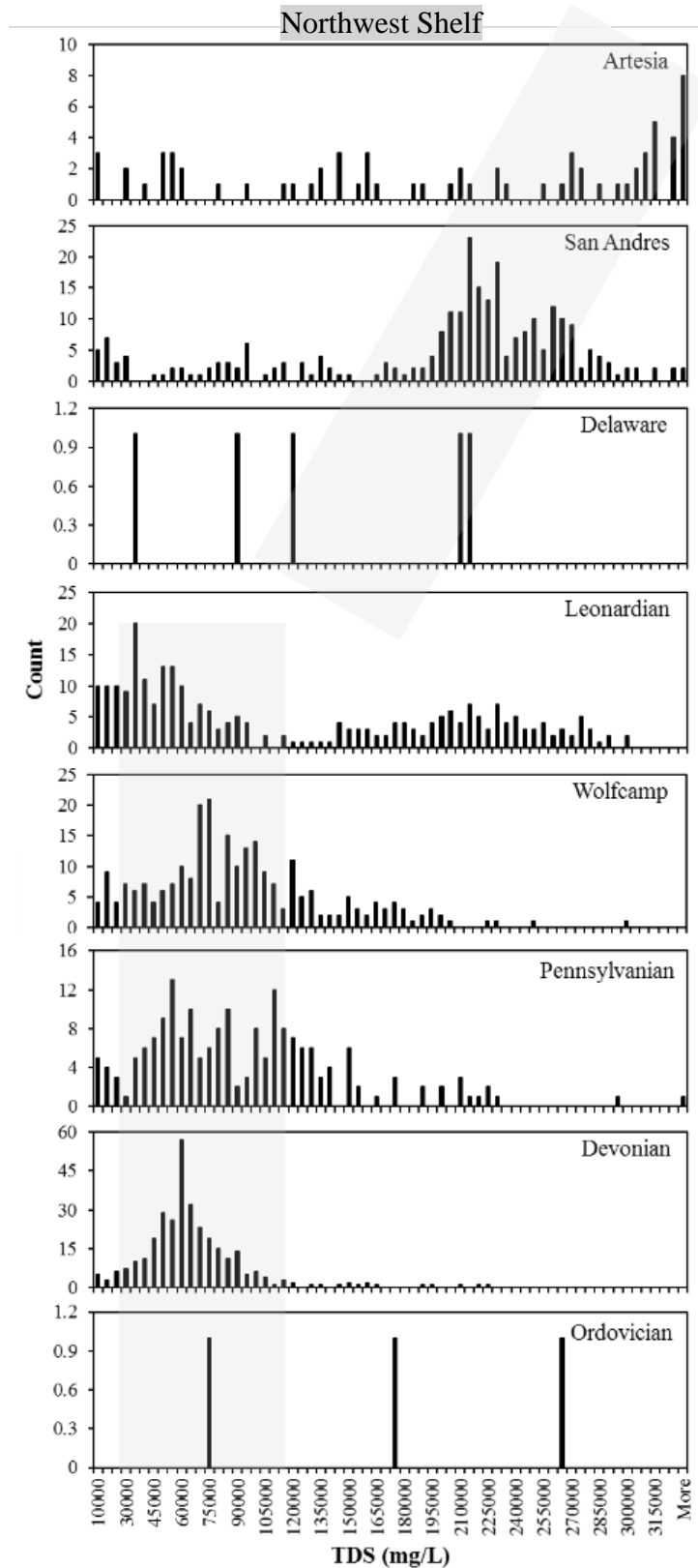


Figure 2.3 Histograms of TDS from Guadalupian (Permian) to Ordovician age formations in three sub-basins.

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 2.4). 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.

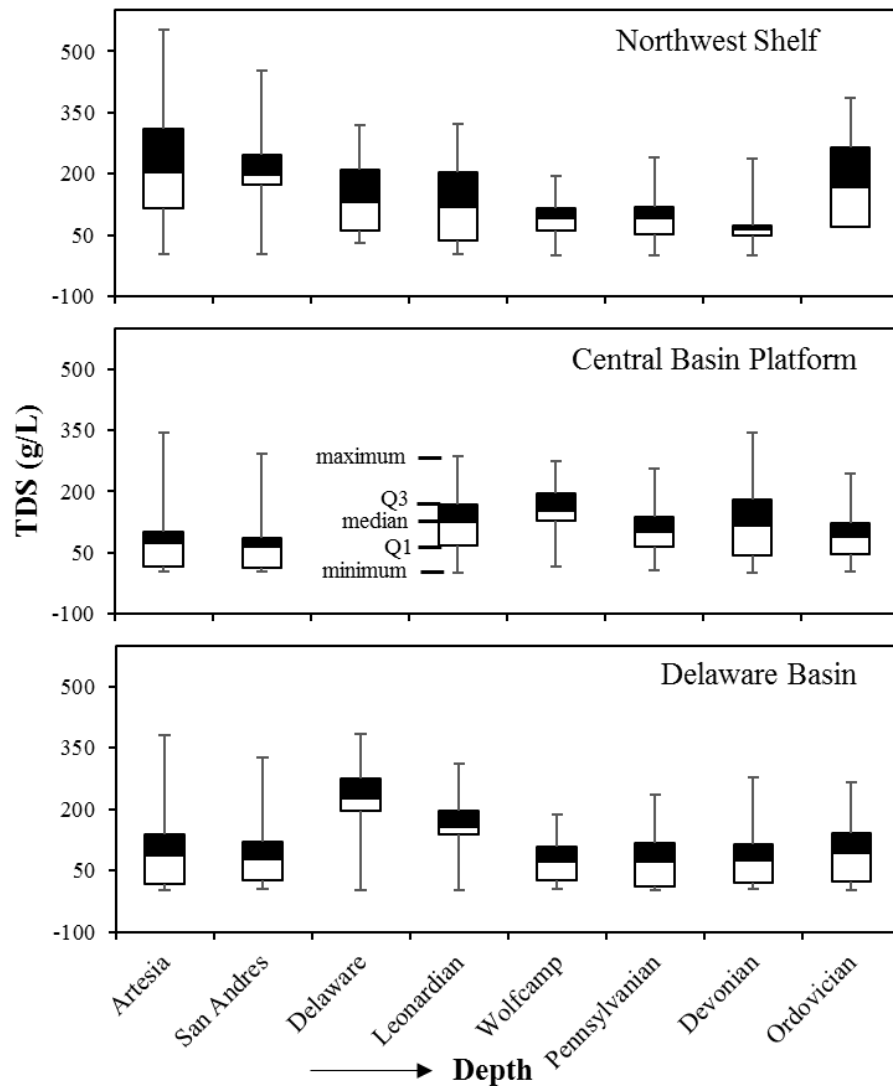


Figure 2.4 Relative distribution of the statistical parameters of the TDS in the three sub-basins.

Figure 2.5 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.

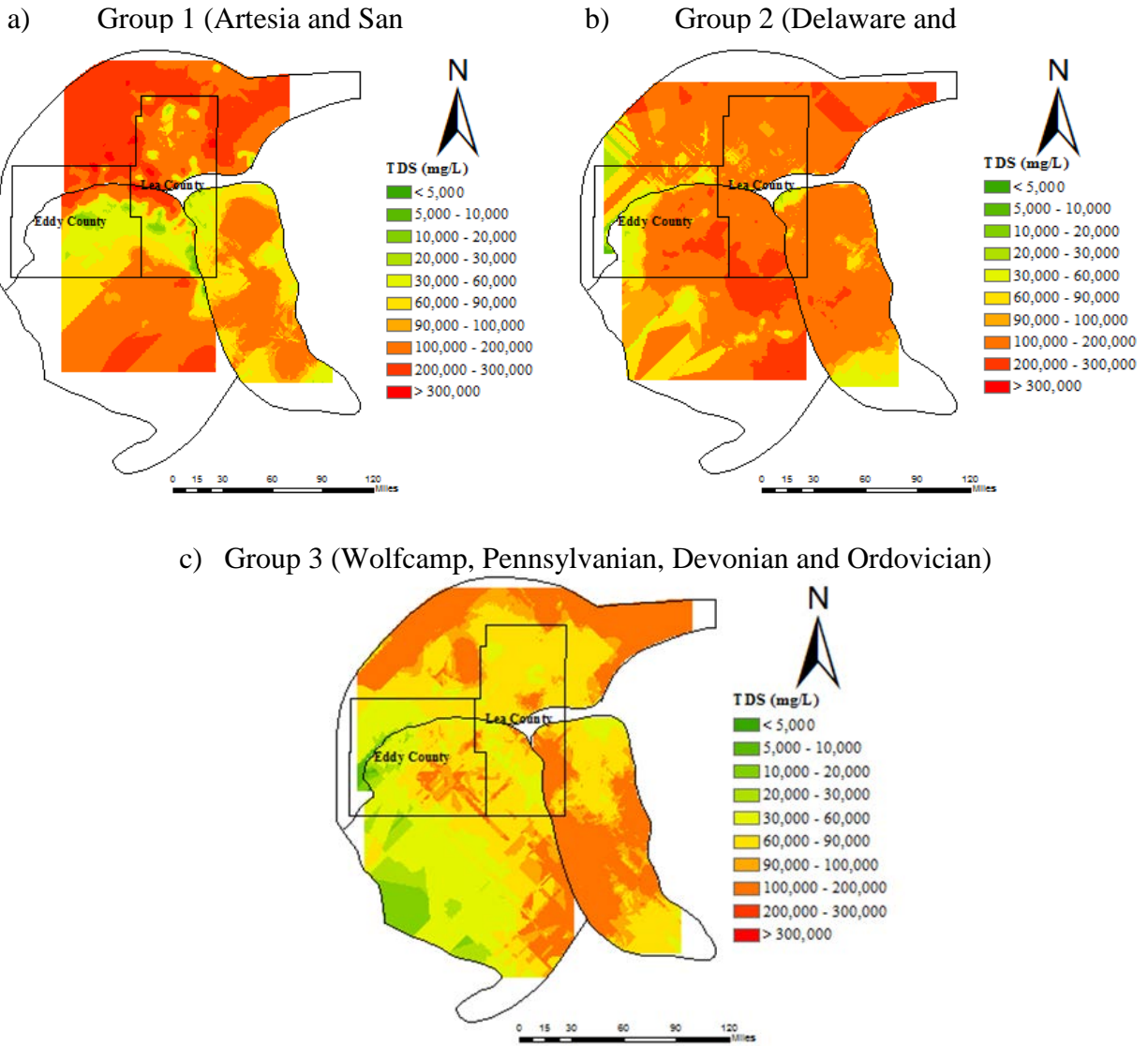


Figure 2.5 Kriged contour maps of TDS from Guadalupian to Ordovician age formations in the three sub-basins.

The statistical and spatial analysis of major cations (Na, Ca and Mg) and anions (Cl, SO₄ and HCO₃) were also performed to compare variability of the salinity. Figure 2.6 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 2.6). 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 2.7). 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.

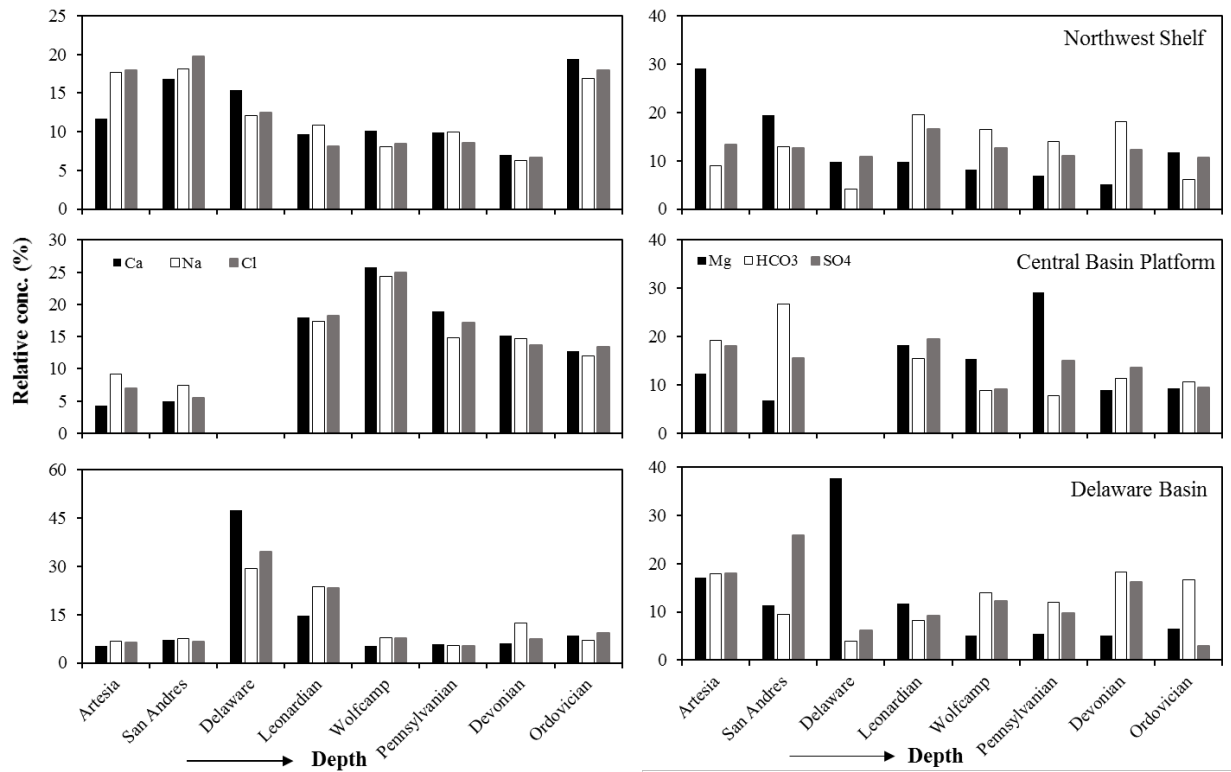


Figure 2.6 Relative abundances of major ions (geometric mean values for each constituent were normalized to 100%) in three sub-basins.

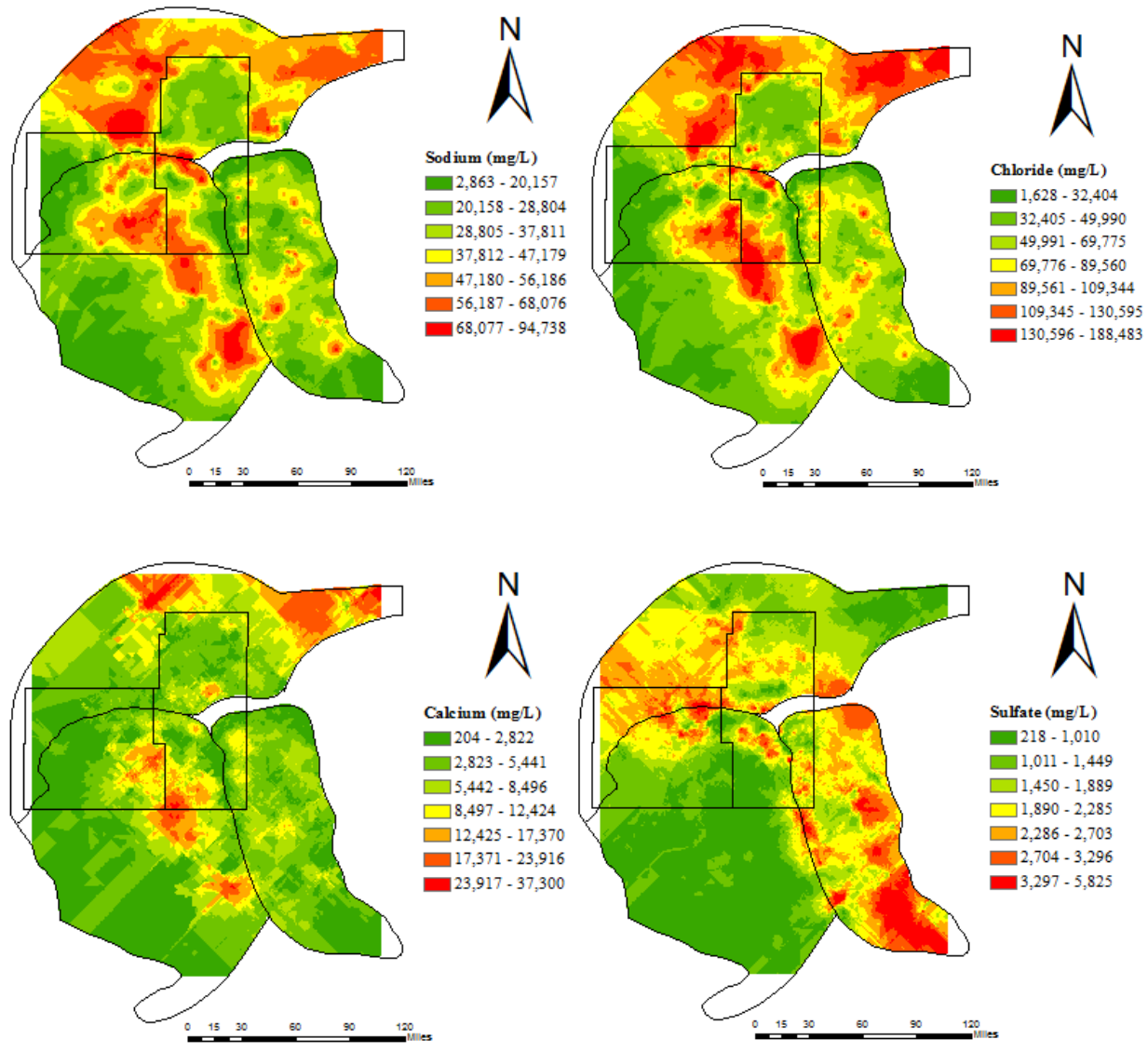


Figure 2.7 Kriged contour maps of major ions in the three sub-basins.

Classification of Produced Water

Figure 2.8 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 2.8).

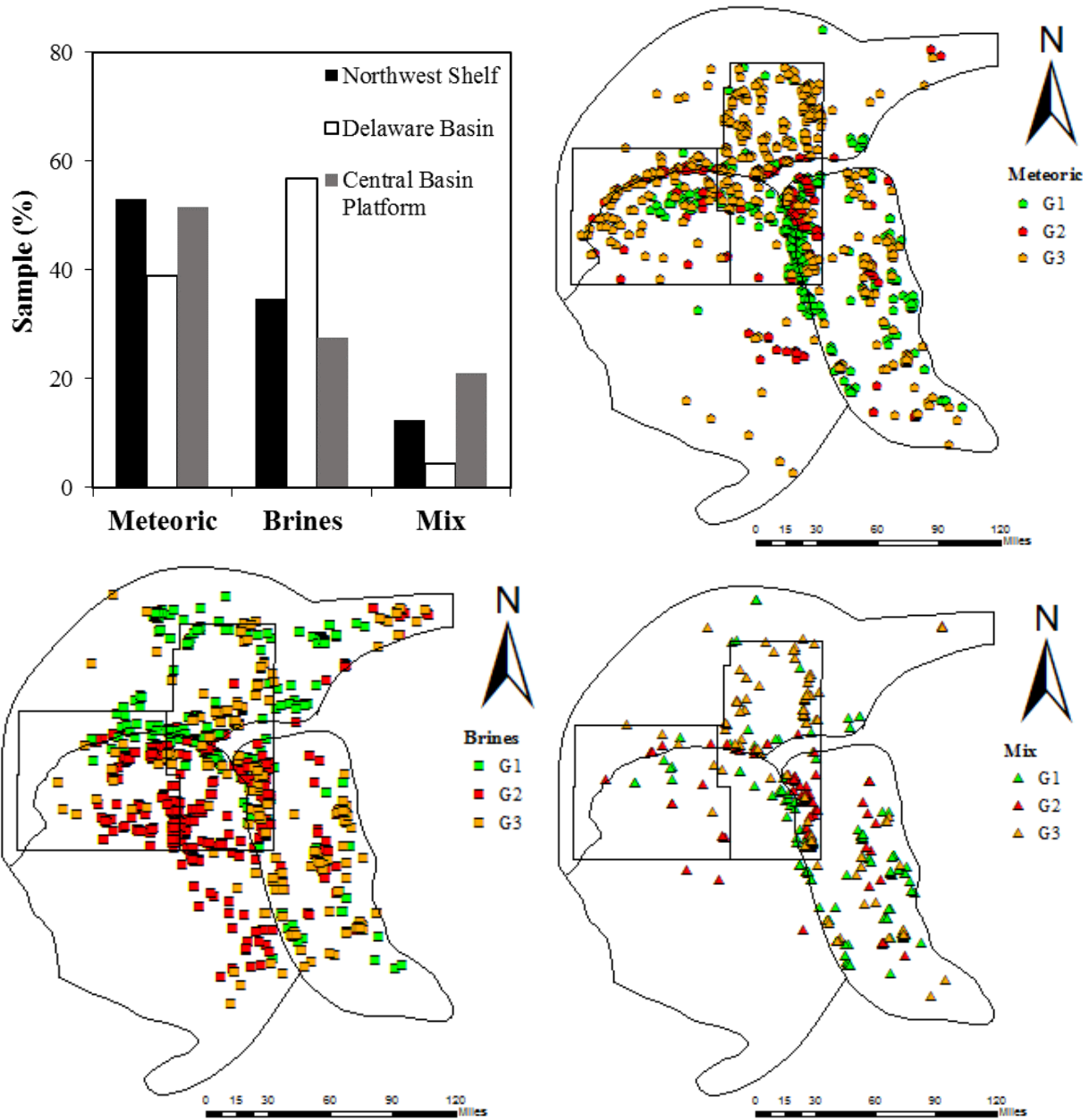


Figure 2.8 Fractional distribution of various water types and their locations in the three sub-basins. G1: group 1 formations; G2: group 2 formations and G3: group 3 formations.

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 2.9. 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 2.9). 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.

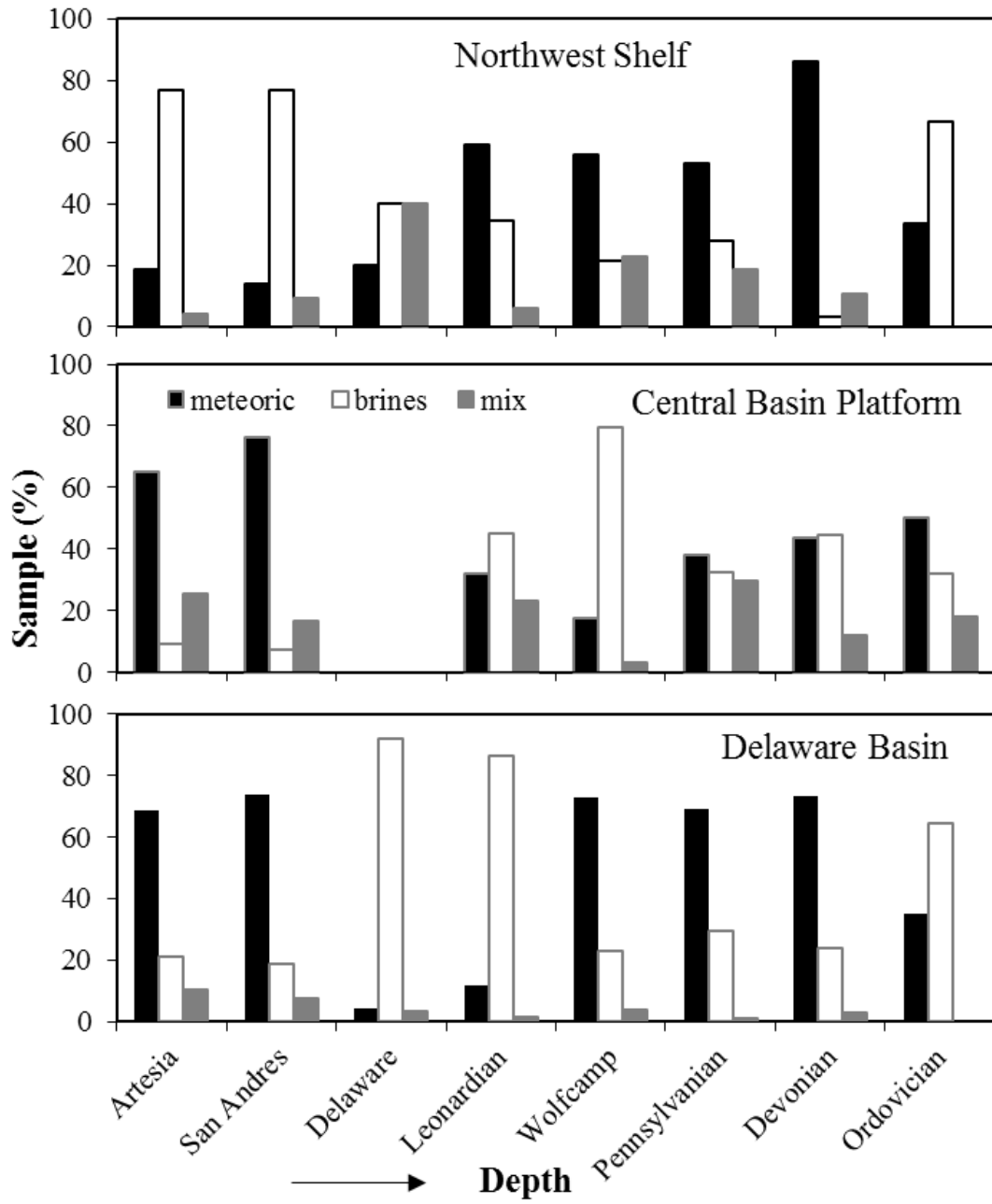


Figure 2.9 Distribution of samples by water types from Guadalupian to Ordovician age formations in three sub-basins. Percentage of samples by water type was calculated considering total number of samples to 100% in each formation.

Origins of Produced 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. (Hounslow, 1995). 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 2.2: Correlation coefficients between major ions by formations in three sub-basins.

Geologic Age(group)	Correlation coefficient (R ²)								
	Delaware Basin			Central Basin Platform			Northwest Shelf		
	Na vs Cl	Ca vs Cl	Ca vs SO ₄	Na vs Cl	Ca vs Cl	Ca vs SO ₄	Na vs Cl	Ca vs Cl	Ca vs SO ₄
Artesia	0.9668	0.4029	0.0560	0.0265	0.0053	0.1939	0.9016	0.2889	0.1661
San Andres	0.9299	0.6549	0.4296	0.8918	0.3852	0.0319	0.4293	0.3535	0.3874
Delaware	0.7465	0.5414	0.2927	–	–	–	0.9989	0.9718	0.7195
Leonardian	0.8963	0.3570	0.0160	0.9440	0.4236	0.0150	0.8148	0.4694	0.2150
Wolfcamp	0.9498	0.6696	0.0070	0.9508	0.0153	0.3162	0.7677	0.3922	0.1475
Pennsylvanian	0.9456	0.1981	0.0880	0.7250	0.7410	0.0086	0.6491	0.4279	0.0547
Devonian	0.9474	0.1161	0.1570	0.4724	0.2787	0.0094	0.8176	0.5017	0.0343
Ordovician	0.9335	0.4054	0.0360	0.8298	0.2677	0.0012	0.9971	0.9632	0.7958

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 2.2). 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 2.10). 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 (Engle et al., 2016). 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 (Alcala and Custodio, 2008; Davis et al., 1998). 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 (McCaffrey et al., 1987).

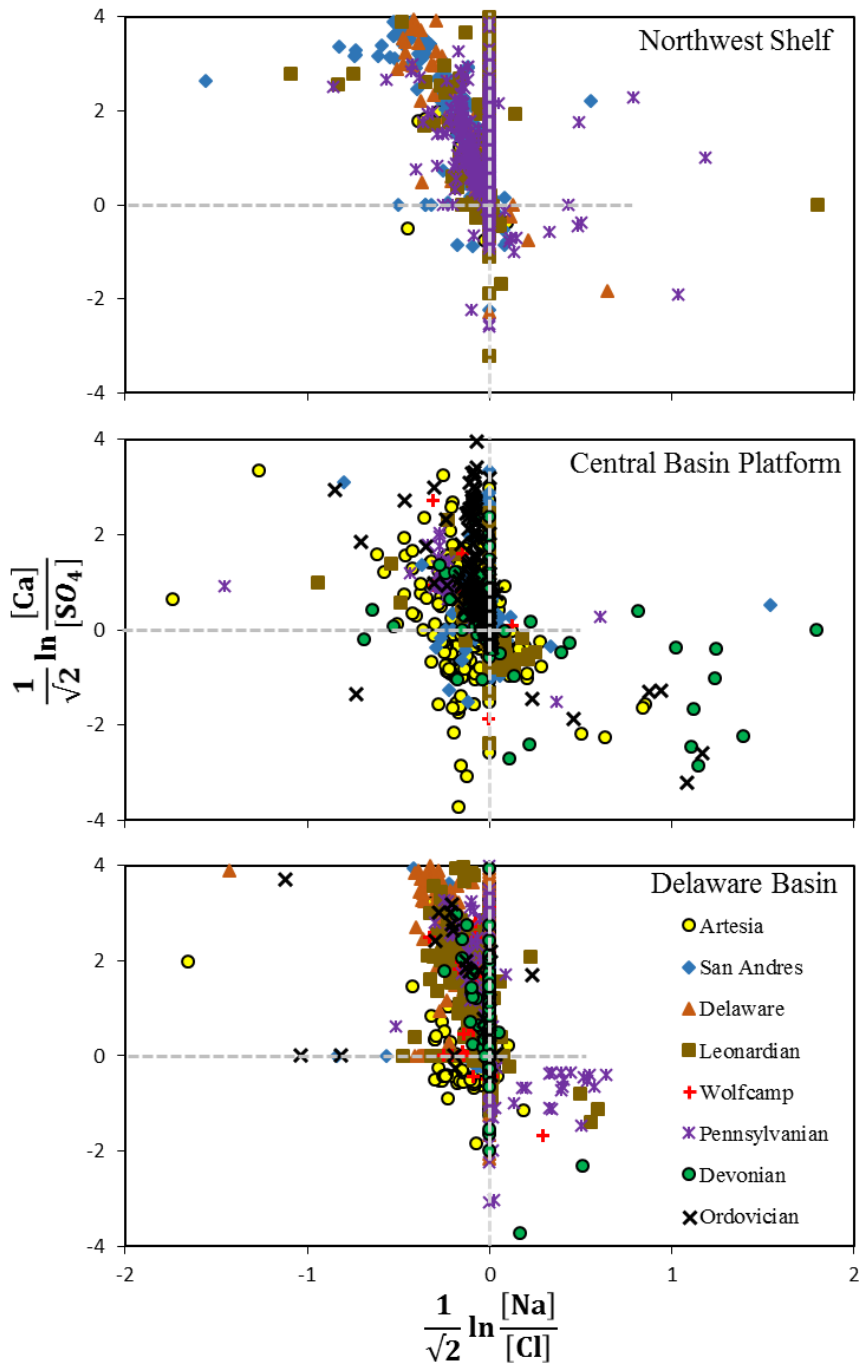


Figure 2.10 Scatter plot of isometric log ratios for sub-compositions (Na, Cl, Ca and SO₄) in three sub-basins.

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 2.11). These results also confirmed dilution effect with meteoric water as reported in a previous study (Engle and Rowan, 2013). The 1lr transformation coordinates were also used to explore further for possible sources of Br in the produced water. Figure 2.12 shows zones in 1lr scatter plots where different water constituents might have been originated (Engle and Rowan, 2013). 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 2.12.

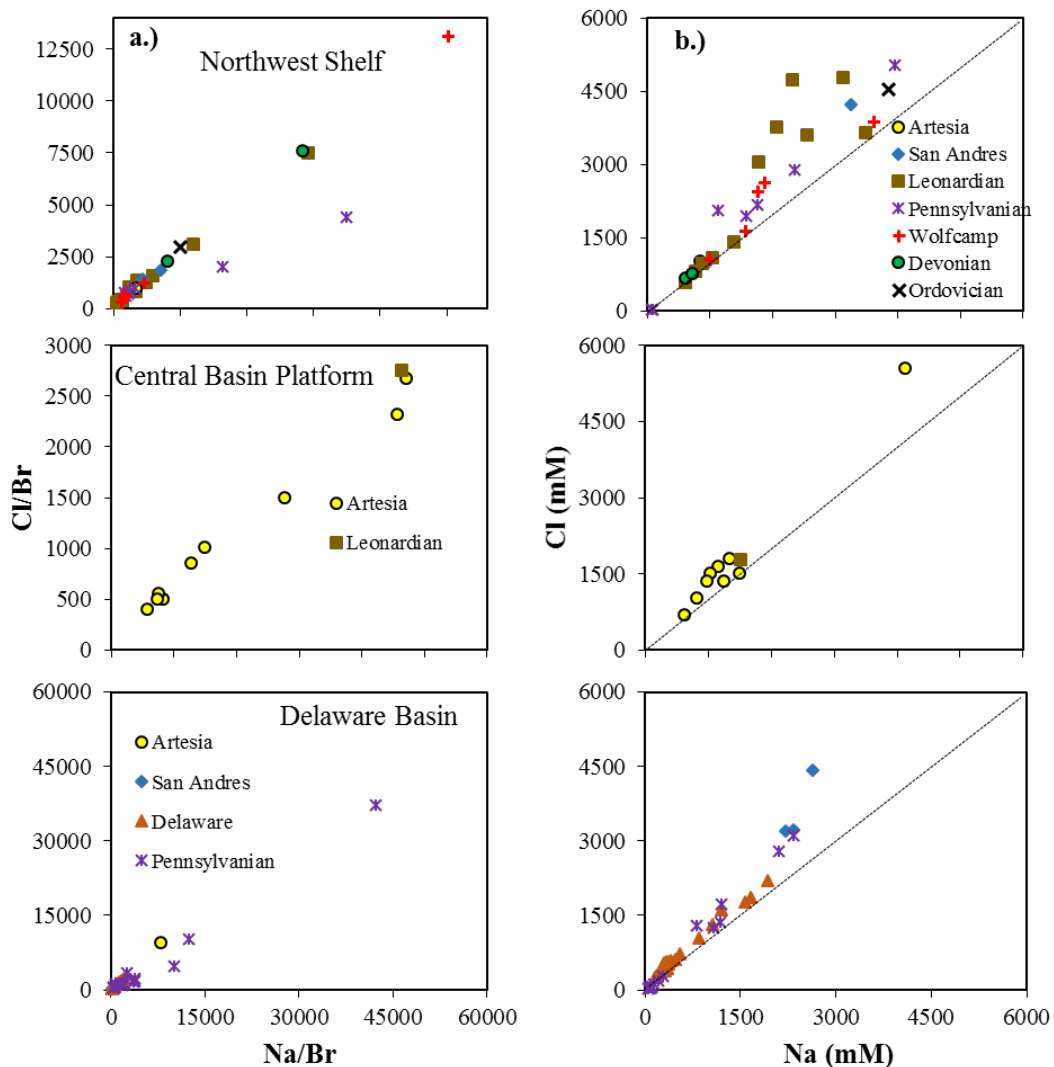


Figure 2.11 Scatter plots of a.) molar ratios of Na/Br vs. Cl/Br and b.) molar concentrations of Na and Cl in the three sub-basins.

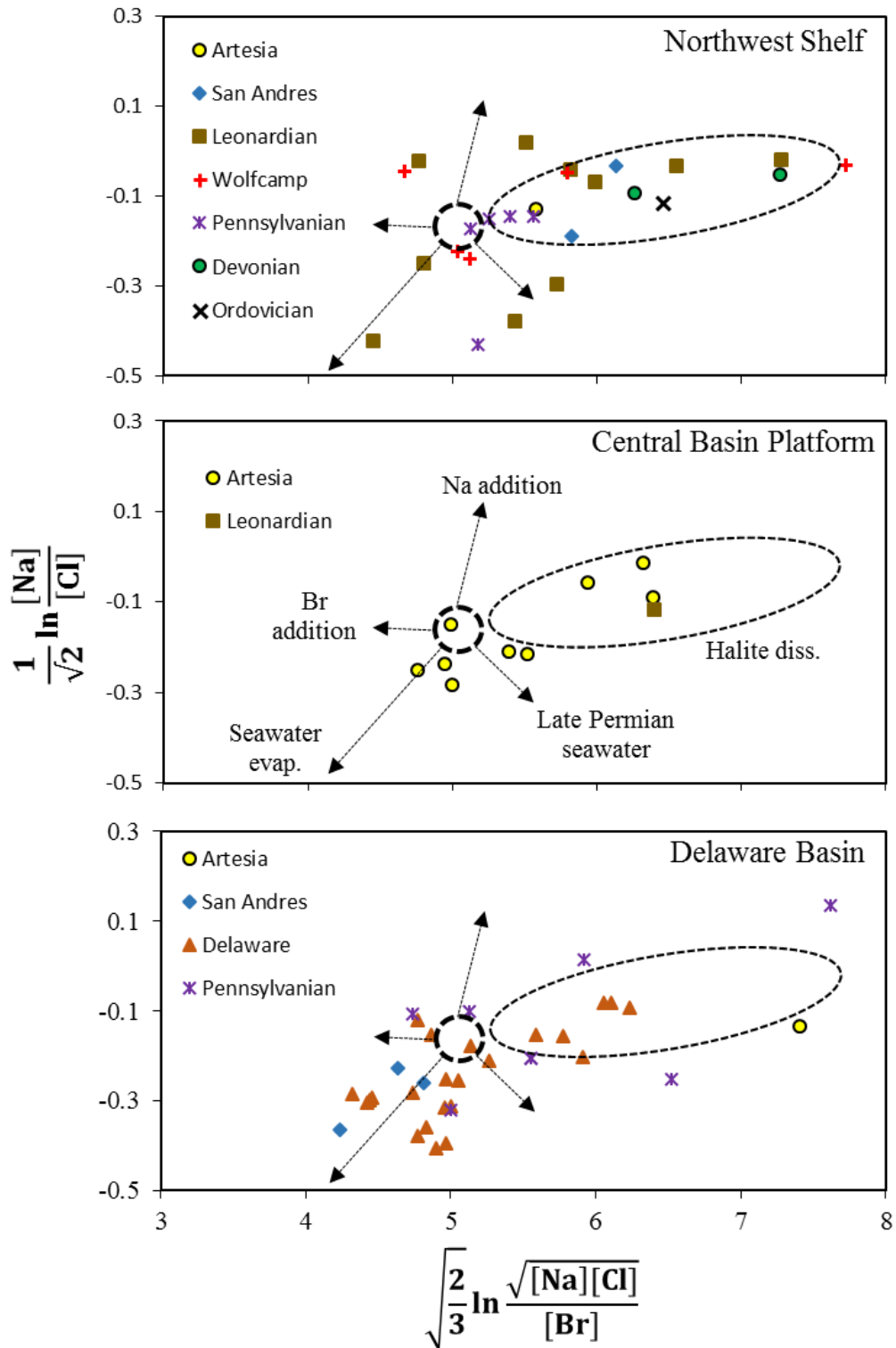


Figure 2.12 Scatter plots of isometric log ratio transformation of Na, Cl and Br in the three sub-basins.

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.

Acknowledgements

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CHAPTER 3: SPATIAL DATA AND WEB-MAPPING APPLICATIONS OF PRODUCED WATER IN SOUTHEAST NEW MEXICO

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Introduction

Persistent drought, increasing population, and increasing water demands in Eddy and Lea Counties New Mexico has raised the need for further scrutiny of unconventional alternative water sources to augment the water supply. Oil and gas production has also increased in Southeast New Mexico over the past decade leading to large volumes of produced water that is co-produced during oil and gas extraction. An estimation of over 100,000 acre-feet (acre-ft) of produced water is annually drawn out of oil and gas wells in Eddy and Lea Counties and is most often trucked or piped to be disposed of in salt-water injection wells. The water quality is such that until recently, produced water was only thought of as a waste product. Advances in treatment technologies and water shortages are changing the consideration of produced water as an alternative water source, however, decision-makers and stakeholders need better geographic information on the volume and quality of produced water in Eddy and Lea County.

Geographic information plays a key role in assessing produced water volume and quality by illustrating the spatial patterns, concentrations, and location of produced water. Access to Geographic Information System (GIS) produced water data is limited. Oil and gas producers are not required to report produced water quality data, thus any reporting is voluntary and not standardized. In New Mexico, previous work provided an online GIS database with produced water data for use by the oil and gas industry (Cather et al., 2005). The entire database and web-mapping application was taken offline in 2013 due to internet security concerns (Cather, 2016). While the [GO-TECH](#) website has since been restored with access to tabular oil and gas production data, the GIS portion of the resource is retired. The United States Geological Survey (USGS) maintains a [national produced water database](#) which is accessible as a web-mapping application (Blondes et al, 2016), but this resource lacks data coverage for some of the new oil and gas wells in Southeast New Mexico. The New Mexico Oil Conservation Division (NM OCD) hosts a [web-mapping application](#) with information on active oil and gas wells in New Mexico and data accessible through a file transfer protocol (FTP) site which is updated monthly with oil and gas production by well (NM OCD, 2016). The OCD application is not optimized to

display or explore produced water volume or produced quality data. This report address the need for produced water GIS data by describing the development of three produced water web-mapping applications that provide users interactive access to produced water volume and quality data, as well as the ability to look at some potential options for produced water reuse.

Methods

Study Area

The study area of this project is Eddy and Lea Counties, with an area of approximately 12,150 mi², in Southeast New Mexico (Figure 3.1; central geographic coordinates 32.539°N, 103.723° W). The region is typical of a semi-arid climate, receiving less precipitation than the potential evapotranspiration and natural vegetation dominated by short woody scrub. The 2010 U.S. Census estimated the populations of Eddy County to be 53,829 and Lea County to be 64,727 (U.S. Census Bureau, 2010). Both counties economies are heavily reliant on oil and gas production, agriculture, livestock, and mining. The total number of oil and gas wells in Eddy and Lea Counties as of January 2016 were 16,049 and 15,532, respectively (NM OCD, 2016).



Figure 3.1. Study area location.

Data Processing

Data for the web-mapping applications were obtained from several sources. These data were processed and aggregated to provide intuitive information when displayed on the web-mapping applications. A shapefile with the locations of all oil, gas, and injection wells was downloaded from NM OCD.

Produced Water Volume Data

The NM OCD provided produced water volume data. These data came as three .xml files with monthly data dating back to 2004 for all oil and gas wells in New Mexico. Individual well data were identified by their unique American Petroleum Institute (API) number. Produced water volume data were filtered first by wells in Eddy and Lea Counties, then by wells that reported water being produced rather than injected. The monthly data were then summarized to annual produced water volume by well for each year between 2004 and 2015. The tabular data were joined to a shapefile by the unique API number and exported to a geodatabase. The units of the data come in barrels (bbls), the oil and gas industry standard for measuring volume. Many stakeholders measure water volume in acre-ft. Additional fields were created to convert bbls to acre-ft for each year using the conversion of 1 acre-ft equal to approximately 7,758.4 bbls.

The large number of wells in Eddy and Lea Counties make it difficult to visualize trends in the data. Two processes were used to address this issue. First, data were aggregated by Public Land Survey System (PLSS) 6-mile-square townships. A time-enabled feature was created for use with a time slider to show changes in produced water volume over time by township. A second process identified hot-spots of produced water volume using the Hot-Spot Analysis tool in ArcMap 10.3. The statistical tool assumed a null hypothesis that produced water volumes at unique wells were randomly distributed throughout Eddy and Lea Counties. The alternative hypothesis as produced water volumes at unique wells exhibit spatial clustering. A surface was interpolated from the Z-scores, based on the standard deviations from the mean, of the hot spot analysis to display areas where there is a high concentration of wells with high volumes of produced water.

Produced Water Quality Data

Produced water quality data were provided by the Petroleum Recovery Research Center at New Mexico Institute of Mining Technology in a Microsoft Access database. The dataset included all available produced water quality samples in New Mexico. These data included measurements of several water quality parameters from oil and gas wells, each well identified by the 10-digit API unique identification number. Tabular data were joined to an oil and gas well shapefile by the API number and exported as a feature class into an ArcMap geodatabase. The entire dataset was processed into point data, however, the subsequent aggregation of point data was only performed on a subset of data within Eddy and Lea Counties. Eight of the produced water quality parameters (bicarbonate, calcium, chloride, magnesium, sodium, pH, sulfate, and TDS) with the largest number of samples were aggregated by PLSS 6-mile townships. Available data did not support time-series analysis.

Ancillary Data

Three additional datasets were used for the web-mapping applications. Agricultural areas for Lea and Eddy Counties were based on the 2014 U.S. Department of Agriculture Cropland Data Layer (USDA, 2014). The cropland data come as a classified raster. The original classified raster was reclassified into five classes; agriculture, development, fallow/idle cropland, grassland/pasture, and shrubland. The reclassified raster was converted into grouped polygons of similar classes. Point centroids were derived from the grouped polygons. The agricultural points were isolated and compared to high spatial resolution imagery from 2014 for accuracy. Misclassified points were deleted. The agricultural point feature class created from the reduction is not exhaustive, but does eliminate several areas where dense vegetation had grown near arroyos and other misclassified areas. This visual assessment of the agricultural data was necessary to ensure that analyses looking for minimum distances to agricultural areas were not selection incorrect locations. Tabular injection well data for produced water disposal and locations of active mines were obtained from NM OCD and NM EMNRD, respectively, and exported as a feature classes into a geodatabase.

Web-mapping applications

Web-mapping applications interface with spatial data and facilitate data accessibility. The web-mapping applications use data published as REST services to the NM WRRI web-GIS server. REST services are available for consumption by ArcGIS online web-maps or can be downloaded and imported into Google Maps as a .kmz file. The actual web-mapping application is included as an option with ArcGIS Online, customizable using WebAppBuilder. Widgets were incorporated into the three applications to allow stakeholders and decision-makers the capability to explore the data in more detail. The incident widget on the produced water volume and quality application lets users define a point or polygon, set a buffer distance, and retrieve summaries for produced water volume and quality within the defined buffer area. The nearest potential endpoint tool lets users set a point and buffer distance, and then determine where the closest users or endpoints for produced water are located.

Results and Discussion

Processed data were made publicly available through three online [web-mapping applications](#). The three applications all include the capability to turn layers on/off, view a dynamic legend, search for individual wells by API, measure distances and areas, zoom in/out, download .csv files, switch base-maps, and apply basic geoprocessing tools.

Produced water volume data is available by clicking on a specific well (Figure 3.2). A pop-up window displays volume data by year, links to the NM OCD files for each specific well, and a small graph illustrating changes in volumes over time. Volume data units are displayed in the legend in both bbls and acre-ft. When turned on in the layer list, the time-enabled data layer will play an animation of the changes in produced water at the township scale between 2004 and 2015.

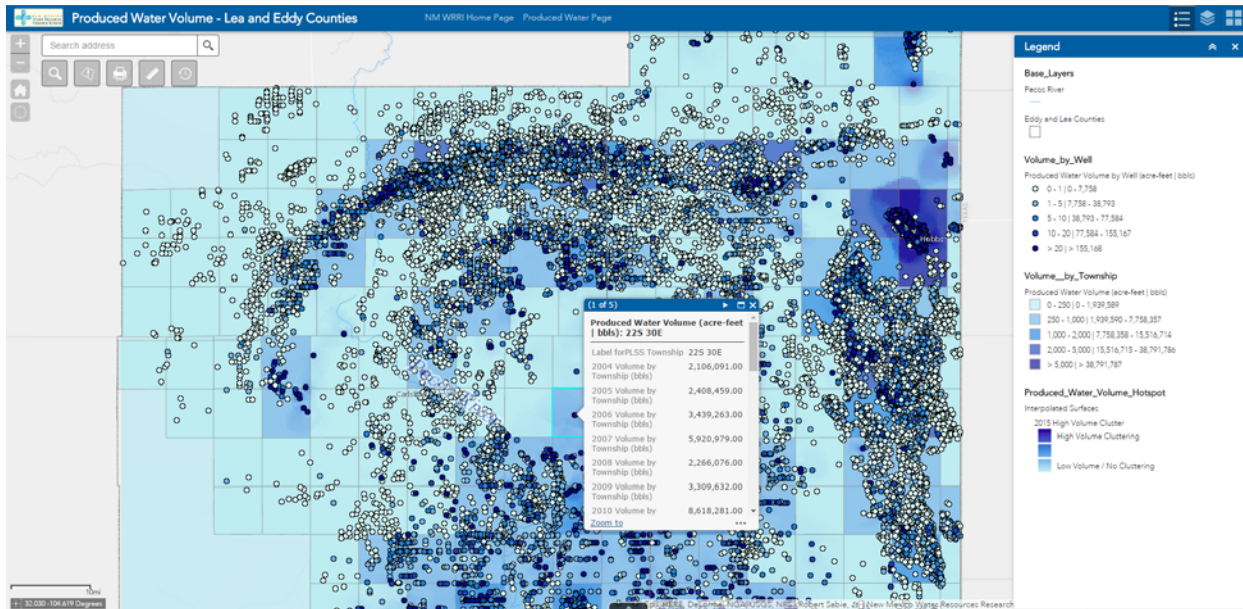


Figure 3.2 Produced water web-mapping application interface.

The produced water quality web-mapping application provides several options for examining produced water quality data in Eddy and Lea Counties. Produced water quality data from the PRRC produced water display values of seven produced water constituents in mg/L (Figure 3.3). Data are available for download as .csv files. The service also displays predictive surfaces from a concurrent portion of the produced water project (Chaudhary et al., 2016).



Figure 3.3 Produced water quality web-mapping application interface.

Locating places that could benefit from utilizing treated produced water is one of the first steps stakeholders and decision-makers would need to take in planning for potential beneficial

use of produced water. The ‘Potential Uses’ web-map application (Figure 3.4) is useful for decision-makers and stakeholders to select a location and view the closest potential endpoints for produced water within a defined buffer. Users can access additional information about disposal wells and mining operations. Estimated centroids for agricultural areas illustrate where there may be a concentration of agricultural areas that could use produced water. The application measures distance using Euclidean distance and would be improved if Manhattan distance was an option.

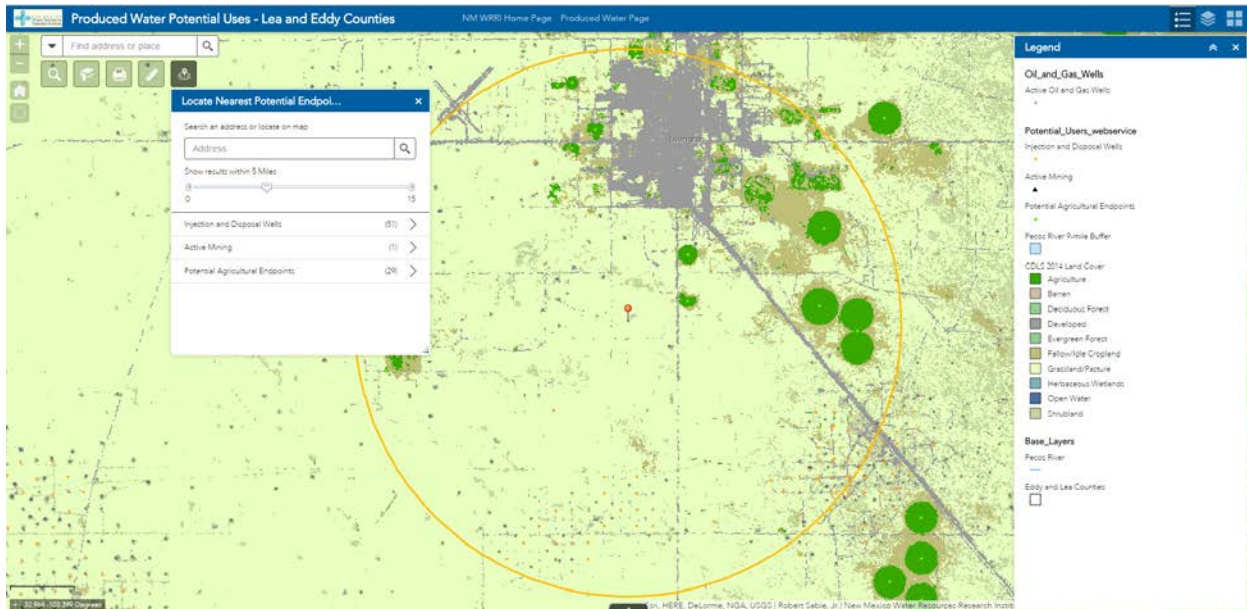


Figure 3.4. Produced water potential uses web-mapping application interface

Conclusion

Produced water volume and quality data were processed and made available through three web-mapping applications, helping fill the need for produced water GIS data. These applications can now be used by decision-makers and stakeholder to interact with the data and answer questions about the availability of produced water and what the expected produced water quality might be. Further work needs to address separating out oil and gas production wells that are using water flooding, such as some of the wells near Hobbs, New Mexico, where the actual produced water volume may be exaggerated. More water quality data would also improve the mapping efforts. Some of the water quality samples in the produced water database date back to the 1930s. A logical next step for using spatial data for decision making would be to integrate GIS and a decision-support tool.

Data Disclaimer

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CHAPTER 4: THE REGULATORY FRAMEWORK SURROUNDING PRODUCED WATER IN NEW MEXICO AND IMPACTS ON POTENTIAL USE

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Introduction

Water brought to the land surface as a part of oil and gas extraction is known as co-produced or “produced” water. This water is normally considered a waste product, and most of it is reinjected into deep reservoirs either to dispose of it or to use it in active reservoirs for enhanced oil recovery processes.

Recently, the oil and gas industry began to reuse produced water for drilling, stimulating, and completing oil and gas wells in unconventional (tight shale) formations. Industry is also beginning to reuse the produced water for hydraulic fracturing operations. This is occurring most frequently in areas where there is limited availability of disposal wells (e.g., Pennsylvania Marcellus Shale region) or where there is limited fresh water availability for drilling (e.g., arid regions such as in the Permian Basin of Texas and New Mexico). Also new to the industry is the application of water treatment technologies to create useable product streams from produced water. While these treatment methods can be expensive, the relative value of the products is increasing and treatment costs are being driven down by technological innovation. The regulatory framework surrounding these product streams is of interest; because to date produced water is categorized as an oilfield waste material, and is regulated as such. Treated product streams, however, may be useful in many applications, and may not retain the characteristics that render produced water a waste (e.g., toxic organic compounds, metals, or high levels of salt). Therefore, it is appropriate to define the point at which a product stream derived from produced water is no longer a waste, or at least, changes its characteristics from a regulatory, legal, and ownership standpoint.

Wastewater generated from oil and gas extraction comes in large quantities. An estimated volume of 21 billion barrels (bbl; 1 bbl = 42 US gallons) of produced water was generated in the United States in 2007 (Clark and Veil, 2009). The total volume of produced water from New Mexico wells in 2012 was 775,930,303 bbl or 100,012 acre-feet (Veil, 2012). Of this water, 87%

of the water was generated from conventional oil production. Conventional gas wells generate 8% of the total, and unconventional gas wells produced the remaining 5% of the water. By comparison, water withdrawals for all purposes (e.g., primarily fresh water) in New Mexico in 2010 totaled 3,815,945 acre-feet; water for agricultural use totaled 3,000,155 acre-feet, and water for public use totaled 317,410 acre-feet (Longworth, 2013). Produced water usually has high levels of total dissolved solids (TDS) and other constituents (organic chemicals, inorganic chemicals, metals and naturally occurring radioactive materials, NORM) that are potentially harmful to human health and the environment when released, and that require treatment prior to many uses.

Recent studies in New Mexico and the U.S. have addressed many questions surrounding treatment, reuse or repurposing of produced water, either within the oil and gas industry, or outside of the industry (Al-Haddabi and Ahmed, 2007; Plumlee et al., 2014; Shaffer et al., 2013; Silva, 2012; Sullivan Graham et al., 2016). Veil (2015) and (Clark and Veil, 2012) addressed the volumes of produced water extracted, handled, and disposed in each state. The Dagger Draw study by (McGovern and Smith, 2003), addressed many issues related to supply, treatment design and costs, and regulations for treatment and use of produced water as a local fresh water supply in the Pecos River region of southeastern New Mexico, which includes the current study area of Lea and Eddy Counties (McGovern and Smith, 2003). This region is severely stressed for fresh water supplies, and in many parts of the region, groundwater from the High Plains/Ogallala aquifer is the only source of fresh water. Of many water-stressed regions in New Mexico, this region could clearly benefit from having access to alternative sources of water. The McGovern report summarized a list of questions that remained unanswered at the end of their study. Some of the questions could be answered by government entities (local, state, or possibly federal):

- Who has ownership and jurisdiction before and after treatment?
- Where in the system/process does ownership change?
- Where does the liability end/change hands?
- Who defines specifications for treatment?
- Who has responsibility/jurisdiction for reject/wastes?
- What funds can government provide?

Some of the questions could be answered by non-governmental public or private entities, including market forces:

- Who provides treatment?
- Who pays for treatment?
- Who will define and provide treatment specifications?
- Who will pay for the water as an end user?
- Who provides the management, storage, and conveyance of the treated water?

Obtaining answers to these questions is the focus of this report. We point readers to sections below on Jurisdiction and on New Mexico Regulatory Agencies for a discussion of relevant laws and jurisdictional illustrations; to the section on Federal Regulatory Agencies for a discussion of relevant federal laws including discharge to waters of the United States; and to Example Use Cases under the Discussion Section which are helpful to describe treatment strategies, ownership chains, and points for transfer of liability and regulatory authority. Other chapters in this report evaluate potential uses; identify potential users of treated produced water, the quality, quantity, and location of produced water in the study area, and treatment methods and costs for those specific treatments.

While definitive policy directions cannot be fully answered by scientific research, we point to case studies and opportunities found to address these issues from New Mexico and other states facing similar challenges. We also describe policy gaps that we found, in order to assist agencies dealing with questions about produced water handling and reuse.

Finally, we note the complexity surrounding produced water regulations and rules. This report is intended as a brief overview of pertinent factors. It is not a definitive policy statement and should not be relied upon for legal decision making. It is intended as preliminary guidance for readers with interest in the topic. Those who wish to know more, or who have specific legal and regulatory needs, should consult with the appropriate regulatory agencies such as the United States Environmental Protection Agency (USEPA) and the New Mexico state agencies listed below.

Source of Produced Water

The flowchart below gives an overview of the treatment process crude oil from wells (Figure 4.1). The separation process employs the use of gravity and density differences of the

various liquids (produced oil, produced water and gas). A series of separation tanks are used in the treatment/separation process. The heavier liquid, produced water, settles in the bottom of the tank, the produced oil floats on the water and the gas occupies the open space in the separation tank/separator. The water that is separated from this process, i.e. produced water, has the potential to address various water needs and challenges in the study area if treated in an efficient and economical way.

Typical crude oil treatment system (separation, heating, dehydration, stabilization, storage, metering, pumping)

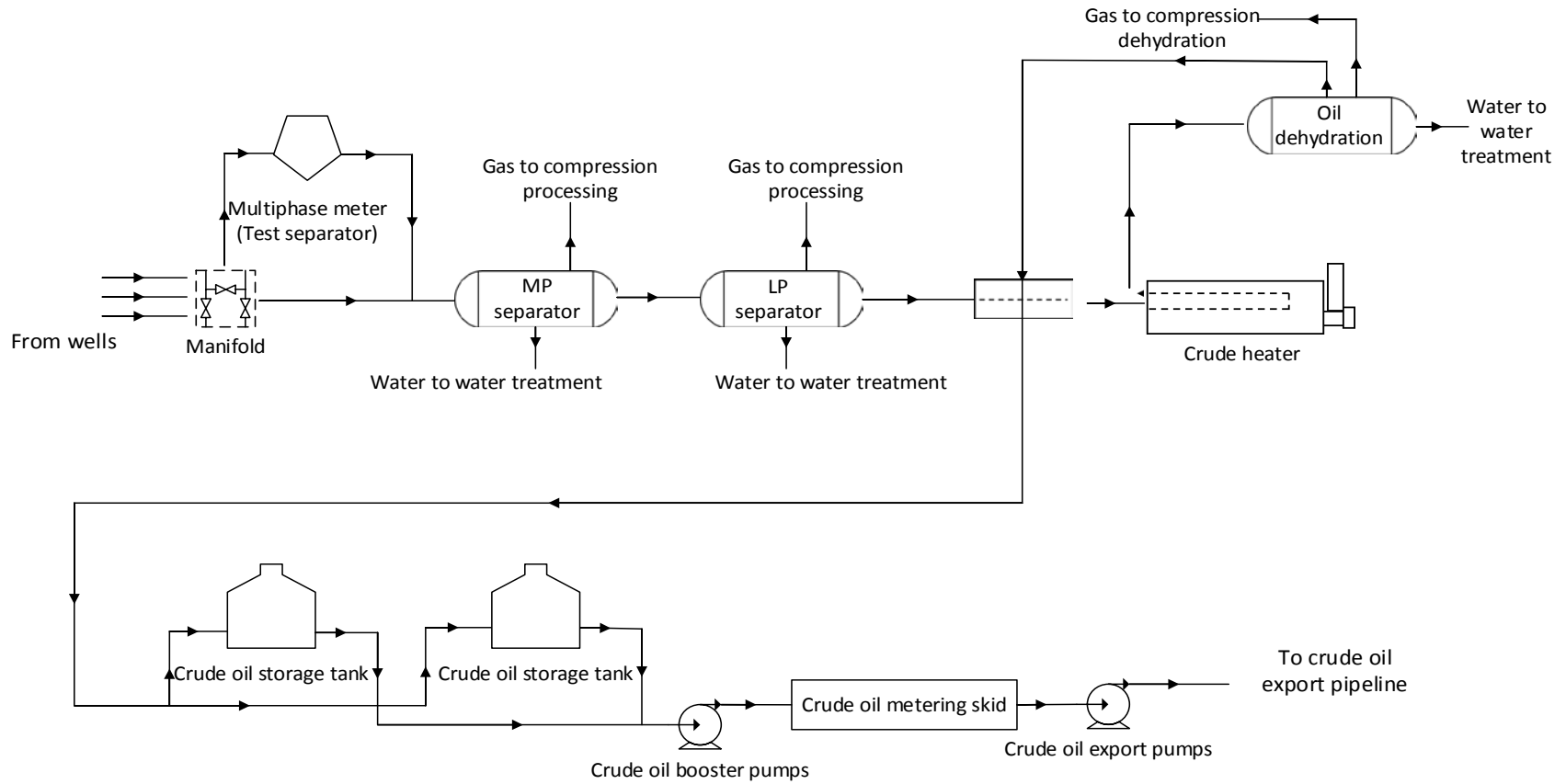


Figure 4.1 Crude Oil Treatment Process (Schlumberger, 2016)

Potential Beneficial Uses of Produced Water

The ability to use produced water for beneficial uses will depend upon quantity, quality, location, and sustainable yields; no less important will be the economics of treatment, transport, supply, and demand. At this time, desalination remains an expensive option for brackish- and saline-quality waters. The additional costs of desalination and waste disposal above and beyond the costs of supplying fresh surface and groundwater require favorable market conditions and a strong need for supplemental water resources. Infrastructure costs, financing, and planning also can become prohibitive. A clear regulatory and legal framework supports the opportunity costs of treatment and use/reuse.

Treatment Processes

All treatment processes are separations processes, and result in multiple product streams. Some of these streams are useable (e.g., purified water), and some may remain waste streams (e.g., salt concentrate) that require appropriate disposal. Research in recent years has focused on reducing the energy and costs, and increasing the efficiency of separations to maximize recovery of desirable products and minimize the volume of wastes. An undesirable effect of this trend is that waste stream toxicity may increase with increased concentration factors, complicating disposal. One example of this is the case where radioactive isotopes in produced water are concentrated during treatment and the resulting solid waste must be sent to a disposal facility approved for radioactive waste. The objective remains to create a stream of fresh water, or saline water that has a specific use, while minimizing wastes, preventing environmental degradation, and reducing treatment costs.

Finished Water Products

There are several types of finished water products that can be derived from produced water. Some produced waters are low in salinity, either naturally in a few cases, or via treatments; some waters are treated minimally, e.g. by filtration or microbicial treatments; and some may be extensively treated to remove high levels of salts and other constituents. These products include, but are not limited to:

- Untreated produced water for direct reuse in drilling and completions, or in enhanced oil recovery (EOR)

- Filtered produced water for use as hydraulic fracturing fluid
- “Clean Brine”-produced water that has been more extensively filtered and pretreated for removal of specific mineral components and microbes, for hydraulic fracturing fluid, other drilling and completion uses, and potentially for industrial uses.
- Fresh water (<1,000 mg/L total dissolved solids)-a quality that can be used for industry, irrigation, biofuel systems, dilution, and possibly land application (e.g., dust control).
- Potable fresh water (<500 mg/L total dissolved solids, meeting Drinking Water quality standards)
- Water for agricultural use in stock watering and irrigation (~1,000 mg/L but usually less than 3,000 mg/L total dissolved solids).

Waste Products

Waste products arise from separations processes including filtration, sedimentation, and mechanical filtration methods. Wastes from produced water treatment remain under New Mexico Oil Conservation Division (NMOCD, or OCD) jurisdiction and, thus, permit requirements for transport, handling, and disposal. Most wastes are required to be landfilled (solid wastes), or reinjected (fluid wastes) following OCD permitted methods at permitted locations (see OCD section below). Transport also requires appropriate permits. These products include:

- Solid or semisolid filtrate from produced/hydraulic fracturing fluid separations processes
- Fluid concentrate from desalination or mineral component separations
- Solid salts
- Waste materials resulting from the treatment processes, including spent filters, filter media (filter cartridges, zeolites, walnut shells, activated carbon, e.g.) and other spent/used materials (tanks, pipes, pipe scale) and miscellaneous materials.

Valuable Co-products

Co-products are created as a result of separations processes. They are not classified as wastes, because they have a use or value to another process or industry. They may include:

- Industrial chemicals including salts, gypsum, magnesium salts, and sulfates
- Brine for industrial use including acid or alkaline chemical production
- Brine or salts for road applications to reduce dust or to mitigate ice and snow.

Federal Regulations

We present a brief review of relevant Federal regulations pertinent to produced water and oil and gas wastes. Federal law does not specifically address treatment and beneficial use of produced water, except in the case of uses described by the Clean Water Act (CWA, Subpart E, below).

RCRA

The [Resource Conservation and Recovery Act](#) (RCRA) is the public law that creates the framework for the proper management of hazardous and non-hazardous solid wastes. RCRA regulations are intended to prevent environmental contamination from industrial processes, and are a “cradle-to-grave” regulatory framework for waste materials. The law was passed by Congress giving the Environmental Protection Agency (EPA) the authority to describe the waste management program of RCRA (McGovern and Smith, 2003).

Wastes from the oil and gas production process include drilling fluids, solids, and water used during the production of economic quantities of oil and gas. In 1979 and in subsequent amendments, these wastes were excluded from regulation by RCRA. According to the American Petroleum Institute (API), it is estimated that 149 million barrels of drilling wastes, 17.9 billion barrels of produced water and 20.6 million barrels of other associated wastes were generated in 1995 from exploration and production (E&P) operations.

Hazardous Waste

According to RCRA, waste is defined as hazardous if it exhibits at least one of the characteristics defined in 40 CFR Part 261 subpart C:

- **Ignitability (D001)** – Ability to start fires under certain conditions, naturally combustible or have a flash point less than 140° F (60° C)
- **Corrosivity (D002)** – Ability to corrode metal containers, usually acids or bases (compounds with very high or very low pH)
- **Reactivity (D003)** – unstable under normal conditions i.e. they can cause explosions, generate toxic fumes, gases or vapors or explosive mixtures when heated, compressed or mixed with water, undergo violent reactions.
- **Toxicity (D004 –D005)** – Ability to cause harm or fatal when ingested or absorbed by the body. (EPA)

The EPA proposed a hazardous waste management standard that included reduced requirements for several large-volume wastes in December 1978. The EPA believed that these large volume wastes were lower in toxicity than other wastes being regulated under RCRA. The wastes covered by the proposal included gas and oil drill muds and production brines. However, this later expanded to include drilling fluids, produced water, and other wastes associated with the exploration, development and production of crude oil and natural gas.

In 1988, EPA issued a regulatory determination stating that control of E&P wastes under the RCRA Subtitle C regulations is not warranted, hence the exemption of wastes from E&P under the RCRA Subtitle C. This however did not exclude them from control under other state and federal regulations. The exemption does not mean these wastes are non-hazardous to humans and the environment if not properly handled.

Waste Exemptions

Only wastes generated from primary field operations were included in the exemptions. Primary field operations in this case refer to activities directly involved in the exploration, development, or production of crude oil and natural gas. Examples include:

- Water separation
- Demulsifying
- Degassing
- Storage at tank batteries associated with specific wells.

Additionally, since natural gas often requires processing to remove water and other impurities prior to entering the sales line, gas plants are considered to be part of the production operations irrespective of their locations. Wastes associated with transport and manufacturing operations are, however, not exempted. To determine if a waste is exempted from the RCRA regulations, the answers to the following questions should be YES.

- Has the waste come from down-hole, i.e. was it brought to the surface during oil and gas E&P operations?
- Has the waste otherwise been generated by contact with the oil and gas production stream during the removal of produced water or other contaminant from the product?

Exempt E&P Wastes

Below are lists of some of the wastes exempted under the RCRA regulations. This list is, however, not comprehensive.

- Produced water
- Drilling fluids
- Rigwash
- Produced sand
- Accumulated materials such as hydrocarbons, solids, sands, and emulsion from production separators, fluid treating vessels, and production impoundments.
- Well completion, treatment, and stimulation fluids.

Nonexempt E&P Wastes

Below are lists of some of the wastes not exempted under the RCRA regulations. This list is however not comprehensive.

- Unused fracturing fluids
- Painting wastes
- Gas plant cooling tower cleaning wastes
- Used equipment lubricating oils
- Laboratory and sanitary wastes
- Oil and gas service company wastes such as empty drums, drum rinsate, sandblast media, painting wastes, spent solvents, spilled chemicals and waste acids.

[Appendix B](#) shows figures that summarize the rules for classifying wastes mixtures as either exempt or non-exempt, and contains additional discussion regarding waste classification steps.

Radioactive Waste

Oil and gas wastes can contain [Technologically Enhanced Naturally Occurring Radioactive Material](#), or TENORM, that forms in pipe scale and drill fluid wastes. Radioactive compounds are also found in produced water, and can accumulate in filtration media or precipitates during handling or treatment processes. These wastes must be disposed in approved landfills as covered in regulations promulgated on a state-by-state basis. In New Mexico, the disposal of radioactive oil and gas waste is regulated by the NMOCD under the Oil and Gas Act rules, 19.15.35 NMAC, and by the EIB and the NMED under the Radiation Protection Act and

its rules, NMSA 1978, Section 74-3-1 et seq. and 20.3.14 NMAC (“Naturally Occurring Radioactive Materials (NORM) in the Oil and Gas Industry”) (<http://164.64.110.239/nmac/parts/title20/20.003.0014.htm>).

Solid Waste Disposal

Solid wastes from oil and gas (non-radioactive) are disposed in landfills approved for this disposal process. This includes drill muds and other solid and semi-solid materials that are byproducts of drilling, as well as membranes, filters, and pit liner materials. The NMOCD retains jurisdiction over solid and semisolid wastes produced from drilling operations (OCD, 70-2-12 NMAC).

Disposal of Oil and Gas Wastes-Landfills, Class II ReInjection Wells

Produced water must be disposed via any of several approved surface or subsurface methods, including Class II reinjection wells, evaporation ponds, and sometimes other methods such as crystallization (which produces a solid waste product). Reinjection wells are regulated through by the NMOCD as [Class II Underground Injection Control wells](#) (19-15-26 NMAC). Class II wells are designated specifically for oil and gas waste disposal. Class II wells are designated specifically for oil and gas waste disposal. These wells have specific construction requirements and are used for 1) enhanced recovery, 2) disposal, or 3) hydrocarbon storage. <http://water.epa.gov/type/groundwater/uic/class2/index.cfm>.

The USEPA Clean Water Act and NPDES Permits

Discharges to waters of the United States are regulated by the 1972 [Clean Water Act](#) (CWA) (<https://www.epa.gov/laws-regulations/summary-clean-water-act>). The CWA establishes the basic structure for regulating discharges into the waters of the United States and regulating quality standards for surface waters. The basis of the CWA was enacted in 1948 and was called the federal Water Pollution Act, but the Act was significantly reorganized and expanded in 1972. The Act is administered by the USEPA. The CWA made it unlawful to discharge any pollutant from a point source into navigable waters unless a permit was obtained. This led to the creation of the permit program “National Pollution Discharge Elimination System” ([NPDES](#)) to control such discharges (<https://www.epa.gov/npdes>). The NPDES program aims to protect and restore the quality of water bodies (rivers, lakes and coastal waters) through permit requirements to monitor and control pollutants discharged from point sources. The CWA requires all point source

dischargers to obtain an NPDES permit and report compliance with NPDES permit limits via monthly Discharge Monitoring Reports (DMR) submitted to the permitting authority. NPDES permits will be needed if produced water is treated and subsequently discharged to a receiving water body. This is true for all states, signaling primacy of the Federal regulation for surface waters. Treated water that is used without discharge to a surface water body is unlikely to need an NPDES permit, but may be subject to other state and federal regulations depending upon the use (e.g., drinking water regulations for groundwater discharge permits).

NPDES permits are issued for New Mexico by USEPA Region VI (Dallas, Texas) with assistance from the New Mexico Environment Department (NMED) (<https://www.epa.gov/npdes>). NPDES permits must include technology-based effluent limitations. For direct dischargers of unconventional oil and gas extraction wastewater (produced water) from onshore oil and gas facilities, with the exception of coal bed methane (CBM), [40 CFR Part 435](#) is the source of technology-based effluent limitations. Direct discharges from unconventional oil and gas extraction are subject to NPDES regulations [40 CFR Parts 122 through 125](#). Indirect discharges are subject to the General Pretreatment Regulations ([40 CFR Part 403](#)).

Permits for onshore oil and gas facilities must include the requirements listed in 40 CFR Part 435, including a ban on the discharge of pollutants. The exception is for wastewater (produced water) that is defined to be “of good enough quality”. This quality is achievable through the best practical control technology currently available, best conventional pollutant control technology, or best available technology economically available, for specific uses in agricultural or wildlife propagation. This applies to onshore facilities located in the continental United States located west of the 98th meridian. 40 CFR Part 435 does not presently include categorical pretreatment standards for indirect discharges to Publicly Owned Treatment Works (POTWs) for onshore oil and gas wells (i.e. Pretreatment Standards for Existing Sources, PSES and Pretreatment Standards for New Sources, PSNS).

Some subparts of the CWA and later amendments are relevant to produced water use and handling, as described in [Appendix C](#). Details about the Clean Water Act as related to oil and gas development can be found here:

http://www.oilandgasbmps.org/laws/federal_water_quality_law.htm.

Unconventional Extraction in the Oil and Gas Industry

Unconventional oil and gas (UOG) refers to oil and gas produced by fracturing impermeable shale formations to create channels for the flow of the hydrocarbons. Under the Oil and Gas Extraction Category, the EPA promulgated the Oil and Gas (O&G) Effluent Guidelines and Standards ([40 CFR Part 435](#)) in 1979, and amended the regulations in 1993, 1996 and 2001. The regulations cover wastewater discharges from field exploration, drilling, production, well treatment and well completions activities on land, in coastal areas and offshore. The Oil and Gas Regulations apply to both conventional and unconventional oil and gas extraction excluding coalbed methane.

These regulations apply to facilities organized into five subcategories namely:

- a) Offshore
- b) Onshore
- c) Coastal
- d) Agricultural and Wildlife Water Use
- e) Stripper Wells

Wastewater from UOG extraction is frequently disposed by underground injection into Class II disposal wells where available. In areas with limited injection wells and/or no wastewater treatment alternatives, operators turned to public and private wastewater treatment facilities to manage their wastewaters. Negative consequences can occur because wastewaters from UOG extraction are not typical influents for a POTW. Some UOG extraction constituents (McGovern and Smith, 2003; EPA, Natural Gas Extraction-Hydraulic Fracturing):

- can be discharged, untreated, from the POTW to the receiving stream.
- can disrupt the operation of the POTW (for example, by inhibiting biological treatment).
- can accumulate in biosolids (also called sewage sludge), limiting their use.
- can facilitate the formation of harmful disinfection by-products.

Because of these potential disruptions to POTWs, EPA this year (June 13, 2016) enacted a zero-discharge pretreatment standard for unconventional oil and gas discharges to POTWs (https://www.epa.gov/sites/production/files/2016-06/documents/uog-final-rule_fact-sheet_06-14-2016.pdf).

Coalbed Methane Extraction Industry

Coalbed Methane (CBM) is a form of unconventional natural gas extracted from coal beds. During the extraction of the CBM, groundwater (produced water or CBM wastewater) is pumped out of the formation to depressure the coal seam (also called dewatering) thereby allowing the methane molecules to desorb from the coal. The gas flows from the seam up to the surface via a gas well, and is compressed and piped to market. Discharges from CBM extraction from onshore oil and gas facilities are not subject to effluent limitations guidelines and standards under the Oil and Gas Extraction Category [40 CFR Part 435](#). Nonetheless, NPDES permits for the CBM discharges are currently developed according to the best professional judgment (BPJ) of the permit authority based on the factors specified in [40 CFR 125.\(c\)\(2\)](#). The BPJ-based requirements that have been applied to the management of coalbed methane wastewater vary from state to state. There are some limitations on some conventional pollutants prior to discharge, to prohibition of direct discharges to waters of the US. While coalbed methane extraction is common in the northwest corner of New Mexico, in the San Juan Basin region, this type of extraction is not done in southeastern New Mexico.

EPA published a report based on its detailed study of the CBM extraction industry in 2010 (U.S. EPA 2010). From this report, EPA commenced a rulemaking to develop controls for pollutant discharges from the CBM industry. Data were collected and analyzed after the commencement of the CBM rulemaking. EPA concluded that though effective technologies exist, have been demonstrated, and may be affordable for some sites, these technologies are not economically achievable for the CBM extraction industry as a whole. Thus, the Agency is not developing national effluent limitations guidelines for these operations at this time.

Drinking Water

Drinking water regulations require that water that can be used as a source of drinking water must remain uncontaminated. The [Safe Drinking Water Act](#) (SDWA) (42 U.S.C. § 300f et seq.) (2006) is the main federal law that ensures drinking water quality in the U.S. The SDWA sets the framework for reinjection of wastes, as well (see below, Class II wells). Source water protection zones are also a critical part of drinking water protection for municipalities.

Provisions of the SDWA most pertinent to oil and gas development include the Underground Injection Control (UIC) program to prevent contamination of underground sources of drinking water. This program covers injection of oil and gas wastes to UIC Class II, and sometimes Class V, wells.

States often establish their own UIC programs, which are reviewed and approved by the EPA under the SDWA. The New Mexico program for Class II wells, which is administered by the NMOCD, was approved by the EPA effective March 7, 1982 (40 CFR 147.1600). The State authority for the Class II program is found in the Oil and Gas Act, NMSA 1978, Section 70-2-12(B) and the regulations of the OCD (19.15.26 NMAC). The New Mexico program for Class I, III, IV and V wells, which is administered by the NMED and NMOCD, was approved by the EPA effective August 10, 1983 (40 CFR 147.1601). The State authority for the Class I, III, IV and V well program is found in the Water Quality Act, NMSA 1978, Section 74-6-4, and the regulations of the Water Quality Control Commission, 20.6.2 NMAC (<http://164.64.110.239/nmac/parts/title20/20.006.0002.htm>).

Additionally, oil pollution prevention is covered by 40 CFR part 112, to prevent oil discharge into navigable waters of the U.S. or nearby areas. 40 CFR parts 435.30-435.32 prohibits discharge of water pollutants associated with oil and gas operations. More information can be found here: http://www.oilandgasbmps.org/laws/federal_water_quality_law.htm.

New Mexico State Regulations

There are three agencies within the State of New Mexico that are responsible for regulations that apply either to produced water (New Mexico Oil Conservation Division or New Mexico Environment Department), or to deep non-potable waters that might be used in oil and gas operations, among other uses (New Mexico Office of the State Engineer).

New Mexico Oil Conservation Division

The [Oil Conservation Division](http://www.emnrd.state.nm.us/OCD/) (OCD) is the part of the New Mexico Energy, Minerals and Natural Resources Department (EMNRD) that regulates oil and gas activity in New Mexico (<http://www.emnrd.state.nm.us/OCD/>). The agency collects and disseminates well production data; issues permits for new wells; enforces OCD rules and the state's oil and gas statutes; makes certain that abandoned wells are properly plugged; and ensures that land used in oil and gas

operations is restored responsibly. OCD also regulates the use and disposition of produced water from oil and gas operations. Under the Oil and Gas Act, NMOCD is the primary regulatory body for the use and disposal of produced water. NMOCD has the authority to “regulate the disposition of water produced or used in connection with the drilling for or the producing of oil and gas or both and to direct surface or subsurface disposal of the water...” (NMSA 1978, Section 70-2-12(B) (15)). This includes disposal (surface and subsurface methods) and “disposition by use”. The Oil Conservation Commission has enacted regulations that deal with specific processes or facilities associated with produced water. These include rules governing injection including disposal wells and enhanced recovery wells, 19.15.26 NMAC, rules governing pits, closed loop systems, below grade tanks and sumps, 19.15.17 NMAC, rules governing recycling facilities, 19.15.34 NMAC, and rules governing surface waste management facilities, 19.15.36 NMAC.

The New Mexico Oil and Gas Act defines “produced water” as water that is “an incidental byproduct from drilling for or the production of oil and gas” (70-2-33(K) NMSA 1978). The Oil and Gas Act (70-2-12.1 NMSA 1978) assigns the authority for produced water to OCD. Specifically, no permit from the state engineer for disposition of produced water in accordance with Section 70-2-12 NMSA 1978 is required.

Recent changes to OCD regulations addressed the potential for reuse of produced water within NMOCD jurisdiction. Rules were promulgated to direct “transportation, disposal, recycling, re-use, or the direct surface or subsurface disposition by use” of produced water (19.15.34.2 NMAC). The rule also applies to uses of produced water “in road construction or maintenance, or other construction; in the generation of electricity or in other industrial processes”. The rule also applies to the transportation of drilling fluids and liquid oil field waste. In addition, rules allow OCD to set test requirements for treated water for other uses (19.15.34.8 A2 NMAC). In 2013, the NMOCD Director issued a notice regarding permits for reuse of produced water (posted 9/9/2013; <http://www.emnrd.state.nm.us/OCD/announcements.html>), stating that:

“ No OCD permit or authorization is required for the re-use of produced water, drilling fluids or other oil field liquids as a drilling or completion fluid or other type of oil field fluid, including makeup water, fracturing fluid or drilling

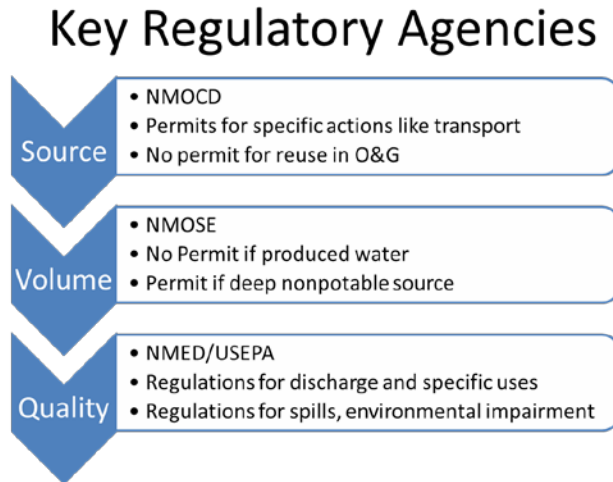
mud, at a permitted drilling, production or plugging operation. However, the re-use of produced water is NOT permitted for any use which involves contact with fresh water zones. No permit is required for the delivery of produced water to permitted salt-water disposal facilities, secondary recovery, pressure maintenance or EOR projects, surface waste management facilities, or to well sites for use in drilling, completion, or plugging operations. Produced water must be stored and re-used in a manner that protects fresh water, public health, and the environment. Produced water, brine makeup water, or frac flowback water can be stored in permanent pits or in temporary multi-well fluid management pits when used only on wells identified in the multi-well fluid management pit permit.”

This notice clarifies the use of permits in handling of produced water for reuse under the jurisdiction of NMOCD. NMOCD encourages reuse of produced water in order to conserve fresh water resources in New Mexico.

In addition to upstream water production, OCD administers and enforces regulations pertaining to surface and groundwater discharges at oil and gas production sites and oil refineries, natural gas processing plants, geothermal installations, carbon dioxide facilities, natural gas transmission lines, and discharges associated with activities of the oil field service industry pursuant to the Oil and Gas Act and the Water Quality Act. The Water Quality Act requires the WQCC to assign responsibility for administering its regulations to “constituent agencies”. Section 74-6-4(F); See Section 74-6-2(K) NMSA 1978 (listing the 8 constituent agencies). A [“Delegation of Responsibilities” Memo](#) from the Water Quality Control Commission (<http://www.emnrd.state.nm.us/OCD/tab2att2.html>) assigns responsibilities to 2 constituent agencies (NMED and NMOCD) and defines NMOCD’s jurisdiction and related enforcement of regulations regarding discharges from refinery activities.

Brines are a special case of water administered by OCD (i.e., not fresh, produced, or deep non-potable waters), including brine manufacturing operations, discharges to ground or surface water at brine manufacturing operations, and including all brine production wells, holding ponds and tanks, transportation and disposal (via UIC Class II injection wells) of the brine. Interestingly, brine may be a viable co-product of desalination treatment and could be regulated by OCD under this framework (Source: 6/13/89, Commission minutes).

The OCD also regulates surface waste management facilities used for oil and gas wastes. NMAC regulation 19.15.36 NMAC - Surface Waste Management Facilities-regulates disposal of oil field wastes and construction, operation and closure of surface waste management facilities.



Only exempt or non-hazardous wastes may be disposed.

Pits, closed-loop systems, and below-grade tanks and sumps used in connection with oil and gas operations are regulated by OCD for the protection of fresh water, public health, and the

environment. This includes pits containing “low-chloride fluids”-water-based fluids containing less than 15,000 mg/L chlorides; and pits containing fluids that are not low-chloride fluids (separate provisions)(19.15.17 NMAC).

New Mexico Office of the State Engineer

The Office of the State Engineer in New Mexico (NMOSE) administers the state’s water resources and has authority over the supervision, measurement, appropriation, and distribution of both surface and groundwater in New Mexico (<http://www.ose.state.nm.us/OSE/index.php>). New Mexico’s water resources are administered under the Prior Appropriation Doctrine (N.M. Const. art. 16 § 2), where the user who first places water to beneficial use becomes the senior water right owner to those who subsequently place water to beneficial use from the same source. In times of a shortage, such as a drought, a senior water right owner has priority over junior water right owners.

The NMOSE implements state statutes governing the appropriation of underground water (NMSA 1978, Section 72-12-1 through 72-12-28). However, permitting authority over the disposition of water produced or used in connection with the drilling or production of oil and gas is assigned to OCD under NMSA 1978, Section 70-2-12(B)(15). The New Mexico State Legislature’s passage of NMSA 1978, Section 70-2-12.1 in 2004 states that no permit from NMOSE is required for the disposition of produced water. This action by the Legislature

clarified that no water right is acquired through the disposition by use of produced water at any time, regardless of the type of use or whether the produced water is treated.

A former oil and gas well may be utilized for the diversion of water, assuming the well owner follows the applicable Sections of NMSA 1978, Section 72-12-1 through 72-12-28. Specifically, if the well owner desires to utilize the former oil and gas well to appropriate any unappropriated fresh water, they must file an application with the NMOSE, pursuant to NMSA 1978, Section 72-12-1 through 72-12-3, and comply with any additional requirements Sections 72-12-4 through 72-12-24. If the well owner seeks to utilize a former oil and gas well to appropriate non-potable water from a deep saline aquifer, they must file, with the NMOSE, a Notice of Intent (“NOI”) to drill or recomplete the well, pursuant to NM SA 1978, Section 72-12-26, and follow any additional requirements under NMSA 1978, Section 72-12-25 through 72-12-28.

Water appropriated from deep saline aquifers may be used in oil and gas drilling and for other uses. Deep saline aquifers containing non-potable water, for purposes of Section 72-12-25, are aquifers the top of which is at a depth of 2,500 feet or more below ground surface and contain non-potable water (defined as >1,000 mg/L total dissolved solids). NMOSE may also require additional pertinent data to be filed with respect to each well for appropriations from deep saline aquifers pursuant to NMSA 1978, Section 72-12-27.

A useful summary of groundwater rights information can be found in (Adams et al. 2004); a discussion of water rights in New Mexico also can be found in Ortega Klett (2002); and in DeMouche et al., (2010). Figure 2 provides a general breakdown of agencies, code references, and waters covered under different jurisdictions. However, the Statutes listed above offer the most up-to-date information on current rules regarding produced water.

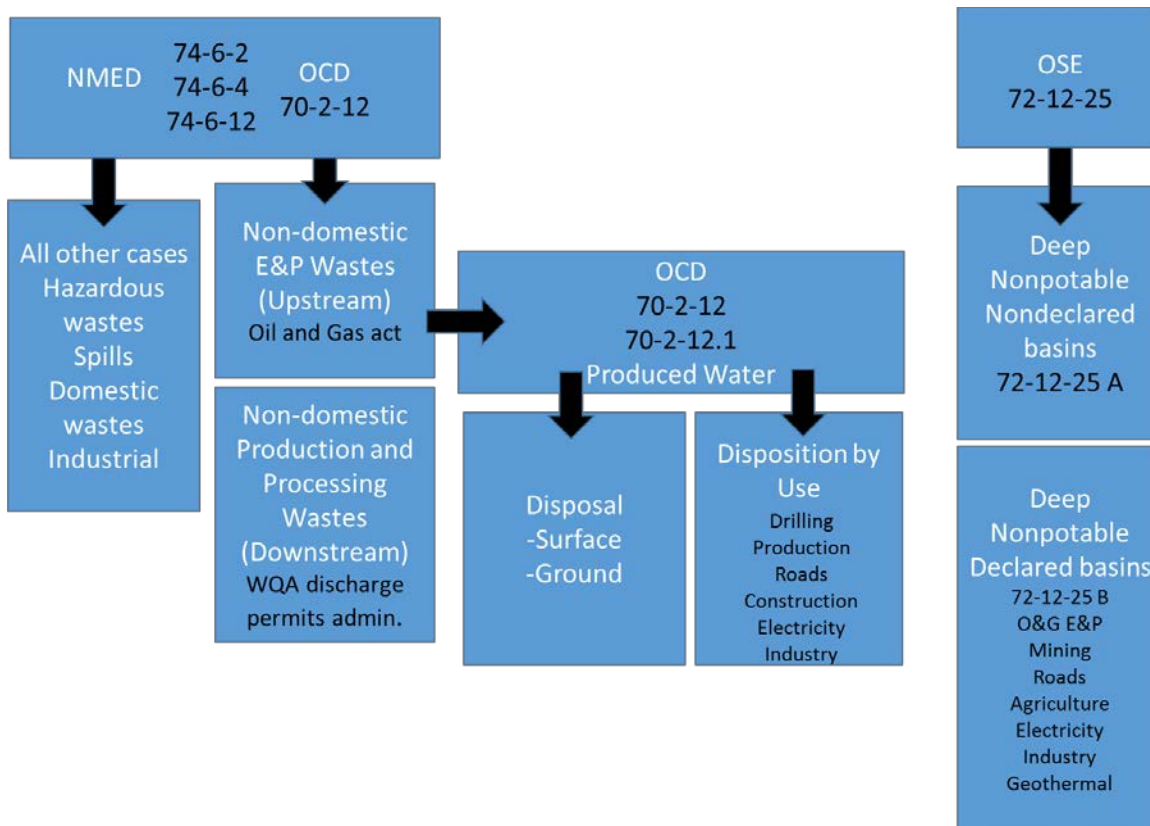


Figure 4.2 Schematic of jurisdiction and rules applicable to non-potable waters, produced waters, and all other water cases. Numbers refer to NMAC sections.

New Mexico Environment Department

The [New Mexico Environment Department](https://www.env.nm.gov/) is the environmental agency for the state of New Mexico which is tasked with the responsibilities of protecting the environment. This includes cleanups, permits, and licenses pertinent to air, water, wastes, health and safety, and environmental cleanups. The NMED has water quality programs and regulatory information on drinking water, groundwater, surface water, wastewater, water and wastewater infrastructure and cleanups and monitoring for water resource protection. The NMED Drinking Water program is responsible for overseeing water infrastructure and water quality issues throughout the state (<https://www.env.nm.gov/water/>).

Drinking Water

The Safe Drinking Water Act (SDWA) is the primary law governing public water systems, however, the NMED (Drinking Water Program) has primacy for the SDWA, i.e. it has the authority to implement and enforce the SDWA regulations. The SDWA regulates over 90 separate contaminants and sets the Maximum Contaminant Level (MCL) for each. The contaminants include microorganisms, disinfectants, disinfection byproducts, inorganic chemicals, organic chemicals and radionuclides. Appendix B (Table B-2) shows the MCLs for the listed contaminants.

The basic authority for water quality management in New Mexico is provided through the State Water Quality Act which establishes the [Water Quality Control Commission](#) (WQCC). The WQCC is the state water pollution control agency for purposes of the Federal Clean Water and portions of the Safe Drinking Water Acts. The [Environmental Improvement Board](#) (EIB) is responsible for rules relating to water supply and capacity development.

Groundwater

The New Mexico Water Quality Act and the WQCC mandate the NMED to prevent waste pollution in the state at sites which pose a significant risk to human health and the environment. The NMED also monitors and issues Ground Water Discharge Permits through [20.6.2 NMAC](#). Table 1, below, shows the groundwater standards for human health, domestic water supply and irrigation use.

Table 4.1 Groundwater standards for New Mexico (20.6.2 NMAC).

A. Human Health Standards			
Contaminant	mg/L	Contaminant	mg/L
Arsenic (As)	0.1	1,2-dichloroethane (EDC)	0.01
Barium (Ba)	1.0	1,1-dichloroethylene (1,1DCE)	0.005
Cadmium (Cd)	0.01	1,1,2,2-tetrachloroethylene (PCE)	0.02
Chromium (Cr)	0.05	1,1,2-trichloroethylene (TCE)	0.1
Cyanide (CN)	0.2	ethylbenzene	0.75
Fluoride (F)	1.6	total xylenes	0.62
Lead (Pb)	0.05	methylene chloride	0.1

Total Mercury (Hg)	0.002	chloroform	0.1
Nitrate (NO ₃ as N)	10.0	1,1-dichloroethane	0.025
Selenium (Se)	0.05	ethylene dibromide (EDB)	0.0001
Silver (Ag)	0.05	1,1,1-trichloroethane	0.06
Uranium (U)	0.03	1,1,2-trichloroethane	0.01
Radioactivity ¹	30	1,1,2,2-tetrachloroethane	0.01
Benzene	0.01	vinyl chloride	0.001
Polychlorinated biphenyls (PCB's)	0.001	PAHs:	0.03
Toluene	0.75	Benzo-a-pyrene	0.0007
Carbon Tetrachloride	0.01		
B. Standards for Domestic Water Supply		C. Standards for irrigation use	
Chloride (Cl)	250.0	Aluminum (Al)	5.0
Copper (Cu)	1.0	Boron (B)	0.75
Iron (Fe)	1.0	Cobalt (Co)	0.05
Manganese (Mn)	0.2	Molybdenum (Mo)	1.0
Phenols	0.005	Nickel (Ni)	0.2
Sulfate (SO ₄)	600.0		
Total Dissolved Solids (TDS)	1,000.0		
Zinc (Zn)	10.0		
pH	6 to 9		

Surface Water

The NMED is responsible for the monitoring and assessment of all surface waters, overseeing discharges to surface water (through the NPDES, assisting EPA in this role), developing water quality standards, and protecting the New Mexico watersheds (<https://www.env.nm.gov/water/>).

Wastewater

The NMED regulates municipal and industrial operations discharging water to surface water by assisting the EPA in implementing the NPDES permitting program. The NMED also issues permits to regulate groundwater discharges. It also issues permits or registrations for septic systems through the NMED Liquid Waste Program.

Water and Wastewater Infrastructure

Through the Drinking Water Bureau and the Construction Programs Bureau, the NMED works with communities to develop, track and inspect the infrastructure needed to manage water and wastewater. The Operator Certification Program certifies wastewater operators, as well.

Cleanups and Monitoring for Water Resource Protection

The NMED, through the following bureaus (The Ground Water Quality Bureau, the Surface Water Quality Bureau, the Hazardous Waste Bureau and Petroleum Storage Tank Bureau) works in conjunction with the Department of Energy (DOE) Oversight Bureau in developing rigorous monitoring and assessment programs to protect the quality of our surface and groundwater sources from existing or potential contaminants. Pretreatment of produced water is likely to be needed prior to any use outside of the oil and gas industry in order to prevent releases of potential contaminants. Treatment levels will vary depending upon the initial quality of the water and the potential use. The potential use is most likely to define any type of regulation, or quality criteria that may be relevant. For example, use in agriculture may require that specific constituents fall within crop tolerance ranges, and soil quality regulations will also apply.

In summary, NMED regulates areas where spills of produced water or hazardous wastes may occur, and also regulates discharges from users or industries where produced water could be used in processes with emissions or otherwise discharged to the environment (e.g., agriculture, streamflow, groundwater recharge). Users need to be aware of process limits and regulations and consult with NMED for appropriate permits for the process being considered.

CASE STUDY EXAMPLES OF REGULATORY FRAMEWORK LEADING TO BENEFICIAL USES

Case studies that include the use and reuse of produced water in New Mexico and other states are described below. Where possible, the pertinent regulatory framework or permit structure is described. If ownership information is available, it is included.

New Mexico- Farmington pilot treatment study

In this study, produced water from a Coal Bed Natural Gas (CBNG) well (~10,000 mg/L TDS) was treated and used for improvement of rangeland in a multi-month experimental study. The produced water was first pretreated to remove coal fines and dissolved organics using sand filter media, modified zeolite test media (surfactant-modified zeolite or SMZ), and an Advanced BioSystems filtration unit (for COD)(Atkinson, 2005). This was followed by reverse osmosis (RO) to remove the salts from the produced water. Table 4.2 below shows the results from this study.

Table 4.2. Results from Farmington Pilot treatment study. Note: Values are in mg/L.

<u>Feed</u>			<u>Bio Unit Product</u>				<u>R RO Unit</u>			
COD	Salinity	TSS	COD	Corrected COD	Salinity	TS S	COD	Salinity	TSS	TDS
730 - 1130	10,000 - 16,000	38- 112	120- 440	12-44	9,000- 14,000	24- 58	ND	ND	ND	84 - 119

About 90% of the COD value was a result of the salt content and the remaining carbon was too low for microbial use. The corrected values were 12 – 44 mg/L. The study was able to produce water that met the New Mexico groundwater standards ([NMAC 20.6.2.2101](#)). Treated water was discharged to the land surface plots. The research evaluated the differences in rangeland plant growth and plant diversity between plots irrigated with different irrigation water sources (desalinated water, mixed water, and non-desalinated produced water).

The New Mexico Oil Conservation Division and the US Bureau of Land Management provided consultation and guidance on regulatory and permitting issues. ConocoPhillips also provide the site for the study as well as key personnel on the project. The Navajo Agricultural

Products Industry, Agriculture and Testing Research Laboratory and the Assaigai Analytical Laboratories also provided personnel, testing and analytical services of the produced and purified water. Research was conducted by Sandia National Laboratories, Los Alamos National Laboratories, and ConocoPhillips.

This test showed that there are technologies available that can treat produced water to regulatory standards for land application. Permitting for the treatment and land application was provided by the New Mexico Oil Conservation Division and the Bureau of Land Management. The site was handled as a short-term research test case for the purpose of the permits. A copy of the permit letter from NMOCD is included in [Appendix C](#). Waste concentrate from the reverse osmosis unit was stored in a tank and was disposed via a Class II reinjection well after the test.

The Bureau of Land Management follows federal law and case precedent regarding oil and gas operations. In *Center for Biological Diversity v. Bureau of Land Management*, the U.S. District Court for the Northern District of California ruled that BLM must look at impacts from hydraulic fracturing in issuing oil and gas leases. Other operations require impact analyses under National Environmental Policy Act (NEPA) (<http://elr.info/litigation/43/20076/center-biological-diversity-v-bureau-land-management>). Presumably if the above-described testers had requested a permanent or longer-term permit, then NEPA analysis would have been necessary.

New Mexico-Pecos River Recharge and HB 388

In 2002, the New Mexico House passed [House Bill 388](#), providing for an income tax or corporate tax credit for investments in treating produced water (<https://www.nmlegis.gov/sessions/02%20Regular/bills/house/hb0388.HTML>; [Appendix E](#)). The bill was designed to promote the treatment of produced water and subsequent discharge into the Pecos River system, to meet Pecos River Compact delivery obligations. The legislation covered some very important aspects of jurisdiction, ownership, and water quality criteria for produced water use outside of the oil and gas industry. The bill expired in 2006, with no entities ever taking advantage of the relatively substantial (\$1,000/acre-foot) tax credit.

Specifically, the bill required that discharges be in compliance with the New Mexico Water Quality Act, New Mexico water quality control commission regulations, and the Federal CWA. The water was made available only for appropriation to meet the terms of the Pecos River Compact (addressing Interstate Stream Commission rules) and also required that the water

must be “produced from oil and gas drilling from a depth of three thousand feet or more below the surface”; this language means that a water right would not be assigned by the OSE. Today, brackish water rules state that the water must be extracted from a reservoir whose top is greater than 2,500 feet below ground surface—a construct designed to protect fresh water resources from brackish water extraction. Finally, a provision of the rule specifically addressed transfer of title of the water from the operator/provider to the interstate stream commission, “which shall indemnify the operator from future liability”—clearly addressing the issue of ownership and liability for the produced water.

Wyoming

There are a number of instances where produced water from coalbed methane has been used for cropping production and life stock watering in the state of Wyoming. For example, in the [Pinedale Anticline](#) of southwest Wyoming, produced water is treated with 75% redelivered to industry and 25% discharged to a local river after further treatment to drinking water standards (<http://www.highsierrawater.com/pinedale-anticline/>). Limitations on disposal volumes are the prime reason for reuse (Brockmann, 2009). We also discuss a project managed by Fidelity and Williams (Guerra et al., 2011), below.

Fidelity Exploration and Production conducted a project where produced water from coalbed methane was used for the production of livestock forage (Harvey et al., 2005). The project by Fidelity was performed in 3 phases, including laboratory bench-scale testing, large-scale (100 acres) pilot testing, and a full-scale (800 acres) operation (All Consulting, 2003).

Permitting body

The permitting of the Produced water was issued by Mr. John Wagner of the Wyoming Department of Environmental Quality, Water Quality Division, permit number WY0051772. The permit application included discharge specifications for a WYPDES (Wyoming NPDES) permit, flow rate specifications, landowner information, outfall description and location, and other pertinent information related to the discharge. A key aspect of the permit was the requirement that the discharged effluent be of equal to or better quality than the ambient quality of the perennial class 2 receiving water. The permit is provided in [Appendix C](#).

Laboratory Pilot Testing

The aim of the pilot project was to determine the best method for managing high sodium levels and bicarbonate in the Coalbed methane produced water. Controlling the sodium and bicarbonate levels meant reducing the Sodium Adsorption Ratio (SAR) of the soil which leads to a reduced chance of forming sodic soil conditions. The bench-scale test was done using soil columns made from PVC pipes to simulate the irrigation area, and produced water was obtained from the Tongue River Basin. Three treatment strategies were tested in the lab in finding the best method for managing high sodium and bicarbonate levels. They were:

- Application of amendments directly to the soil
- Adding amendments to the produced water
- Blending the produced water with irrigation water from local water source

The produced water used exhibited an initial Electrical Conductivity (EC) of 2.5 and an SAR of 60. The effects of the treatment methods were found by measuring the pH, electrical conductivity (EC) and SAR of the soil in the various columns. Table 4.3 summarizes the results.

Table 4.3 Results of soil sampling and analysis from the Fidelity bench-scale managed irrigation tests.

Treatments	Average pH	Average electrical conductivity (dS/m)	Average SAR
Gypsum and sulfur applied to the soil and irrigated with CBNG produced water	7.8	2.9	7.5
Gypsum and sulfuric acid added to the CBNG produced water and irrigated on the soil	7.5	2.8	8.9
Untreated CBNG produced water irrigated on the soil	8.3	1.6	20
Untreated Tongue River water irrigated on the soil	7.7	0.69	0.69
Non-irrigated control where no water or treatments were applied to the soil	7.9	0.41	0.44

Results from the bench-scale test showed that the average soil pH values after treatment were within the typical range of 6.5 – 8.4 for most undisturbed range soils. There was an increase in the soil EC in all the treatments when compared to baseline conditions. Soils treated with amendments recorded an increase in EC. Soil samples from all the treatment methods recorded

an average EC of less than 4 dS/m, which is below the range of soil salinity thresholds (4 to 12 dS/m) for western rangeland and forage plant species (Harvey et al., 2005). Soils watered with produced water without any soil amendments recorded average SAR value of 20, while irrigation with produced water on soils treated with amendments showed average SAR of 7.5. In short, the laboratory test confirmed the feasibility of using produced water from coalbed methane extraction, together with agricultural soil amendments (elemental sulfur and gypsum) for irrigation.

Large Scale Pilot Testing

Following the success of the results from the laboratory testing, a large scale pilot test was carried out on a 100 acre piece of land where sulfur and gypsum were applied to the soil and produced water was applied to the field using center-pivot irrigation method. Results from the large-scale test showed slight change in pH values for pre-irrigation and post irrigation soil samples. It was also reported that there was an increase in average soil EC levels from 0.38 to 2.4dS/m. The reason of using gypsum as soil amendment was to add calcium to the soil to offset the effect of sodium added by the produced water. Again, SAR values in the amended soils increased slightly after irrigation with the produced water.

The large-scale pilot testing showed that the use of elemental sulfur was effective in controlling bicarbonates in the produced water, and also the use of gypsum added calcium to counterbalance the sodium introduced in the soil by the produced water.

Full-Scale Operation

The success in the full-scale test led Fidelity to employ managed irrigation as one of its preferred methods of managing produced water from coalbed methane. Fidelity irrigates over 850 acres of land in its Tongue River project, and produces about 4 tons per acre of alfalfa annually for local ranchers. Fidelity employed an intensive soil-monitoring program which included soil sampling at the beginning and end of every irrigation season to track the soil chemical and physical condition. Soil samples were analyzed in lab to monitor the pH, EC, and exchangeable sodium percentage (ESP). The ESP is a more accurate laboratory method that measures the amount of sodium ions held on the soil exchange sites while SAR is a less expensive method to estimate ESP.

A four year study of the management practices from four of Fidelity’s managed irrigation areas using the center pivot irrigation method showed the following results (Table 4.4):

Table 4.4 Summary of managed irrigation results.

Parameter	Pre-irrigation range	Managed irrigation range
pH	6 – 8.5	7 - 8
EC (dS/m)	1 – 5	4 - 6
ESP (%)	1 - 5	< 10

Colorado

The town of Wellington, and the northern area of Larimer County, Colorado, were running short of drinking water in the early 2000’s. The Town contracted with Stewart Environmental Consultants Inc. to construct the first oil production water treatment plant for beneficial use in the U.S. The produced water was treated to meet stream standards in Colorado. The treated water was then used to augment groundwater via a shallow reinjection well. Treatment methods include ceramic microfiltration, a dissolved air flotation prefilter, and an activated carbon bed polish. System design size was 125 gpm (0.18 mgd) and the system cost ~\$2M for construction in 2006.

http://www.stewartenv.com/php_uploads/stewart_lg_20100604154748.pdf.

Jurisdiction for permitting falls under the State Engineer, and the Colorado Energy Office. Wellington, CO. water is recharged via a shallow groundwater well to an aquifer that ultimately is a supply for local town after RO treatment (Bridger, 1996).

In March, 2008, the Colorado State water court granted two decrees, allowing beneficial use of produced water (for irrigation), and allowing a transfer of water rights used for irrigation to domestic use (http://www.northfortynews.com/Archive/A200804photo_01N-WellingtonWaterWorks.htm). Wellington Water Works and Wellington Operating Co. were the beneficiaries of the decrees.

In Colorado, there is a distinction between tributary and non-tributary groundwater. Tributary water is subject to Colorado’s priority withdrawal system (Witt, 2015). Recent court cases surrounding the extraction of coal-bed methane (CBM) water led to a Colorado Supreme Court decision declaring that CBM produced water is subject to Colorado water rights administration (Colvin, 2011). The Colorado State Engineers office (SEO) interpreted this ruling

to include all produced waters. The Colorado State Legislature subsequently developed House Bill 09-1303 and Senate Bill 10-165, to give the SEO authority to initiate rule-making for Produced Water regulations. By 2009, the SEO had designated several geologic units as non-tributary groundwater based on modeling and structural evaluations. At this time, a process, while unique to Colorado, has been defined for identifying and handling of non-tributary produced water (Witt, 2015). While court cases led to determination of jurisdiction in Colorado, subsequent legislation was needed to define rulemaking for permitting and use.

Current Colorado rules allow for reuse of produced water among oil and gas producers located within the same geologic basin. This includes roadspreading, enhanced recovery, drilling, well stimulation, well maintenance, pressure control, pump operations, dust control on- or off-site, pipeline and equipment testing, fire suppression, and discharge into state waters (C.R.S. § 37-90-137(7)(a)), (Curtis, 2014). Ownership of the withdrawn water, however, is still unresolved, even though reuse can occur while “mining of minerals” is ongoing (C.R.S. § 37-90-137(7) (a)) (Curtis, 2014).

Texas

Texas recently passed several new rules (“House Rule” or HR) that address produced water use, reuse, handling, and disposal. The intent is clearly to promote the use of produced water as a substitute for fresh water, and to clarify ownership, liability, and jurisdiction.

The Railroad Commission of Texas Oil and Gas Division issued a permit to Energy Water Solutions (May 2013 to October 2015) in pursuant to the Statewide Rule 8 ([Texas Administrative Code Title 16 Part 1 Chapter 3 Rule §3.8\(d\) \(7\)](#)). The intended purpose of treating the water was for use in a test plot for growing cotton at the Texas A&M Agricultural Research Center in Pecos, TX. Cotton growth tests were conducted by Dr. Katie Lewis of TAMU Agrilife from June 2, 2015 to November 24, 2015 (Lewis, 2016).

Tests were carried out to determine the cotton growth and yield response to irrigating with treated produced water blended with groundwater, and also to determine the effects of treated produced water on the soil chemistry. The cotton plants were planted on June 2, 2015 and harvested on November 2015. The study compared irrigation with 100% groundwater against blended treated produced water (4:1 ratio, groundwater: treated produced water). Table 4.5 below summarizes the water qualities of the both types of irrigation water.

Table 4.5 Water sample analyzed quality (Lewis, 2016).

Parameters	Units	Water Source		
		Groundwater	Treated Produced Water	Blended
Sodium (Na)	ppm	999	42	766
Calcium (Ca)	ppm	167	4	127
Magnesium (Mg)	ppm	50	1	40
Carbonate (CO ₃)	ppm	<1	<1	<1
Bicarbonate (HCO ₃)	ppm	122	37	122
Chloride (Cl)	ppm	1,900	20	1,450
Conductivity	μS/cm	4,950	150	3,800
pH		7.6	7.8	7.4
Phosphorus (P)	ppm	<0.01	<0.01	<0.01
Potassium (K)	ppm	18	5	14
Nitrate (NO ₃)	ppm	5	6	4
Sulfate (SO ₄)	ppm	1,204	31	1,362
Boron	ppm	0.5	4.1	0.8
TDS	ppm	3,218	98	2,470
SAR	ppm	17.4	4.9	15.2

The soil chemistry was also determined prior to the study and post harvesting. Tables 4.6 and 4.7 summarize the soil characteristics.

Table 4.6 Hoban Silty Clay Loam characteristics (Lewis, 2016).

pH	Conductivity mmhos/cm	NO ₃ -N	P	K	Ca (ppm)	Mg	S	Na	SAR
8.7	1.8	22.1	30	450	17,634	516	482	1,373	16.7

Table 4.7 Post harvest soil characteristics (Lewis, 2016),

Irrigation source	Sample depth	pH	Conductivity (mmhos/cm)	NO ₃ - N	P	K	Ca	Mg	S	Na	B	Cl	SAR
Blended	0-6"	9.0	1.5	9	35	531	14,915	575	654	1,230	1.6	1,018	13.8
	6-12"	9.1	1.2	12	26	474	16,896	513	476	1,347	1.2	896	17.6
	12-24"	8.8	1.7	19	19	425	24,243	485	528	1,349	1.2	1,256	15.3
Ground- water	0-6"	8.9	2.2	36	35	528	15,054	596	835	1,751	1.6	1,637	17.5
	6-12"	9.0	2.1	18	26	471	16,352	514	503	1,496	1.1	979	17.3
	12-24"	8.8	1.8	26	16	409	25,706	485	504	1,487	1.2	1,609	16.9

The produced water for this research was provided by Anadarko. The treatment of the produced water was done by Energy Water Solutions using a patented technology treatment train. This included several unspecified methods treatment stages including tar and oil removal, volatile organic removal, metal and inorganics removal, suspended solids removal, chlorine removal, and salt removal and water polishing (Lewis, 2016). The salinity of the treated water, and many other quality parameters (Table 5) were much lower than in native groundwater from the site.

Results from the studies showed that using blended water for irrigation reduced the soil salinity parameters as compared to the using 100% groundwater. Furthermore, the cotton yield or lint quality was not affected by irrigating with treated produced water. Irrigating with groundwater produced a lint yield of 587 lbs./acre whiles blended water produced a lint yield of 568 lbs./acre.

The precedent for using treated produced water for a non-food crop irrigation test and the results showing a net improvement to soil properties is encouraging. Further testing to quantify long-term effects on the crop and soils is planned (Lewis, 2016). The treatments used, while not specified, appear to be suitable to accommodate the variety of constituents of concern that can be found in produced water. No information was given regarding the cost-effectiveness of the treatment, however.

California-Cawelo Field Example

In recent years, the state of California has experienced serious and widespread drought conditions. The state is one of the leading producers of oil and gas in the United States, and one of the largest producers of agricultural products in the U.S. Produced water has been utilized in California as an additional water source for irrigation and aquifer recharge, as described in the following three studies.

California state laws govern land application of wastes and apply to surface discharges such as to an irrigation canal. Oil producers wanting to discharge produced water into the environment (land or water) must obtain a permit, Waste Discharge Requirement (WDR) from their Regional Water Quality Control Board. The WDR spells out the requirements for water treatment, set limits for the quantity of discharge, and establishes the maximum allowed limit of certain pollutants. The WDR also establishes requirements for monitoring and reporting water

quality (Guerra et al., 2011). Table 4.8 below shows the WDR for Chevron’s delivery of water to the Cawelo Water District.

(http://www.waterboards.ca.gov/centralvalley/board_decisions/adopted_orders/kern/r5-2012-0058.pdf)

Table 4.8 Discharge limits and sampling required by the water board for Chevron’s discharge of water to the Cawelo Water District.

Parameter	Maximum allowed under permit	Sample type	Minimum sampling frequency
Flow	33.5 million gpd	Meter	Continuous
Electrical conductivity	940 µmhos/cm	Meter	Continuous
Arsenic	10 µg/l (10 ppb)	Grab	Monthly
Oil and grease	35 mg/l	Grab	Monthly
Boron	1.3 mg/l, annual average	Grab	Monthly
Chloride	200 mg/l (200 ppm)	Grab	Monthly
pH	No limit set by permit	Grab	Monthly
Total suspended solids	No limit set by permit	Grab	Monthly
Sodium	142 mg/l, annual average	Grab	Quarterly
General minerals¹	No limit set by permit	Grab	Quarterly
Priority pollutants²	No limit set by permit	Varies	Every 5 years

1 Standard minerals shall include the following: boron, calcium, iron, magnesium, potassium, sodium, chloride, manganese, and phosphorus; total alkalinity (including alkalinity series); and hardness; as well as verification that the analysis is complete (i.e., cation/anion balance).

2 Priority pollutants include several dozen inorganic and organic compounds, pesticides, and dioxin congeners

California-San Ardo Field Example

The San Ardo project in the Monterey region takes produced water of relatively low salinity (~6,000 mg/L TDS) and treats it to recharge the local ground-water basin via a wetlands discharge, as well as for the production of Once-Through Steam Generator (OTSG) make-up

water for heavy oil production. The project is contracted to Veolia Water Solutions and Technologies by Chevron, and is permitted by the California Regional Water Quality Control Board (Central Coast Office) with a “Waste Discharge Requirements” order (WDR). The WDR order includes a California NPDES permit for this use. These orders normally include background information, prohibitions, discharge specifications, monitoring and reporting provisions, and sample frequency and volume reporting requirements (http://www.waterboards.ca.gov/centralcoast/board_info/agendas/2005/july/item20/item20_attach1_wdr.pdf).

For the San Ardo project, the produced water is treated using oil removal/sorption, softening, filtration and reverse osmosis (RO) to achieve the desired water quality. Table 4.9, below, shows a summary of the produced water qualities at different treatment stages.

Table 4.9. Results of treatment of produced water (Heberger et al 2015).

Constituent	Produced Water	Double Pass RO Permeate	Final Treated Effluent	Effluent Specifications
TDS (ppm)	6,500	76	120	510
Sodium (ppm)	2,300	43	43	85.0
Chloride (ppm)	3,400	Non-Detect	11	127.5
Sulfate (ppm)	133	Non-Detect	120	127.5
Nitrate (ppm)	10.0	Non-Detect	Non-Detect	4.25
Boron (ppm)	26.0	0.24	0.24	0.64
pH (S.U)	7.5	10.7	7.0	6.5 – 8.4

California-Kern River Field Example

Produced water from the Kern River Field has been used for many years in agricultural irrigation. The water is extracted with heavy oil production from a shallow formation (1,500-2,000 ft below ground surface). Treatment and handling steps are described in the WDR order as follows:

- a. Primary and secondary surge tanks used for initial oil/water separation;
- b. Additional oil recovery using flotation clarifiers (“Wemcos”) to separate emulsified oil droplets from the water;
- c. Walnut shell filtration for further reduction of remaining oil in the water through a filtering process;
- d. Reclaiming water for steam injection;
- e. Blending produced water with available surface water supplies and groundwater to achieve specified discharge limits for beneficial reuse through crop irrigation and groundwater recharge;
- f. Management of produced water to maximize reuse;
- g. Diversion of local surface water flood flows to the storage basins whenever available to further improve percolation water quality; and
- h. Monitoring of discharges to and from the storage reservoir and discharges to the storage Basins, the overall groundwater quality of the District, and groundwater quality near the storage basins.

http://www.waterboards.ca.gov/centralvalley/board_decisions/adopted_orders/kern/r5-2015-0127.pdf

No desalination is needed because of the low total dissolved solids content. The water is blended with other fresh water sources (surface and groundwater) before use in irrigation. It is regarded as a valuable resource during times of drought. Predominant crops irrigated include permanent tree fruits and nuts, and vine crops. This use is regulated by the California Regional Water Quality Control Board (Central Valley Office) with the objectives of providing water for beneficial use while not degrading groundwater in the district. The WDR for this operation includes a California NPDES permit. Characteristics of the water monitored include flow rate in million gallons per day, electrical conductivity in $\mu\text{mhos/cm}$, oil and grease (mg/L), arsenic ($\mu\text{g/L}$), boron (mg/L), chloride (mg/L), and sodium (mg/L). Best management practices and monitoring limits for the operation are specified in detail in the WDR order.

Recent concerns in the news media about the use of produced water in agriculture has prompted the Board to set up a Food Safety Panel consisting of academics, regulators, and consulting scientists to review the practices used for treatment and the use of produced water in agriculture. The Panel is expected to recommend studies to fill data gaps, and possibly new sampling and testing requirements.

http://www.waterboards.ca.gov/centralvalley/water_issues/oil_fields/food_safety/index.shtml

California-Additional Information

California has witnessed a number of projects in which treated produced water has been used for irrigation and other uses. Table 4.10, below, shows a summary of these projects. These projects stated can serve as a guideline for New Mexico to follow in addressing issues regarding agricultural use of produced water. All were permitted by the state, and many include blending with other (fresh) sources of water. In addition, another company in California, Water Planet, is currently carrying out pilots test to treat produced water from oilfields by utilizing an integrated mechanical and membrane filtration system. The process uses ceramic membranes to filter the water followed by reverse osmosis (Hazmat, 2016). The purpose of this pilot study is to test treated produced water from oilfield operations as irrigation water for crops.

Table 4.10 Projects where produced water has been used for crop irrigation in California. (Heberger & Donnelly, 2015) Note: Blank spaces indicate unknown data.

Date permitted	County	Oil field	Operator	Permitted volume (acre-feet per year)	Water Treatment	Blending	Application	Crops irrigated	User
	Tulare	Deer Creek			Mechanical separation with addition of coagulants	No	Irrigation	Alfalfa	Private land
	Tulare	Deer Creek			Mechanical separation with addition of coagulants	No	Irrigation	Alfalfa	Private land
	Kern	Jasmin			Mechanical separation with addition of coagulants	Blended with canal water some of the time	Irrigation	Citrus	Jasmin Ranchos Mutual Water Company
	Kern	Mount Poso					Irrigation		Cawelo Water District
2012	Kern	Kern River	Chevron	37,500	Mechanical separation, sedimentation, air flotation, and air filtration (walnut hull filters)	Treated wastewater, imported surface water, groundwater	Irrigation groundwater recharge	99% permanent crops (citrus, almonds, pistachios, apples, peaches, plums, and vineyards); 1% (alfalfa, potatoes, corn, grains, vegetables, melons)	
2012	Kern	Kern River	California Resources Corporation	16,600		Treated wastewater, imported surface water, groundwater	Irrigation, groundwater recharge	Same as above	Cawelo Water District

2011	Kern	Kern Front	Hathaway LLC	70	No treatment requirements	7% wastewater; 93% groundwater	Irrigation; during non-irrigation season, disposed of via underground injection	Citrus	Concordia Ranch
2015	Kern	Kern Front	California Resources Corporation	21,200	Gas separation, free-water knock-out tanks, air flotation, and skimming	Produced water, surface water, and groundwater blended in the Lerdo Canal	Irrigation, groundwater recharge in the Rosedale Basin	80% permanent crops of nuts, vineyards, and fruits	North Kern Water Storage District
2014	San Luis Obispo	Arroyo Grande	Freeport-McMoran Price Canyon	940	Mechanical, Chemical, reverse osmosis	Yes (indirect reuse)	Discharged to Pismo Creek to improve habitat and water quality in the creek is recharging groundwater and reused indirectly by downstream irrigators with wells.	Vineyards, row crops	Private land

DISCUSSION

These case studies illustrate potential pathways to answer some of the questions posed by the Dagger Draw study (McGovern and Smith, 2003). In addition, the methods used in each study are helpful to understand what types of analyses, treatment methods, collaborations, and approaches are useful. The use of test case permits is one option (New Mexico/BLM and Texas) that allows agencies to gather data from the studies without a long-term commitment. In all cases, extensive analytical information for the produced water treatment and use, for surface discharges, and for soil applications was obtained.

Jurisdiction

Jurisdiction is important because it dictates which authority, regulations, rules, and permits apply to any given stage of storage, transport, treatment, or use of produced water. Jurisdiction for the case studies primarily fell under State agencies, as follows:

- New Mexico Oil Conservation Division; US Bureau of Land Management (Federal), and the New Mexico Environment Department
- New Mexico Interstate Stream Commission, New Mexico Environment Department and New Mexico Water Quality Control Commission
- Wyoming Department of Environmental Quality, Water Quality Division.
- Colorado Office of the State Engineer, and the Colorado Energy Office
- The Railroad Commission of Texas (regulates oil and gas operations) and MOUs with the Texas Department of Environmental Quality (Texas DEQ).
- California Regional Water Quality Control Boards (various regions)
- California also has primacy for NPDES permits in California.

We do not know if this is a complete picture of the jurisdictions, only what was reported. The case studies also do not completely describe the conditions where jurisdictional transfer might occur between agencies either before, during, or after the presented use.

In New Mexico, there are several statutory provisions that describe the jurisdictional framework for produced water. These include:

- 70-2-12.1 Disposition of produced water; no permit required
 - This rule indicates that no permit is needed from the state engineer for disposition of produced water as long as OCD rules are followed.
- 70-2-12 Enumeration of Powers

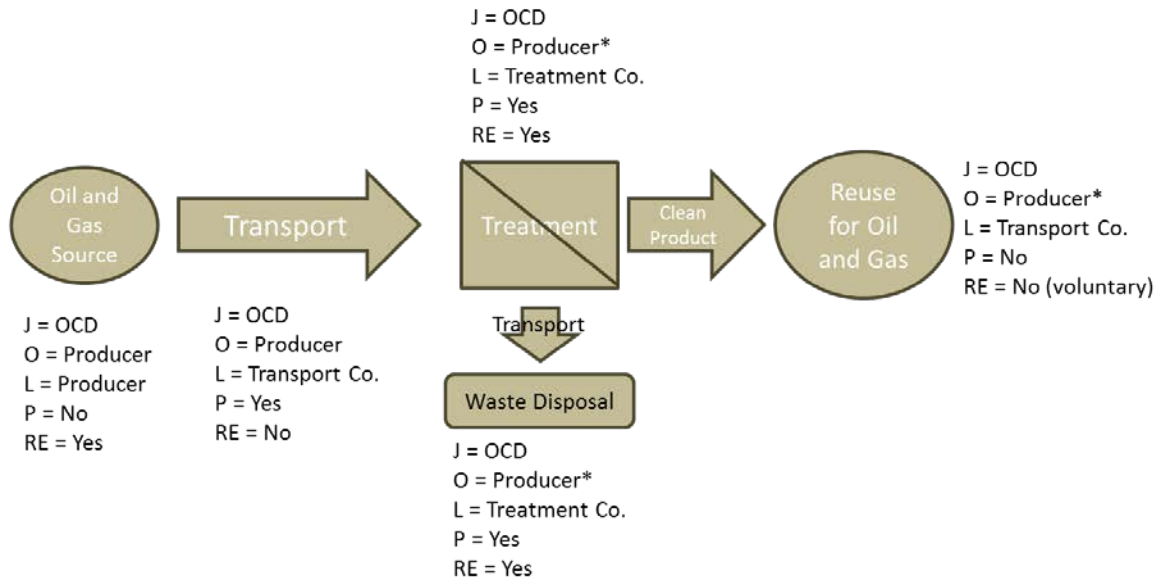
- This rule authorizes OCD to regulate the “disposition” of produced water. This includes surface or subsurface disposal, and also a process known as “disposition by use”, where the water is used in drilling or production of oil and gas; but also can be used in road construction or maintenance, other construction, in electricity generation, and in other industrial processes, as long as the environment is protected and fresh water supplies are not contaminated.
- 72-12-25 Declaration of basin; non-potable deep aquifers
 - This rule is sometimes known as the Brackish Water rule.
 - The rule places deep aquifers with an aquifer formation top greater than 2,500 feet below ground surface, AND ALSO having a total dissolved solids content greater than 1,000 mg/L, under the administration of the state engineer.
 - A notice of intent to drill must be filed with the state engineer, and in declared basins, metering and additional quality analysis may be required by the engineer’s office.
 - If the formation is in a declared underground basin, then uses of this water specifically for oil and gas exploration and production, prospecting, mining road construction, agriculture, generation of electricity, geothermal use, or industrial processes remain under the jurisdiction of the state engineer.
 - In declared basins, impairment and subsequent dispute of existing water rights also is covered by the jurisdiction of the state engineer, under a process similar to that of other water rights.
- Water Quality Authority division between NMED and OCD
 - 74-6-12 Limitations
 - This rule describes the limitations of the Water Quality Act. In this case, there are provisions that confer jurisdiction on the OCD to prevent or abate water pollution (70-2-2 and 70-2-12).
 - The OCD is authorized to make rules, regulations, and orders to protect public health and the environment in regulating the disposition of wastes generated from exploration, development, production and storage of oil or gas, and;
 - The OCD also is authorized to do the same for disposition of wastes resulting from oil and gas service industries, transport, and “downstream” treatment or refining.
 - 74-6-4 Duties and powers of commission
 - This rule assigns responsibilities for administration to different agencies to prevent duplication of effort with regard to water classifications and water contaminants.
 - 74-6-2, Definitions
 - Matches responsibilities with agencies such as NMED, the state engineer, OCD, the parks division of EMNRD, the NM department of agriculture, and others.

Water that is treated and used outside of oil and gas would need to follow NM Environment Department/state water quality control commission/CWA rules or permit requirements that apply to the industry or process that uses the water. For example, if an industry chose to use the water in a process, then a discharge permit relevant to the process could be required by NMED.

Example use cases

Figures 3-5 illustrates a hypothetical set of scenarios where water is extracted by an oil and gas producer, transported, treated, and reused within the oil and gas industry (Figure 3), or used outside of the industry (Figures 4 and 5). We show the potential ownership of the water at each stage, the jurisdictional agency for New Mexico, the holder of liability at each stage, and permitting needs. These use cases are for illustration only and do not constitute a final determination of jurisdiction, ownership, or liability. We present these in order to evaluate the potential use of oil and gas produced water not as a waste product, but as a resource, and to evaluate where gaps may exist in the regulatory framework. A key concept is the function of ownership sales, including legal liability transfers, which are accomplished contractually upon sale from the oil and gas producer to either the treatment/transport entity, or by the latter entity to the final user. In the former case, the treatment/transport entity may be contracted by the oil and gas company. In the latter case, the treatment/transport entity is either independent of the oil and gas producer, or may be contracted by the final user/purchaser. The treatment/transport company may also be completely independent, contractually.

In Figure 4.3, the use of the water is entirely within the oil and gas industry. This is the simplest case for jurisdiction, because the jurisdiction lies entirely within the purview of the OCD. This includes production, transfers, treatment (or, case-by-case uses) and reuse. Ownership of the water is held by the producer. Waste materials are disposed under existing regulations and permits; transportation is by permit. Liability is held by the owner, the transporting agent, or the treatment company. If the treatment system is defined as a commercial recycling system, then specific rules apply to that entity for permitting and reporting. Changes in ownership or liability may be specified by contract between entities. This exemplifies the use of produced water as a privately-owned material or product, not as a “water of the state”.



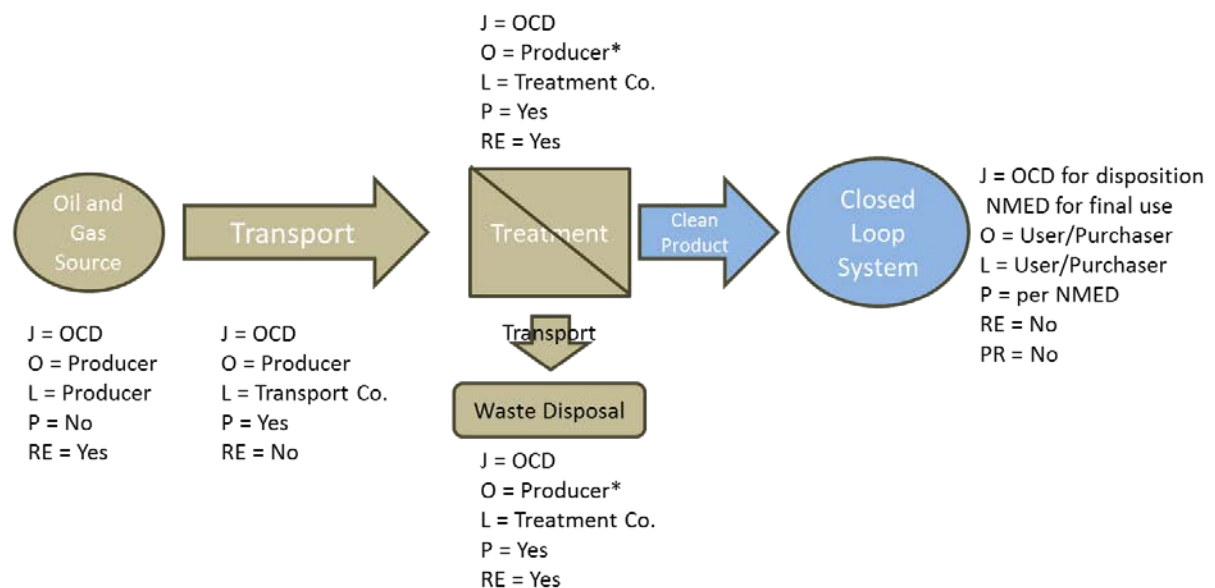
Key:
 Jurisdiction= J
 Ownership = O
 Legal Liability = L
 Permit = P
 Reporting = RE
 Permit+Right = PR (OSE only)
 * Unless sold/transferred by contract

Hypothetical Case for Reuse within Oil and Gas Industry

Figure 4.3 Hypothetical Case for Reuse within the Oil and Gas Industry

In Figure 4.4, a scenario is shown where the water is produced within the oil and gas industry, then treated and sold/transferred outside of the oil and gas industry to a fully consumptive use. One example of this might be a sale of treated water to an electric power company for consumptive cooling. As shown here, the jurisdiction lies with OCD until after treatment. Waste materials are disposed under existing OCD regulations and permits; transportation is by OCD permit. Liability is held by the owner, the transporting agent, or the treatment company. The reason for this is because it simplifies disposal of wastes by leaving them within OCD jurisdiction. The oil and gas industry has well-developed methods for disposal, the wastes are mostly RCRA-exempt, and there is precedent for this pathway in New Mexico law and in multistate oil and gas operations. Ownership of the water is held by the producer, until after treatment when it could be sold or transferred to a non-oil-and-gas entity as a disposition-by-use (public or private). At this point, NMED and the USEPA may also elect to have jurisdiction over quality issues at this stage depending upon the use. In addition,

the purchaser/user will likely have quality requirements for their specific process/use. Changes in ownership or liability would be specified by contract between entities because produced water is viewed by NMOSE as a private commodity-there is no water right associated with further use. Most importantly, after treatment in this scenario, the receiving entity would use the water entirely within a closed-loop system, and/or the water would be totally consumed. In this situation, no NPDES permit is required by EPA. The use of this water could replace existing fresh water withdrawals, conserving natural fresh ground or surface waters for other uses or later use. For land applications, if no surface water body is encountered, then NMED would consider this to be land application and would apply those pertinent regulations in a Ground Water Discharge Permit. All of these scenarios must be evaluated on a case-by-case basis by the agencies involved.



Key:
 Jurisdiction= J
 Ownership = O
 Legal Liability = L
 Permit = P
 Reporting = RE
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 * Unless sold/transferred by contract

Hypothetical Case for Reuse outside of Oil and Gas Industry
 Closed-Loop system, no discharge to Waters of the State
 Full consumption of clean water product

Figure 4.4 Hypothetical Case for Reuse outside of Oil and Gas Industry; Closed-Loop system, no discharge to Waters of the State; Full consumption of clean water product.

In Figure 4.5, we illustrate a hypothetical case where the treated water is utilized in an open system, or is deliberately discharged to righted waters of the state. This was the scenario described in the Pecos River case study (described above), where treated produced water was intended to supplement the Pecos Compact requirements. Legislation was written to support this kind of use (Appendix E). In the legislation, jurisdiction, legal liability, and ownership were clearly established. The tax credit was designed to reduce economic barriers to the treatment. Many barriers to produced water beneficial use were reduced by this legislation; however, they were not sufficient at the time to accomplish this goal.

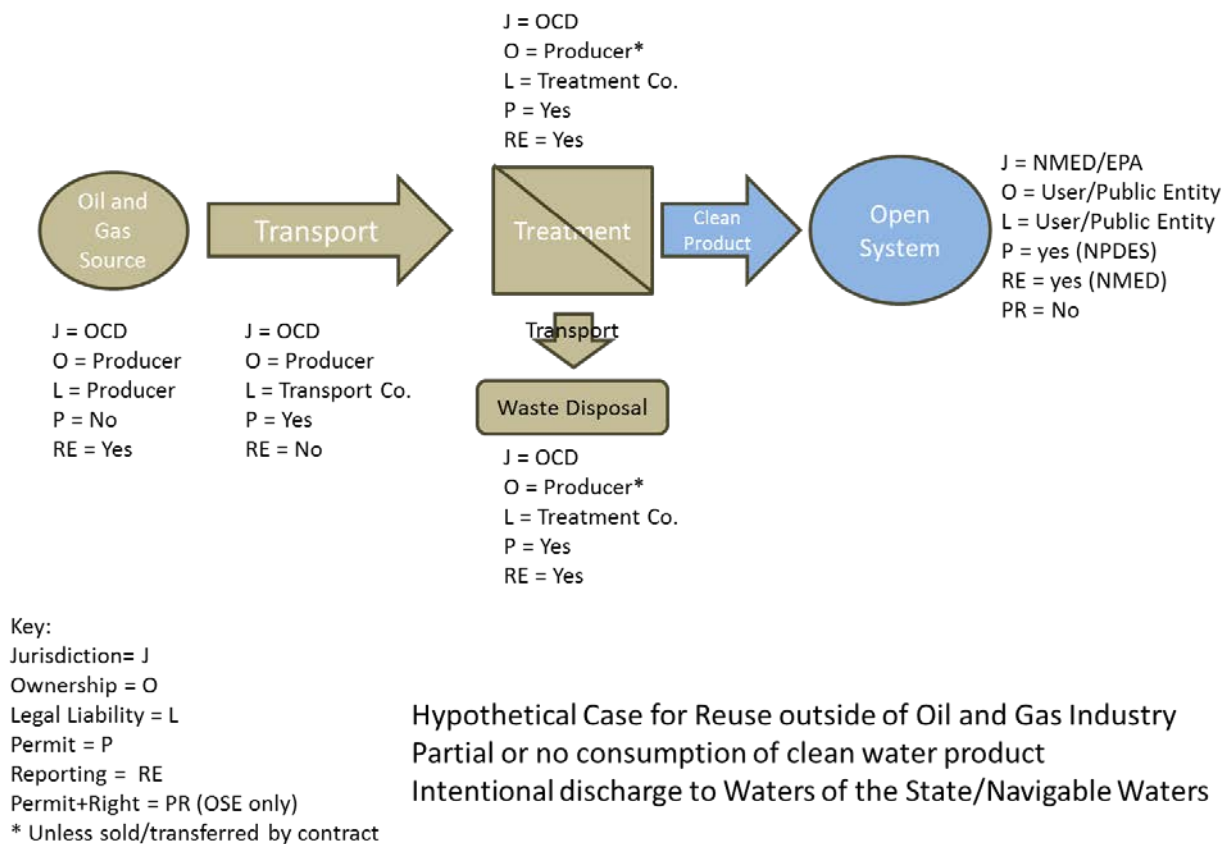


Figure 4.5 Hypothetical Case for Reuse outside of Oil and Gas Industry; Partial or no consumption of clean water product; Intentional discharge to Waters of the State/Navigable Waters

Because this legislation has expired, there is no current precedent for this kind of use. Additional legislation to renew the prospects for this pathway may be helpful, but not critical. Alternately, the agencies involved may be able to develop a system of memoranda of understanding, regulations or rulemaking, and permits that could support this kind of use.

Because no water right is attached to the use of produced water, the two agencies involved are OCD and NMED.

Further, we considered the questions (from the beginning of this report):

- Who defines specifications for treatment? Specifications for use?
- Who provides treatment?
- Who pays for treatment?

The regulations under the CWA or the New Mexico WQA provide treatment specifications for waters that would be released to the environment, such as to the Pecos River or to an agricultural irrigation plot. NPDES/CWA (EPA) permitting might also be needed if the discharge is to a surface water body; NMED would permit discharge or recharge to an underground aquifer. End users of water that is treated for an industrial purpose, such as cooling, would need to provide their own process specifications. More stringent requirements are expected for more sensitive or higher-quality receiving waters. Many different companies are capable of treating water to high quality standards. Examples of localities where water desalination is being done or will be done include El Paso, Texas (brackish groundwater) and Alamogordo, New Mexico (brackish groundwater). The costs of planning, financing, and implementation can be found in references including (Hazmat, 2016; Gorder, 2009; and Guerra et al, 2011). Produced water treatment is covered in Dahm and Chapman (2009).

- Who provides the management, storage, and conveyance of the treated water?
- Who will pay for the water as an end user?

Provision of and payment for treatment depends upon market conditions, and also upon the degree of perceived or measured water scarcity in a region. The study area (this report) relies upon the High Plains/Ogallala aquifer for drinking water and irrigation. Increased demands in drought years can have severe impacts on this resource, as is evident in declining well water levels. Surface water sources are unavailable in Lea County, and fully allocated elsewhere. The costs of treatment are addressed in other chapters of this report. The willingness of a client to pay for treatment will depend upon how critical their need is for fresh water and upon their financial

resources. In municipalities, the water costs are usually born by the taxpayers and by ratepayers on public water systems.

- What funds can government provide?

The government can sometimes fund tax credits, grants for planning and construction, and research funding. The Federal government provided significant funding for the KBH plant in El Paso, for example. In New Mexico, there are state water grant programs for studies.

Gap Identification

Gaps in regulation or unclear regulatory guidance were found in the following points of the use cases:

- In the transfer between OCD and NMED jurisdiction (what is the specific point of transfer?)
- In the definition of produced water as a “waste” under OCD versus as a “product” or as “water” outside of OCD.
- In the ownership and legal liability train between production/transport to treatment, and transfer of treated water to use outside of the oil and gas domain
- In the use of treated produced water as a supplement to surface or groundwater supplies via mixing with “righted” water.
- In the regulation of constituents of concern that might exist in produced water that are not explicitly identified in current water quality or land discharge regulations (note these are being updated at the time of this report).

Some resolution of these gaps can be found in the case studies, particularly in the Colorado, Texas and New Mexico (Pecos) examples. Permits can be constructed (e.g. in Texas, New Mexico, California) to allow for specific uses in open (land application) systems, particularly where direct mixing with surface water or groundwater is unlikely (arid region, deep water table). Contracts can also be devised to direct ownership of produced water as a privately owned product. The use of produced water for agricultural purposes has raised a great deal of interest, both for irrigation purposes and stock watering. The California examples show ways in which these uses can be accomplished. Framing the liability for these uses would be of great interest to landowners, farmers, and ranchers.

Conclusions and Recommendations

We reviewed Federal and State regulations pertinent to produced water use and the use of treated produced water outside of the oil and gas industry. We analyzed several case studies and developed hypothetical use cases in order to illustrate possible use scenarios relative to jurisdiction, liability, ownership, and permitting. These scenarios led us to identify specific gaps in the regulatory system that are creating perceived barriers to the potential beneficial use of produced water.

This report provides information that we hope will simplify the understanding of the produced water regulatory framework. Our aim is to improve the potential for uses of alternative water resources in New Mexico, without compromising the environment or other water resources. We hope to reduce some of the many barriers to supplementing our limited fresh water supplies with alternative water sources. Utilization of test cases and temporary permits, to facilitate research and data gathering, are proposed here to help inform agencies and regulators of key problems or benefits. Continued strong public interest in utilizing alternative water resources is a motivation for continued examination of regulatory pathways to beneficial uses.

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CHAPTER 5: ASSESSMENT OF TREATMENT TECHNOLOGIES FOR PRODUCED WATER TO IMPROVE WATER SUPPLY SUSTAINABILITY IN SOUTHEASTERN NEW MEXICO

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Introduction

The Permian Basin, located in Southeast New Mexico, is a rapidly developing unconventional oil and gas field with a 68% oil production increase from 2008 to 2013 (Sullivan et al, 2015). The rapidly expanding exploration and production has resulted in significant increases in freshwater demand, hydraulic fracturing flowback water, and produced water production. Unconventional oil and gas development consumptively used 663.6 million gallons (15.8 million barrels, 1 barrel = 42 gallons) of freshwater in Lea and Eddy County in 2010 (Longworth et al., 2013), with no return to freshwater aquifers or surface streams. Groundwater aquifers are major freshwater sources for oil and gas development in Lea and Eddy County, where deletions are noted since. Drinking water well depth in Lea County dropped from 120 ft. to 180 ft. in 2015 (Cox, 2016).

Hydraulic fracturing flowback and produced water, the largest volume by-product generated during unconventional oil and gas production, contains hydraulic fracturing chemical additives, minerals, organic matters, and many other naturally occurring constituents. The total production of oil and gas produced water in southeastern New Mexico increased by 21% during 2008 - 2015, from 663.3 to 840.7 million barrels per year (NMOCD, 2016). This large amount of water can be either a waste or a resource depending on how it is managed. The New Mexico Oil Conservation Division (OCD) encourages the recycling and reuse of produced water as a drilling or completion fluid or other type of oil field fluid, including makeup water, fracturing fluid or drilling mud, at a permitted drilling, production or plugging operation (NMOCD, 2013). No OCD permit or authorization is required for the onsite re-use of produced water. However, the re-use of produced water is NOT permitted for any use which involves contact with fresh water zones (NMOCD, 2013). Most of the produced water in Permian Basin is disposed through deep well injection (Clark et al., 2009). Produced water is transported to the disposal sites by trucking and pipeline. The disposal cost is approximately \$1/bbl.

Currently, the most feasible beneficial use option is to treat flowback and produced water for hydraulic fracturing. Considering the volume of produced water production, it is possible to offset the freshwater demand for oil and gas development in Permian Basin (15.8 million barrels) by reusing produced water only. To reuse flowback and produced water, treatment is required to meet water quality requirements. The nature of produced water determines its high amount of salinity and various contaminants, which needs multiple treatment processes to achieve target water quality requirements. Considering the high variability in the quality and quantity of produced water, an integrated decision support tool (DST) is in great need to assist the decision-making process for produced water beneficial reuse.

This project included a technology assessment of produced water treatment processes and further development of a DST that integrates multiple factors/criteria into the decision-making process, such as produced water quality and quantity, product water quality, removal capacity, energy consumption, and costs.

Technology Assessment

Produced water varies greatly in quality and quantity and in some cases the water can be a useful resource to recover salable products. Produced water has a complex composition. Its constituents can be broadly classified into organic and inorganic substances, such as suspended particles, sand, colloidal particles, dissolved and dispersed oils, grease, salts, heavy metals, radionuclides, production chemicals, and dissolved gases. Depending on the beneficial use water quality requirements, treatment processes may include removal of dispersed oil and grease (e.g., de-oiling), suspended particles and sand (e.g., settling and hydrocyclone), soluble organics (e.g., adsorption), desalination (e.g., membrane processes and thermal distillation), dissolved gases (e.g., air stripping), excess water hardness (e.g., softening and ion exchange), and microorganisms (e.g., disinfection).

To achieve produced water treatment goals, operators have applied various standalone and combined physical, chemical and biological processes (RPSEA, 2009; Dahm and Guerra, 2014). Some of these technologies that are relevant to the Permian Basin produced water treatment are reviewed in this section. To better understand the salinity levels and more accurately determine desalination technologies, TDS concentrations of produced water are classified into five TDS bins, defined as Bin 1: TDS < 8,000 mg/L; Bin 2: 8,000 – 25,000 mg/L;

Bin 3: 25,000 – 40,000 mg/L; Bin 4: 40,000 – 70,000 mg/L; and Bin 5: TDS > 70,000 mg/L. The TDS bins are determined based on the salinity concentration range in produced water that a treatment process can typically handle.

The technologies are categorized as preliminary, pre-treatment and desalination. Preliminary treatment refers to the process of removing suspended solids and de-oiling. Pre-treatment refers to the treatment units before desalination process that are necessary to remove substances that are detrimental to the desalination process. Some pretreatment processes can be main treatment units depending on produced water quality and when desalination is not required.

Preliminary Treatment Processes

American Petroleum Institute (API) Oil/Water Separator

API oil-water separators are used to separate suspended solids and oil from produced water by gravity based on the density and size of oil droplets or particles. Suspended solids settle to the bottom of the separator as sludge, oil and grease rise to the top of the separator. Typically, the oil layer is skimmed off and subsequently re-processed or disposed of. The bottom sediment layer is removed by a chain and flight scraper (or similar device) and a pump.

The device is able to remove oil droplets with diameter down to 150 μm , at 33% to 68% total suspended solids (TSS) and 16% to 45% chemical oxygen demand (COD) removal. Performance of API separator depends on retention time, tank design, oil particles, operating conditions and coagulation/flocculation effects. Most API oil/water separators are not able to reduce oil concentrations below 50 mg/L therefore the effluent may need further treatment by air floatation or other processes. The solids waste generated needs proper disposal.

API oil/water separators were widely used in petroleum industry as a pre-treatment technology because of easy operation. But recently the industry has abandoned the use of API separators because most separators are built of concrete and with the high cost of labor and the need to reinforce these tanks with steel, new construction costs rise quickly. Plus API units have an excessively large footprint and it is costly to clean out the large tank (Refining Department, 1990; ALL Consulting, 2005; Mercer, 2016). The costs of oil-water separators are highly variable in the range of \$13,000 – \$120,000 (\$0.08 – 0.4 per kgal/min water treated) depending upon the water flow rate (corresponding to 0.034 kgal/min to 1.52 kgal/min), configuration,

mechanical components, and vendors (Xerxes, 2011). The energy consumption is low because it requires only pumps to pump water or sludge and a chain and flight scraper.

Hydrocyclone

Hydrocyclone separators are devices used to separate suspended solids from liquid based on the densities of materials to be separated and have been used extensively to treat produced water (Burnett and Barrufet, 2005). A hydrocyclone normally has a cylindrical section on top for feeding liquid, and a conical base at bottom with an angle to determine separation characteristics. They can remove particulates and oil from produced water through centrifugal force generated through spinning motion.

Depending on the model of hydrocyclone employed, they can remove particles in the range of 5 to 15 μm , however, will not remove soluble oil and grease components (Dyakowski et al., 1999). The waste generated from a hydrocyclone is slurry of concentrated solids that requires disposal.

Infrastructure is low for the hydrocyclone whereas it is the only piece of equipment necessary. The device operates within a small footprints and does not require chemicals. The energy requirement is low because it requires a forwarding pump to deliver water to the hydrocyclone. Depending on the size and configuration of the hydrocyclone, a large pressure drop can occur across the hydrocyclone. Operating cost for the hydrocyclone is low and the capital costs vary in the range of \$60,000 - \$90,000 (\$0.03 – 0.19 per kgal/min water treated) depending upon the water flow rate (corresponding to 0.5 kgal/min to 2.2 kgal/min), design particle sizes to be separated, and vendors.

Settling and Storage Tank

During settling, particulates with sizes greater than 0.1 mm can be removed by gravity force. Determined by feed water quality and target water quality, settling tanks are most often used in combination with other treatment processes. There are no chemical requirements but chemicals can be used to enhance sedimentation through coagulation. The degree of particle removal and size of particles removed depends on the water detention time in the tanks, and solid disposal is required. Waste from the settling tanks need to be removed and disposed to landfill.

Settling tanks require a large footprint. Operating cost is minimal and construction costs are highly variable in the range of several thousands to tens of thousands dollars depending on the storage volume. Tanks are normally operational for 20 years.

Pre-treatment and Main Treatment Processes

Dissolved Gas/Air Flotation

Dissolved air flotation has been widely used for treatment of produced water. Flotation is a process in which fine gas bubbles are used to float small, suspended particles to the surface. These particles are difficult to separate by settling or sedimentation. Gas is injected into water to attract particulates and oil particles suspended in the water, then float to the surface and form a foam layer that is removed by skimming. The dissolved gas can be air, nitrogen, or another type of inert gas. Dissolved gas/air flotation can also be used to remove volatile organics, oil and grease.

The efficiency of the flotation process depends on the density differences of liquid and contaminants to be removed, and also on the oil particle size and temperature. Minimizing gas bubble size and achieving an even gas bubble distribution are critical to removal efficiency. Flotation works well in cold temperatures to increase gas dissolvability and can be used for waters with a broad range of organic concentrations. It is also excellent for removal of natural organic matter (NOM). Dissolved air flotation can remove particles as small as 25 μm without flocculants, and 3-5 μm with flocculants. In one reported study, flotation achieved an oil removal of 93% (ALL Consulting, 2003). The effluent water quality from air flotation is higher than other physical pre-treatment such as settling, hydrocyclone, and API separator. The skimmed foam needs to be disposed or reprocessed.

The cost of setting up a dissolved gas/air flotation treatment ranges from \$75,000 to \$100,000 (\$0.034 – 0.19 per kgal/min water treated) depending on the vendors, flow rate (corresponding to 0.5 kgal/min to 2.2 kgal/min), construction and configurations. The operating costs include mainly energy for pumping, mixing, air compressor, and coagulants. The coagulants costs vary from \$300-2500 /ton depending on the chemicals.

Air Stripping

Air stripping is used to remove dissolved gas (e.g., hydrogen sulfide, ammonia, and carbon dioxide) and volatile organic compounds (VOCs) (e.g., BTEX [Benzene, Toluene, Ethylbenzene & Xylenes]) in produced water. Air stripping involves the interphase mass transfer by forcing air through produced water to remove dissolved gases and evaporate volatile contaminants from water to air. The common types of air stripper include:

- (a) Aeration tank with sparger nozzles or mixers providing air bubbles in produced water;
- (b) Packed column providing contacts between air and produced water in countercurrent flow;
- (c) Tray column where air bubbles rise through flowing produced water in each tray.

The typical packed tower air stripper includes a spray nozzle at the top of the tower to distribute water over the packing materials in the column, a fan to force air countercurrent to the water flow, and a sump at the bottom of the tower to collect treated water. Packed tower air strippers are installed either as permanent installations on concrete pads or on a skid or a trailer.

Aeration tanks strip volatile compounds by bubbling air into a tank through which contaminated water flows. A forced air blower and a distribution manifold are designed to ensure air-water contact without the need for any packing materials. The baffles and multiple units ensure adequate residence time for stripping to occur. Aeration tanks are typically installed as continuously operated skid-mounted units. The advantages of aeration tanks are considerably lower profiles (less than 2 meters or 6 feet high) than packed towers (5 to 12 meters or 15 to 40 feet high) where height may be a problem, and the ability to modify performance or adapt to changing feed composition by adding or removing trays or chambers. The discharge air from aeration tanks can be treated using the same technology as for packed tower air discharge treatment.

Air stripping is effective to separate VOCs from water but ineffective for inorganic contaminants. Henry's law constant is used to determine whether air stripping will be effective. Generally, organic compounds with constants greater than 0.01 atmospheres · m³/mol are considered amenable to stripping, such as BTEX, chloroethane, perchloroethylene (PCE), trichloroethylene (TCE), dichloroethylene (DCE) (FRTR, 2016). Removal efficiencies can be improved by adding a second air stripper in series with the first, heating the water, or changing

the configuration of packing material. The performance of aeration tanks can be improved by adding chambers or trays, or by increasing the air supply, depending on the design of the tank.

Air stripping requires pretreatment to remove particulate matter, iron and hardness, to avoid clogging of packing materials or spray nozzles. The presence of inorganics in produced water (e.g., iron greater than 5 ppm, hardness greater than 800 ppm) or microorganisms may cause scaling and biological fouling of the equipment, thus requiring pre-treatment or periodic column cleaning (FRTR, 2016). Air emission control and treatment systems of off-gas may include activated carbon units, catalytic oxidizers, or thermal oxidizers. Besides waste gas, there is no solid waste for disposal.

A major operating cost of air strippers is the electricity required for water pump and the air blower. The unit costs range from \$0.4 to \$3/kgal depending on influent flow rate, relative contaminant volatility, off-gas treatment (when necessary), and the types of strippers (tray or packed tower) (FRTR, 2016).

Chemical Coagulation and Softening

Coagulation involves the addition of a chemical coagulant or coagulants for the purpose of conditioning the suspended, colloidal, and dissolved matter for subsequent processing by flocculation and sedimentation/filtration, or to create conditions that will allow for the subsequent removal of particulate and dissolved matter in produced water. Coagulants such as alum, ferric chloride, and ferric sulfate hydrolyze rapidly when mixed with the water to be treated. As these chemicals hydrolyze, they form insoluble precipitates that will sweep particles from solution or adsorb dissolved constituents. Natural or synthetic organic polyelectrolytes (polymers with multiple charge-conferring functional groups) can also be used for particle destabilization, or enhanced coagulation during de-emulsion of oil and grease in produced water. To remove sparingly soluble salts such as calcium, magnesium, barium, and heavy metals, softening process with lime and soda ash is usually used.

Coagulation and chemical softening have been widely used for produced water treatment. A modified hot lime process treated produced water containing 2000 mg/L hardness, 500 mg/L sulfides, 10,000 mg/L TDS, and 200 mg/L oil to steam generator quality feed water. In this process, alkali consumption and sludge production was reduced by 50% in comparison with conventional hot lime (Garbutt, 1997; Garbutt, 1999). An inorganic polymeric flocculent (mixed

metal polynuclear polymer with Fe, Mg, and Al) was reported to effectively reduce suspended solids and oil by 92% and 97%, respectively (Zhou et al, 2000). Lime softening was also able to remove heavy metals in produced water by over 95% (Houcine, 2002). In a study on treatment of oil and gas fields produced water, an oxidant, ferric ions, and flocculants were used to remove hydrocarbons, arsenic, and mercury. In this process, the oxidation–reduction potential of the wastewater was controlled by oxidant addition to allow the required arsenic oxidation to occur while maintaining the mercury in elemental form. Results showed that effluent streams had < 10 µg/L of mercury, < 100 µg/L of arsenic, and < 40 mg/L of total petroleum hydrocarbons (Frankiewicz et al., 2000).

Coagulation and chemical softening process is easy to operate and maintain. Disadvantages of the process are generation of sludge for disposal, high chemical demand, and increased concentration of metals in effluents that increase the demand of coagulants. The installation consists of reaction tanks with mixers, a polymer-creation system, lamella separator or sedimentation basin, sludge storage tank and possibly a filter compressor. Further, there will also be costs for piping, electricity and automation. The system installation may range from \$0.050 to \$0.3 per kgal/min water treated. The coagulants costs vary from \$300-2500/ton depending on the chemicals.

Electrocoagulation (EC)

Electrocoagulation (EC) is a process that utilizes sacrificial anodes to generate active coagulants that are used to remove contaminants by precipitation and flotation (Eames, 2013). The EC process involves three successive stages: (i) formation of coagulants by electrolytic oxidation of the sacrificial anode; (ii) destabilization of the contaminants, particulate suspension, and breaking of emulsions; (iii) aggregation of the destabilized phases to form flocs (Chaturvedi, 2013). Current passing through the solution compresses the diffuse double-layer around charged ions. Counter ions generated by sacrificial anodes neutralize the ionic species in wastewater, resulting in reduction of electrostatic inter-particle repulsion, so that van de Waals attraction predominates and coagulation occurs. Flocs form as a result of coagulation, and entrap and bridge colloidal particles in the solution (Chaturvedi, 2013; Mollah et al., 2001).

EC has been successfully adopted to remove hardness, COD, heavy metals, oil, dyes, and other organic substances. During the treatment of produced water with TDS concentration

ranging from 13,200 mg/L to over 30,000 mg/L, EC achieved removal of turbidity over 95%, TOC 35-64%, boron 43-74%, calcium 5-90% (Esmailirad et al., 2015). The removal efficiency was dependent on the chemical doses for softening, the position of softening (before or after EC), and high organic matter concentration in produced water samples. Other factors that would affect experimental results include residence time, pH, and electrode materials (Gomes et al., 2009).

EC process that designed and operated by CleanWave™ was reported to be very efficient regarding energy consumption and flow rate. The process could handle TDS concentration from 100 to 300,000 mg/L at 20 barrels per minute flow rate. The process was automated, and allowed on-site treatment for on-site recycling of flowback and produced water to be used as fracturing fluids and drilling muds. The process also eliminated biological contaminants such as bacteria (Halliburton, 2010). Energy consumption of EC process decreases as solution conductivity increases, as illustrated in Figure 5.1.

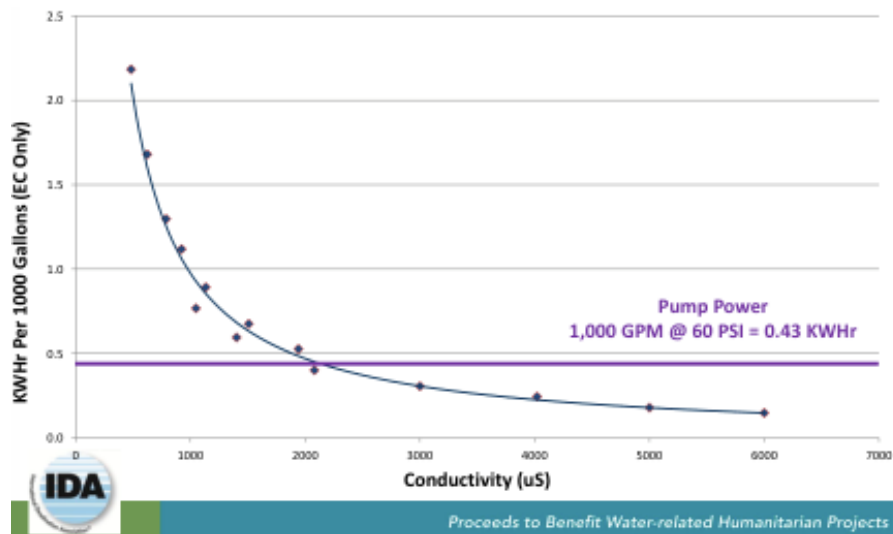


Figure 5.1 Energy consumption for EC under different solution conductivities (Eames, 2013).

The costs of electrocoagulation are higher than chemical coagulation and highly variable in the range of \$4,000 – \$25,000 (\$2.7 – 21.8 per kgal/min water treated) depending upon the water flow rate (corresponding to 0.002 kgal/min to 0.009 kgal/min). Electrocoagulation also generates large amount of sludge that needs to be dewatering and disposed.

Media filtration

Filtration is a widely used technology for produced water treatment. Many vendors provide media filtration technologies that are specialized for produced water treatment, using a variety of types of media, including walnut shell, sand, anthracite, and others (Dahm and Guerra, 2011).

Filtration applies to all TDS ranges, independent of salt type and concentration. Filtration can be used to remove oil and grease particles at over 90% removal efficiency, and TOC from produced water. Minimum size of particle removed by traditional media filter range from 0 to 10 microns (ECO-TEC, 2015), while an improved filter provided by Spectrum Plus Filter™ has the size cutoff at 2 microns. Removal efficiencies can be improved by employing coagulation upstream from the filter. Nearly 100% water recovery can be achieved.

The operation and maintenance of media filter is simple. The construction costs vary from \$650 – \$1200 (\$0.005 – 0.0005 per kgal/min water treated) depending upon the water flow rate (corresponding to 0.13 kgal/min to 2.2 kgal/min). Minimal energy is required for operation. Pumping is required for backwashes. Solid waste disposal may be required for backwashes. Media may need to be replaced due to loss during backwash.

Organic Removal and Biological Treatment

Produced water may contain high concentrations of petroleum hydrocarbons. Organics can be removed by adsorption on to activated carbon, zeolites and walnut shells. Air stripping is highly effective for removal of volatile organic contaminants such as benzene, toluene, ethylbenzene, and xylenes (BTEX). Membrane processes such as microfiltration and ultrafiltration are designed to remove large organic compounds while nanofiltration and reverse osmosis (RO) are effective for removal of organic contaminants with sizes larger than the membrane molecular weight cut-off (MWCO). The disadvantage of membrane processes is membrane fouling and extensive pretreatment is usually performed prior to treating produced water.

Activated sludge is an aerobic biological treatment process for wastewater treatment that is designed to remove nitrogen, phosphorus and dissolved organic compounds. Large reactor volumes combined with aeration allow active sludge to treat wastewater at relatively low hydraulic retention times (~8 hours) while producing high quality effluents. Conventional

activated sludge (AS) process was pilot-tested to treat produced water of Permian Basin, New Mexico. The pilot-scale activated sludge treatment system consisted of a 453 L pretreatment skimming and pre-aeration skimmer tank, 945 L activated sludge basin and a 1069 L post-treatment settling/clarifying tank (Tellez et al., 2002). Produced water was obtained from an oil-water separator facility, and contained 35,235 mg/L TDS, 431 mg/L COD (chemical oxygen demand), 126 mg/L TPH (total petroleum hydrocarbons), and 147 mg/L O&G (oil and grease). The skimmer and AS process alone reduced COD by 90% and TAN (total n-alkanes), BTEX (benzene, toluene, ethyl-benzene, and o-, m-, p-xylene), O&G & TPH were reduced by more than 98%. With further treatment by settling and clarification, 97% COD removal was achieved. Energy cost was estimated to be \$0.17 per barrel (\$0.004 per gallon) at energy cost of \$0.08 kW-h.

Another study investigated the feasibility of activated sludge coupled with chemical pretreatment processes to remove a polymer, hydrolyzed polyacrylamide (HPAM), from oilfield produced water in China. The produced water contained a lower concentration of TDS (4830 mg/L) and TPH (62 g/L) but higher concentrations of organics, measured by COD (1130 mg/L) and HPAM (237 mg/L) (Lu and Wei, 2011). Although adding polymers to injecting fluids increases oil recovery (Taylor et al., 1998; Han et al., 1999), polymer flooding produced water is more difficult to treat than water flooding produced water (Deng et al, 2002). Chemical oxidation pretreatment generated hydroxyl radicals, in-situ, partially oxidizing the polymer and increasing its biodegradability. The combined system removed 96% of COD, 97% of TPH, and 92% of HPAM at an HRT of 40 hours with EDTA (ethylenediaminetetraacetic salt) and iron concentrations of 150 mg/L and 20 mg/L, respectively (Lu and Wei, 2011).

Despite the varying outcomes of the AS process alone, both studies demonstrated the merit of applying AS to treat produced water with high petroleum hydrocarbons. AS process can treat produced water at salinities comparable to seawater. Biological treatment combined with chemical pretreatment can treat produced water containing difficult to biodegrade polymers (HPRAM) and achieved over 97% COD and TPH removal. Disadvantages of biological processes include the high operating costs (mainly of aeration and cost of maintenance), sensitivity to varying feed water quality, sludge disposal and large footprint (Tellez et al., 2002). Due to the complex nature of and difficulty in treating produced water, biological processes may

have to be coupled with physical, chemical and electrical pre- and/or post- treatments to achieve high removal efficiencies. Another limitation of biological treatment is the high TDS level in produced water that may inhibit the microbe's growth.

Desalination Processes

Reverse Osmosis (RO) and Nanofiltration (NF)

Reverse osmosis (RO) and nanofiltration (NF) are pressure driven membrane processes that utilize hydraulic pressure to diffuse permeate (pure water) through a dense, non-porous membrane and retain solutes on the feed water side of the membrane. Feed water with higher concentration of TDS has greater osmotic pressure, therefore requires higher hydraulic pressure to produce permeate.

In general, RO is capable of treating water with TDS concentration up to 40,000 mg/L due to the limitation of pressure vessels. High TDS concentration will result in low water recovery efficiency (40% - 65%) due to scaling and fouling potential. New RO technologies and membranes allow treatment of TDS concentration up to 45,000 mg/L at a rate of 6,300 bbl/day (ALL Consulting, 2010). However, to achieve higher water recovery, TDS concentration is recommended to be below approximately 25,000 mg/L.

RO treatment is effective in removing almost all inorganic and organic contaminants in water. To minimize membrane fouling and scaling, RO requires extensive pretreatment to remove sand, silt, clay, algae, microbes, colloidal particles and large molecular organics (e.g., petroleum hydrocarbons), and sparingly soluble salts. Based on the feedwater TDS, RO can be classified as seawater RO and brackish water RO.

Seawater RO (SWRO) is designed to treat feed stream with TDS concentration up to 47,000 mg/L, approximately seawater level, utilizing dense, highly selective thin-film composite (TFC) membranes that are capable of rejecting contaminants as small as 0.0001 micron. SWRO has high rejection rate to monovalent and multivalent ions, organic molecules, and metal ions. High rejection (over 99%) of NaCl is designed for SWRO. For other small uncharged inorganic compounds, such as boron, pH adjustment is needed to achieve high rejection. Rejection of organic compounds ranges from 20% to 99.7%, depending on their chemical structure and feed solution physicochemical parameters (Xu et al., 2005). Removal efficiency of radioactive matters

is high (99%) because of their large molecular weight. SWRO water recovery is restricted to 30% - 60%, because of high osmotic pressure of feed water caused by high concentration of salts (RPSEA, 2009).

Brackish water RO (BWRO) is designed to treat feed stream with TDS concentration 500 – 25,000 mg/L to achieve a higher water recovery (85%) than SWRO. BWRO has high rejection to metals and divalent ions, and similar rejection to organic compounds as SWRO. Rejection of NaCl is over 94%. BWRO has relatively lower costs than SWRO because of the lower hydraulic pressure requirement to overcome osmotic pressure. BWRO systems have similar parameters with SWRO in reliability, flexibility, mobility, modularity, and footprint (RPSEA, 2009).

RO has been applied to Marcellus Shale, Barnett Shale, Fayetteville, and Woodford in pilot or full scale to treat shale gas produced water. A pilot-scale testing of RO treatment conducted by Ecosphere technology in Newfield, Woodford Shale showed efficient removal of key constituents. TDS concentration was reduced from 13,833 mg/L to 128 mg/L (99.1% removal), chloride from 8,393 mg/L to 27 mg/L (99.7% removal), TSS from 64.5 mg/L to 0.0 mg/L (100% removal), and barium from 34.9% to 0.0 mg/L (~100% removal). Water recovery was estimated to be 50% - 70%, at 14,400 bbl/day flow rate (ALL Consulting, 2010).

Pre-treatment is required before RO process, including media filters to remove TSS, softening process to remove hardness, adjusting pH, adding scale inhibitor to prevent scaling, and using active carbon to remove organics, or bisulfite to remove chlorine residuals. For produced water treatment, petroleum organic matters need to be removed before RO, which include free and dissolved oils that will result in reduced membrane permeability. Removal of volatile acids and BTEX is also required because they can reduce membrane separation performance by promoting biological fouling. These fouling problems are the primary reasons for the lack of deployment success of RO in oil and gas industry (Hayes and Arthur, 2004).

RO treatment is generally less expensive than thermal desalination processes because of its lower energy requirement. Depending on feed water quality, RO treatment capital cost ranges from approximately \$0.0006 - \$0.005 per kgal/min water for large scale municipal desalination plants, to \$0.2-1.2 per kgal/min water for small scale wellhead treatment (2 gpm to 88 gpm). A full scale RO treatment process developed by Global Petroleum Research Institute (GPRI) was constructed and operated in Barnett Shale by Marathon Oil Company. With 714,000-gallon

product water flow rate, the cost was reported less than \$2.50 per 1,000 gallons (ALL Consulting, 2010). Product water was used as feed water for steam injection as an enhanced oil recovery (EOR) method, which was projected to boost oil production in the Yates Field by more than 100,000 barrels (Burnett, 2007).

NF membranes are designed to achieve high rejection of divalent ions, metals (>99% of $MgSO_4$), and radionuclides. NF is best suited for softening applications and removal of most metals; this indicates that the product stream from conventional NF systems will tend to have higher sodium adsorption ratio than the feed stream. Organic compounds are removed to varying extents with NF membranes (Bellona and Drewes, 2005). The nominal TDS range for NF applications is between 1,000 and 35,000 mg/L (by using two stage NF process developed at Long Beach Water Department LBWD, 2006). Water recovery ranges from 75-90%, but may require application of scale inhibitors or extensive pretreatment depending on feed water quality.

The costs of NF membranes are similar to RO but energy required for NF membranes to perform separation is less than that required for SWRO and BWRO; while maintenance, robustness, reliability, flexibility, mobility, modularity, and operational footprint of NF membrane systems are equivalent to those of RO processes.

Electrodialysis (ED) / Electrodialysis Reversal (EDR)

Electrodialysis (ED) and electrodialysis reversal (EDR) are desalination technologies driven by electrochemical charge force. An electrical potential gradient is generated by the cathode and anode that provides the force to move cation and anion towards the two ends. An ED stack consists of a series of ion exchange membranes made from ion exchange polymers, which provide the ability to selectively transport positively charged cations (cation-exchange membrane, CEM) and negatively charged anions (anion-exchange membrane, AEM). CEM and AEM are arranged alternatively between cathode and anode, so that cations move toward the cathode, passing CEM and rejected by AEM, while anions move toward anode, passing AEM and rejected by CEM. As a result, ion concentration increases and decreases alternatively in the compartments, forming concentrate flows and dilute flows. Uncharged particles cannot be removed through ED or EDR, as they are not affected by the charge gradient, neither passing through any membranes. EDR process is similar to ED process, but using periodic reversal of

polarity, in order to prevent membrane scaling and fouling by removing ions that attached to membranes at the time of polarity change (RPSEA, 2009).

ED and EDR are capable of removing most charged dissolved ions, but not uncharged particles. ED/EDR is an Environmental Protection Agency Best Available Technology (EPA BAT) for removal of barium, nitrate, nitrite, selenium, and TDS. Pre-treatment is required for ED/EDR, including removal of suspended solids, pH adjustment and addition of scale inhibitor to reduce Langelier saturation index (LSI) below 2.1 to prevent scaling. ED membranes are more tolerant to chlorine residual than RO membranes so chlorine residual concentration can remain at 0.5 -1 mg/L to prevent biological growth. Benefits of ED/EDR include minimal chemical addition, low pressure requirement, long membrane lifetime under proper maintenance (12 – 15 years), wide pH tolerance (2 – 11), and easy maintenance. Water recovery in ED/EDR ranges from 70% to 90%, depending on feed water quality, but lower for highly saline produced water. Standard ED has the ability to treat feed water TDS concentration from 4,000 mg/L to 15,000 mg/L, while emerging ED technologies are reported to be able to treat approximately 35,000 mg/L TDS at flow rate of 10,000 bbl/day, with 75% water recovery. TOC is limited to 15 mg/L to prevent organic fouling, turbidity up to 2 NTU, iron II up to 0.3 mg/L and magnesium up to 0.1 mg/L to prevent scaling on CEM, and hydrogen sulfate (H₂S) up to 1 mg/L (USBR, 2010). Waste disposal includes concentrate stream, electrode and membrane cleaning flows, and spent membranes.

Generally, ED/EDR is comparable or slightly more expensive than RO. However, with higher resistance to scaling and fouling, reduced membrane cleaning and replacement can reduce the ED operation and maintenance costs for treating produced water. For coalbed methane lower TDS produced water, treatment cost was estimated to be under \$0.15/bbl (\$0.0063/kgal) at 0.34 MGD (ALL Consulting, 2010). ED/EDR is under consideration to treat shale gas produced water, but has not been utilized by the industry.

Thermal Separation Processes

Thermal separation processes use energy to heat feed water that evaporates and then condenses to become purified water. Thermal separation technologies that are used for desalination include multi stage flash (MSF) distillation, multiple effect distillation (MED), and vapor compression distillation (VCD) (USBR, 2003).

In MSF, the feed water is heated, the pressure is lowered, and the water "flashes" into steam. This process constitutes one stage of a number of stages in series, each operating a lower temperature and pressure (CCC, 1993). In MED, the feed water passes through a number of evaporators in series. Vapor from one series is subsequently used to evaporate water in the next series. The VCD process involves evaporation of feed water, compression of the vapor, and then recovering the heat of condensation to evaporate more feed water. Some distillation plants are hybrids of more than one desalination technology, such as MED-VCD (Hamed, 2004). The waste product from these processes is a solution with high salt concentration. By using hybrid thermal technologies, zero liquid discharge can be achieved through brine concentrator and crystallizer.

Mechanical vapor compression (MVC) is a commercial technology for seawater and brackish water desalination, and has been applied for produced water treatment with enhancements. MVC is able to treat feed water with TDS over 40 g/L, and produces high quality product water. All most all of the organic and inorganic contaminants can be separated from the product water, except the volatile compounds. Water recovery is approximately 40%, with relative lower energy demand. Electricity consumption for MVC is approximately 30 kWh/kgal of produced water. If zero-liquid discharge (ZLD) is required, energy demand for evaporation and crystallization is 100 to 250 kWh/kgal (Khawaji et al., 2008).

Thermal evaporation processes require pre-treatment to remove suspended solids and organic matter. Scale inhibitor and acid are required to control scaling and corrosion. Regular cleaning is required to remove scaling. Monitoring is required during the process. Product water needs remineralization because of the low TDS level. This may be achieved by lime bed contacting or by blending small amounts of filtered and sterilized feedwater with the distillate. Post-treatment may also include carbon adsorption or oxidation if volatile organic substances are present in product water. Concentrate disposal is required. The system also includes interconnecting pipes and electrical connections, and a natural gas generator. According to Devon Energy, the cost to treat frac-water is \$79.6/kgal (\$3.35/bbl) using Aqua-Pure - Mechanical Vapor Recompression (MVR) Evaporation system (Tronche, 2008).

Forward Osmosis

Forward osmosis (FO) is an emerging osmotic pressure driven membrane process. Water diffuses from a feed stream with low osmotic pressure through a semi-permeable membrane to a draw solution with high osmotic pressure. No external high pressure is required by FO system. Traditional FO membranes are dense, nonporous barriers, composed of hydrophilic cellulose acetate active layers (Hickenbottom et al, 2013). Development of FO membranes focuses on increasing water flux, reducing reversal salt transport, minimizing concentration polarization, and decreasing membrane fouling (Xu et al., 2013).

FO draw solution is required to generate high osmotic pressure gradient, and to be easily separated and re-concentrated with low energy consumption. Typical FO draw solution is NaCl solution, but other solutions composed of NH_4HCO_3 , sucrose, and MgCl_2 have been studied (Cath et al., 2006). As permeate dilutes the draw solution, osmotic pressure gradient that provides the driving force decreases. An additional draw solution re-concentration process is required to separate pure water from the draw solution. RO is widely adopted as the separation and re-concentration technology that separates pure water from the draw solution that composed of dissolved salts. The technical pressure limitation of RO, however, cannot meet the conditions to re-concentrate FO draw solution because extremely high osmotic pressure is needed to draw pure water from highly saline produced water, which limits the application of FO/RO in desalting produced water with TDS higher than seawater (approx. 40,000 mg/L)

To treat highly saline produced water, thermolytic salts solution that re-concentrates through phase change by changing temperature, could be a suitable FO draw solution candidate (Shaffer et al., 2013). Low-grade heat, such as geothermal sources, makes it possible to significantly reduce the costs to re-concentrate FO draw solution. Currently, ammonia-carbon dioxide is the most mature thermolytic draw solution that can treat highly saline produced water by generating osmotic pressure higher than 200 atm, and decompose into gas phase ammonia and carbon dioxide at approximately 60°C at atmospheric pressure (McCutcheon et al., 2005). A study showed significant water flux using ammonia-carbon dioxide draw solution FO to treat highly saline feed solution with TDS concentration of 140,000 mg/L (McCutcheon et al., 2006).

A pilot-scale study of treating shale gas produced water using an ammonia-carbon dioxide draw solution FO system was conducted to treat Marcellus Shale produced water with

average TDS 73,000 mg/L. Product water average TDS concentration was approximately 300 mg/L, showing a 99.6% rejection. FO also achieved significant high removal efficiency of most inorganic salts, metal ions, and organic compounds. Concentrated feed stream TDS concentration was 180,000 mg/L. Water flux of FO was relatively low at 3 L/m²-h (McGinnis et al., 2013). Improvements on membrane design and module hydrodynamics are expected to increase the flux (Shaffer et al., 2013). Energy demand for FO system ranges from 25 to 150 kWh/m³, depending on the scale of FO system and the efficiency of draw solution re-concentration (Thiel et al., 2015). Future improvement would be focused on draw solution regeneration, as it is the most energy-demanding portion in FO system. New FO membranes could be another way to enhance the efficiency of FO system. Hydrophilic membrane surface could minimize oil and gas foulant deposition and increase membrane permeability.

Membrane Distillation

Membrane distillation (MD) is an emerging technology that utilizes low-grade heat to provide driving force to achieve membrane separation. Feed stream is separated from permeate by a hydrophobic, microporous membrane that prevents liquid from passing. Driving force is provided by the partial vapor pressure difference due to the temperature gradient between the feed and permeate streams. High temperature feed stream provides higher partial vapor pressure that drives water vapor to pass through the membrane. Lower temperature permeate allows water vapor to condense, thus reducing the vapor pressure on the permeate side and allowing the process to continue. Membrane materials commonly employed by MD include polytetrafluoroethylene (PTFE), polypropylene (PP), and polyvinylidenedifluoride (PVDF) (RPSEA, 2009), in either flat-sheet or hollow-fiber configuration.

Basically there are four configurations to operate MD: direct contact MD (DCMD), vacuum (VMD), air gap (AGMD), and sweeping gas (SGMD) (Khayet, 2011). During DCMA, warm feed stream and cool permeate stream flow on both sides of the membrane. Water vapor passes through the membrane from feed water, condenses on the other side, and merge into the permeate stream. Instead of contacting permeate stream directly, AGMD utilizes an air gap next to the permeate side of membrane, next to a cooling plate. AGMD has the highest energy efficiency, but a relatively low vapor flux obtained. In VMD, the permeate side is vapor or air under reduced pressure. Volatile constituents can be removed from an aqueous solution. SGMD

utilizes stripping gas as permeate flow that carries away volatile constituents (Camacho et al., 2013).

MD has a high potential to be applied in produced water treatment because high TDS concentration has less impact on membrane performance as compared to RO. It is reported that product flux reduced 5% when feed stream TDS concentration increased from 35,000 mg/L to 75,000 mg/L (Shaffer et al., 2013). MD has almost 100% theoretical rejection to all non-volatile solutes. For highly volatile solutes, such as BTEX (acronym of benzene, toluene, ethylbenzene, and xylenes) and other organic compounds, rejection is significantly low as these compounds diffuse faster through the membrane than water vapor. Water recovery for MD is similar to BWRO, while higher recovery can be achieved through proper pre-treatment.

MD requires pre-treatment to completely remove surfactants to prevent wetting of membrane by feed stream and pore flooding. Filtration is required to remove large particles to prevent fouling. Dissolved gas and some small organic compounds that may transport through the membrane and contaminate permeate need to be removed. Elevated temperature is required for feed stream to provide vapor pressure gradient. Energy recovery may be applied from compressors and pumps to provide low-grade heat, in order to reduce costs. Maintenance of MD is easier compared with other pressure-driven membrane processes as fouling is not compacted on the membrane and can be easily removed.

MD has a high potential to become a low energy input desalination technology together with energy recovery equipment. Heat exchangers are also able to recover thermal energy from heated permeates. Without energy recovery devices, MD energy requirement is approximately 680 kWh/m³, while a recent study showed approximately 40 kWh/m³ with heat recovery (Shaffer et al., 2013).

A pilot scale spiral-wound AGMD system designed by AquaStill was utilized to treat brine (14 g/L) from a pilot ultrafiltration (UF)/RO system that desalinated coal seam gas (CSG) produced water in Australia (Duong et al., 2014). The AGMD system circulation flow rate was 450 L/h in order to minimize the risk of scaling, while 55°C was chosen as evaporator inlet temperature at a balance of low scaling potential and high distillate production rate. At the steady state, temperature difference of 4°C and a stable distillate production rate of 10 L/h were achieved. Removal efficiencies of TDS and major ions are over 93%, while that of turbidity is

50%. The specific thermal energy consumption (STEC) of the pilot MD system was 250 kWh/m³, while specific electric energy consumption (SEEC) was 1.1 kWh/m³, showing that thermal energy was the major power input into the MD system. Viable energy sources for MD system could be waste heat onsite, or solar thermal energy. Considering Australia as the study field, 1 ha of flat-plate solar thermal collector could provide sufficient thermal energy for MD system to treat CSG produced water at a flow rate of 3,000 bbl/day (Duong et al., 2014).

Research using DCMD to treat oilfield produced water with TDS concentration 247,900 mg/L, TOC 18.10 mg/L, total inorganic carbon (TIC) 22.62 mg/L showed MD as a cost-competitive technology for produced water treatment. Considering 5-year membrane lifetime, feed water temperature at 20°C and 50°C gave \$4.85/kgal (\$1.28/m³) and \$2.73/kgal (\$0.72/m³) as overall costs, respectively (Macedonio et al., 2014).

Guidance of Selecting Produced Water Treatment Technologies for Permian Basin

This technology assessment documented the existing and emerging processes for produced water treatment. The project aimed to provide a guidance framework on the constraints and opportunities of the produced water treatment technologies. Their uses for produced water treatment and beneficial use in Permian Basin were evaluated in case studies discussed in another related project report.

The technologies were evaluated based on (i) applicable produced water quality including salinity and constituents of concern for treatment processes (e.g., hydrocarbons, suspended solids, hardness); (ii) contaminants removal efficiency (iii) production efficiency in terms of product water recovery, which is directly related to waste (liquid or solids) generated on site that has to be disposed offsite; (iv) energy consumption and costs; (v) and other considerations such as O&M considerations, pretreatment and post treatment requirements. Table 1 summarizes the comparison of the treatment technologies. Generally most of the preliminary treatment technologies can treat water in all TDS bins. For desalination technologies, their treatment capacities vary significantly depending on their separation method as shown in Figure 5.2. . It should be noted that the technology assessment in this project was focused on produced water treatment for beneficial water uses. The technologies for recovery of oil, salts and other valuable minerals are under investigation but not included in the review.

Permian Basin produced water characterization showed an average TDS around 90,000 mg/L in Eddy and Lea counties, with half of the wells producing water with TDS over 70,000 mg/L. Based on beneficial use requirements, SWRO and ED are mature technologies commercially available to treat produced water with TDS lower than 40,000 mg/L. For high salinity water, SWRO and ED may still be applicable if the salt rejection requirement is low (such as 30-50% instead of 70-99%). Thermal technologies are applicable to salinity higher than 40,000 mg/L but treatment costs are very high. FO and MD are under development to treat high salinity water. To protect desalination processes from fouling and scaling, suspended solids, oil and grease, and hardness need to be removed. Oil-water-solids separators including API separators, hydrocyclones, settling, DAF, media filtration, and chemical precipitation are applicable to all TDS bins of the produced water. Electrocoagulation is typically applicable to TDS concentration lower than 30,000 mg/L. Biological treatment is effective to treat dissolved organic matter, but this current application is limited to TDS around 40,000 mg/L.

Produced water treatment costs vary greatly depending on the treatment capacity (flow rate), feed water quality, required removal efficiency, local construction costs, labor costs, materials, process configuration, vendors, and other site specific conditions. Due to the smaller scale of produced water treatment facilities, the treatment costs can be orders of magnitude higher than the treatment costs of large-scale treatment plants. The costs provided in this documents were collected through literature review and previous experiences, and are for information purpose only. The actual treatment costs should be determined through field testing and engineering design.

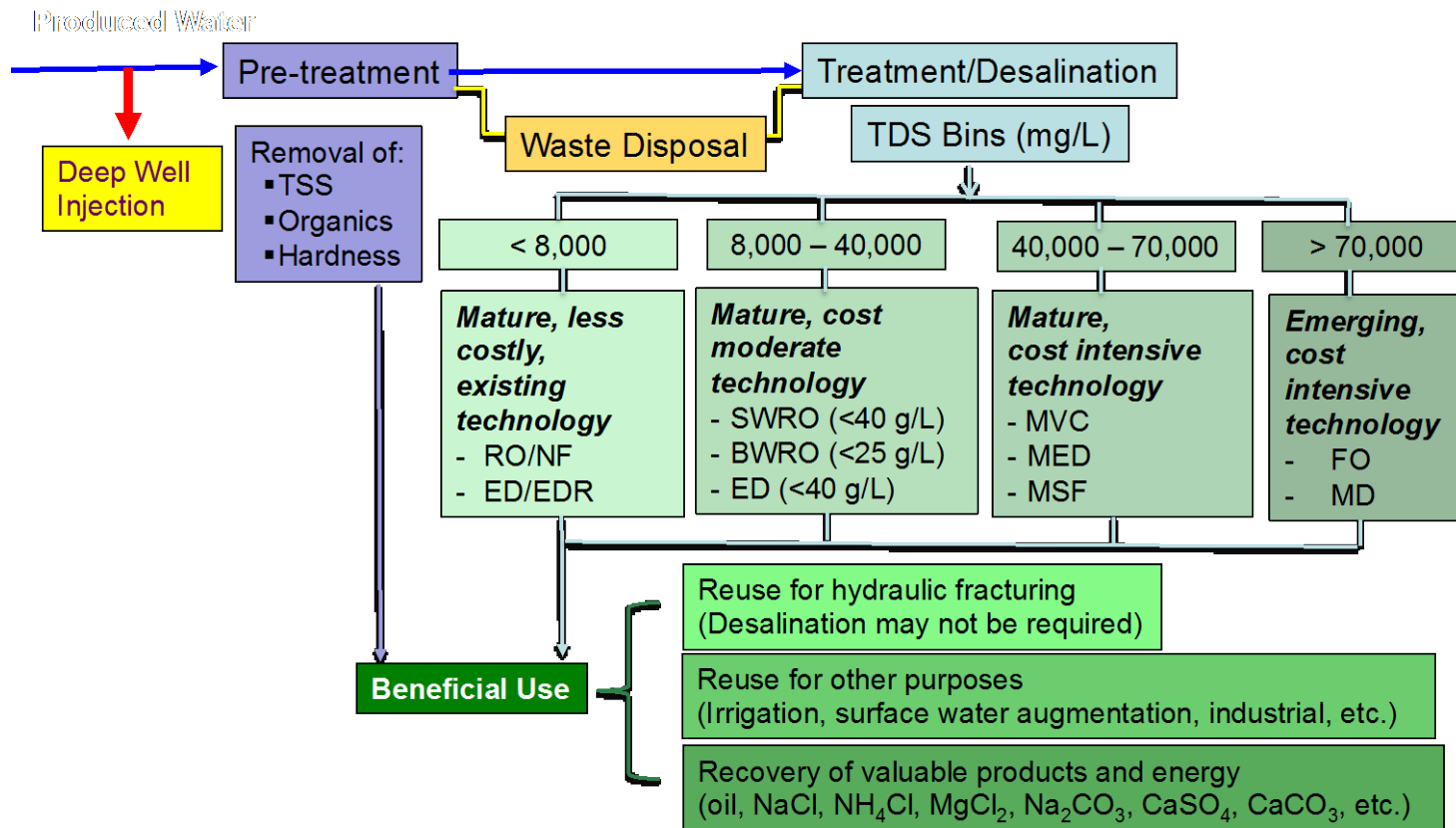


Figure 5.2 TDS bins and major desalination technologies.

Note: ED – Electrodialysis; EDR – Electrodialysis reversal; RO – Reverse osmosis; NF- Nanofiltration; SWRO – Seawater RO; BWRO – Brackish water RO; MVC – Mechanical vapor compression; MED – Mechanical effect distillation; MSF – Multi stage flash; FO – Forward osmosis; MD – Membrane distillation.

Table 5.1 Summary of technologies for produced water treatment.

Treatment Technology	Industrial status	Applicable TDS Range	Removal Efficiency	Water recovery/waste	Energy demand	Costs
Oil-water-sand Separator (API)	Mature and commercially available	All	Remove oil droplets with sizes > 150 µm, 33% to 68% total suspended solids (TSS) and 16% to 45% chemical oxygen demand (COD)	High water recovery. Solid wastes need to be disposed.	Low	Equipment costs \$0.08 – 0.4 per kgal/min water treated
Hydrocyclone	Mature and commercially available	All	Remove particles with sizes >5 to 15 µm	High water recovery. Solid wastes need to be disposed.	Low	Equipment costs \$0.03 – 0.19 per kgal/min water treated
Settling	Mature and commercially available	All	Removal of suspended solids with sizes >0.5 mm	High water recovery. Solid wastes need to be disposed.	Low	Depending on local construction and material costs
Dissolved air/gas flotation (DAF/DGF)	Mature and commercially available	All	Particles as small as 25 µm without flocculants, and 3-5 µm with flocculants. 93% oil removal	High water recovery. Solid wastes need to be dried and disposed.	Low to medium	Equipment costs \$0.034 – 0.19 per kgal/min water treated
Air stripping	Mature and commercially available	All	Up to 99% removal of volatile organic compounds	High water recovery. Off gas needs to be treated	Low to medium	Unit treatment costs \$0.4 - \$3/kgal

Media filtration	Mature and commercially available	All	90% removal of oil and grease particles from 0 to 10 μm .	High water recovery, backwater water waste needs to be dried and disposed	Low	Filter costs \$0.005 – 0.0005 per kgal/min water treated. Media costs vary.
Chemical Coagulation	Mature and commercially available	All	Oil and suspended solids removal at 97% and 92%	High water recovery. Solid wastes need to be dried and disposed.	Low	Equipment costs \$0.050 to \$0.3 per kgal/min. coagulants costs \$300-2500/ton depending on the chemicals.
Electrocoagulation	Emerging and commercially available	Typical TDS limit 30,000 mg/L	95% removal of turbidity, 35- 64% TOC, 43 - 74% boron, 5 - 90% calcium	High water recovery. Solid wastes need to be dried and disposed.	Energy consumption decreases with increase of conductivity of feed water (3.5-0.8 kwh/kgal)	Equipment costs \$2.7 – 21.8 per kgal/min water treated
Biological Treatment	Mature and commercially available	Typical TDS limit <40,000 mg/L	Over 90% COD removal, over 98% BTEX removal	High water recovery. Solid wastes need to be dried and disposed.	Low to medium	Depending on construction and material costs

Reverse osmosis (RO)	Mature and commercially available	Brackish Water RO <25,000 mg/L; Seawater RO <40,000 mg/L	Rejection of salts is high (over 99%) under lower TDS, and is lower (40% - 65%) under high TDS due to scaling and fouling potential. Rejection of organic compounds ranges from 20% to 99.7%. Rejection of radioactive matters is high (99%).	Water recovery varies depending on feed water quality from 40-85%. Brine needs to be disposed.	Energy increases with increasing feed TDS (2-16 kWk/kgal)	\$0.0006 - \$0.005 per kgal/min or large plants, to \$0.2-1.2 per kgal/min for small plants. Unit cost \$2.5/kgal for produced water
Nanofiltration (NF)	Mature and commercially available	Generally <8,000 mg/L	Rejection of salt and organics is lower than RO (40% - 90%). Rejection of multi-valent ions is high (~90%).	Water recovery varies depending on feed water quality from 40-90%. Brine needs to be disposed.	10% less energy demand than RO	Equipment costs similar to RO
Electrodialysis (Electrodialysis Reversal (ED/EDR))	Mature and commercially available	Generally EDR <8,000 mg/L ED <40,000 mg/L	Can achieve partial removal of salts. TDS rejection up to 90%, depending on energy input and feed water quality	Water recovery varies depending on feed water quality from 40-90%. Brine needs to be disposed.	Energy and cost increase with increasing Feed TDS	Comparable or slightly higher than RO

Thermal distillation	Mature and commercially available	Can be applied to all Bins. More efficient for TDS <40,000 mg/L. Higher TDS may cause sever scaling problem	~100% rejection to non-volatile solutes. Not applicable to volatile contaminants	Water recovery varies depending on feed water quality from 40-80%. Brine needs to be disposed.	30 kWh/kgal of product water. 100 - 250 kWh/kgal of product water for zero-liquid discharge	\$79.6/kgal (\$3.35/bbl) treating frac water
Forward osmosis (FO)	Emerging and commercially available	All Bins. More efficient for TDS <70,000 mg/L	Over 99% TDS removal.	Water recovery varies depending on feed water quality from 70-90%. Brine needs to be disposed.	94.5 to 567 kWh/kgal product water	Not available
Membrane Distillation (MD)	Emerging	All bins. Product flux reduces with 35,000 mg/L or higher TDS	~100% rejection to non-volatile solutes. Not applicable to volatile contaminants	Water recovery varies depending on feed water quality from 70-90%. Brine needs to be disposed.	945 kWh/kgal thermal and 4.16 kWh/kgal electricity	Not available

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CHAPTER 6: ANALYSIS OF LONG-TERM OPPORTUNITIES FOR PRODUCED WATER USE IN NEW MEXICO; AGRICULTURE, INDUSTRIAL, ONSITE OIL AND GAS

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Background

The Permian Basin is the largest natural gas reserve in the United States and covers parts of southeastern New Mexico and western Texas (Figure 6.1). The Basin covers an area of approximately 190,000 km² and comprises two sub-basins, the Delaware Basin to the west and the Midland Basin to the east, separated by the Central Basin Platform (Engle et al., 2016). There are more than 20 sub-formations that generate produced water during oil and gas production. Sections of the Permian Basin exist in conjunction with the Ogallala aquifer which is rapidly depleting due to groundwater pumping (Freyman, 2014; Tillary, 2008). Within this last decade the region has experienced an increase in oil production due to hydraulic fracturing because it promotes greater oil and gas recovery. Coincidentally, the region has also experienced what was below average precipitation during this time (Sullivan et al., 2015). This caused a noticeable strain in water availability in this already water scarce area.

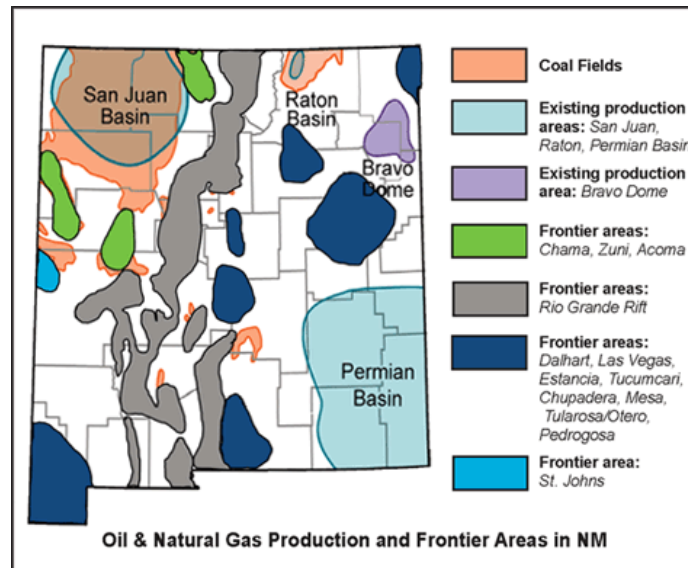


Figure 6.1 Location of Permian Basin in New Mexico. (Source: NMOCD).

Produced water, a byproduct from conventional (vertical) or unconventional (horizontal) oil and gas drilling (New Mexico Oil & Gas act), is defined as any water present in oil reservoirs with hydrocarbons and is brought to the surface with crude oil and natural gas (Veil et al., 2004). Fresh water supplies have been used in the drilling process in order to complete a well. When freshwater comingles with produced water it becomes a waste stream that is either evaporated, re-injected into the oil field strata or injected into a saltwater disposal well (ALL Consulting, 2005). The age of the well influences the amount of produced water that is being extracted (Figure 6.2) (Adebambo, 2011). On average, the ratio of water to oil is about 7:1 (Burnett, 2004) but varies over time and space. This is an important issue to account for as hydraulic fracturing production is expected to double in the Permian basin by 2020 (Freyman, 2014). One concern is the use of freshwater that is used for oil and gas drilling that is consequently turning freshwater water into produced water.

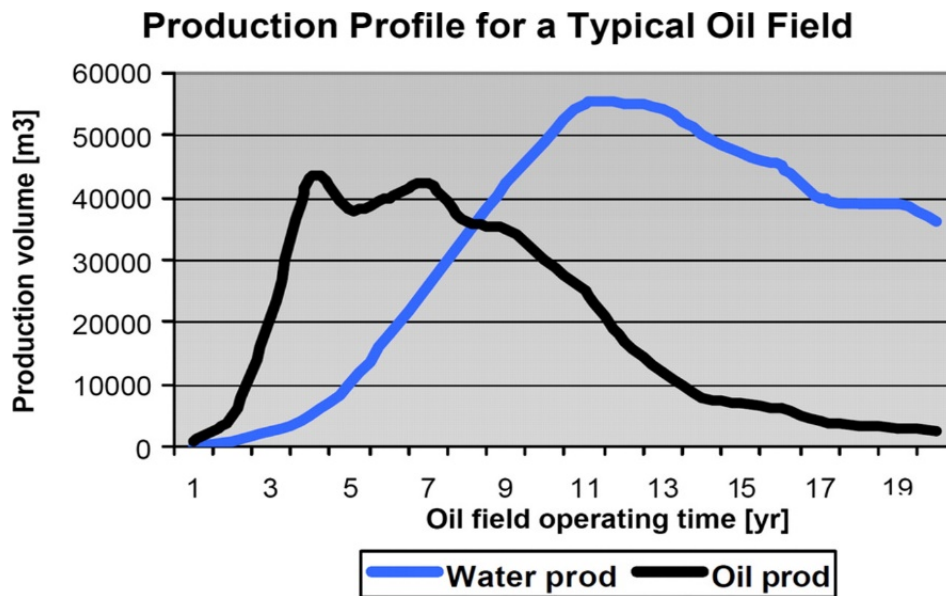


Figure 6.2 Expected volume of oil and water from a well through a 20 year period (Igunnu et. al., 2012).

The amount of water produced during the life of the well is more than the amount of oil that is recovered. The use of produced water as an alternative water source continues to be of interest to researchers, water-planners, industry, and other stakeholders, and for good reason. It was reported that in 2007 the US averaged about 21 billion barrels of produced water per year (Clark, 2009). In Southeast, New Mexico, an estimated 647 million cubic meters (approximately

4 billion barrels) of produced water was brought to the surface between 2008-2013 (Sullivan et al., 2015), averaging 678.2 million barrels per year. Produced water is the largest liquid waste stream associated with oil and gas production. Not long ago, produced water was only considered to be a waste product that costs the oil and gas industries money during both extraction and disposal. As freshwater resources in Southeast New Mexico continue to diminish from the Ogallala aquifer (Tillary, 2008) and the Pecos River (Williams, 2012), and water treatment technology improves, the use of treated produced water for agriculture and industrial applications has become more realistic.

The purpose of this report is to analyze the opportunities for potential uses of treated produced water for southeastern New Mexico, focusing on agricultural irrigation, industrial uses, and onsite oil and gas operations. Many criteria must be met prior to the reuse of treated produced water for a specified purpose and this report outlines some of the main considerations. Water quality is a prime concern when using treated produced water and each potential use has unique considerations. Agricultural purposes require that soil and water quality be considered in conjunction with crop tolerance levels. Industrial typically has lower water quality standards but there are also environmental standards that must be considered prior to reuse. Oil and gas companies have the most at stake when looking for opportunities for reuse of produced water and several companies are already championing efforts to reuse produced water for hydraulic fracturing.

Water accounting in New Mexico

Agriculture and industry play important economic and cultural roles in Southeast New Mexico converting large volumes of freshwater into commodities. There are some concerns over the accounting of water use within the state when it comes to groundwater that traditionally has been solely used for crop production. Water right holders are allowed to use water for beneficial purposes and as such can be sold to oil and gas industries for purposes of drilling (personal communication; Van Dyke, 2016). According to the Office of the State Engineer (Longworth et al., 2010), New Mexico's mining industry uses 1.1% of the state's total water. Sequentially only 5.4% of that total 1.1% is used for oil and gas production (Diemer et al., 2014). This equates to 0.000594% of the state's water but does not, however, take into account the amount of water purchased from farmers or other water-right holders. If oil and gas industries can use treated

produced water within their businesses, the potential use of good quality freshwater for drilling can be minimized and vitally reduce the loss of New Mexico's freshwater supply.

There has been an increase in demand for water use within the oil and gas industry because of the hydraulic fracturing process. Agriculturalists often sell their water to oil and gas companies because of the premium that industry are willing to pay for clean water. From a monetary standpoint, agriculturalists can make more money selling their water to industry than growing crops (Van Dyke, 2016). With the recent oil boom from hydraulic fracturing, farmers and other water right owners are using water sales to their advantage as an additional form of income; in some cases as a way to pay mortgage (Van Dyke, 2016). More and more farmers are transitioning into selling their water to oil and gas industries, which is heavily dependent on the oil and gas market. Farmers from other states are facing the same challenges.

Although the state of New Mexico allows for the transfer and selling of water rights, there is no clear guidance regarding New Mexico's water marketing opportunities. There is no formal "market" for the sale of water such as auctions or clearing houses (Oat et al., 2013). The Office of the State Engineer (OSE), however, does have certain regulations embedded into water rights, such as having to go through a permit process when changing the purpose of the water's beneficial use. Unfortunately, there is no clear way of tracking the sale of water in the state. By tracking these changes in water use, there would be a better representation of the state's freshwater supply that can potentially help address additional freshwater usage problems. Another problem that has been encountered is the lack of knowledge regarding the economic value of water rights (DeMouche, 2010). It has been suggested that a viable water marketing plan would be beneficial in addressing water scarcity in New Mexico.

Current management of produced water

Produced water is usually brackish to saline in quality that can have traces of oil residue and other chemicals depending on the method for drilling (shale, coal bed methane, tight gas sands, etc.). It is difficult to generalize the quality of produced water because of its inconsistency due to the well site location, geomorphology, and methodology of drilling used at the site (Clark, 2009).

The reuse of produced water is a fairly new concept that dates back to the 1980s and 1990s which before then was not considered an option. The US-EPA has been regulating discharges of produced water since the 1960s to prevent contamination into other water resources (USEPA, 40 CFR Part 435). Produced water has been: 1) reused within the industry; 2) discharged offshore if the quality of the water meets discharge regulations; 3) used for preventing the production of produced water onto the surface by the use of polymer gels that block the water during drilling operations; and 4) a resource used in other treatments to meet water quality regulations for alternative uses (ALL Consulting, 2005). All these alternatives hinge on the quality of the available produced water. The treatment level as well as the type of water quality expected after treatment depends mainly on the proposed use. Three possible uses for produced water include industrial, municipal, and agriculture reuse. Dahm and Guerra (2014) described how a drilling company in Barnhart, Texas, used a blend of brackish and recycled flow-back water for hydraulic fracturing operations. The purpose was to minimize the use of freshwater for hydraulic fracturing.

Alternative Uses of Produced Water

Using produced water as an alternative water source can be problematic because of the potential for liability associated with accidental or deliberate discharges. However, California, Colorado, Oklahoma, Texas, and Wyoming have started implementing alternative uses for produced water other than re-injection (ALL Consulting, 2005; Dahm and Guerra, 2014). The primary limiting factor for beneficial alternative uses is the cost associated with treating produced water itself. Factors that need to be addressed include treatment facilities, transportation, and the proper disposal of the accumulated waste stream. The level of treatment, however, can be defined by the end user's water quality needs and the regulations that may be imposed or enforced by local, state, or federal government. For example, there are some areas where farmers are faced with high total dissolved solids that already restrict optimum crop growth. It could be that Dahm and Guerra's (2014) example has a counterpart in agriculture where produced water is treated to a point that is less saline than available groundwater and used to improve irrigation water quality through dilution.

Agriculture

In the western region of the US, 83% of freshwater withdrawn is for irrigation (Maupin et al., 2014). Irrigation for agricultural purposes is the primary water consumer in the seventeen western states where average rainfall is less than 20 inches per year. Rainfall averages less than 10 inches per year in much of the southern regions of New Mexico where most of the precipitation is expected during the “monsoon” season from July through August (WRCC, 2016). About 79% of New Mexico’s water is used for irrigated agriculture (NMOSE, 2015; Longworth et al., 2013). The remaining water withdrawals supply public or commercial purposes, which only average about 8% and 1%, respectively (NMOSE 2015; Longworth et al., 2013). Agriculture has been the largest water user in the state for most of its history. However, agriculture is also a major contributor to New Mexico’s gross domestic product. The combination of agriculture and food processing in New Mexico accounted for \$10.6 billion in 2012 which was roughly 12% of the state’s economy (Diemer et al., 2014). There were about 24,700 New Mexico farms in 2012 and 2014 averaging 1,749 acres (Bustillos et al., 2015). New Mexico agriculture has also helped produce nearly 42,000 jobs to processors, ranchers, and farmers across the state (Diemer et al., 2014).

Eddy and Lea Counties are located on the southeastern part of the state and contribute to some of the most significant crops to New Mexico’s agriculture. In 2012, harvested cropland in Eddy County totaled 41,775 acres yet 43,254 acres were irrigable (USDA-NASS, 2014). Lea County had 49,664 acres of harvested cropland from a total of 51,581 irrigable acres (USDA-NASS, 2014). This primary production accounted for \$119.6 million dollars in agricultural sales in 2012 in Eddy County and \$188.9 million from Lea County NASS (2012). Cotton, corn, and hay were the dominant crops in 2012 with a few acres in pecans and other specialty crops (NASS, 2012). Lea County grew significant acreage of cotton, corn, hay, and peanuts in 2012. Hay was primarily alfalfa which is New Mexico’s third largest cash crop (USDA-ERS, 2015). Additionally, Eddy County had 551 farms that averaged 2,073 acres (Bustillos et al., 2015). Lea County had 460 farms averaging 1,806 acres. Ash (1963) described groundwater conditions in northern Lea County as very limited (“tens of years”) at the rate of withdrawal in 1953. It is one of many areas in New Mexico in which groundwater is being mined (Ash, 1963). With expected long-term droughts combined with possible longer growing seasons due to climate change the

amount of freshwater availability in the future is vague (Repetto, 2012). As these wells go dry (farmer, personal communication, Konikow, 2013) there may be recourse to treated produced water to assist and, at some level, stabilize economic production from this region.

With new and advanced treatment technologies, treating produced water to an acceptable level has the potential to be used for multiple resources including agriculture. Because of agriculture's large economic, cultural, and water footprint to the state, it is important to begin addressing these new alternative methods from which agriculture could benefit.

Water quantity for agriculture use

Longworth et al. (2013) reported that Eddy County agricultural groundwater withdrawals totaled 109,738 acre-feet (~0.832 billion barrels) in 2010 and Lea County withdrew 172,297 acre-feet (~1.31 billion barrels) for the same purpose to help drive agriculture's economic and cultural benefits to the state. The quantity of water needed by a particular crop is dependent on the consumptive use of each crop (USDA-NRCS NM, 2005) which is driven by the potential evapotranspiration in each region. Consumptive use for common crops grown in Eddy and Lea counties are given in Figure 3. The New Mexico USDA-NRCS has published in their field office technical guide (USDA-NRCS, 2005) consumptive use for selected regions in the state. The information is presented in tables for selected New Mexico counties by month for both dry years and normal years. Historic effective rainfall is also included for consideration. Eddy and Lea Counties also have dormant periods for summer crops such as alfalfa, corn, cotton, and sorghums (grain or forage). Winter forages include the small grains such as barley, oats, or wheat. Crop rotations that include winter production of small grains or other winter-hardy crops can utilize water all year round.

Using alfalfa as an example, the USDA-NRCS of New Mexico (2005) estimated from historical data the net irrigation requirement for alfalfa from March to November to be 34.1 acre-inches (21,534 bbls/acre) in a normal year or 35.6 acre-inches (22,481 bbls/acre) in a dry year excluding rainfall (Figure 4). In Lea County, net irrigation for alfalfa was estimated at 43.24 acre-inches (27,306 bbls/acre) for the same time period under normal year conditions. Alfalfa in a dry year would need 45.5 acre-inches (28,733 bbls/acre) of irrigation water (Figure 6.3). A typical 120 acre pivot, therefore, would need ~3.5 million barrels of irrigation water. The amount of water is further adjusted to maintain a leaching fraction of water in order to keep the soil

electrical conductivity (E.C.) in an optimum range for specific crops. Figure 4 illustrates the monthly irrigation needs for selected crops in Eddy and Lea counties in barrels per acre.

The consumptive use of alfalfa grown in the Carlsbad area in a dry year requires 35.26 acre-inches from March to October or November (NRCS Staff, 2005). This equates to ~2.227 million barrels per season per acre. An 80 acre field of alfalfa in Eddy County would need a little more than 178 million barrels of acceptable quality irrigation water. Alfalfa’s peak demand for water usually occurs in June while very little water is required in January, February, and October-December. Irrigation efficiencies and leaching fractions increase the amount of water needed to grow the crop year after year.

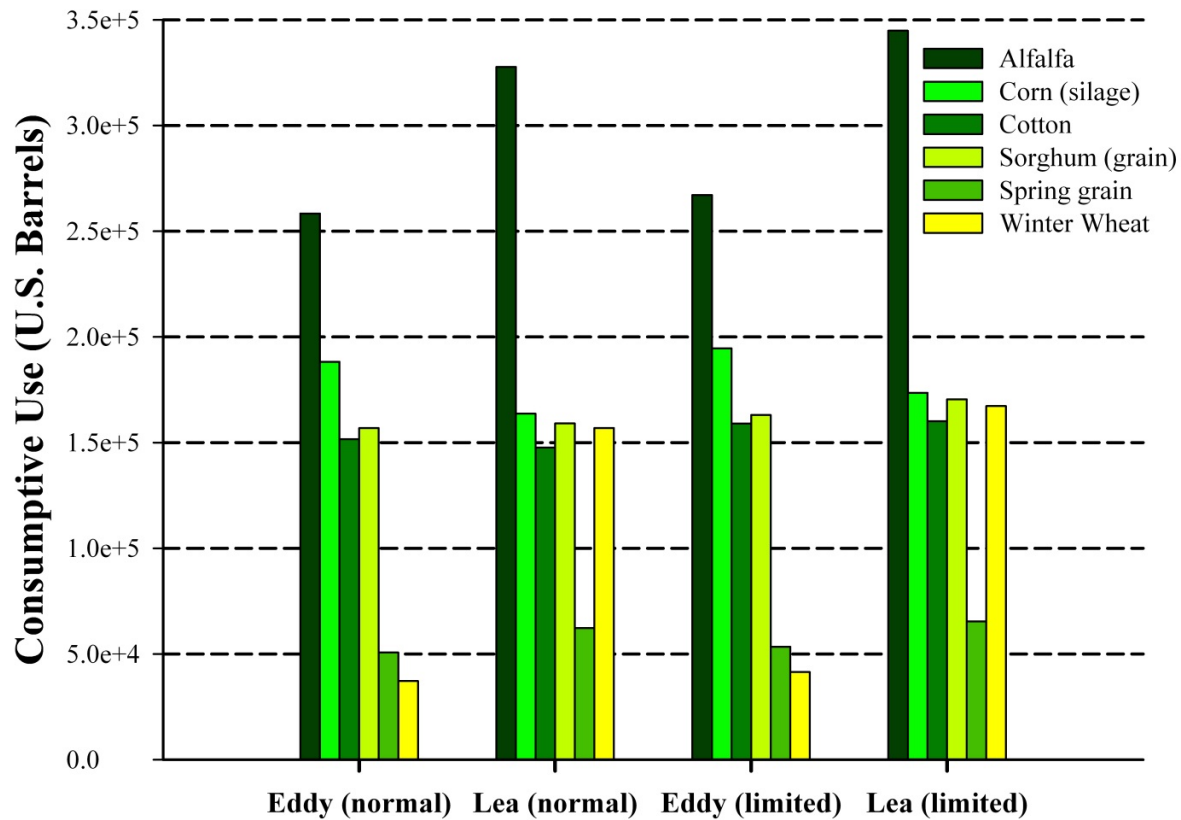


Figure 6.3 Consumptive use of selected crops from Eddy and Lea Counties (USDA-NRCS-NM, 2005).

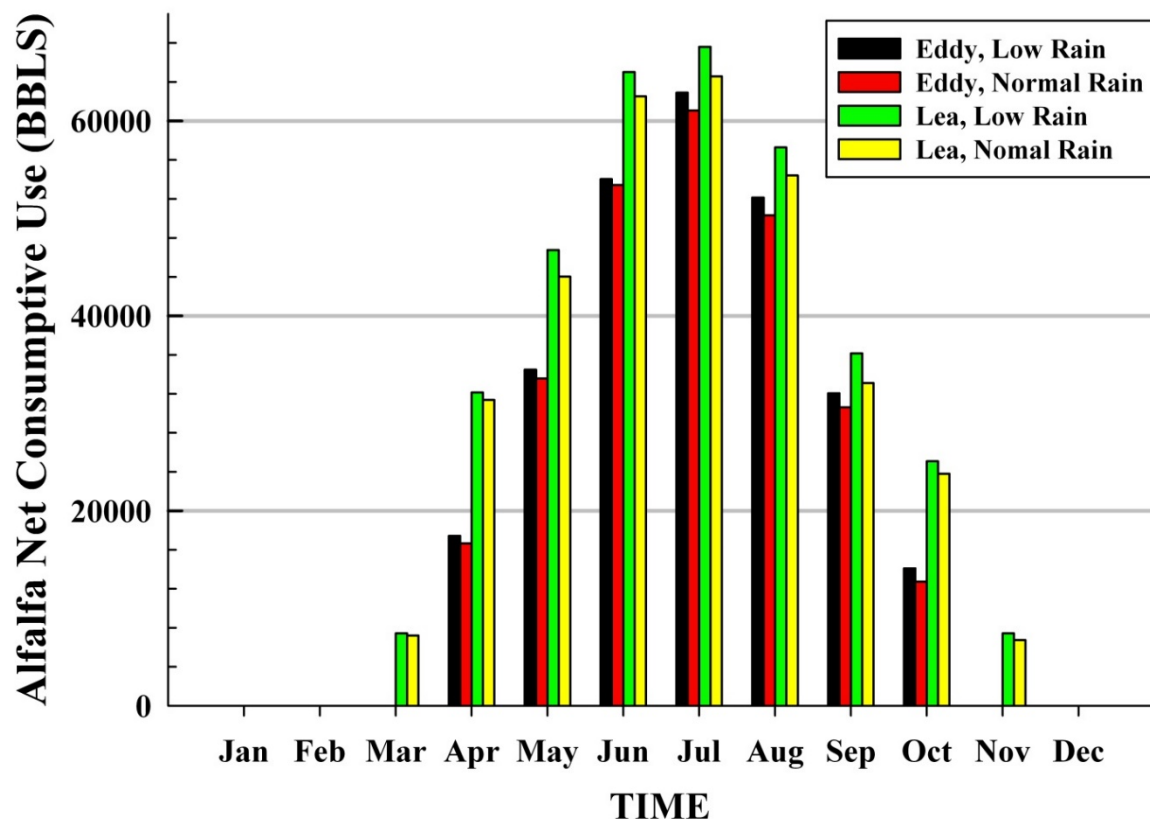


Figure 6.4 Alfalfa average water requirements per month as affected by location, time of year, and yearly rain (USDA-NRCS-NM, 2005).

Crop irrigation requirements

As stated earlier (section 2.1.1) each crop has a “consumptive use” which is the amount of water needed to bring a crop to maturity for harvest. Crop consumptive use is dependent on the potential evaporation of the area (climate) and the physiological needs of the crop. If leaching is needed to keep a crop healthy and productive from the effects of salinity then more water will be required.

The type of irrigation system also plays an important factor in water as the water quality can impair the infrastructure if used with low quality water. A sprinkler system is more vulnerable to clogging and impairment due to poor water qualities but is also more efficient in water delivery. Water in Eddy and Lea Counties is susceptible to high mineral content such as calcium. New Mexico fresh waters have also been found to have issues regarding sand particle size that comes up from wells and biological concerns. Therefore, a filtration system is a helpful

tool in preventing clogging issues. It does not, however, always prevent all plausible causes of clogging. Flushing the irrigation system from time to time can help prevent these impairments. Flood irrigation systems are less efficient than sprinkler systems and would need additional water to assure proper uniformity and productivity.

Salinity is a major limitation for many crops in New Mexico which vary in their response to salinity (Figure 6.5). Additionally, the number of crops that can be grown decreases with increasing soil salinity (Flynn and Ulery, 2011). Irrigation water salinity impacts soil salinity and can also have specific effects on actively growing crops if water salinity and specific ions come in contact with plant tissue. Salinity is generally managed by increasing the amount of water applied to some level above its consumptive use by calculating a leaching fraction based on water quality and a target soil EC. This practice leaches excess salts out of the crop root zone. Choosing crops that are more tolerant to salinity (Flynn and Ulery, 2011) is another alternative that can help reduce the leaching fraction.

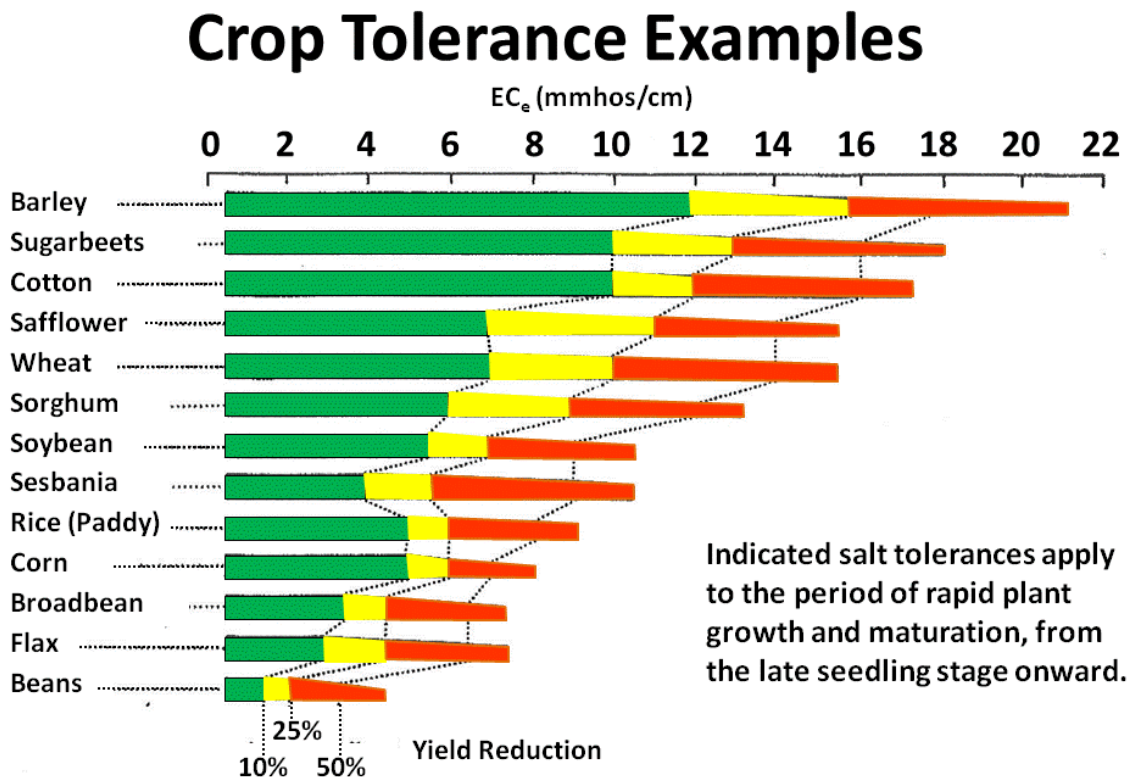


Figure 6.5 Crop tolerance examples illustrating soil EC_e where yield reduction will likely be less than 10%, between 10 and 25%, and greater than 25% with maximum tolerable salinity at the end of the horizontal bar. Tapering of the bars from left to right reflects degree of yield loss at higher levels of total salinity. Original graphic from Bernstein, L. 1964. "Salt Tolerance of Plants" USDA Info Bulletin 283.

Produced water for agriculture in southeastern New Mexico

While no specific regulation addresses the use of treated produced water in agriculture, the New Mexico Environment Department’s Ground and Surface Water Quality Bureau does have water quality guidelines and regulations (NMAC 20.6.2.3103) for domestic and agricultural groundwater use. These standards have been set to protect all ground and surface waters of the state of New Mexico (Table 6.1) for present and potential future domestic or agricultural use. These regulations also protect those segments of surface water which gain groundwater inflow (NMAC 20.6.2.3103). The main concern for these regulations is to meet human health standards. These standards can stand as an established target for the treatment of produced water. Not all water needs to be treated to human standards but could be treated to levels that are acceptable for livestock or crop use. Dahm and Guerra (2011) have summarized, in tabular form, National Science Foundation guidelines for water quality (Table 6.2) that can be used for livestock watering.

Table 6.1 Guidelines of groundwater quality for domestic use. (NMAC 20.6.2.3103).

Constituent	(mg/l)	Constituent	(mg/l)
Arsenic (As)	0.10	1,2 Dichloroethane (EDC)	0.01
Barium (Ba)	1.00	1,1 Dichloroethylene (1,1-DCE)	0.005
Cadmium (Cd)	0.01	1,1,2,2 Tetrachloroethylene (PCE)	0.02
Chromium (Cr)	0.05	1,1,2 Trichloroethylene (TCE)	0.10
Cyanide (CN)	0.20	Ethylbenzene	0.75
Fluoride (F)	1.60	Total xylenes	0.62
Lead (Pb)	0.05	Methylene chloride	0.10
Total Mercury (Hg)	0.002	Chloroform	0.10
Nitrate (NO ₃ as N)	10.00	1,1Dichloroethane	0.025
Selenium (Se)	0.05	Ethylene dibromide (EDB)	0.0001
Silver (Ag)	0.05	1,1,1 Trichloroethane	0.06
Uranium (U)	0.03	1,1,2 Trichloroethane	0.01
Radioactivity	30 pCi/l	1,1,2,2 Tetrachloroethane	0.01
Benzene	0.01	Vinyl chloride	0.001
Polychlorinated Biphenyls (PCB)	0.001	PAHs:	0.03
Toluene	0.75	Benzo-a-pyrene	0.0007
Carbon tetrachloride	0.01		
Domestic Water Supply	(mg/l)	Standards for Irrigation Use	(mg/l)
Chloride	250	Aluminum	5.0
Copper	1.0	Boron	0.75
Iron	1.0	Cobalt	0.05

Manganese	0.2	Molybdenum	1.0
Phenols	0.005	Nickel	0.2
Sulfate	600		
Total Dissolved Solids	1000		
Zinc	10		
pH	6–9		

Table 6.2 Recommended water quality limits for livestock use from NSF (Dahm and Guerra 2011).

Constituent	Upper limit (mg/L)	Constituent	Upper limit (mg/L)
Aluminum	5.0	Mercury	0.01
Arsenic	0.2	Nitrate + Nitrite	100.0
Boron	5.0	Nitrite	10.0
Cadmium	0.1	Selenium	0.1
Chromium	1.0	Vanadium	0.1
Cobalt	1.0	Zinc	24.0
Copper	10.5	Total Dissolved Solids	10000.0
Fluorine	2.0	pH	5.5-8.5
Lead	0.1	Sulfate	2,000

Two important components for productive crops are water and soil quality. Water quality for irrigation depends on the type of crop, as well as soil types (texture, depth). Crops vary in their tolerance to total salinity and specific ions such as sodium, chloride and boron. Soil is most adversely affected by sodium as it causes clay particles to disperse and prevent water from entering into the soil. The choice of crops that can be grown declines as total soil or water salinity increase. However, plants vary in their tolerance to these components. Therefore, treatment industries would have to assure certain water quality standards that are dependent on the crop that the treated produced water would be applied to. However, every crop has a salinity threshold after which yield declines and a rate at which they lose yield as salinity increases (Figure 6.5). It may be fiscally unrealistic to treat produced water to a level that would support any type of crop. Point of delivery water treatment may be required to make use of produced water for higher value crops with low tolerance to salinity. The higher the crop salinity threshold the more salinity can be tolerated which could afford industry reduced treatment options.

Soils have different physical, chemical, and biological indicators in which agronomists and farmers monitor in order to have a thriving growing season (Friedman et al., 2001; Flynn,

2012). Fertile soils are responsible for multiple functions such as sustaining plant productivity, providing essential nutrients, retaining water for the roots, decomposing organic material, recycling nutrients, and other key functions. Preventing soils from degrading due to soil erosion is essential as this will not only have an effect on crop production, but also to the water quality as it can cause excessive runoff (Friedman et al., 2001). Soil quality is most adversely affected by sodium as it leads to dispersed soil particles that prevent water from entering the soil.

Factors that affect crops negatively are salinity, sodicity, and specific ion toxicity. Crops have variable response to salinity and are dependent on species (Figure 6.5) and variety. Salinity is a major soil quality parameter that impacts crop yield, but the threshold limit varies depending on crop tolerance. Salinity is measured both in soil and water, and can influence the levels from one another. Within each crop there are also variety of differences in response to salinity with specific varieties that have been bred to tolerate higher levels of total salinity. The higher the crop threshold the more salinity can be tolerated which could afford industry reduced treatment options. Salinity is measured using electrical conductivity (mmhos/cm or dS/m) and often interpreted as total dissolved solids (TDS) with units of mg/l (or ppm). Crops are classified as being sensitive, moderately sensitive, moderately tolerant, and tolerant.

Water TDS <450 mg/l is considered good quality provided sodium is not too high. Water quality with TDS >2000 mg/l has severe restrictions on use for crop production. Total soil salinity above 4 mmhos/cm (saturated paste method) is, by definition, saline and severely restricted on what can be grown (U.S. Salinity Laboratory Staff, 1954; Fipps, 2003). Management practices for reducing the effects of salinity to crops includes applying excess water to promote leaching of salts to below the root zone. This is only productive if there is good soil water drainage that will allow salts to move through the soil and away from the root zone (Flynn, 2011). This is an important component to consider as most produced waters have been measured with TDS levels ranging from 20,000 mg/l up to 200,000 mg/l or more in the Permian basin. Much of the TDS parameter for New Mexico is composed of calcium and magnesium minerals which defines water as being “hard”. Soft water, on the other hand, results when sodium is a dominant mineral in the water. Soft water causes more problems for soil structure when applied to the soil and at high concentrations can also damage crops. The ratio of sodium to calcium and magnesium (SAR) is an important factor to measure as these ions can have an effect in the soil quality (Flynn, 2011) and must be interpreted together with the total salinity of the water in order

deem the water acceptable for plant growth and development as well as soil health. The type of dissolved salts that are found present in the irrigation water can also have an influence in the performance of a crop. Sodium content and salinity are both seen as guidelines to the level of water quality (Ayers and Wescot, 1994). Water and soil testing analyses including pH, salinity, sodium, bicarbonate, chloride, calcium, magnesium, sulfate, nitrate, and boron along with a few other elements are expected to not exceed crop water and soil standards if produced water is to benefit crop production. There is a wide range of water pH levels in New Mexico with most being in the alkaline range and below pH <8.4. Most irrigation well waters have a pH greater than 7 and less than 8.

Heavy metal accumulation can have a negative impact on the crop performance. Although some heavy metals; such as Fe, Cu, Zn are essential for plant and animal growth, they can also become toxic in high concentrations (Sharma et al., 2005). Heavy metals, or trace metals, are labeled as “heavy” because of their specific weight, and although they are found naturally in rock formation, they have also been largely dispersed from industrialization and urbanization (Hu et al., 2013). Soils can act as a filter for metals, but when excessive toxic metals have accumulated the capacity for soils to retain these metals is impaired which can consequently be exposed to groundwater and plant uptake (Mapanda et al., 2004). With high concentration of heavy metals, plant physiological capabilities such as photosynthesis, gas exchange and nutrient absorption can be altered (Sharma et al., 2005). This, in turn, can also cause reduction in plant growth. The type of plant, specific metal, the concentration, soil composition and pH as well as other environmental factors can have an effect on the toxicity levels. Therefore it is important to monitor and maintain a set of acceptable concentration levels for heavy metals (Table 6.3) as they are commonly found in raw produced water, such as cadmium, chromium, copper lead, mercury, nickel, silver, and zinc (Ahmadun et al., 2009).

Table 6.3 Acceptable concentration levels of heavy metals in soil and crops (Sharma et al., 2005).

Heavy Metals	Range in Soil (ppm)	Range in agricultural crops (ppm)
Cd	0.01–0.7	0.2–0.8
Co	1–40	0.05–0.5
Cr	5–3,000	0.2–1.0
Cu	2–100	4.5
Fe	7,000–550,000	10–400
Mn	100–4,000	15–100
Mo	0.2–5	1–100
Ni	10–1,000	1
Pb	2–200	0.1–10
Zn	10–300	15–200

Economic crops of southeastern New Mexico

Some of the most economically significant crops in New Mexico are alfalfa, chile, pecans, cotton, corn, and wheat (NMASS, 2015). While all these crops are grown in Eddy and Lea counties, this review focuses on the tolerance levels of alfalfa, cotton, sorghum, and wheat as these are the largest acreage crops in both Eddy and Lea counties. They are also some of the most salt tolerant crops. A water quality assessment is needed to mitigate the response expected for crop growth and soil response to sodium. This assessment needs to identify: 1) the total concentration of soluble salts, 2) the proportion of sodium to calcium and magnesium (SAR), 3) the bicarbonate concentration in relation to the concentration of calcium and magnesium, and 4) the concentration of other elements such as boron and chloride as well as other minerals and compounds (Fipps, 2003). Best management practices to keep crop foliage from being damaged by specific ion effects are to water at night or from beneath the canopy. This could be done with low energy precision application directly to the ground. Table 4 summarizes crop tolerance levels for the major crops of the area of interest.

Table 6.4 Selected crop, soil, and water quality tolerances (Ayers and Wescot, 1994; Maas, 1986).

	Alfalfa	Corn	Cotton	Sorghum	Wheat
pH	6.5-8.44	6.5-8.4	6.5-8.4	6.5-8.42	6.5-8.43
TDS (ppm)	1280	1152	4928	4352	1344
Salinity Tolerance Rating	Moderately Sensitive	Moderately Sensitive	Tolerant	Moderately Tolerant	Moderately Tolerant
Threshold EC _e (mmhos/cm)†	2	1.8	7.7	6.8	2.1
50% Emergence EC	8-13	24	15	15	14-16
50% Yield EC	8.9	5.9	17	13	17
Soil Exchangeable Sodium percentage (ESP)	40-60	40-60	ESP>40	(15-40)	(15-40)
Na ppm (water) ppm	<460	<460	<460	n/a	n/a
Cl ppm (water) ppm	<709	<709	<709	n/a	n/a
Boron (water) ppm	4-6	2-4	6-10	6-10	0.75-1

Alfalfa

Alfalfa is moderately sensitive to salinity with a soil saturated paste (EC_e) threshold of 2.0 mmhos/cm (Maas, 1986). Without salt tolerant varieties, alfalfa is expected to experience a 7.3% reduction in yield for every unit above 2 mmhos/cm. Some varieties have been bred to withstand higher levels of salinity but are limited to areas where non-dormant varieties can be grown. Alfalfa grown in soil with a saturated paste EC_e of 8.9 would be expected to yield half its potential yield and would have 50% or less emergence if the soil had a saturated paste salinity of 8-13 mmhos/cm at germination (Maas, 1986). Alfalfa, however, can tolerate 4-6 ppm boron in soil solution (Eaton, 1944). Most alfalfa can also withstand up to 460 ppm Na or 709 ppm Cl depending on environmental conditions. There are also varieties of alfalfa available on the market that are considered tolerant as they have been bred to tolerate more total salinity.

Corn and Chile

Chile and corn have the lowest tolerances to salinity. Soil salinity should not go beyond 1.8 mmhos/cm in total salinity for corn and chile should not be exposed to levels above 1.5 mmhos/cm. Chile, however, is slightly more tolerant than corn as salinity rises above its threshold. If soil salinity is as high as 24 mmhos there will be a 50% loss of a corn stand at emergence. Soil kept at 5.9 mmhos/cm would result in a 50% corn yield potential. Corn is similar to alfalfa in its tolerance to foliar injury from Na or Cl in the irrigation water. Chile,

however, does not tolerate more than 115 ppm of Na or 177 ppm of Cl on its foliage. Chile will only tolerate 1 – 2 ppm boron and corn tolerates slightly more at up to 4 ppm.

Sorghum / Sudangrass

Sorghum and sudangrass can be substitutes for corn grown for silage as processed seed corn can be added to the diet to improve the starch and protein content that sorghum and sudangrass are short on. Sorghums tolerate more total salinity with a 2.8 mmhos/cm threshold and is considered moderately tolerant of salinity. The sorghums tolerate from 230 – 460 ppm Na on the leaves and 355 – 709 ppm Cl. Boron tolerance ranges from 6 -10 ppm before damage occurs.

Wheat and other small grains

Wheat is also grown for forage in southeastern NM along with a few other small grains. The soil salinity tolerance level for wheat is 4.5 mmhos/cm and is considered moderately tolerant to salinity. Wheat is expected to have 50% emergence and germination if soil salinity is between 14-16 mmhos/cm. If the soil is kept at 17 mmhos/cm wheat yields will be half of what they could be under non-saline conditions. Oats, however, are moderately sensitive. Like wheat, barley is moderately tolerant but at a higher threshold (6.0 mmhos/cm). Soil salinity kept at 16-24 mmhos/cm during barley germination is subject to 50% reduction in emergence and 50% yield potential if kept at 18 mmhos/cm. Oats and barley can tolerate 2-4 ppm of boron in the irrigation water making them moderately tolerant to boron. Wheat, however, is sensitive to boron as it tolerates only 0.75 – 1 ppm on its foliage.

Livestock watering

Livestock watering is classified as any water used or connected to any on farm needs such as livestock watering, feedlots, or dairy operations (USGS, 2005). Both Eddy and Lea Counties combined averaged about 136,000 head of cattle of both beef and milk cows (Bustillos et al., 2015). Eddy and Lea counties accounted for ~3,521 AF for supplied water for livestock in 2010 (Longworth et al., 2013). The amount of water used for livestock watering was much smaller compared to the amount of water used for irrigated agriculture. However, high levels of specific ions and high salinity levels have been shown to cause serious harm to cattle. Dahm and Guerra (2011) mention the importance of having levels of sulfate and alkalinity below 2,000 mg/l as greater values can cause sickness and death to animals. Recommended TDS values range from less than 1,000- to 3,000 mg/l as acceptable levels for livestock (Table 2). Using treated

produced water for livestock watering could serve as an additional beneficial use in both Eddy and Lea Counties since livestock and dairy ranching is common within the region.

CBM produce water for Irrigation-Study Case

Perhaps some of the most commonly used produced water comes from Coal Bed Methane (CBM) production as these waters may be of very high quality water to low quality (low TDS concentrations). CBM produced water has shown the potential to be used for direct discharge, livestock watering, irrigation (ALL, 2003). Because many CBM productions are located in arid regions the management and treatment of produced water from CBM productions has gained interest. A study case was done in Johnson County, Wyoming where William's Company implemented an irrigation project on open land that was covered mostly by grasses and other drought-resistant plants. Produced water was implemented beginning of Sept 2001, and monitored through the following year. CBM water had measured SAR to be greater than 20. Water quality needs to be continuously monitored for the need of any new additives such as calcium sources, sulfur, or dry gypsum. Throughout the studied year the land showed a large amount of plant growth. Future scopes of work were planned to measure changes in the soil from the produced water application.

Industrial

Mining, oil and gas productions, and power generations are the three major *industrial* water consumers within the state (NRCE, 2004). Mining operations use water for mineral extraction and processing, metal recovery, and dust control (Maupin et al., 2014). In 2010, mining itself used about 11,309 acre-feet of water for production (Longworth et al., 2013). Potash mining was responsible for using 20% of the water usage under the *industry* use category for the entire state. Using treated produced water for potash mining would be ideal as New Mexico is the leading producer of potash for the US (U.S dept. of the Interior; Longworth et al., 2013), producing 85% of the domestic production of potash in Carlsbad, NM (Willet, 2004). Most of the production in the region is done by 2 companies, Mosaic Company, and Intrepid Potash, Inc. (Jasinski, 2016) over 4 mines. Potash is a term used for the accumulation of mined and manufactured salts containing potassium (UNEP, 2001; Austin, 1980), which serves as a manufactured fertilizer. Potassium is one of the 3 essential nutrients for plant growth, and maturation (alongside soluble phosphorus and fixed nitrogen) (Willet, 2004). Although there are

other micronutrients (i.e. boron, calcium, chlorine) which can be added and substituted for plant health, but there are no substitutions for potassium by a different nutrient (UNEP, 2001). Potash has also been used for aluminum recycling, metal electroplating, oil-well drilling mud, snow and ice melting, and water softening (Willet, 2004). Currently at Intrepid potash mining Inc., water is pumped from the Rustler formation for mining. For solution mining, the water is salt saturated in order to extract the potassium; high levels up to 100,000 ppm TDS are acceptable. The mine also requires a saline water stream to support an evaporation rate of 1,000 gallon/min. Director of technical services of Intrepid Potash (Ryan, 2016), mentioned that the biggest challenges with produced water in potash mining are not in the high TDS levels, but in the different constituents that can be found in produced water. Raw produced water exhibit high salinity (Dahm and Guerra 2014) but also:

- Suspended Solids
- Oil & Grease, Hydrocarbons
- Dissolved Gas and Volatile compounds
- Trace Metals
- Radionuclides
- Well additives and fracturing chemicals

These constituents and other cations in produced water can cause complications during production as it can cause scaling. Treatment technologies would be focused in removing these constituents in order to prevent any malfunctions. Not only can treated produced water facilitate potash mining but also be used in salt mining, a common mining industry in southeastern New Mexico as well. The treated water could potentially be used for washing of the salt minerals as they go through an extensive washing period (United Salt Corporation, 2006).

When treating produced water both a freshwater and waste stream will be created. Minimizing that waste stream would be in the best interest by the producers. In the case of brine water, there currently exist a number of technologies that can treat brine to a range of desire water quality standards. However, because these technologies still leave behind concentrates that are of no value and are potential hazards for the environment, finding a beneficial use to these leftover concentrates can help alleviate the waste stream. Selective Salt Recovery (SSR) can be

used to harvest individual salts from these concentrates in commercial grade qualities (Table 6.5) (Mickley, 2009).

Table 6.5. Major salts and application areas (Mickley, 2009).

Chemical Formula	Name	Areas of application
CaCO₃	Calcium carbonate	Paper coating pigment, filler for plastics and rubbers, special inks, paints and sealants
CaSO₄·2H₂O	Gypsum	Remediation of sodic soils, manufacture of building products
CaCl₂ (liquor)	Calcium Chloride	Dust suppression, road base stabilization, sodic soil remediation, cement/concrete stabilizer, construction industry
KNaSO₄	Glacerite	Potassium fertilizer
Mg(OH)₂ slurry	Magnesium hydroxide	Water/waste water treatment, Animal stock feed, Feed for magnesium metal production, Fire retardant & refractories, Acid neutralization
xMgCO₃·yMg(OH)₂*zH₂O	Magnesium carbonate light	Fire retardant, Feedstock for magnesium metal production, Filler for paper manufacturing, rubber and paint.
NaOH	Caustic soda	Many applications industrially, Basic feedstock for chemical processes, pH adjustment, etc.
NaCl	Halite	Food and industrial processes, Chlor-alkali production, Many industries require bulk salt supply
Na₂CO₃	Soda ash	Water treatment, chemical industry, etc.
Na₂SO₄	Thenardite	Surfactants manufacture, Detergents manufacture, Glass manufacture, Remediation of calcareous soil
NaOCl	Sodium hypochlorite	Disinfection, Chemical industries, Pool chlorine
NaClO₄	Sodium Chlorate	Paper bleaching, Chemical industries

GEO-Processors USA, is a private company which specializes in the application of SSR for industrial benefits. SAL_PROCTM is GEO-Processors patented, integrated process for sequential or selective extraction of dissolved elements from inorganic saline waters in the form of valuable salts and chemical compounds (mineral, slurry and liquid form) (GEO-PROCESSORS, 2016). According to GEO-Processors, they have conducted a number of field trials, piloting and operational analysis to confirm its capacity to convert a number of saline

waste streams into saleable products and achieve zero or regulated discharges (GEO-PROCESSORS, 2016). These same technology tools can be applied to produced water and its high salinity levels, and can potentially add an additional beneficial production to produced water. The waste stream can be minimized by making most use of the salts that can be retracted.

Onsite Oil & Gas

Reusing produced water for oil and gas industries is not as unusual as using it for irrigation or surface water discharge. With recent technology, more industries are advancing their ability to develop methods that can incorporate the reuse of produced water within their own facility. This is most often an economic benefit to the industry as it is less costly than disposing of produced water through re-injection and the continual need for fresh water. Given the scarcity of water in the semi-arid region of southeastern New Mexico any step toward reducing the need for fresh water is a benefit to the region. The primary concern for beneficial alternative uses is the cost associated with treating produced water. Factors that need to be addressed include the treatment facility itself, transportation to and from the treatment facility, and disposal of the accumulated waste stream. The level of treatment, however, can be defined by the end user's water quality needs and the regulations that may be imposed or enforced.

Perhaps the most economic use of produced water is its use within the industry "as a drilling or completion fluid or other type of oil field fluid, including makeup water, fracturing fluid or drilling mud, at a permitted drilling, production or plugging operation" (NMOCD Notice under NMAC 19.15.34.12). However, the produced water must not come in contact with any fresh water zones of the state.

Some states like Colorado have introduced legislative bills (HB1018, 2014) to consider the use of produced water for onsite dust suppression. In North Dakota, however, "only brine from production waters shall be distributed for use as ice or dust control. No drilling fluids, exploration fluids or work-over liquids shall be used in this capacity" (NDAC 33-24-02-02(5) (a) (2)). Many unpaved roads are already watered for dust control using freshwater sources making produced water a more attractive alternative. However, as reflected in North Dakota's rule, there may be liabilities associated with dust control from produced water.

Shpiner et al., (2009) focused on the importance of removing pollutants from produced water if the intent is to use it for municipal or agricultural purposes. Pollutants can include:

organics (dispersed and dissolved oil), TDS, ammonia, boron, and other heavy metals. This research was focused on the removal of certain hard pollutant metals such as cadmium (II), chromium (III), and nickel (II) through chemical precipitation in biological treatment that would bring the produced water to European water quality standards. The study also identified the possibility of using continuous artificial ponds, joined with intermittent sand filters to treat the produced water and meet irrigation quality standards.

Treatment technologies such as plate settlers, reverse osmosis, dissolved air flotation, electro-coagulation, and bio-reactors have already been installed and used in several industries for the purpose of treating produced water (Dahm and Guerra, 2014; Funston et al., 2002; Burnett, 2004; Ramirez, 2002). Ultimately, there will be multiple methodologies employed with produced water treatment as it is unrealistic to expect one treatment to be able to address all the different scenarios and alternative water streams that the treated water will be used for. One of the most important managements found throughout the study is having a primary treatment that will treat oily water in order to prevent any malfunctions to the machinery due to leftover oil residue (Burnett, 2004). Removal of salts through desalination with the process of Reverse Osmosis (RO) (Burnett, 2004; Dahm and Guerra, 2014; Adebambo, 2011) was a common treatment technology used. Desalination is a well-established technology that is being used for other water streams (potable, municipal), and has shown to be a cost-effective treatment.

Devon Energy, an independent natural oil and gas company located across US and Canada was able to implement facilities that treated and transported produced water for re-use within their own production in New Mexico (Sawyer, 2016). Due to the company experiencing freshwater stress from the lack of surface water in the area, and groundwater competition from other corporations and water right holders, Devon Energy required additional water sources to support their production. The NMOCD Rule 34 was really a stepping stool that allowed Devon Energy and other industries to re-use produced water within their own facilities by allowing storage of produced water in double-lined impoundments. This eliminated a long application process from industries that was creating a barrier to the re-use of produced water. With this new regulation Devon Energy was able to reuse 3.5 million barrels within the Delaware Basin in the state (Sawyer, 2016). With new and improved regulations such as Rule 34, industries will be able

to achieve more with their produced water and broaden the options towards what beneficial uses it can be useful for in addition to be used within oil and gas.

Selected Case Studies

California usage of produced water- Study Case

Funston et al, (2002) conducted a pilot study to evaluate the economic and technical feasibilities associated with beneficial reuse of produced water for industrial, agricultural (irrigation), and drinking water purposes. The study was conducted by Kennedy/Jenks Consultants in Placerita Canyon, at the Canyon oil field, near Los Angeles, California. At the time, California lacked regulations for produced water reuse as they lacked enforceable drinking water quality standards. The study relied on reclamation standards, as well as other state and federal regulations. Several contaminants were addressed including TDS, organics, silica, ammonia, boron and water hardness. Reverse osmosis was determined to be the preferred technology for TDS removal. Silica and water hardness were effectively controlled by chemically precipitating these constituents. Adding magnesium chloride to the produced water also helped to reduce boron and silica levels. The final cost for treating produced water for industrial purposes was estimated at \$0.12/bbl. Treatment for agricultural and domestic water use was approximately \$0.50/bbl.

Discharge of treated Produced Water into Wetlands-Study Case

Wyoming is one of the few states that allow produced water to be discharged into wetlands and used as beneficial purposes for livestock and wildlife. Ramirez (2002) reported that produced water was discharged into sixty-six wetland sites. In order to prevent contamination to the wetlands there must be efficient separation of oil from the water. This step is important to prevent chronic fatalities to wildlife and poor response by plants. The oil separation ponds also have to be constructed to prevent migratory birds from landing into the oil pits to prevent additional mortality. Ramirez (2002) used a closed containment system that had low cost and prevented migratory birds from landing in any oil. The system also prevented oil from contaminating the soil.

The Nimr Water Treatment Project in Oman (Breuer 2011) was installed to treat ~283,000 bbls/d of produced water. Water is separated from the oil then delivered to a series of

wetland terraces by gravity. The final stage of the system is used to evaporate the water for salt recovery. Additional plans include adding a third project phase which would include biomass utilization from the wetland plants. The Nimr system has been shown to be a plausible method of produced water “treatment” especially in arid climate conditions. It should be noted that the water being treated was brackish with TDS between 7,000-8,000 ppm.

Potential water use for Bakken Oil Formation, North Dakota- Study Case

In North Dakota, using freshwater from glacial and bedrock aquifer systems for hydraulic fracturing was the most common source. However, with increased oil production alongside freshwater sources certain environmental and sustainability stresses necessitated the Northern Great Plains Water Consortium (NGPWC) alongside the Energy and Environmental Research Center (EERC) to find alternatives to current practices. Stepan et al. (2010) were faced with only 17-47% recovery of the water used for fracturing in less than 10 days and was further hindered by TDS levels reaching 220,000 ppm. Because of the low quality and quantity of flow-back water it was difficult to provide cost effective strategies to support the treatment of flow-back water. Water for hydraulic fracturing in Bakken formation requires large amounts of water (10,000 to 60,000 barrels) with the most used in multi-stage fracturing. Furthermore, hydraulic fracturing requires that the water used for fracturing have low TDS and be bacteria free.

The Bakken formation is also different from most in that it contains oil-wet rock with little to no free water. Once fractured, the flow-back water has a different chemical composition than other formations such as natural gas shales, making it difficult to find suitable treatment options (Stepan et al., 2010). In the short term, flow-back from the well contains both oil and water with water content decreasing over time. Typical salinity of the flow-back water was 100,000 ppm TDS and levels of 200,000 ppm were not unusual. High salinity water such as this necessitates alternative treatment such as mechanical vapor recompression after pretreatment for scale (Stepan et al., 2010). Water such as found in the Bakken formation is expensive to treat and would require high salinity flow-back water recycling technologies that include thermal and membrane treatment.

Logistics of the Decision Support Tool

The decision-support tool (DST) consists of four macro-enabled Excel workbook modules: Water Quality Module (WQM), Treatment Selection Module (TSM), Beneficial Use

Screening Module (BSM), and Beneficial Use Economic Module (BEM) (Figure 6.6). The WQM stores various water quality data, such as oil and gas hydraulic flowback and produced water quality of different basins and formations. Users can input their water quality data into the template provided by the WQM. In the TSM, the tool selects proper treatment technologies based on feed water quality, user preferences, and desired product water quality. The BSM stores water quality requirements for different beneficial use purposes, such as potable use, irrigation, hydraulic fracturing liquid, livestock watering, and surface discharge. The BEM calculates costs based on selected treatment technologies, desired product water flow rate, and economic inputs assigned by user, and outputs unit cost in \$/gallon and annual cost in \$/year for capital cost, operation and maintenance cost, energy consumption.

The DST framework provides a quick analysis and screening of various produced water treatment and management options. The Graphic User Interface (GUI) of the DST and model inputs are illustrated in [Appendix F](#).

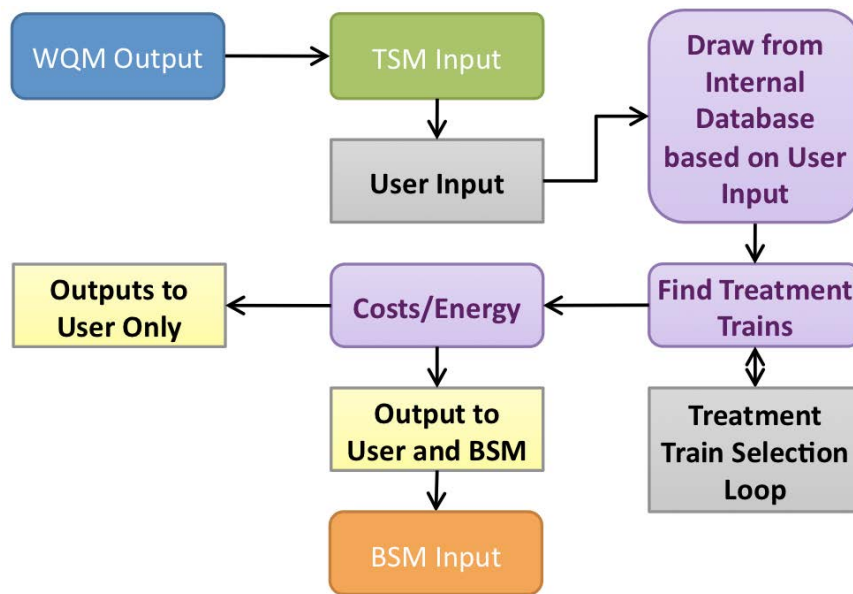


Figure 6.6 Schematic diagram describing the DST.

A produced water quality database was obtained from Martha Cather with the New Mexico Institute of Mining and Technology, in the form of spreadsheet with well information, sampling information, major cations and anions, and bulk water quality parameters. Other water

quality data sources include oil and gas producers, previous work conducted at New Mexico State University, and U.S. Geological Survey (USGS).

Quality assurance and quality control (QA/QC) was conducted to exclude data with experimental errors, human errors, and from samples that were polluted or improperly stored/transported. QA/QC standards were adopted from the method used by the U.S. Geological Survey (USGS) National Produced Waters Geochemical Database v2.1 (Provisional). QA/QC standards include: (i) concentration of magnesium lower than calcium; (ii) concentration of potassium lower than chloride; (iii) concentration of potassium smaller than sodium times five; and (iv) pH value between 5 and 10. Exceedance of standards may be caused by extended lag time between sampling and analysis, typing error, poor analysis, poor sampling, and/or contamination by drilling mud, cement wash, and acid wash (Hitchon et al., 1994). Table 6.6 summarizes the number of data sets exceeding standards in Eddy and Lea County produced water quality database. Total numbers of data sets after QA/QC are 862 and 2,864 for Eddy and Lea Counties, respectively.

Table 6.6 Summary of QA/QC for produced water quality database in Eddy and Lea Counties.

Standards	Eddy County	Lea County
Mg < Ca	126	58
K < Cl	1	1
K < 5Na	1	2
5 < pH < 10	17	1

Average total dissolved solids (TDS) levels for Eddy and Lea Counties are 93,840 and 87,956 mg/L, respectively. To better understand the salinity levels and more accurately determine desalination technologies, TDS levels are classified into five TDS bins, defined as Bin 1: TDS < 8,000 mg/L; Bin 2: 8,000 – 25,000 mg/L; Bin 3: 25,000 – 40,000 mg/L; Bin 4: 40,000 – 70,000 mg/L; and Bin 5: TDS > 70,000 mg/L. The classification is based on the treatment capacities of different water desalination technologies, such as 25,000 mg/L for brackish water reverse osmosis (BWRO), 40,000 mg/L for seawater reverse osmosis (SWRO), 70,000 mg/L for forward osmosis (FO). Desalination of feed water in the higher bin have significantly higher costs than that in the lower TDS bins.

Figure 6.7 summarizes the number of wells and mean TDS values in each TDS Bin. Average TDS is around 90,000 mg/L in both counties, with half of the wells falling in Bin 5 with TDS over 70,000 mg/L. Produced water in Eddy County has slightly higher salinity than in Lea County, but both are sodium-chloride type of water, as shown in Figure 6.8. For these hypothetical case studies, produced water quality data were classified based on geological formations to more accurately determine treatment processes required, and thus evaluated for the potential beneficial reuse.

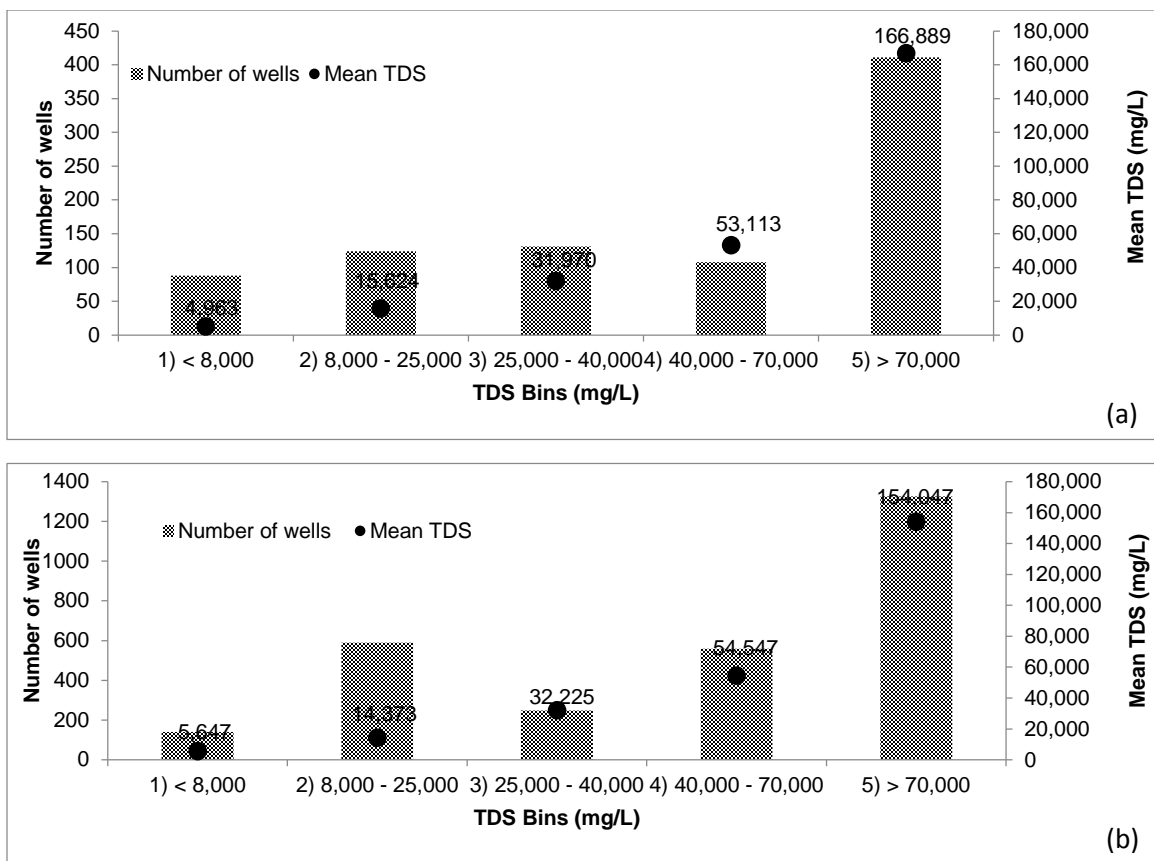


Figure 6.7 Number of wells and mean TDS levels in each TDS Bin in (a) Eddy and (b) Lea Counties.

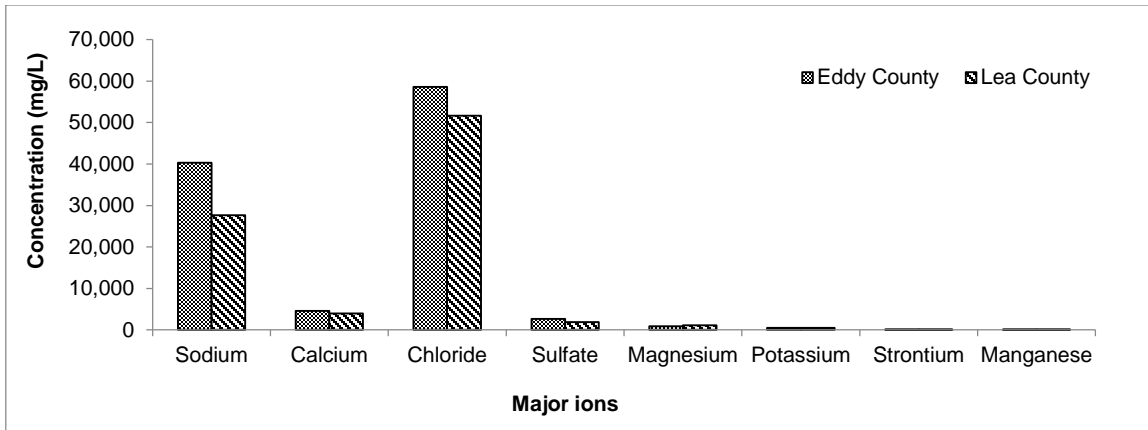


Figure 6.8 Major ions in produced water in Eddy and Lea Counties.

Beneficial Use Options

Potential produced water beneficial use options in the Permian Basin region include hydraulic fracturing fluid and agricultural irrigation. Other beneficial use applications, such as groundwater recharge, require better water quality thus leading to high desalination costs, which make it economically unfeasible. Two common hydraulic fracturing liquid compositions are slickwater and cross link gel systems. Slickwater system requires water having TDS lower than 40,000 mg/L, while cross link gel system does not have strict TDS requirement but have specific requirements on certain ions (Table 6.7). Both water quality requirements are achievable by treating Permian Basin produced water while keeping the costs feasible.

Table 6.7 Hydraulic fracturing water quality requirements.

Hydraulic Fracturing System	Cross Link Gel System	Slickwater System
pH	6.0 - 8.0	> 5
Total Suspended Solids		< 0.1
Microbes	Require disinfection	
Hardness (Ca+Mg)	< 2,000 mg/L	-
Iron	< 20 mg/L	-
Sulfate	200 - 1,000 mg/L	-
Chloride	< 40,000 mg/L	-
Bicarbonate	< 1,000 mg/L	-
Boron	< 10 mg/L	-
Multivalent Ions	-	< 5,000 mg/L
TDS	-	< 40,000 mg/L
Reducing Agent	< 25 mg/L	-

Agricultural irrigation water quality requirement is determined to prevent severe conditions for plant growth as shown in Table 6.8. Sources of the requirement are collected from previous projects, New Mexico regulations, and in cooperation with New Mexico State University Extension Plant Sciences Department (Flynn, 2016; Dahm and Guerra 2011).

Table 6.8 Agricultural irrigation water quality requirement in Lea and Eddy County.

Constituents	Crop Irrigation (mg/L)
Aluminum	5
Arsenic (III)	0.1
Arsenic (V)	0.1
Chromium, total	0.5
Copper	1
Fluoride	1.6
Lead	0.05
Lithium	15
Nickel	0.2
Selenate	0.02
pH	6 to 9
TDS	2000
SAR	6
Chloride	250
Sodium	460
Boron	0.75
Bicarbonate	518.5
TSS	100
Iron	1.5
Manganese	1.5
Hydrogen Sulfide	2
Bacteria	0.002
Virus	0.0004

Reusing produced water for Pecos River augmentation is another potential beneficial use endpoint. Previous studies include a preliminary technical and cost analysis for delivery of treated produced water from Indian Basin and Dagger Draw to the Pecos River

(Hicks, 2003) and a feasibility study on produced water reuse conducted for Water Reclamation Committee of the JPA Lea/Carlsbad Soil and Water Conservation Districts (NRCE, 2004). Preliminary effluent limitations of Pecos River augmentations are regulated by U.S. Environmental Protection Agency (USEPA). Detailed water quality requirement is listed in Table 6.9. Other potential beneficial use options include potash mining, on-site dust and fire control, and thermal power plant cooling.

Table 6.9 Pecos River augmentation water quality requirements.

Parameter	Concentration (mg/L)
TDS	5000
Aluminum	0.096
Mercury	0.0132
Selenium	0.00333
Silver	0.0023
Sulfate	2500
Chloride	4000
Copper	0.2
Cadmium	0.01
Arsenic	0.1
R 226 + 228 (pCi/L)	60

Case Study Assumptions

Eleven assumptions were made for cost analysis. Electricity price was assumed at \$0.119/kWh, while labor cost was estimated at \$60,000/year, considering the salary level in Lea and Eddy County area. Product water flow rate was assumed to be 9,000 bbl/day, according to the treatment facility operated by Devon Energy. Price of coagulants and other chemical additives were assumed to be \$1000/ton, according to market price. Pumping cost was assumed to be 10% of capital cost. Water recovery of desalination processes was assumed to be 50%, as it's a reasonable level for highly saline feed water, which led to 9,000 bbl/day waste water (brine) production and requires disposal. Liquid waste disposal rate was assumed to be \$1/bbl, including

pumping, transportation, and injection. Solid waste was assumed to be disposed twice a week. Landfill facilities were identified from NMED website. Distances from treatment facilities to landfill facilities were estimated using Google Earth. Average truck speed was assumed to be 40 mph for liquid transport and 50 mph for solid transport. Labor cost for trucking was assumed to be \$90/hr. Liquid trucking was regulated to not exceeding 120 bbl/load. Overall unit costs followed Engineering Class V level conceptual design, with the range at -30% to +50%. The costs for produced water collection system were not included in the cost analysis because of lack of data and highly variable construction costs.

Case Study Results

Agricultural Irrigation

The study area for produced water use in agricultural irrigation was determined based on geospatial mapping of the Lea and Eddy Counties, with layers of active wells and agricultural areas (Figure 6.9). Water volume and quality data were aggregated at the township scale. A number of townships near Hobbs, New Mexico were selected, having both high volumes of produced water and lower average TDS. A buffer of 9-miles was created around the mean center of all wells located within the selected townships. Produced water in the selected area has an average TDS of 39,050 mg/L, with other parameters listed in Table 6.10. Produced water transport distance was set to be 10 miles from mapping information.

Table 6.10 Major produced water quality parameters in selected irrigation area.

Water Quality Parameter	Produced Water Concentration	Irrigation Requirement
pH	7.27	6 – 9
TDS	39,050 (mg/L)	1,500 (mg/L)
Sodium	27,590 (mg/L)	460 (mg/L)
Calcium	2,272 (mg/L)	-
Magnesium	1,449 (mg/L)	-
Chloride	23,323 (mg/L)	250 (mg/L)
Bicarbonate	1,246 (mg/L)	518.5 (mg/L)
Sulfate	1,482 (mg/L)	-

Based on the TDS concentration of produced water, seawater reverse osmosis (SWRO) was chosen as the desalination technology to recover 50% of the produced water for irrigation use. A three-phase separator is required to remove crude oil and gas, followed by settling and storage tank. Suspended solids and hardness (calcium and magnesium) need to be removed to prevent SWRO membranes fouling and scaling using chemical softening and media filtration. The solid waste generated from softening and filtration needs appropriate disposal, and the SWRO brine can be disposed through deep well injection. The final treatment train is 1) three-phase separator, 2) settling and storage tank, 3) chemical softening, 4) media filtration, 5) seawater RO, and 5) solid and liquid waste disposal.

Treatment costs were estimated based on selected technologies, feed and target water quality, and product water quantity. Operational cost is \$9.59/kgal, capital cost \$1.13/kgal (assuming 10 years life time), and energy consumption 16.76 kWh/kgal as SWRO is a high pressure process. Overall average treatment cost is \$12.81/kgal. Considering the cost range of -30% to +50% for the Engineering Class V Conceptual Design, the unit treatment cost may vary from \$8.97 /kgal to \$19.22/kgal. Total waste disposal cost is \$23.85/kgal. Compared with full-scale municipal seawater desalination costs (\$2.5-7.9/kgal) (Xu et al., 2009), the cost of produced water treatment is much higher. Reasons include economic scale of treatment facilities (small produced water treatment system versus large scale SWRO plant), high salt concentration, and pre-treatment to remove sparingly soluble salts, water delivery system, and labor cost.

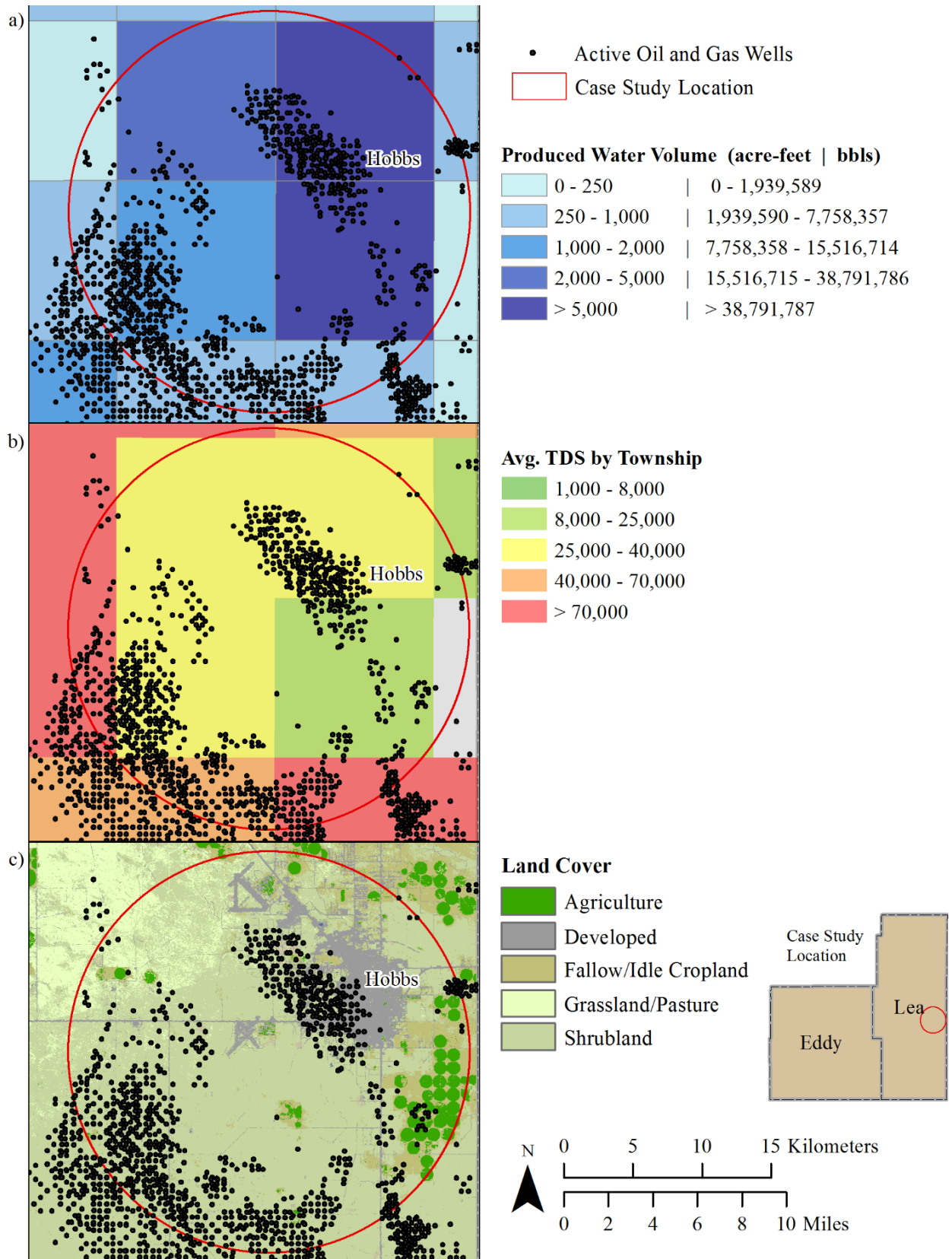


Figure 6.9 Location of analysis based on a) volume, b) TDS, and c) proximity to agriculture.

On-site Reuse for Hydraulic Fracturing

Reusing produced water on-site reduces the transport of freshwater and produced water. Hydraulic fracturing requires relative lower water quality. Cross-link gel system does not require TDS concentration, but limits hardness, while slickwater system requires 40,000 mg/L TDS level, but has minimal requirements on other ions.

Feed water quality for this end use is based on the mean value of produced water quality in Lea County for a more general case (Table 6.11). Produced water TDS concentration is 62,814 mg/L and production was assumed to be 1.1 bbl/well/day, calculated from the annual produced water quantity in Lea County and number of active wells. A cluster of 100 wells was assumed.

To reuse for hydraulic fracturing, suspended solids, petroleum hydrocarbon, and microbes are required to be removed. After three-phase separator and preliminary settling in storage tank, produced water will be treated by chemical coagulation/flocculation/settling and media filtration. For cross-link gel system, no desalination is required, but the concentrations of Ca and Mg (2788 mg/L), and concentration of sulfate (1560 mg/L) in produced water do not meet the water quality requirement for gel system, 2000 mg/L and 200-1000 mg/L, respectively. Lime needs to be added to soften the water and precipitate sulfate as gypsum. Previous studies demonstrated semi-passive limestone/lime process could reduce sulfate in mine waters to < 1000 mg/L (Bowell, 2004). But to achieve lower sulfate concentrations, barium salts such as (e.g., BaCO_3 , $\text{Ba}(\text{OH})_2$) and lime would be added to the effluent to soften the water and produce a precipitate. CaCO_3 is necessary to act as a seed to encourage BaSO_4 formation from BaCO_3 due to the insolubility of the latter ($K_{sp} \sim 10^{-8}$). The slurry from the reactor is then sent to a thickener where clean water can be decanted and reused for hydraulic fracturing. The thickened slurry is then filtered, dried and disposed. The solids can also be treated to recycle barium.

For slickwater system, preliminary settling followed by chemical coagulation/flocculation/settling and media filtration may be required to remove suspended solids and organic matter. Produced water TDS concentration (62,814 mg/L) is higher than the required 40,000 mg/L TDS for slickwater system. Desalination using seawater RO is an alternative to reduce the TDS by 37%. Blending the filtered produced water with lower TDS water at proper ratio to reach 40,000 mg/L TDS concentration is another lower cost alternative.

As no desalination process is required, reusing for cross-link gel system hydraulic fracturing and for slickwater system using blending have a relatively low cost, with operation

cost at \$5.13/kgal, capital cost at \$1.07/kgal. As no liquid waste is generated, the overall average cost is much lower, at \$6.33/kgal, with variation of \$4.43-\$9.50/kgal for Engineering Class V Conceptual Design). Reusing for slickwater system hydraulic fracturing with SWRO desalination has the treatment cost at \$7.07/kgal, in range of \$4.95 – \$10.61/kgal, Energy consumption is 5.99 kWh/kgal and waste disposal cost is \$23.84/kgal. Operation and capital costs are similar to other options.

Table 6.11 Major ions in selected study area for Pecos River augmentation.

Parameters (mg/L)	Lea Produced Water	Cross Link Gel System	Slickwater System
pH	7.05	6.0 - 8.0	> 5
TDS	62,814	-	< 40,000 mg/L
Sodium	18,954	-	-
Barium	0.11	-	-
Iron	1.58	< 20 mg/L	-
Calcium	2140	Ca + Mg < 2,000 mg/L	-
Magnesium	648	-	-
Potassium	320	-	-
Strontium	51	-	-
Manganese	0.55	-	-
Chloride	35992	< 40,000 mg/L	-
Carbonate	-	-	-
Bicarbonate	582	< 1,000 mg/L	-
Sulfate	1560	200 - 1,000 mg/L	-
TSS	-	< 0.1	-
Multivalent Ions	-	-	< 5,000 mg/L

Currently there is limited understanding on the water quality requirements for hydraulic fracturing. It depends on the fracturing method and geological formation. The water quality requirements listed in Table 6.11 are just examples that illustrates produced water in the Permian Basin can be used for hydraulic fracturing with minimal treatment.

Pecos River Augmentation

The location of this analysis was in central Eddy County west of where the Pecos River runs through Carlsbad (Figure 6.10). Townships were selected based on the average aggregated TDS values. Approximately 759 active wells were included in the cluster, with total annual produced water production of 17 Mbbbls. Produced water transport distance is 4.5 miles, according to the mapping. Produced water quality in the selected area is relatively good, with TDS of 34,120 mg/L. Major ion concentrations are shown in Table 6.12.

Pecos River augmentation requires the effluent TDS less than 5,000 mg/L, for which ED is recommended to achieve partial removal. No hardness standard is required, but softening is required to avoid scaling of ion exchange membranes. Final treatment train is 1) three-phase separator, 2) settling and storage tank; 3) chemical softening/settling, 4) media filter, 5) electro dialysis, and 6) waste disposal. The produced water quality data used in this case study is lacking detailed information on heavy metals such as mercury and arsenic, as well as information on radioactive matters that significantly affect human and animal health. More detailed analysis of produced water and treated water is required for further study before discharging treated water into the Pecos River.

Operation cost and energy consumption are \$4.68/kgal and 4.48 kWh/kgal, both lower than SWRO. Capital cost is \$4.89/kgal, relatively higher than others as ED was adopted. Solid and liquid waste disposal are required, with the cost at \$23.83/kgal. Overall treatment cost is \$10.62/kgal (ranging from \$7.43/kgal to \$15.92/kgal). Produced water quantity in the selected area is higher than others, leading to higher capital cost but lower unit cost. The good feed water quality also contributes to the lower operation cost energy and consumption.

Table 6.12 Major ions in selected study area for Pecos River augmentation.

Parameters	Produced Water (mg/L)	Pecos River Augmentation Requirement
pH	7.37	-
TDS	34,120	5,000
Sodium	5,079	-
Calcium	1,471	-
Magnesium	472	-
Chloride	19,398	4,000
Sulfate	1,652	2,500
Bicarbonate	1,442	-

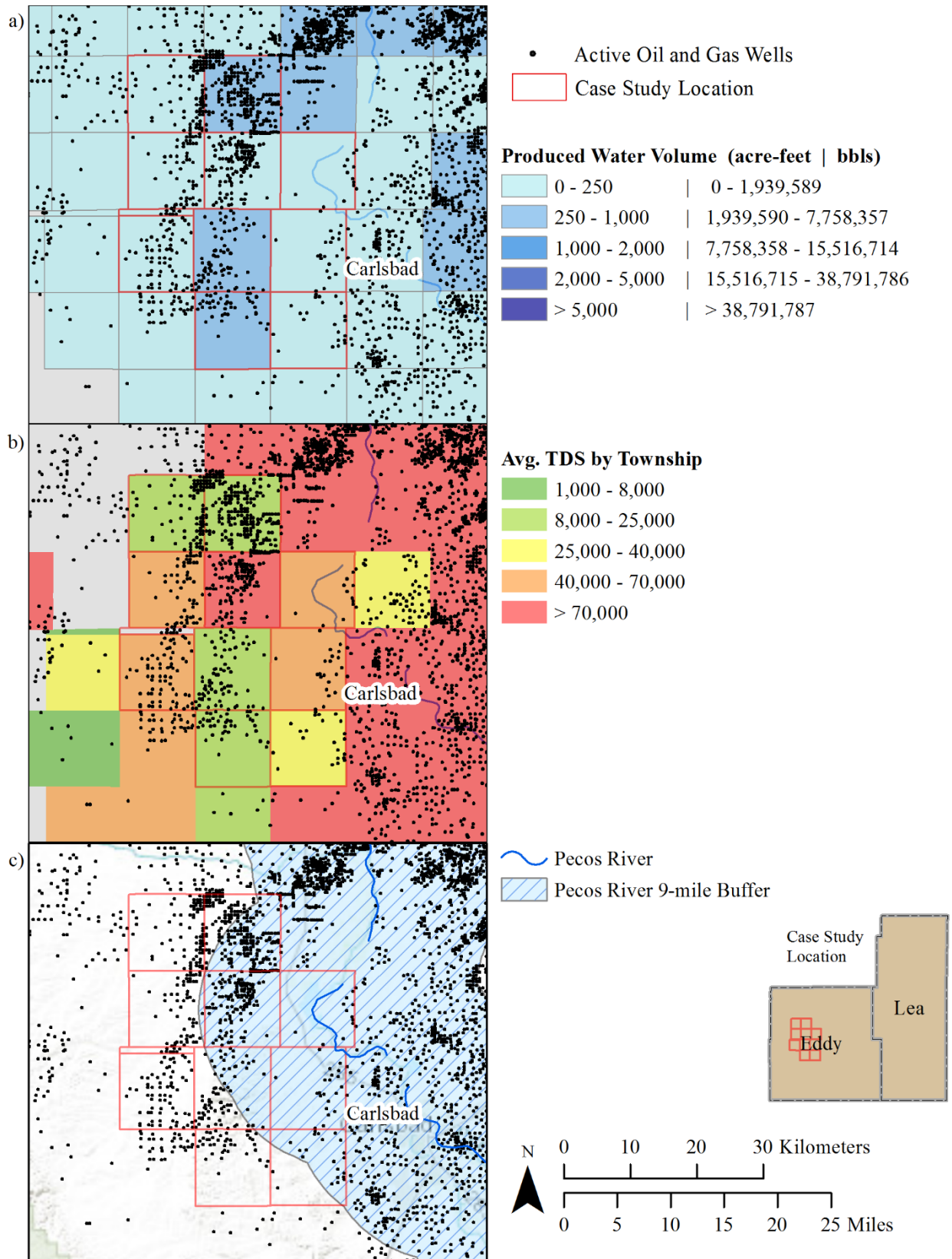


Figure 6.10 Location of analysis based on a) volume, b) TDS, and c) proximity of Pecos River.

Mining

Potash mining consumes 20% of water usage under industry catalog, primarily used for mineral extraction and process, metal recovery, and dust control. Acceptable water quality is 100,000 mg/L TDS, with limited suspended solids, hydrocarbons, radioactive matters, trace metals, and fracturing additives. Based on the study area selected, average TDS level is 145,517 mg/L (Table 6.13). At this high level of TDS, very few technologies have the ability to remove salts in the water. However, most pre-treatment technologies can apply to all TDS levels, to remove the contaminants mentioned above to produce clean brine. To achieve the required TDS level, the cleaned brine is blended with freshwater with proper ratio. Produced water transport distance is 10 miles according to mapping.

Table 6.13 Major ions in selected area for mining.

Parameters	Concentration (mg/L)	Mining water quality requirement
pH	6.52	-
TDS	145,571.4	100,000
Sodium	58,208	-
Calcium	11,887	-
Iron	107	-
Magnesium	2,008	-
Manganese	2.65	-
Chloride	93,238	-
Bicarbonate	420	-
Sulfate	1,165	-

Treatment processes include 1) three-phase separator, 2) settling and storage tank, 3) chemical softening/coagulation/flocculation/sedimentation, 4) media filter, and 5) waste disposal. Estimated operation cost is \$1.069/kgal, similar to that for cross-link gel system hydraulic fracturing, as they have similar treatment processes. Longer transport distance leads to a higher operation cost at \$9.59/kgal. As no liquid waste was generated, overall treatment cost is relatively low, at \$10.82/kgal, with the range of \$7.57 - \$16.23/kgal.

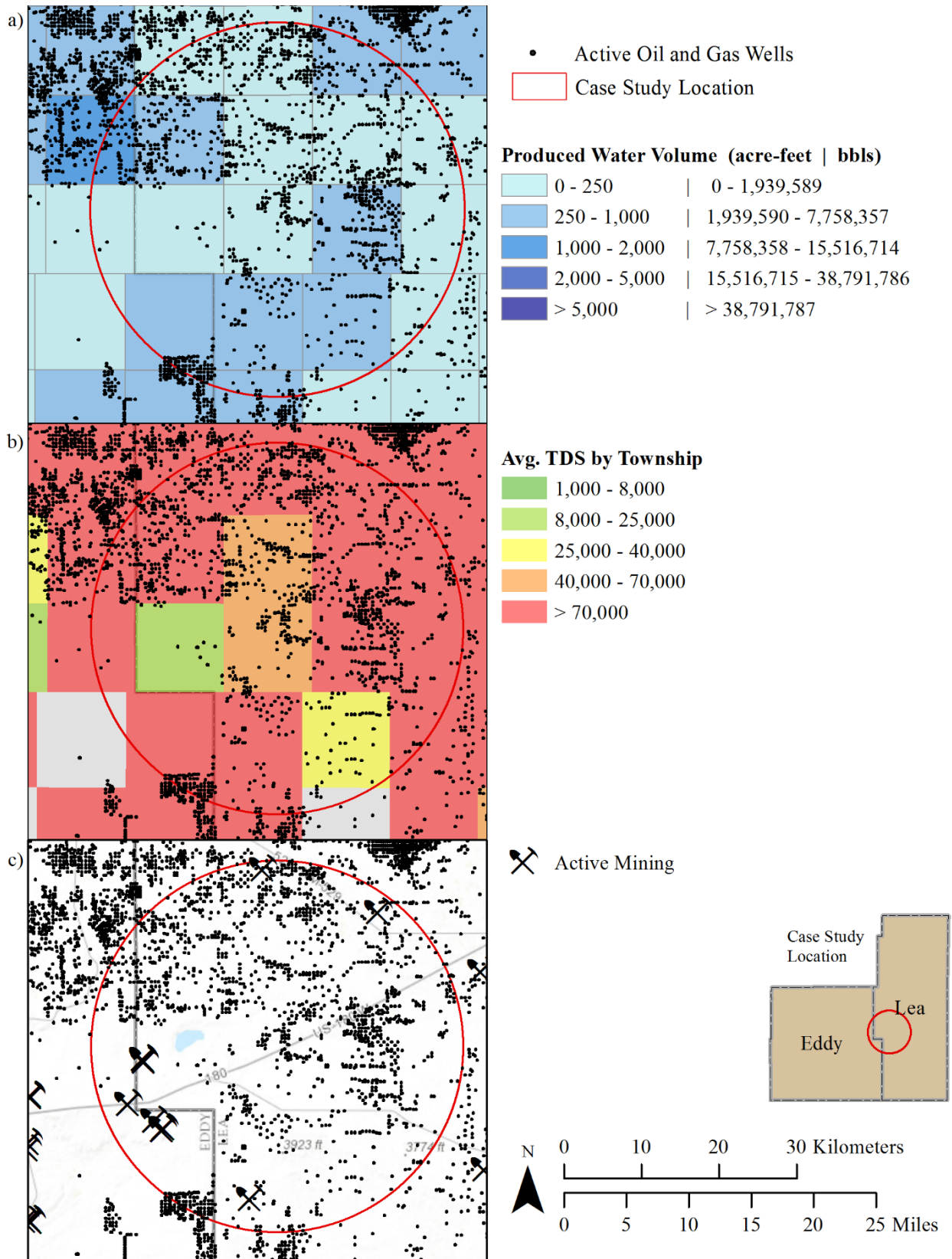


Figure 6.11 Location of analysis based on a) volume, b) TDS, and c) proximity to active mines.

Conclusion

This research provided an overview of four potential beneficial uses of produced water in Lea and Eddy Counties. A summary of considerations for irrigation use was provided for four commonly grown crops in the region. From a quality standpoint, treatment technologies are available to treat the produced water to the desired standards, but may not be economically feasible depending on the feed water quality. Some areas of Lea and Eddy Counties appear to have large volumes of water that could support agricultural use. Further analysis on conveyance costs and optimally locating treatment facilities would need to be performed prior to any specific application of produced water.

This study also used a recently developed decision-support tool (DST) to evaluate potential beneficial use of produced water in Permian Basin for four hypothetical scenarios: hydraulic fracturing (cross-link gel system and slick water system), agricultural irrigation, Pecos River augmentation, and potash mining. Uses of the produced water for hydraulic fracturing is the most feasible and economic viable option followed by potash mining, and river augmentation. Reusing produced water for agricultural irrigation has the highest cost because desalination processes are needed to reduce the salt concentration.

Due to limited data on produced water quality, the treatment processes selected and cost estimates are very preliminary and subject to dramatic change after we gain a better understanding on produced water quality through actual field water sampling, analysis, and pilot testing of the treatment processes.

Based on the preliminary economic analysis, all reuse options are beneficial considering the expensive disposal cost of produced water (\$1/bbl). Table 6.14 summarizes the results of cost and benefit analysis, considering all kinds of costs including raw produced water disposal, treatment, and waste stream disposal from treatment. Reusing produced water for hydraulic fracturing with cross-link gel system and slickwater system with blending are the most beneficial options, saving over \$13,000 per day, plus extra saving on buying freshwater, which is approximately \$2-10/kgal. Reusing for mining costs higher for treatment, but still saves over \$9,800 per day, plus extra saving on buying water. Other options require desalination process, which leads to higher treatment cost and liquid waste disposal. But with extra savings on buying water, all potential options are economically beneficial.

6.14 Summary on benefit analysis of produced water reuse.

	Irrigation	Cross-link Gel	Slickwater w/ SWRO	Slickwater w/ Blending	Pecos River Augmentation	Mining
Disposal Cost (\$/day)	18,000	18,000	18,000	18,000	18,000	18,000
Liquid Waste Disposal (\$/day)	9,000	-	9,000	-	9,000	-
Unit Treatment Cost (\$/kgal)	12.81	6.33	7.07	6.33	10.62	10.82
Unit Treatment Cost (\$/bbl)	0.538	0.266	0.297	0.266	0.446	0.454
Treatment Cost (\$/day)	4,842	4,787	2,672	4,785	4,014	8,180
Product Flow Rate (bbl/day)	9,000	18,000	9,000	18,000	9,000	18,000
Marginal benefits (\$/day)	4,158	13,213	6,327	13,215	4,986	9,820
Additional benefits	With additional agricultural benefit	With extra save on buying freshwater	With extra save on buying freshwater	With extra save on buying freshwater	Makes up water withdrawal	With extra save on buying freshwater

In addition to technical viability and economic feasibility, beneficial use of produced water needs to consider environmental impact and public acceptance to utilize produced water. Some water users may be concerned about water quality and liability issues related to produced water. With the continuous drought, depletion of groundwater supplies, and technology advances in particular for highly saline water treatment, beneficial use of produced water will become more attractive to protect local fresh water resources. Other factors to consider for evaluation the beneficial use potential should include water demand, reliability, quality, price, value, and how those factors compare with alternative water supplies in the region.

The analysis suggests that produced water does have the potential for reuse. Treatment for produced water will vary depending on the ultimate desired quality of the final product of water. Cost and treatment technologies increase in value when the produced water is intended for demanding quality parameters such as in agriculture, as it not only follows specific water quality levels but also requires to meet human and environmental health concerns. It is less demanding if it is to be re-used within the industry, and shows to be the most beneficial location for re-use. Although it might seem unreasonable and highly expensive to treat produced water to such high

quality of water, the market for this new water stream can be a potential benefit in the future for the producers and end users. As treated produced water becomes a new source of water stream, the costs for treatment can fluctuate and become more competitive as more technologies are being developed and implemented. With treatment technologies advancing and giving the industries the capability to reach high levels of water quality; the question has really changed from ‘how can we clean this water’ to ‘what level of treatment would you like to apply to this water?’ The treatment technologies have continuously advanced that the restrictions are no longer in the treatment process but rather in the absence of directional jurisdictions that are essential in moving forward with these promising plans. It has also shown to be a much larger recycled source of water stream than the available freshwater resources in the region (Sullivan Graham et al., 2015). With direct organization and management from state and federal agencies we can advance in the possibilities of implementing a helpful layout for farmers/ranchers to work closely with oil and gas industries for future usage of produced water. Literature reviews have been done in regards to re-using in produced water, however, future pilot studies done in Southeast New Mexico, implementing produced water through different treatment technologies for alternative uses can help mitigate some changes in regulations that are currently restraining future usage.

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APPENDICES

Appendix A: Produced Water Data Description

There are seven tables in the Produced Water Quality Database. Relationships between the tables are shown in Figure A1. The relationships are discussed in the following paragraph. Individual tables are described more completely in subsequent paragraphs and attributes and attribute descriptions shown in subsequent figures and tables.

Table Relationships

PRRC_PWQ_SampleInfo is the master table for the water quality part of the database. This table contains the unique sample ID for each record. Sample ID relates one-to-one to the Sample ID in the **PRRC_PWQ_Sample_Quality** table. **PRRC_PWQ_SampleInfo** contains well identification and location information along with information about formations and pools for individual samples. **PRRC_PWQ_Sample_Quality** contains the actual numerical data. The table **PRRC_PWQ_SampleInfo** does not have a one-to-one relationship with the **NM_Well_Locations** table. The API number does relate in both tables, but both tables have records in them that are mutually exclusive to the table. **NM_PRRC_PWQ_SampleInfo** does have some data from the adjacent states of Colorado and Texas, and a few samples that do not have API numbers. **NM_Well_Locations** contains location information for all the wells in New Mexico that are currently recorded in the NM OCD ONGARD database. Location information is derived from either the NM OCD, or through a location-calculation routine based on the footage and section/township/range description. **NM_Water_Volumes** contains information about volumes of produced and injected waters including cumulative totals and annual totals for 2014 and 2015, the last complete years for reported water volumes. This information is derived from the ONGARD database using volume data reported by month and year. **Last_Water_Inj** and **Last_Water_Prod** contain the last year that a volume was reported for a given combination of API and pool. This information would be necessary in identifying potential areas for water reuse projects. Two additional tables are provided for reference. **Pool_Codes** contains a list of OCD pool IDs, their official name and a cleaned and standardized version of that name for pools found in the database. Not all New Mexico pool codes are included in this list. **Well_Location_Codes**

contains a listing and descriptions of various codes used in several attribute fields in **NM_Well_Locations** and is a lookup table.

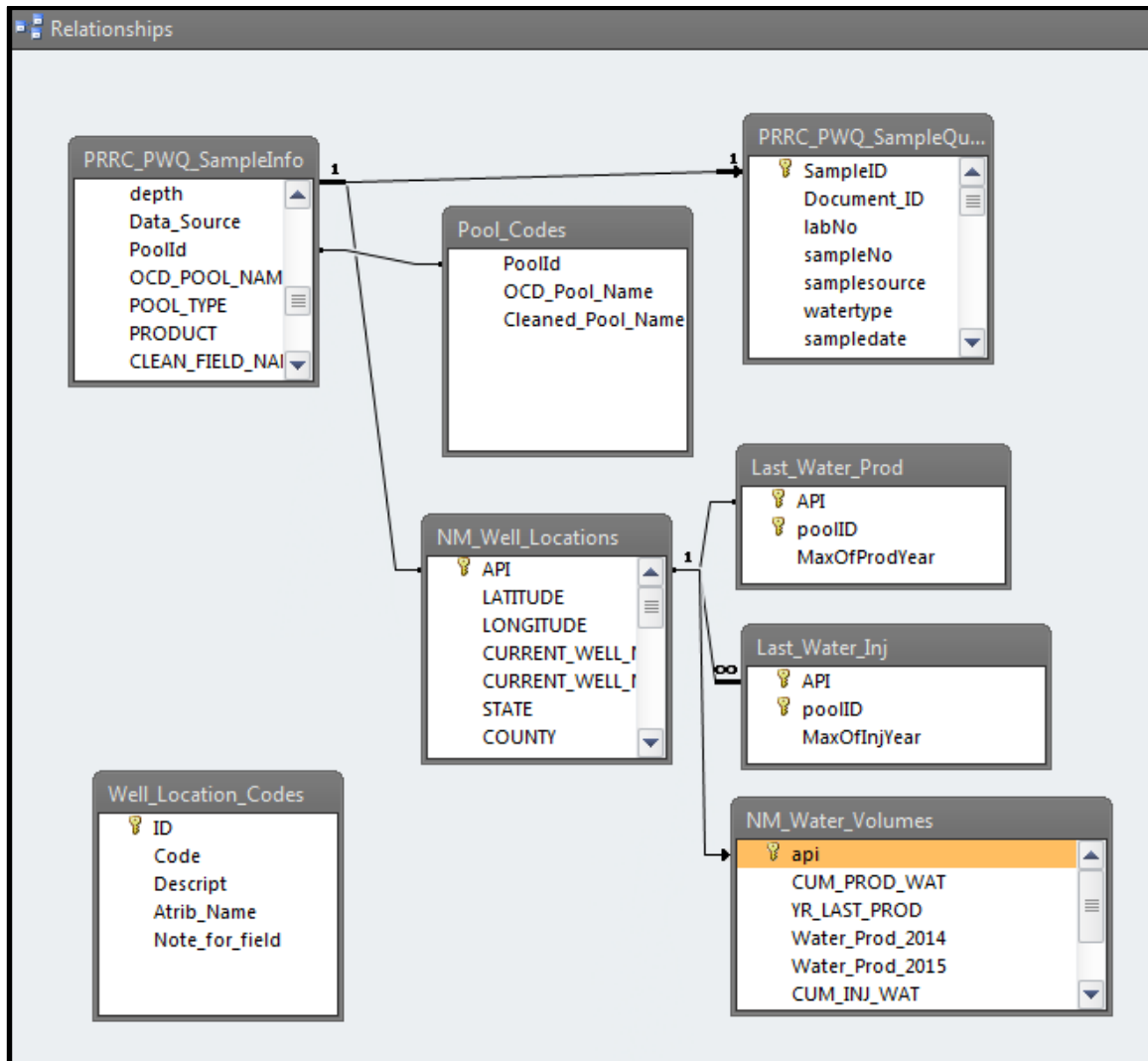


Figure A1 Relationship diagram for tables in database.

All wells in the **Last_Water_Inj**, **Last_Water_Prod**, and **NM_Water_Volumes** tables are found in the **NM_Well_Locations** table, and relate to sample information via the API, and, where available, the Pool ID. Not all wells can be assigned a pool identification number. If a well does not produce (dry hole, shut in, etc.) or is not in an area defined as a regulatory pool there may insufficient information to assign pool, formation, or play information.

Table Descriptions

Table A1 shows attribute descriptions and table property for the PRRC_PWQ_SampleInfo table. Table A2 shows the same information for PRRC_PWQ_SampleQuality. They are related through SampleID. Table A3 shows the number of non-zero records for various water quality parameters.

Table A1. Attributes and description of PRRC_PWQ_SampleInfo table.

Field Name	Data Type	Description
SampleID	Number	ID Number
Well_Name	Text	Current well name
WellId	Text	Current well ID number, usually 3-digit, sometimes followed by alpha-numeric, variable in Colorado
api	Text	10-digit API number assigned by NM OCD
Document_ID	Text	name of document data is from, if available
latitude	Number	latitude, most derived from NM OCD UTM NAD83 well file
longitude	Number	longitude, most derived from NM OCD UTM NAD83 well file
section	Text	section designation (1-36)
township	Text	Township number
township_dir	Text	Township direction, N or S
range	Text	Range number
range_dir	Text	Range direction, N or S
ftgns	Text	Footage call - feet from north or south section line
ftgns_dir	Text	Direction of footage from section line - N would mean X number of feet from the north section line, S means from the south line
ftgew	Text	Footage call - feet from east or west section line
ftgew_dir	Text	Direction of footage from section line - E would mean X number of feet from the east section line, W means from the west line
unit	Text	Unit or smallest parcel of land, Usually A-P unless the unit is in an irregularly-sized parcel of land, then has a number designation
County	Text	County of surface location
state	Text	State of surface location
company	Text	Company, if reported, in original database
field	Text	Cleaned version of NM OCD field name
formation	Text	Cleaned version of NM OCD production formation name
depth	Text	depth of sample, where provided
Data_Source	Text	Source for data. NMWAIDS = old version of database

PoolID	Number	Official NM OCD Pool Code. Efforts were made to use pool that well was producing from in the year the sample was collected if possible and info otherwise not available
OCD_POOL_NAME	Text	Official NM OCD Pool Name, from which information in other fields is derived
POOL_TYPE	Number	OCD classification of pool
PRODUCT	Text	OCD classification of product
CLEAN_FIELD_NAME	Text	Field name, cleaned of misspellings, odd comments, punctuation, etc.
CLEAN_FM_NAME_SHORT	Text	Formation name, cleaned of misspellings, weird abbreviations, odd punctuation, etc.
CLEAN_FM_NAME_FULL	Text	Same as above but all formation names spelled out
Play_Name	Text	Useful for grouping data - derived from work performed for U.S. BLM Carlsbad and Farmington Field Offices RFD Documents
ALT_NAME1	Text	Something useful in mapping
SWD_WC_ETC	Text	Use this to designate SWD or Wildcat wells - Wildcat wells don't belong to a regular pool even though they produce from named formations
MAP_LABELS	Text	Useful for mapping purposes if trying to categorize by pool or formation
Sample_Year	Text	Year of sample analysis or collection, if available. 1900 means we don't know when but not recent
Last_H2O_Prod	Text	Last year water production was reported for the well and pool
Last_H2O_Inj	Text	Last year water injection was reported for the well and pool
PLSS_ID	Text	Corresponds to PLSS ID in township shape files from CADNSDI v.2 - may need modification for some joins to work. Useful for aggregation in mapping or statistical work.

Table A2. Attributes, descriptions, and table properties for PRRC_PWQ_SampleQuality.

Field Name	Data Type	Description
SampleID	Number	ID Number
Document_ID	Text	name of document data is from, if available
labNo	Text	lab number, as on some source forms
sampleNo	Text	sample number, as on some source forms
samplesource	Text	source of sample, if available, usually a descriptor of part of well or facility sampled
watertype	Text	type of water (produced or other) if available
sampledate	Date/Time	Date sampled
analysisdate	Date/Time	Date analyzed

ph	Number	pH
ph_temp_F	Number	temperature pH measured
specificgravity	Number	specific gravity
specificgravity_temp_F	Number	temperature specific gravity measured
tds_mgL	Number	Total Dissolved Solids in milligrams/liter. Some measurements were converted from epn or ppm
tds_mgL_180C	Number	Total Dissolved Solids in milligrams/liter, measured at 180 C
alkalinity_as_caco3_mgL	Number	alkalinity
hardness_as_caco3_mgL	Number	hardness
hardness_mgL	Number	hardness, mg/l
resistivity_ohm_cm	Number	resistivity, all measurements converted to ohm cm
resistivity_ohm_cm_temp_F	Number	temperature resistivity was measured at
conductivity	Number	inverse of resistivity (almost never given in this dataset)
conductivity_temp_F	Number	temperature conductivity was measured at
sodium_mgL	Number	Sodium, given in milligrams/liter
calcium_mgL	Number	Calcium, given in milligrams/liter
iron_mgL	Number	Iron, given in milligrams/liter. Sometimes iron is given as a descriptor in the anions or general remarks field.
barium_mgL	Number	Barium, given in milligrams/liter
magnesium_mgL	Number	Magnesium, given in milligrams/liter
potassium_mgL	Number	Potassium, given in milligrams/liter
strontium_mgL	Number	Strontium, given in milligrams/liter
manganese_mgL	Number	Manganese, given in milligrams/liter
chloride_mgL	Number	Chloride, given in milligrams/liter
carbonate_mgL	Number	Carbonate, given in milligrams/liter
bicarbonate_mgL	Number	Bicarbonate, given in milligrams/liter
sulfate_mgL	Number	Sulfate, given in milligrams/liter
hydroxide_mgL	Number	Hydroxide, given in milligrams/liter
h2s_mgL	Number	Hydrogen Sulfide, given in milligrams/liter. Sometimes H2S is given as a descriptor in the anions or general remarks field.
co2_mgL	Number	Carbon dioxide, given in milligrams/liter
o2_mgL	Number	Oxygen, given in milligrams/liter

anionremarks	Text	non-numerical comments about sample composition
generalinforemarks	Memo	non-numerical comments about sample
Data_Source	Text	Source dataset

Table A3. Number of non-zero records, out of 9493 total records.

Field Name	Number Records >0	Field Name	Number Records >0
SampleID	9493	conductivity_temp_F	187
samplesource	4830	sodium_mgL	4846
watertype	698	calcium_mgL	5338
sampldate	6850	iron_mgL	2874
analysisdate	2062	barium_mgL	698
ph	6478	magnesium_mgL	5235
ph_temp_F	186	potassium_mgL	998
specificgravity	3175	strontium_mgL	694
specificgravity_temp_F	1649	manganese_mgL	1558
tds_mgL	8297	chloride_mgL	8680
tds_mgL_180C	25	carbonate_mgL	553
alkalinity_as_caco3_mgL	78	bicarbonate_mgL	8346
hardness_as_caco3_mgL	75	sulfate_mgL	7330
hardness_mgL	686	hydroxide_mgL	73
resistivity_ohm_cm	1979	h2s_mgL	578
resistivity_ohm_cm_temp, F	1453	co2_mgL	1795
conductivity	194	o2_mgL	88

The table **Last_Water_Prod** (Figure A2) contains the last year that water production was reported for a particular well. This does not necessarily mean the well is plugged or not producing, only that the operator didn't report water production. Data is reported by API and PoolID, so must be aggregated for all information about a given well. Some wells (APIs) have reported production from multiple pools through the years. Figure A3 shows **Last_Water_Inj** which contains similar information for injection of water. **NM_Water_Volumes** (Figure A4) contains summary information for water production and injection. Data includes cumulative production/injection for the well at the API level, and annual production/injection for 2014 and 2015. **NM_Well_Locations** (Figure A5) contains locations for all wells in New Mexico. Attributes include latitude/longitude data from the NM OCD, as well as the unit letter, section, township, and range information, symbology derived from the NM OCD, and an attribute entitled PLSS_ID useful for aggregation of data at the township level. PLSS_ID is an alphanumeric description of the township for a given location that corresponds to that same PLSS_ID in the Cadastral National Spatial Data Infrastructure (NSDI) CADNSDI publication data set for rectangular and non-rectangular Public Land Survey System (PLSS), version 2, available from the New Mexico Resource Graphic Information System (RGIS) at <http://rgis.nmt.edu>. The data in this attribute may need to be modified somewhat to match other versions of the PLSS. Figure A6 shows the **Pool_Codes** table, and Figure A7 shows the **Well_Location_Codes** table. This table is slightly different in that it contains reference codes for several different attribute fields in the **NM_Well_Locations** table. It is to be used as a data dictionary type of table for looking up codes; thus no single field in this table relates directly to any single field in the locations table.

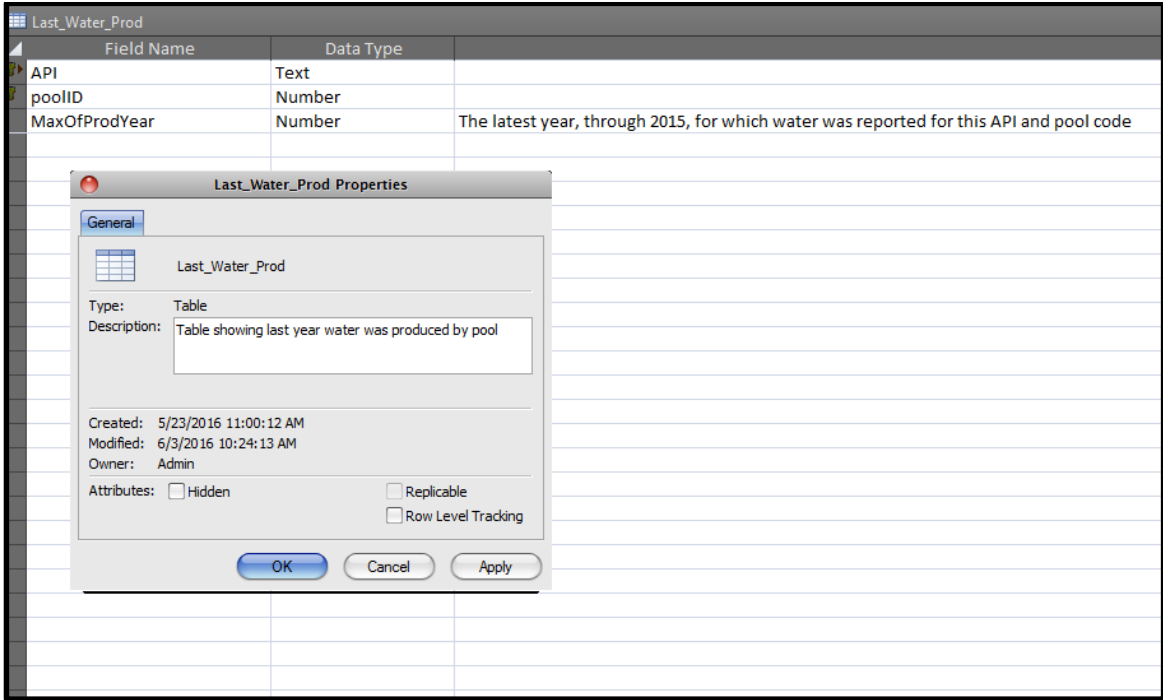


Figure A2 Last_Water_Prod table attributes.

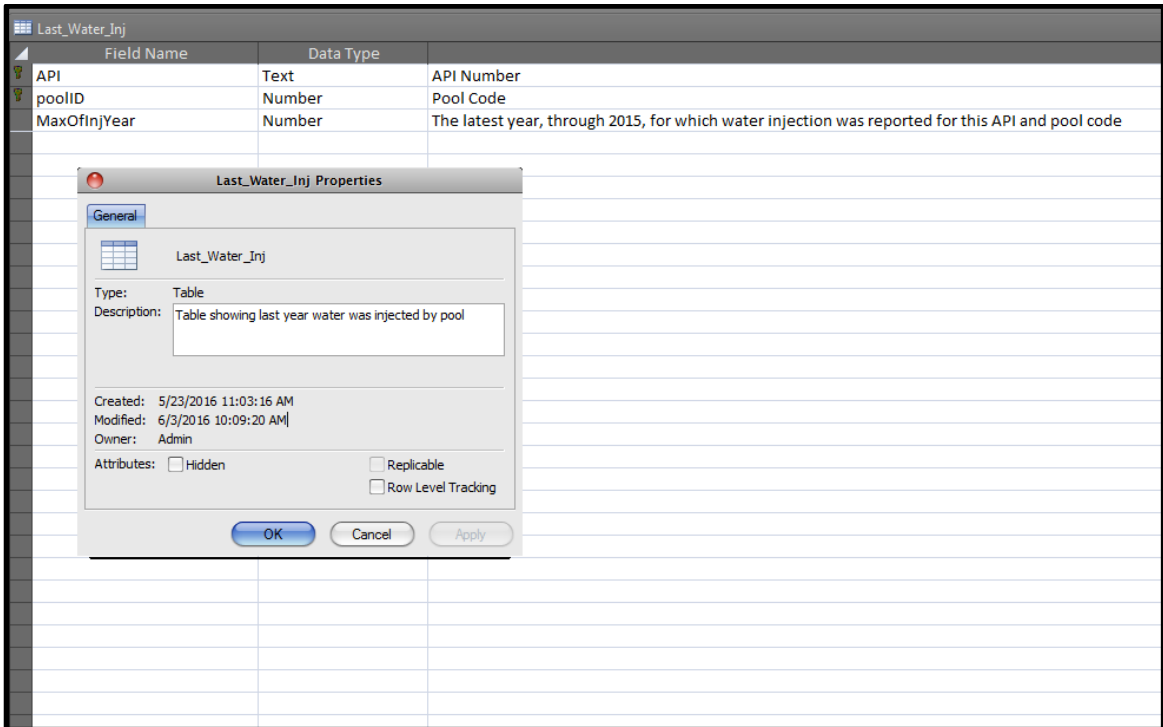


Figure A3 Last_Water_Inj table attributes.

Field Name	Data Type	Description
api	Text	10-digit API number
CUM_PROD_WAT	Number	total reported volume of produced water over lifetime of well, bbls
YR_LAST_PROD	Number	last year of reporting - did not exclude zero-volume years
Water_Prod_2014	Number	total volume of produced water, 2014, bbls
Water_Prod_2015	Number	total volume of produced water, 2015, bbls
CUM_INJ_WAT	Number	total reported volume of injected water over lifetime of well, bbls
YR_LAST_INJ	Number	last year of reporting - did not exclude zero-volume years
Water_Inj_2014	Number	total volume of injected water, 2014, bbls
Water_Inj_2015	Number	total volume of injected water, 2015, bbls

NM_Water_Volumes Properties			
General			
<table border="1"> <tr> <td colspan="2">NM_Water_Volumes</td> </tr> </table>		NM_Water_Volumes	
NM_Water_Volumes			
Type:	Table		
Description:	Table describing production and injection volumes		
Created:	5/17/2016 2:23:36 PM		
Modified:	6/2/2016 10:32:49 PM		
Owner:	Admin		
Attributes:	<input type="checkbox"/> Hidden <input type="checkbox"/> Replicable <input type="checkbox"/> Row Level Tracking		
<input type="button" value="OK"/> <input type="button" value="Cancel"/> <input type="button" value="Apply"/>			

Figure A4 NM_Water_Volumes table containing summary information about production and injection volumes.

Field Name	Data Type	Description
API	Text	10 DIGIT API
LATITUDE	Number	Derived from NM OCD (NAD83) shape files
LONGITUDE	Number	Derived from NM OCD (NAD83) shape files
CURRENT_WELL_NAME	Text	FROM NM OCD EXCEPT THAT PRE-ONGARD DESIGNATION IS NOT USED - LAST KNOWN WELL NAME FROM NM OCD WELL FILE 'NOTES' COLUMN IS USED
CURRENT_WELL_NUMBER	Text	FROM NM OCD EXCEPT THAT PRE-ONGARD DESIGNATION IS NOT USED - LAST KNOWN WELL NUMBER FROM NM OCD WELL FILE 'NOTES' COLUMN IS USED
STATE	Text	STATE WHERE WELL OR FACILITY IS LOCATED
COUNTY	Text	STATE WHERE WELL OR FACILITY IS LOCATED
TOWNSHIP_DES	Number	NUMERIC DESIGNATION FOR TOWNSHIP
TOWNSHIP_DIR	Text	NORTH OR SOUTH
RANGE_DES	Number	NUMERIC DESIGNATION FOR RANGE
RANGE_DIR	Text	EAST OR WEST
SECTION	Number	SECTION DESIGNATION
UNIT_LETTER	Text	UNIT LETTER OR NUMBER
FTGNS	Number	FOOTAGE FROM NORTH OR SOUTH SECTION LINE
NSCODE	Text	DIRECTION FOR FOOTAGE
FTGEW	Number	FOOTAGE FROM EAST OR WEST SECTION LINE
EWCODE	Text	DIRECTION FOR FOOTAGE
Status_1	Text	Derived from NM OCD (NAD83) shape files
Status_2	Text	Derived from NM OCD (NAD83) shape files
well_type	Text	Derived from NM OCD (NAD83) shape files
Symbology	Text	Derived from NM OCD (NAD83) shape files
TOWNSHIP_ALL	Text	ALPHANUMERIC DESIGNATION FOR TOWNSHIP
RANGE_ALL	Text	ALPHANUMERIC DESIGNATION FOR RANGE
PLSS_ID	Text	DESIGNATION TO MAKE GROUPING BY TOWNSHIP AND RANGE - SHOULD CORRESPOND TO PLSS ID IN Cadastral PLSS Standardized Data - PLSS Township - Version 2

NM_Well_Locations Properties			
General			
<table border="1"> <tr> <td colspan="2">NM_Well_Locations</td> </tr> </table>		NM_Well_Locations	
NM_Well_Locations			
Type:	Table		
Description:	Table with locations of all wells in NM. Locations & symbology from IPR/OCD.		
Created:	6/2/2016 10:39:49 PM		
Modified:	6/2/2016 10:09:20 AM		
Owner:	Admin		
Attributes:	<input type="checkbox"/> Hidden <input type="checkbox"/> Replicable <input type="checkbox"/> Row Level Tracking		
<input type="button" value="OK"/> <input type="button" value="Cancel"/> <input type="button" value="Apply"/>			

Figure A5 NM_Well_Locations table attributes.

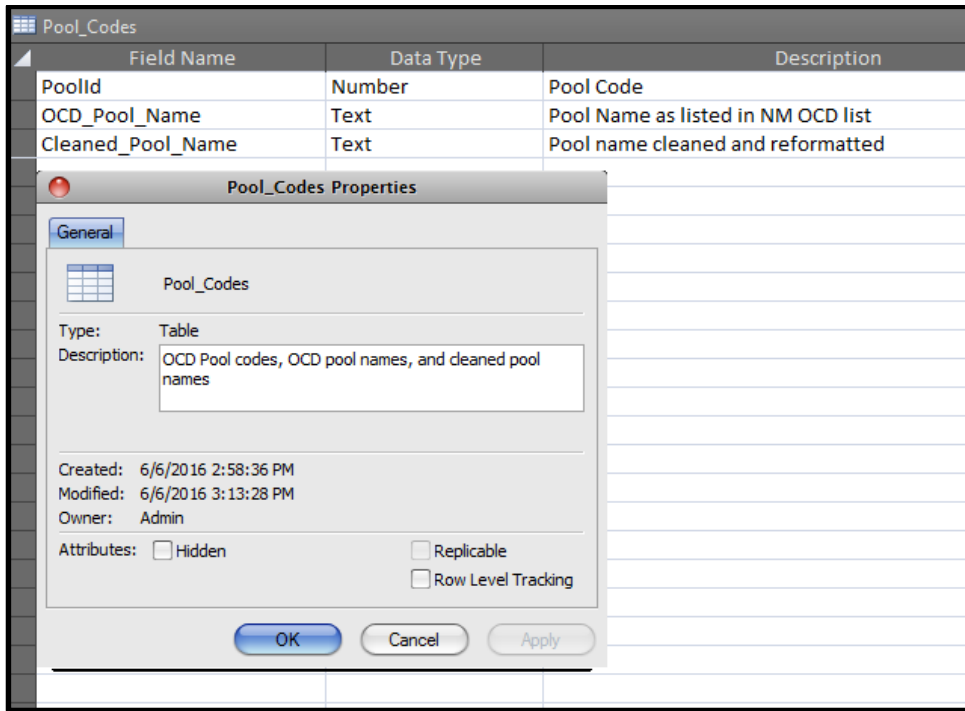


Figure A6 Pool_Codes table attributes.

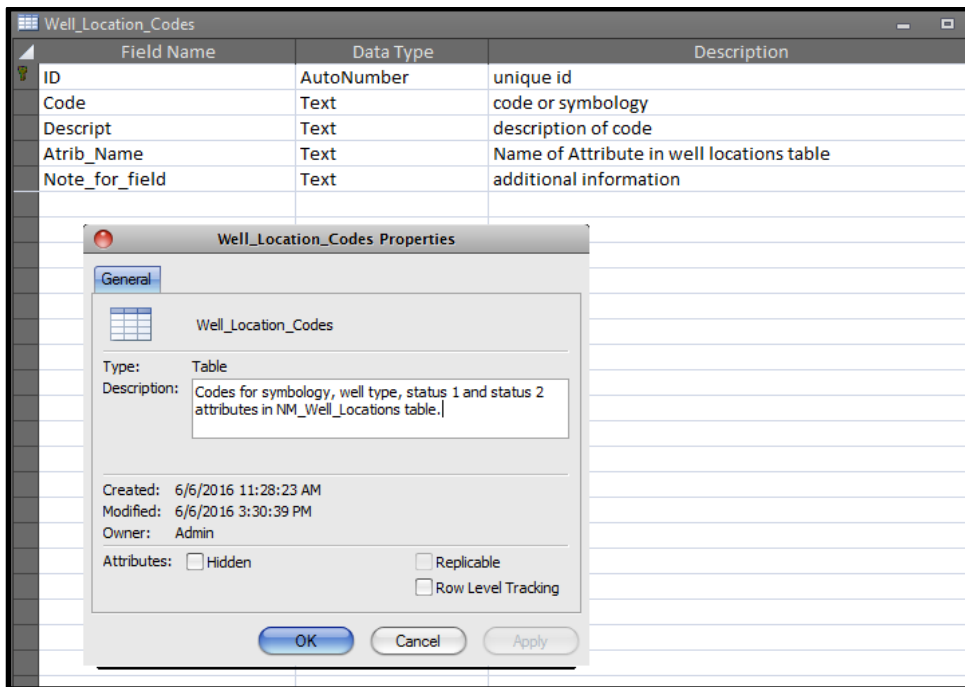


Figure A7. Well_Locations_Codes table and attributes. This is a data dictionary table. The “Code” field contains codes from several different fields in the NM_Well_Locations table, and the field “Atrib_Name specifies the field in NM_Well_Locations that particular record applies to.

Appendix B: Detailed Information on RCRA Oil and Gas Waste Exemptions and Rules

The most preferred method of preventing pollution is to avoid the generation of waste. Operators must be aware of state and federal regulations governing the management and disposal of hazardous and non-hazardous wastes. The RCRA regulations give operators the freedom to choose a waste management action that is less stringent and costly but does not compromise safety and effectiveness.

Waste from Exploration, Development, or Production

These are wastes intrinsically derived from primary field operations associated with the exploration, development and production of the oil and gas. These operations are in basically three stages and each stage has produces different kinds of waste product.

Well Drilling and Completions Stage

Wastes Produced includes:

- Drilling Fluids (drilling mud)
- Drill Cuttings

Wells Stimulation Stage (Hydraulic Fracturing)

Wastes Produced includes:

- Fracturing fluid returns
- Produced Water

Well Production Stage

Wastes Produced includes:

- Produced Water

Uniquely Associated Wastes

These include a wide range of small volume of waste streams that are associated with the exploration and production of oil and gas. They come in different categories. The table below shows the various categories and examples:

Table B-1: Associated Wastes Categories and examples

Categories	Examples
Completion fluids	All fluids from initial well completion activities, including any initial acid stimulation or hydraulic fracturing
Workover/Stimulation fluids	All fluids from subsequent workover and stimulation operations.
Dehydration/Sweetening Wastes	Includes glycol-based compounds, glycol filters, molecular sieves, amines, amine filter, precipitated amine sludge, iron sponge, scrubber liquids and sludge, backwash, filter media and other wastes associated with the dehydration and sweetening of natural gas.
Tanks Bottoms/Oily Sludge Bottoms	Tank sediment and water, produced sand and other tank bottoms.

Waste Mixtures

This is basically the mixing of two or more wastes of different classes. It is explained further in the next section.

Hazardous Wastes

As stated above in the report, these are wastes that exhibit at least one of the following properties: Ignitability, Corrosivity, Reactivity and Toxicity. A complete list of hazardous wastes and their respective hazardous waste numbers can be obtained from [40 CFR Part 261, Subpart D](#).

Hazardous Wastes Subject to RCRA Subtitle C

These are wastes which fall under the EPA’s federal program of managing hazardous wastes from the creation to the disposal of the waste, i.e. throughout the lifecycle of the waste.

Waste Mixture Classification

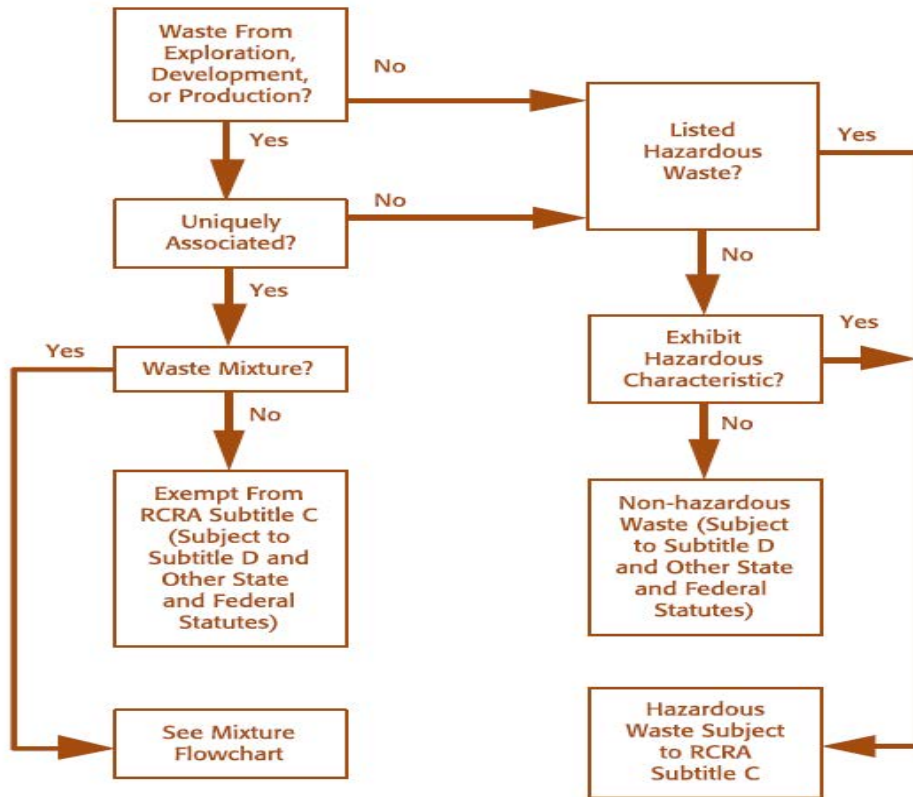
The exemption of waste mixtures can be determined depending on the characteristics of the resulting mixture.

- A mixture of an exempt waste with another exempt waste remains exempt.
- Mixing a non-hazardous waste with an exempt waste result in a waste mixture that is exempt.
- If a waste mixture exhibits any of the hazardous characteristics after mixing an exempt waste with a non-exempt characteristic hazardous waste, the mixture is a non –exempt hazardous waste. However, if the resulting waste mixture does not exhibit any of the hazardous characteristics, then the mixture is an exempt waste.

Note: this mixture is considered as a treatment to remove the hazardous characteristics and generally requires a permit.

- A mixture of a listed hazardous waste with an exempt waste results in a non- exempt waste irrespective of the percentage of the listed hazardous waste in the mixture.

Exempt/Non-Exempt Wastes



Possible Waste Mixtures and Their Exempt and Non-Exempt Status

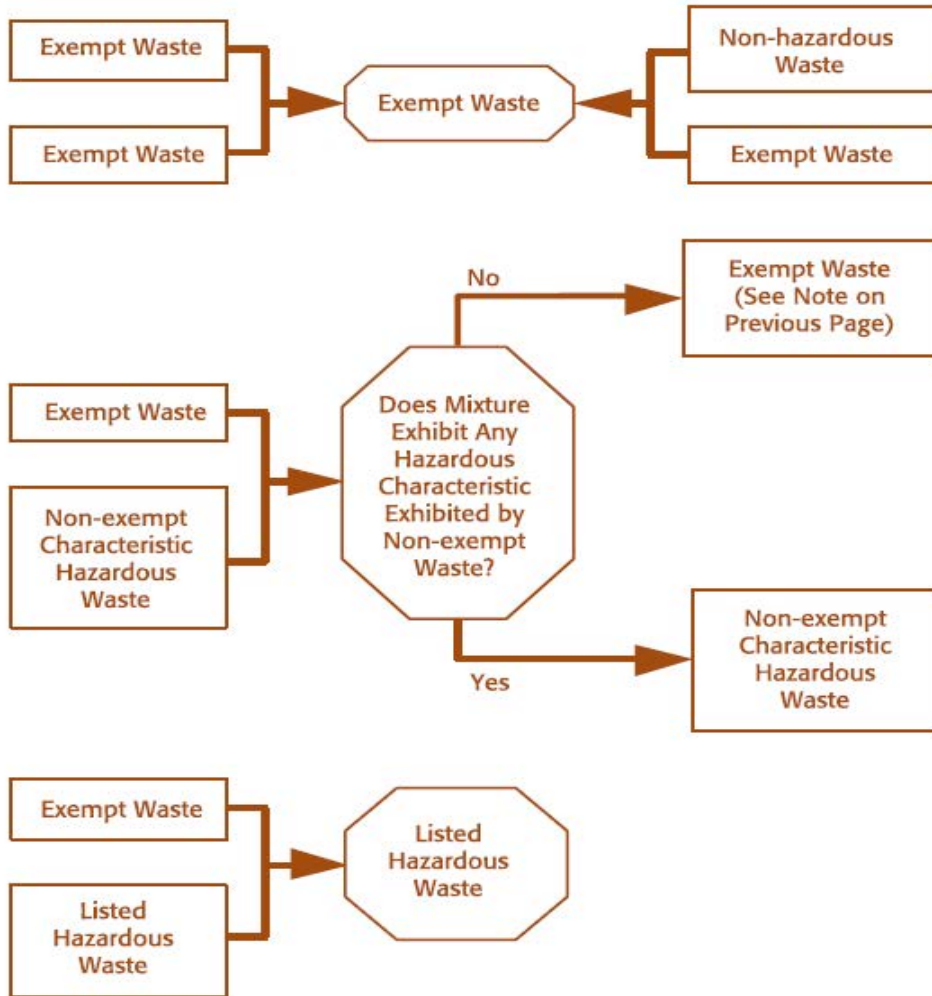


Table B-2 (Appendix B). EPA National Primary Drinking Water Standards (MCL for various drinking water contaminants) (Dahm and Chapman, 2014).

	Contaminant	MCL or TT1 (mg/L) ²	Potential health effects from exposure above the MCL	Common sources of contaminant in drinking water	Public Health Goal
OC	Acrylamide	TT8	Nervous system or blood problems;	Added to water during sewage/wastewater increased risk of cancer treatment	zero
OC	Alachlor	0.002	Eye, liver, kidney or spleen problems; anemia; increased risk of cancer	Runoff from herbicide used on row crops	zero
R	Alpha particles	15 picocuries per Liter (pCi/L)	Increased risk of cancer	Erosion of natural deposits of certain minerals that are radioactive and may emit a form of radiation known as alpha radiation	zero
IOC	Antimony	0.006	Increase in blood cholesterol; decrease in blood sugar	Discharge from petroleum refineries; fire retardants; ceramics; electronics; solder	0.006
IOC	Arsenic	0.010 as of 1/23/06	Skin damage or problems with circulatory systems, and may have increased risk of getting cancer	Erosion of natural deposits; runoff from orchards, runoff from glass & electronics production wastes	0
IOC	Asbestos (fibers >10 micrometers)	7 million fibers per Liter (MFL)	Increased risk of developing benign intestinal polyps	Decay of asbestos cement in water mains; erosion of natural deposits	7 MFL
OC	Atrazine	0.003	Cardiovascular system or reproductive problems	Runoff from herbicide used on row crops	0.003
IOC	Barium	2	Increase in blood pressure	Discharge of drilling wastes; discharge from metal refineries; erosion of natural deposits	2
OC	Benzene	0.005	Anemia; decrease in blood platelets; increased risk of cancer	Discharge from factories; leaching from gas storage tanks and landfills	zero
OC	Benzo(a)pyrene (PAHs)	0.0002	Reproductive difficulties; increased risk of cancer	Leaching from linings of water storage tanks and distribution lines	zero
IOC	Beryllium	0.004	Intestinal lesions	Discharge from metal refineries and coal-burning factories; discharge from electrical, aerospace, and defense industries	0.004
R	Beta particles and photon emitters	4 millirems per year	Increased risk of cancer	Decay of natural and man-made deposits of certain minerals that are radioactive and may emit forms of radiation known as photons and beta radiation	zero
DBP	Bromate	0.010	Increased risk of cancer	Byproduct of drinking water disinfection	zero
IOC	Cadmium	0.005	Kidney damage	Corrosion of galvanized pipes; erosion of natural deposits; discharge from metal refineries; runoff from waste batteries and paints	0.005
OC	Carbofuran	0.04	Problems with blood, nervous system, or reproductive system	Leaching of soil fumigant used on rice and alfalfa	0.04
OC	Carbon tetrachloride	0.005	Liver problems; increased risk of cancer	Discharge from chemical plants and other industrial activities	zero
D	Chloramines (as Cl ₂)	MRDL=4.01	Eye/nose irritation; stomach discomfort, anemia	Water additive used to control microbes	MRDLG=41

	Contaminant	MCL or TT ¹ (mg/L) ²	Potential health effects from exposure above the MCL	Common sources of contaminant in drinking water	Public Health Goal
OC	Chlordane	0.002	Liver or nervous system problems; increased risk of cancer	Residue of banned termiticide	zero
D	Chlorine (as Cl ₂)	MRDL=4.0 ¹	Eye/nose irritation; stomach discomfort	Water additive used to control microbes	MRDLG=4 ¹
D	Chlorine dioxide (as ClO ₂)	MRDL=0.8 ¹	Anemia; infants & young children: nervous system effects	Water additive used to control microbes	MRDLG=0.8 ¹
DBP	Chlorite	1.0	Anemia; infants & young children: nervous system effects	Byproduct of drinking water disinfection	0.8
OC	Chlorobenzene	0.1	Liver or kidney problems	Discharge from chemical and agricultural chemical factories	0.1
IOC	Chromium (total)	0.1	Allergic dermatitis	Discharge from steel and pulp mills; erosion of natural deposits	0.1
IOC	Copper	TT ⁷ ; Action Level = 1.3	Short term exposure: Gastrointestinal distress. Long term exposure: Liver or kidney damage. People with Wilson's Disease should consult their personal doctor if the amount of copper in their water exceeds the action level	Corrosion of household plumbing systems; erosion of natural deposits	1.3
M	<i>Cryptosporidium</i>	TT ³	Gastrointestinal illness (e.g., diarrhea, vomiting, cramps)	Human and animal fecal waste	zero
IOC	Cyanide (as free cyanide)	0.2	Nerve damage or thyroid problems	Discharge from steel/metal factories; discharge from plastic and fertilizer factories	0.2
OC	2,4-D	0.07	Kidney, liver, or adrenal gland problems	Runoff from herbicide used on row crops	0.07
OC	Dalapon	0.2	Minor kidney changes	Runoff from herbicide used on rights of way	0.2
OC	1,2-Dibromo-3-chloropropane (DBCP)	0.0002	Reproductive difficulties; increased risk of cancer	Runoff/leaching from soil fumigant used on soybeans, cotton, pineapples, and orchards	zero
OC	o-Dichlorobenzene	0.6	Liver, kidney, or circulatory system problems	Discharge from industrial chemical factories	0.6
OC	p-Dichlorobenzene	0.075	Anemia; liver, kidney or spleen damage; changes in blood	Discharge from industrial chemical factories	0.075
OC	1,2-Dichloroethane	0.005	Increased risk of cancer	Discharge from industrial chemical factories	zero
OC	1,1-Dichloroethylene	0.007	Liver problems	Discharge from industrial chemical factories	0.007
OC	cis-1,2-Dichloroethylene	0.07	Liver problems	Discharge from industrial chemical factories	0.07
OC	trans-1,2-Dichloroethylene	0.1	Liver problems	Discharge from industrial chemical factories	0.1
OC	Dichloromethane	0.005	Liver problems; increased risk of cancer	Discharge from drug and chemical factories	zero
OC	1,2-Dichloropropane	0.005	Increased risk of cancer	Discharge from industrial chemical factories	zero
OC	Di(2-ethylhexyl) adipate	0.4	Weight loss, live problems, or possible reproductive difficulties	Discharge from chemical factories	0.4
OC	Di(2-ethylhexyl) phthalate	0.006	Reproductive difficulties; liver problems; increased risk of cancer	Discharge from rubber and chemical factories	zero
OC	Dinoseb	0.007	Reproductive difficulties	Runoff from herbicide used on soybeans and vegetables	0.007
OC	Dioxin (2,3,7,8-TCDD)	0.0000003	Reproductive difficulties; increased risk of cancer	Emissions from waste incineration and other combustion; discharge from chemical factories	zero
OC	Diquat	0.02	Cataracts	Runoff from herbicide use	0.02
OC	Endothall	0.1	Stomach and intestinal problems	Runoff from herbicide use	0.1

	Contaminant	MCL or TT ¹ (mg/L) ²	Potential health effects from exposure above the MCL	Common sources of contaminant in drinking water	Public Health Goal
OC	Endrin	0.002	Liver problems	Residue of banned insecticide	0.002
OC	Epichlorohydrin	TT ⁸	Increased cancer risk, and over a long period of time, stomach problems	Discharge from industrial chemical factories; an impurity of some water treatment chemicals	zero
OC	Ethylbenzene	0.7	Liver or kidneys problems	Discharge from petroleum refineries	0.7
OC	Ethylene dibromide	0.00005	Problems with liver, stomach, reproductive system, or kidneys; increased risk of cancer	Discharge from petroleum refineries	zero
IOC	Fluoride	4.0	Bone disease (pain and tenderness of the bones); Children may get mottled teeth	Water additive which promotes strong teeth; erosion of natural deposits; discharge from fertilizer and aluminum factories	4.0
M	<i>Giardia lamblia</i>	TT ³	Gastrointestinal illness (e.g., diarrhea, vomiting, cramps)	Human and animal fecal waste	zero
OC	Glyphosate	0.7	Kidney problems; reproductive difficulties	Runoff from herbicide use	0.7
DBP	Haloacetic acids (HAA5)	0.060	Increased risk of cancer	Byproduct of drinking water disinfection	n/a ⁶
OC	Heptachlor	0.0004	Liver damage; increased risk of cancer	Residue of banned termiticide	zero
OC	Heptachlor epoxide	0.0002	Liver damage; increased risk of cancer	Breakdown of heptachlor	zero
M	Heterotrophic plate count (HPC)	TT ³	HPC has no health effects; it is an analytic method used to measure the variety of bacteria that are common in water. The lower the concentration of bacteria in drinking water, the better maintained the water system is.	HPC measures a range of bacteria that are naturally present in the environment	n/a
OC	Hexachlorobenzene	0.001	Liver or kidney problems; reproductive difficulties; increased risk of cancer	Discharge from metal refineries and agricultural chemical factories	zero
OC	Hexachlorocyclopentadiene	0.05	Kidney or stomach problems	Discharge from chemical factories	0.05
IOC	Lead	TT ⁷ ; Action Level = 0.015	Infants and children: Delays in physical or mental development; children could show slight deficits in attention span and learning abilities; Adults: Kidney problems; high blood pressure	Corrosion of household plumbing systems; erosion of natural deposits	zero
M	<i>Legionella</i>	TT ³	Legionnaire's Disease, a type of pneumonia	Found naturally in water; multiplies in heating systems	zero
OC	Lindane	0.0002	Liver or kidney problems	Runoff/leaching from insecticide used on cattle, lumber, gardens	0.0002
IOC	Mercury (inorganic)	0.002	Kidney damage	Erosion of natural deposits; discharge from refineries and factories; runoff from landfills and croplands	0.002
OC	Methoxychlor	0.04	Reproductive difficulties	Runoff/leaching from insecticide used on fruits, vegetables, alfalfa, livestock	0.04
IOC	Nitrate (measured as Nitrogen)	10	Infants below the age of six months who drink water containing nitrate in excess of the MCL could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue-baby syndrome.	Runoff from fertilizer use; leaching from septic tanks, sewage; erosion of natural deposits	10
IOC	Nitrite (measured as Nitrogen)	1	Infants below the age of six months who drink water containing nitrite in excess of the MCL could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue-baby syndrome.	Runoff from fertilizer use; leaching from septic tanks, sewage; erosion of natural deposits	1

	Contaminant	MCL or TT ¹ (mg/L) ²	Potential health effects from exposure above the MCL	Common sources of contaminant in drinking water	Public Health Goal
OC	Oxamyl (Vydate)	0.2	Slight nervous system effects	Runoff/leaching from insecticide used on apples, potatoes, and tomatoes	0.2
OC	Pentachlorophenol	0.001	Liver or kidney problems; increased cancer risk	Discharge from wood preserving factories	zero
OC	Picloram	0.5	Liver problems	Herbicide runoff	0.5
OC	Polychlorinated biphenyls (PCBs)	0.0005	Skin changes; thymus gland problems; immune deficiencies; reproductive or nervous system difficulties; increased risk of cancer	Runoff from landfills; discharge of waste chemicals	zero
R	Radium 226 and Radium 228 (combined)	5 pCi/L	Increased risk of cancer	Erosion of natural deposits	zero
IOC	Selenium	0.05	Hair or fingernail loss; numbness in fingers or toes; circulatory problems	Discharge from petroleum refineries; erosion of natural deposits; discharge from mines	0.05
OC	Simazine	0.004	Problems with blood	Herbicide runoff	0.004
OC	Styrene	0.1	Liver, kidney, or circulatory system problems	Discharge from rubber and plastic factories; leaching from landfills	0.1
OC	Tetrachloroethylene	0.005	Liver problems; increased risk of cancer	Discharge from factories and dry cleaners	zero
IOC	Thallium	0.002	Hair loss; changes in blood; kidney, intestine, or liver problems	Leaching from ore-processing sites; discharge from electronics, glass, and drug factories	0.0005
OC	Toluene	1	Nervous system, kidney, or liver problems	Discharge from petroleum factories	1
M	Total Coliforms (including fecal coliform and <i>E. coli</i>)	5.0% ⁴	Not a health threat in itself; it is used to indicate whether other potentially harmful bacteria may be present ⁵	Coliforms are naturally present in the environment as well as feces; fecal coliforms and <i>E. coli</i> only come from human and animal fecal waste.	zero
DBP	Total Trihalomethanes (TTHMs)	0.10 0.080 after 12/31/03	Liver, kidney or central nervous system problems; increased risk of cancer	Byproduct of drinking water disinfection	n/a ⁶
OC	Toxaphene	0.003	Kidney, liver, or thyroid problems; increased risk of cancer	Runoff/leaching from insecticide used on cotton and cattle	zero
OC	2,4,5-TP (Silvex)	0.05	Liver problems	Residue of banned herbicide	0.05
OC	1,2,4-Trichlorobenzene	0.07	Changes in adrenal glands	Discharge from textile finishing factories	0.07
OC	1,1,1-Trichloroethane	0.2	Liver, nervous system, or circulatory problems	Discharge from metal degreasing sites and other factories	0.20
OC	1,1,2-Trichloroethane	0.005	Liver, kidney, or immune system problems	Discharge from industrial chemical factories	0.003
OC	Trichloroethylene	0.005	Liver problems; increased risk of cancer	Discharge from metal degreasing sites and other factories	zero
M	Turbidity	TT ³	Turbidity is a measure of the cloudiness of water. It is used to indicate water quality and filtration effectiveness (e.g., whether disease-causing organisms are present). Higher turbidity levels are often associated with higher levels of disease-causing micro-organisms such as viruses, parasites and some bacteria. These organisms can cause symptoms such as nausea, cramps, diarrhea, and associated headaches.	Soil runoff	n/a
R	Uranium	30 ug/L as of 12/08/03	Increased risk of cancer, kidney toxicity	Erosion of natural deposits	zero

	Contaminant	MCL or TT ¹ (mg/L) ²	Potential health effects from exposure above the MCL	Common sources of contaminant in drinking water	Public Health Goal
OC	Vinyl chloride	0.002	Increased risk of cancer	Leaching from PVC pipes; discharge from plastic factories	zero
M	Viruses (enteric)	TT ³	Gastrointestinal illness (e.g., diarrhea, vomiting, cramps)	Human and animal fecal waste	zero
OC	Xylenes (total)	10	Nervous system damage	Discharge from petroleum factories; discharge from chemical factories	10

LEGEND



Disinfectant



Inorganic Chemical



Organic Chemical



Disinfection Byproduct



Microorganism



Radionuclides

1 Definitions

- **Maximum Contaminant Level Goal (MCLG)**—The level of a contaminant in drinking water below which there is no known or expected risk to health. MCLGs allow for a margin of safety and are non-enforceable public health goals.
- **Maximum Contaminant Level (MCL)**—The highest level of a contaminant that is allowed in drinking water. MCLs are set as close to MCLGs as feasible using the best available treatment technology and taking cost into consideration. MCLs are enforceable standards.
- **Maximum Residual Disinfectant Level Goal (MRDLG)**—The level of a drinking water disinfectant below which there is no known or expected risk to health. MRDLGs do not reflect the benefits of the use of disinfectants to control microbial contaminants.
- **Maximum Residual Disinfectant Level (MRDL)**—The highest level of a disinfectant allowed in drinking water. There is convincing evidence that addition of a disinfectant is necessary for control of microbial contaminants.
- **Treatment Technique (TT)**—A required process intended to reduce the level of a contaminant in drinking water.

2 Units are in milligrams per liter (mg/L) unless otherwise noted. Milligrams per liter are equivalent to parts per million (ppm).

3 EPA’s surface water treatment rules require systems using surface water or groundwater under the direct influence of surface water to (1) disinfect their water, and (2) filter their water or meet criteria for avoiding filtration so that the following contaminants are controlled at the following levels:

- **Cryptosporidium** (as of 1/1/02 for systems serving >10,000 and 1/14/05 for systems serving <10,000) 99% removal.
- **Giardia lamblia**: 99.9% removal/inactivation
- **Viruses**: 99.99% removal/inactivation
- **Legionella**: No limit, but EPA believes that if Giardia and viruses are removed/inactivated, Legionella will also be controlled.
- **Turbidity**: At no time can turbidity (cloudiness of water) go above 5 nephelometric turbidity units (NTU); systems that filter must ensure that the turbidity go no higher than 1 NTU (0.5 NTU for conventional or direct filtration) in at least 95% of the daily samples in any month. As of January 1, 2002, for systems servicing >10,000, and January 14, 2005, for systems servicing <10,000, turbidity may never exceed 1 NTU, and must not exceed 0.3 NTU in 95% of daily

samples in any month.

- HPC: No more than 500 bacterial colonies per milliliter
- Long Term 1 Enhanced Surface Water Treatment (Effective Date: January 14, 2005); Surface water systems or (GWUDI) systems serving fewer than 10,000 people must comply with the applicable Long Term 1 Enhanced Surface Water Treatment Rule provisions (e.g. turbidity standards, individual filter monitoring, Cryptosporidium removal requirements, updated watershed control requirements for unfiltered systems).

- Filter Backwash Recycling: The Filter Backwash Recycling Rule requires systems that recycle to return specific recycle flows through all processes of the system's existing conventional or direct filtration system or at an alternate location approved by the state.

4 No more than 5.0% samples total coliform-positive in a month. (For water systems that collect fewer than 40 routine samples per month, no more than one sample can be total coliform-positive per month.) Every sample that has total coliform must be analyzed for either fecal coliforms or E. coli if two consecutive TC-positive samples, and one is also positive for E. coli fecal coliforms, system has an acute MCL violation.

5 Fecal coliform and E. coli are bacteria whose presence indicates that the water may be contaminated with human or animal wastes. Disease-causing microbes (pathogens) in these wastes can cause diarrhea, cramps, nausea, headaches, or other symptoms. These pathogens may pose a special health risk for infants, young children, and people with severely compromised immune systems.

6 Although there is no collective MCLG for this contaminant group, there are individual MCLGs for some of the individual contaminants:

- Haloacetic acids: dichloroacetic acid (zero); trichloroacetic acid (0.3 mg/L)
- Trihalomethanes: bromodichloromethane (zero); bromoform (zero); dibromochloromethane (0.06 mg/L)

7 Lead and copper are regulated by a Treatment Technique that requires systems to control the corrosiveness of their water. If more than 10% of tap water samples exceed the action level, water systems must take additional steps.

For copper, the action level is 1.3 mg/L, and for lead is 0.015 mg/L.

8 Each water system must certify, in writing, to the state (using third-party or manufacturers certification) that when it uses acrylamide and/or epichlorohydrin to treat water, the combination (or product) of dose and monomer level does not exceed the levels specified, as follows:

Acrylamide = 0.05% dosed at 1 mg/L (or equivalent); Epichlorohydrin = 0.01% dosed at 20 mg/L (or equivalent).

**Appendix C: Permit Letter for the San Juan, New Mexico Rangeland Rehabilitation Study;
and NPDES Permit for the Wyoming Case Study.**



**NEW MEXICO ENERGY, MINERALS and
NATURAL RESOURCES DEPARTMENT**

BILL RICHARDSON
Governor
Joanna Prukop
Cabinet Secretary
Reese Fullerton
Deputy Cabinet Secretary

Mark E. Fesmire, P.E.
Director
Oil Conservation Division

July 2, 2007

Certified Mail

Return Receipt #: 7006 3450 0000 0451 8087

Mr. Ed Hasely
ConocoPhillips/ Burlington Resources
PO Box 4289
Farmington, NM 87499

RE: Request to use produced water for Water Pilot Project on the San Juan 32-8 Unit #237A.

Dear Mr. Hasely:

The New Mexico Oil Conservation Division (OCD) has reviewed ConocoPhillips request, dated June 1, 2007 from your office, to use produced water for revegetation. The application is approved for the San Juan 32-8 Unit #237A well location shown in your application.

The following conditions will apply:

1. ConocoPhillips assumes all liability for potential contamination.
2. A record showing volumes of water used and the appropriate analysis will be provided to both the OCD District III Aztec Office and the OCD Environmental Bureau Office, 1220 South Saint Francis Drive, Santa Fe New Mexico 87505.
3. Chloride analysis for the soil will be required after each application of water in addition to the testing previously performed for the pilot project.
4. ConocoPhillips will be required to apply for, and receive any applicable landowner and other regulatory agencies approvals.

To allow adequate time for the pilot project, this approval for the discharge of produced water in accordance with the pilot project will expire December 1, 2007. Due to the scope of work and the ongoing nature of the project, future applications for approval will need to be submitted to the OCD's Environmental Bureau and a copy sent to the district office.

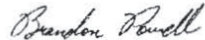
Oil Conservation Division * 1000 Rio Brazos Road * Aztec, New Mexico 87410
Phone: (505) 334-6178 * Fax (505) 334-6170 * <http://www.emnrd.state.nm.us>

Mr. Ed Hasely
ConocoPhillips/ Burlington Resources
Page 2

Please be advised OCD approval does not relieve ConocoPhillips from liability should contamination pose a future threat to surface water, groundwater, human health or the environment. OCD approval does not relieve ConocoPhillips of compliance with other federal, state, tribal, or local laws and regulations.

If you have any questions, please call me at 505-334-6178, ext. 15.

Sincerely yours,



Brandon Powell
Environmental Specialist
Brandon.Powell@state.nm.us

CC: Dave Mankiewicz, Bureau of Land Management

Wyoming Study NPDES Permit:

SUBMIT IN TRIPLICATE

**NATIONAL POLLUTANT DISCHARGE ELIMINATION SYSTEM
APPLICATION FOR PERMIT TO SURFACE DISCHARGE PRODUCED WATER
FROM COAL BED METHANE NEW DISCHARGES, RENEWALS, OR MAJOR
MODIFICATIONS**

Revised 12-19-03

PLEASE PRINT OR TYPE

For Agency Use Only
Application Number WY00
Date Received: JAN 30 2006
(mo/day/yr)

1. Check the box corresponding to the type of application being applied for

- New CBM permit
- CBM permit renewal Permit number _____
- CBM permit major modification Permit number WY0051772

2. Select a permit option

- Option 1A - complete containment to an off-channel man made containment unit(s) (class 4C), no discharge allowed to surface waters of the state outside the containment unit.
- Option 1B - complete containment to a natural closed basin or playa lake (class 3A), no discharge allowed to surface waters of the state outside the basin or playa.
- Option 2 - surface discharge to class 2 or 3 receiving stream of the Belle Fourche River or Cheyenne River drainage (class 2ABWW).
- Option 2 - surface discharge to class 2 or 3 receiving stream of the Powder River or Little Powder Rivers (class 2ABWW).
- Option 2 – surface discharge to class 2 or 3 receiving streams of the Tongue, Clear Creek, or Crazy Woman Creek (class 2AB)– this option requires the permittee to demonstrate that quality of the effluent at the discharge point is equal to or better than the ambient quality of the perennial class 2 receiving water.

3. Name, mailing address, e-mail address, location and telephone number of the individual or company which owns the facility producing the discharge.

Name: Fidelity Exploration & Production Company

Street Address: 1700 Lincoln Street, Suite 4600

City, State, and Zip Code: Denver, CO 80203

Telephone Number: 303-893-3133

E-Mail Address: mike.bergstrom@fidelitvepco.com

4. Name(s) and mailing address(es) of owner(s) of the surface rights on whose land the discharge occurs (in cases where the land is owned by the state or federal government but surface rights are leased to a private individual, provide lessee's name and address)

Name: John E. Rice and Sons
Street Address: 247 Decker Road
City, State, and Zip Code: Sheridan WY 82801
Telephone Number: 307-751-2764

5. Name of the facility producing the discharge (this is the facility name that will appear on the NPDES permit. It is not necessary to name every well contributing to this facility's discharge in this section)

WY0051772 – Wrench Ranch 49 Battery

6. For Option 1A or 1B permit, attach a water balance that demonstrates, considering total maximum projected discharge inflows, natural precipitation, evaporation and infiltration, that the containment unit will be adequately sized to contain all projected discharge and stormwater runoff from a 100 year, 24 hour storm event. If actual flow rates are available, use the maximum flow rate from all active wells within the previous six months of operation in the water balance.
7. For an Option 2 permit utilizing on-channel reservoirs, attach a water balance and mixing analysis documenting the amount of CBM discharge that, under normal operating conditions, can be contained within the reservoirs, the amount and circumstances under which the reservoirs will discharge, and the expected water quality upon discharge from the reservoirs.
See previously submitted water management plan for this permit.
8. Attach a description and a clear, legible, detailed topographic map of the discharging facility. Include the following: See revised map (Figure 1). One Irrigation Monitoring Point (IMP) and two Water Quality Monitoring Stations (WQMS) have been deleted from previously-submitted map.

- a. A legend
- b. Well locations
- c. Ponds
- d. Reservoirs
- e. Stock tanks
- f. Discharge points (outfalls)
- g. Immediate receiving streams
- h. Water quality monitoring stations
- i. Irrigation compliance points
- j. Location of nearest downstream irrigator.
- k. Section, Township, and Range information

If any of the above are not applicable please indicate in the description and include a brief explanation as to why the item is not applicable)

9. Describe the control measures that will be implemented to prevent significant damage to or erosion of the receiving water channel at the point of discharge.
Produced water will be piped to a tire-tank and overflow into the existing irrigation diversion ditch. Crushed rock underlain with fabric will be placed within the ditch at the point of discharge and extend 20 feet downstream to prevent erosion to the receiving channels. See December 6, 2004 Addendum to NPDES Application for Permit (WY0051772) for details of outfall design.

10. Describe the control measures that will be implemented to achieve water quality standards and effluent limits. If proposing to utilize a treatment process, provide a detailed description of the treatment process, including, but not limited to: Water quality analyses demonstrating the effluent quality before and after treatment; waste stream volumes and planned method of disposal; aquatic life toxicity data for any chemicals being used in the treatment process; description of how the chemicals will be handled at the facility and the potential for any impacts to waters of the state in the event of a spill; and diagrams of the facility indicating the water treatment path. Additional sheets and diagrams may be attached.
Produced water quality discharged at Outfall 001 is expected to meet Class 3 end-of-pipe effluent limits. Numerous laboratory reports and mixing analyses tables have been previously provided in support of this permit application in the original application and subsequent addenda.

11. Outfall locations must be established as part of a preliminary field reconnaissance survey using GPS or conventional survey equipment and documented in Table 1. Please document the type of equipment used, the expected accuracy of your measurements, and a brief rationale for locating the outfalls at the requested sites below.

Topcon survey grade GPS receiver was used to measure outfall coordinates. Field GPS units are typically accurate to 2-5 meters.

12. Complete the attached **Table 1**. Provide all the information in the table for each proposed discharge point or monitoring point. If proposing changes (a major modification) to an existing facility, **clearly** indicate the desired changes on the table. Additional tables may be attached. Use the format provided.
See attached revised Table 1.

13. Complete the attached **Table 2**. Provide all the information in the table for each well associated with this proposed discharge authorization. If proposing changes (a major modification) to an existing facility, **clearly** indicate the desired changes on the table. Additional tables may be attached. Use the format provided.

See attached Table 2 previously provided for this facility. Wells completed to the Monarch, Carnev and Dietz coal formations will be discharged at the outfall listed in this application.

14. Provide the results of water analyses for a sample collected from a location representative of the quality of the water being proposed for discharge for the 25 chemical parameters listed below. The sample must be collected from well(s) or outfall(s) within a twenty mile radius of the proposed facility's location, and from the same coal formation(s) and the same approximate depth(s) as proposed in this application. If filing an application for a permit renewal or modification, the representative sample must be collected from the facility being proposed for renewal or modification. Explain why this sample is representative of the produced water to be discharged.

See produced water chemical analyses included in the January 10, 2005 Addendum to NPDES Application for Permit (WY0051772).

Samples from co-mingled coal seams are acceptable as long as the sample(s) meet the following criteria:

- A. all of the coal seams being proposed for development are represented in the co-mingled sample,*
- B. the ratio of each coal seam's contribution is approximately the same in the sample and the proposed development,*
- C. documentation is provided to verify the criteria listed in A. and B.*

The analyses must be conducted in accordance with approved EPA test procedures (40 CFR Part 136). Include a signed copy of your lab report that includes the following:

- a. detection limits
- b. results of each of the 25 chemical parameters at the chemical state given below
- c. quarter/quarter, section, township and range of the sample collection location

- d. Time and date of sample collection
- e. Time and date of analysis for each parameter
- f. Analyst's initials for each parameter
- g. Detection limit for each parameter as achieved by the laboratory
- h. NPDES permit number and outfall number, where the sample was collected.
- i. Origin of produced water (coal seam)

If more than one coal seam is being proposed for development, the permittee must submit a lab analysis and complete information characterizing water quality from each coal seam being proposed for development. If the permittee is proposing to include discharges from a coal seam not previously developed at this facility, the permittee must submit a lab analysis and complete information characterizing water quality from the new coal seam being proposed for development. Analyses must be provided in the units listed below.

Parameter* (See notes following the table on chemical states)	Required Detection Limits and Required Units
Alkalinity, Total	1 mg/l as CaCO ₃
Aluminum, Total Recoverable	50 µg/l
Arsenic, Total	1 µg/l
Barium, Total	100 µg/l
Bicarbonate	10 mg/l
Cadmium, Dissolved	5 µg/l
Calcium, Total	50 µg/l, report as meq/l
Calcium, Total	50 µg/l, report as mg/l
Chlorides	5 mg/l
Chlorides	5 mg/l
Copper, Dissolved	10 µg/l
Dissolved Solids, Total	5 mg/l
Hardness, Total	10 mg/l as CaCO ₃
Iron, Dissolved	50 µg/l
Lead, Dissolved	2 µg/l
Magnesium, Total	100 µg/l, report as meq/l
Magnesium, Total	100 µg/l, report as mg/l
Manganese, Dissolved	50 µg/l
Mercury, Dissolved	1 µg/l
pH	to 0.1 pH unit
Radium 226, Total	0.2 pCi/l
Selenium, Total Recoverable	5 µg/l
Sodium Adsorption Ratio	Calculated as unadjusted ratio
Sodium, Total	100 µg/l, report as meq/l
Sodium, Total	100 µg/l, report as mg/l
Specific Conductance	5 micromhos/cm
Sulfates	10 mg/l
Zinc, Dissolved	50 µg/l

*Discharges into drainages other than the Powder River geologic basin may require analysis of additional parameters, please contact the WDEQ for a separate list.

15. For new facilities, provide the expected (estimated) flow volume from each well in gallons per day, and provide the rationale behind the flow volume estimate. For existing facilities, provide actual flow data from all wells within the last six months.

Fidelity requests a maximum volume of 150 acre-feet per year, with discharge rate of up to 0.288 mgd or 200 gallons per minute (gpm) for the outfall listed in this application. The individual wells within the Wrench Ranch development area are expected to produce approximately 4 gpm.

16. For applications for new facilities, are any of the required chemical constituents in the laboratory analysis present in concentrations above Wyoming Water Quality Standards?

YES NO

If the answer to question # 16 is yes, answer 16.a. – 16.b below. If no, proceed to question 18.

- a. Which constituents? _____
b. Has this constituent been addressed in the response to question 10? _____

17. For applications for existing facilities, has the facility ever exceeded permit limits or water quality standards? **This facility has not discharged at this proposed outfall. Representative water quality samples from wells within this project area indicate compliance with Class 3 effluent limits and with requested SAR and specific conductance limits at the end-of-pipe.**

YES NO

If the answer to question 17 is yes, answer 17.a. – 17.b. If no, proceed to question 18.

- a. Which constituents? _____
b. Has the exceedance been addressed? _____
c. Describe how the exceedance is being addressed.

18. Is there active irrigation, (including but not limited to irrigation of cultivars or flood irrigation) in the drainage of the discharge?

YES NO

If the answer to question #18 is yes, then documentation demonstrating one of the following must be provided: **See attached landowner letter which establishes the protection of irrigation uses on the Wrench Ranch surface when produced water containing specific conductance and SAR values below 2,000 micromhos/cm and 25, respectively, is discharged at the proposed outfall into Windy Draw Reservoir.**

- A. Effluent will meet SAR and specific conductance (EC) values that are equal or of better quality to ambient values in the mainstem or highest quality receiving stream; or
B. Demonstrate that a higher level of EC and SAR at the point of irrigation diversion can be tolerated by irrigated soils and crops without a significant reduction in crop yield and soil quality/permeability.

This information should include, but is not limited to the following:

I (CEO or other authorized person) certify that I am familiar with the information contained in this application and that to the best of my knowledge and belief, such information is true, complete, and accurate. I am requesting one outfall in this application.

Darwin Subart
Printed Name of Person signing*

President
Title*



Signature

January 27, 2006
Date

*All permit applications must be signed in accordance with 40 CFR Part 122.22. "for" or "by" signatures are not acceptable.

Section 35-11-901 of Wyoming Statutes provides that:
Any person who knowingly makes any false statement, representation, or certification in any application ... shall upon conviction be fined not more than \$10,000 or imprisoned for not more than one year, or both.

Mail this application to:

NPDES Permits Section
Department of Environmental Quality/WQD
122 West 25th Street, Herschler Building, 4W
Cheyenne, WY 82002

*Please include unique footer information on each page of this application and on all supporting documentation using the following format:
Company Name: Year/Month/Day/NEW, MOD, RENEWAL/10 Digit HUC Code/Permit # (if a modification or renewal) or Application # (from this particular company) for that particular day*

Appendix D: Additional Resources

- <https://www.epa.gov/eg> - EPA homepage for Effluent Guidelines
- <https://www.epa.gov/eg/unconventional-extraction-oil-and-gas-industry>--EPA information on UOG effluent rulemaking and background.
- <https://www.epa.gov/eg/coalbed-methane-extraction-industry> --Effluent guidelines from EPA on coalbed methane extraction
- <http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OW-2014-0598-0001> EPA information on UOG effluent rulemaking and background- more information and a summary from Regulations.gov information source.
- EPA solid waste (40 CFR §261.2). EPA defines solid waste as garbage, refuse, sludge, or other discarded material (including solids, semisolids, liquids, and contained gaseous materials). If a waste is considered solid waste, it must then be determined if it is hazardous waste (§262.11). Wastes are defined as hazardous by EPA if they are specifically named on one of four lists of hazardous wastes located in Subpart D of Part 261 (F, K, P, U) or if they exhibit one of four characteristics located in Subpart C of Part 261 (characteristic wastes):
[http://waste.supportportal.com/link/portal/23002/23023/Article/22091/What-is-a-RCRA-hazardous-waste?_utma=172919287.658988263.1401825591.1401828189.1413912325.3&_utmb=172919287.12.8.1413912518462&_utmc=172919287&_utmz=172919287.1413912325.3.2.utmcsr=google|utmccn=\(organic\)|utmcmd=organic|utmtr=\(not%20provided\)&_utmv=172919287.11=visitor%20id=658988263=1&_utmik=89205083](http://waste.supportportal.com/link/portal/23002/23023/Article/22091/What-is-a-RCRA-hazardous-waste?_utma=172919287.658988263.1401825591.1401828189.1413912325.3&_utmb=172919287.12.8.1413912518462&_utmc=172919287&_utmz=172919287.1413912325.3.2.utmcsr=google|utmccn=(organic)|utmcmd=organic|utmtr=(not%20provided)&_utmv=172919287.11=visitor%20id=658988263=1&_utmik=89205083)
- Information on Oil and Gas regulations:
<http://water.epa.gov/scitech/wastetech/guide/oilandgas/>
- Current regulatory framework for UOG: <http://water.epa.gov/scitech/wastetech/guide/oilandgas/unconv.cfm>
- Clean Water Act regulation of Coastal subcategory: <http://www.gpo.gov/fdsys/pkg/FR-1996-12-16/pdf/96-28659.pdf>

Some subparts of the CWA and later amendments are relevant to produced water use and handling, as follows:

- Clean Water Act (40 CFR part 435)-1979 and later amendments. “Subpart C covers wastewater discharges from field exploration, drilling, production, well treatment, and well completion activities in the oil and gas industry.” (Onshore)
- CWA Subpart E-applies to onshore facilities located in the continental US and west of the 98th meridian for which the produced water has a use in agriculture or wildlife propagation when discharged into navigable waters. Limits oil and grease and waste pollutants, must be good enough quality, and put to such use during periods of discharge.

- 1979 final rule for all categories:
http://water.epa.gov/scitech/wastetech/guide/oilandgas/upload/O-G-Final-Int-Final-Rule_Apr-13-1979_44-FR-22069.pdf
- Clean Water Act regulation of Coastal subcategory:
<http://www.gpo.gov/fdsys/pkg/FR-1996-12-16/pdf/96-28659.pdf>

Additionally, parts of the CWA apply to reinjection methods for waste disposal and underground storage of water:

- Underground Injection Control rules-UIC rules are intended to protect groundwater-Class II UIC permits.
- Aquifer Storage and Recovery (ASR)

Recent changes to the CWA include rules related to waters from hydraulic fracturing operations:

- Unconventional Extraction in the Oil and Gas industry—Federal Register Notice April 7, 2015-focus on regulating under the Clean Water Act discharges from oil and gas operations to POTWs.
<http://www.gpo.gov/fdsys/pkg/FR-2015-04-07/pdf/2015-07819.pdf>. <http://water.epa.gov/scitech/wastetech/guide/oilandgas/unconv.cfm>
- 1979 final rule for all categories:
http://water.epa.gov/scitech/wastetech/guide/oilandgas/upload/O-G-Final-Int-Final-Rule_Apr-13-1979_44-FR-22069.pdf

NETL regulatory and information page:

<http://energy.gov/fe/science-innovation/oil-gas/shale-gas-rd/produced-water-rd>

NETL state regs link (New Mexico)

<http://www.netl.doe.gov/research/coal/crosscutting/pwmis/fed-state-regulations/new-mexico>

Note: this was clearly part of PWMIS but links directly to PWMIS seem to be broken.

Produced Water Reuse Initiative 2014 conference site:

<http://www.produced-water-reuse-rockies-2014.com/sponsor-or-exhibit/>

CBM rules-Colorado, Aqwaterc at Colo School of mines:

http://aqwaterc.mines.edu/produced_water/regs/state/co/

Veolia Treatment systems information including SAGD and produced water treatments:

<http://www.vwsoilandgas.com/resourcecenter/case-studies/27696.htm>

Appendix E: Text of HR 388 (2002).

HOUSE BILL 388

45th legislature - STATE OF NEW MEXICO - second session, 2002

INTRODUCED BY Robert M. Burpo

AN ACT

RELATING TO TAXATION; PROVIDING FOR INCOME TAX AND CORPORATE
INCOME TAX CREDITS FOR INVESTMENTS IN CLEANING WATER PRODUCED
FROM OIL AND GAS DRILLING.

BE IT ENACTED BY THE LEGISLATURE OF THE STATE OF NEW MEXICO:

Section 1. A new section of the Income Tax Act is enacted to read:

"[NEW MATERIAL] CREDIT FOR PRODUCED WATER.--

A. A taxpayer who files an individual New Mexico income tax return who is not a dependent of another taxpayer and who produces water in the course of drilling for oil or gas may take a tax credit in an amount equal to one thousand dollars (\$1,000) per acre-foot of produced water not to exceed four hundred thousand dollars (\$400,000) per year if the following conditions are met:

(1) the taxpayer discharges the water into the Pecos river in compliance with the requirements of the New Mexico Water Quality Act, the New Mexico water quality control commission regulations and the federal clean water acts;

(2) the taxpayer discharges the water in a manner approved by the interstate stream commission to contribute to delivery obligations pursuant to the Pecos River Compact; and

(3) the produced water discharged into the Pecos river is available for appropriation only to meet terms of the Pecos River Compact.

B. A husband and wife who file separate returns for a taxable year in which they could have filed a joint return may each claim only one-half of the credit that would have been allowed on a joint return.

C. The tax credit provided in this section may only be deducted from the taxpayer's personal income tax liability. Any portion of the tax credit provided in this section that remains unused at the end of the taxpayer's taxable year may be carried forward for three consecutive taxable years.

D. As used in this section, "produced water" means water produced from oil or gas drilling from a depth of three thousand feet or more below the surface."

Section 2. A new section of the Corporate Income and Franchise Tax Act is enacted to read:

"[NEW MATERIAL] CREDIT FOR PRODUCED WATER.--

A. A taxpayer that files a New Mexico corporate income tax return that produces water in the course of drilling for oil or gas may take a tax credit in an amount equal to one thousand dollars (\$1,000) per acre-foot of produced water not to exceed four hundred thousand dollars (\$400,000) per year if the following conditions are met:

(1) the taxpayer discharges the water into the Pecos river in compliance with the requirements of the New Mexico Water Quality Act, the New Mexico water quality control commission regulations and the federal clean water acts;

(2) the taxpayer discharges the water in a manner approved by the interstate stream commission to contribute to delivery obligations pursuant to the Pecos River Compact; and

(3) the produced water discharged into the Pecos river is available for appropriation only to meet terms of the Pecos River Compact.

B. The tax credit provided in this section may only be deducted from the taxpayer's corporate income tax liability. Any portion of the tax credit provided in this section that remains unused at the end of the taxpayer's taxable year may be carried forward for three consecutive taxable years.

C. As used in this section, "produced water" means water produced from oil or gas drilling from a depth of three thousand feet or more below the surface."

Section 3. DELAYED REPEAL.--Sections 1 and 2 of this act are repealed effective January 1, 2006.

Section 4. APPLICABILITY.--The provisions of this act apply to taxable years beginning on or after January 1, 2002.

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Appendix F: Graphic User Interface (GUI) of Decision Support Tool (DST)

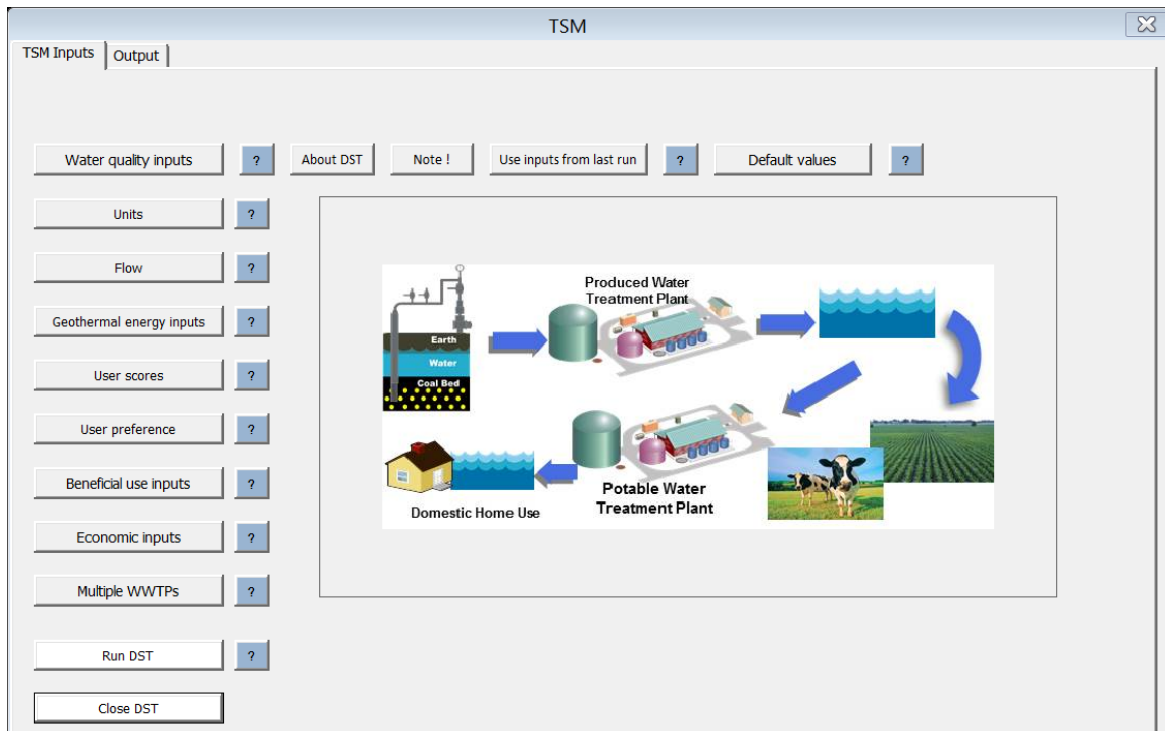


Figure F1 Graphic user input (GUI) interface for Decision Support Tool.

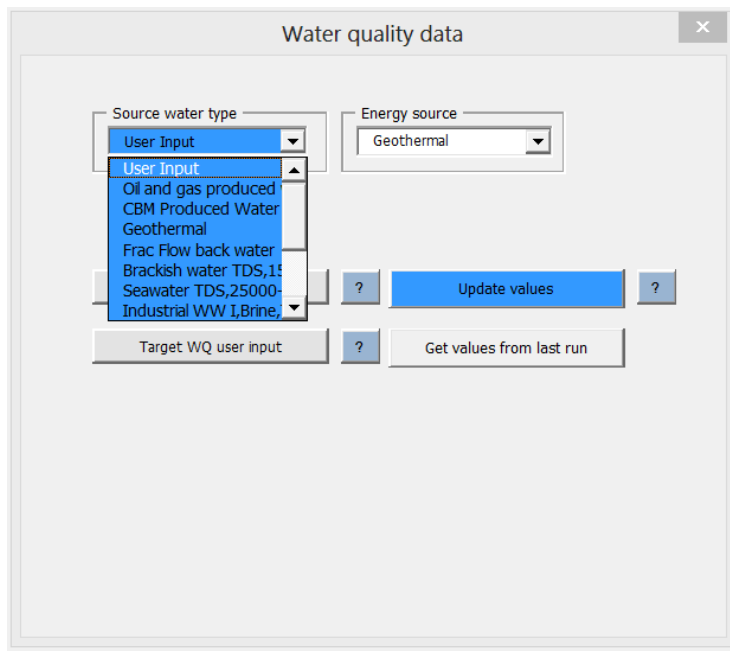


Figure F2 Feed water quality input interface.

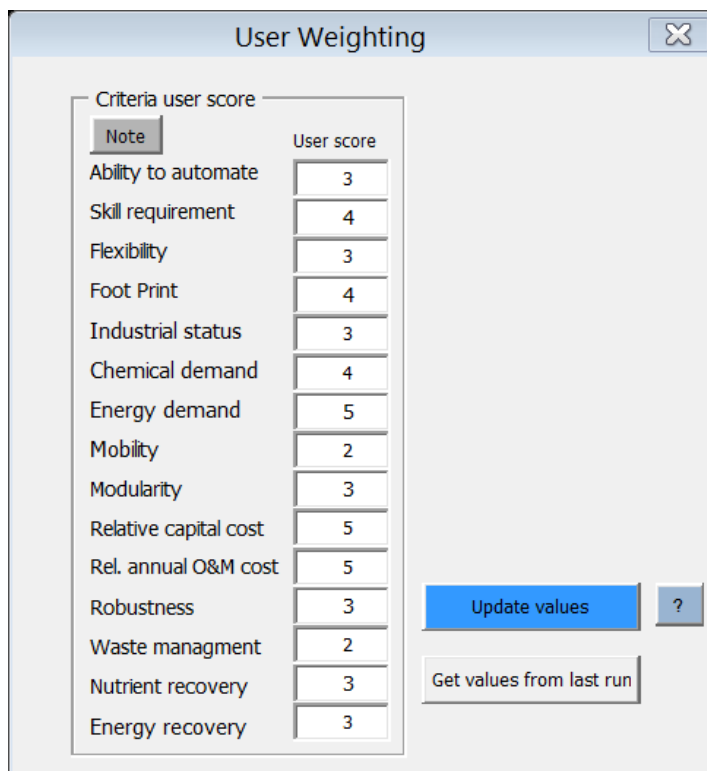


Figure F3 User weighting interface.

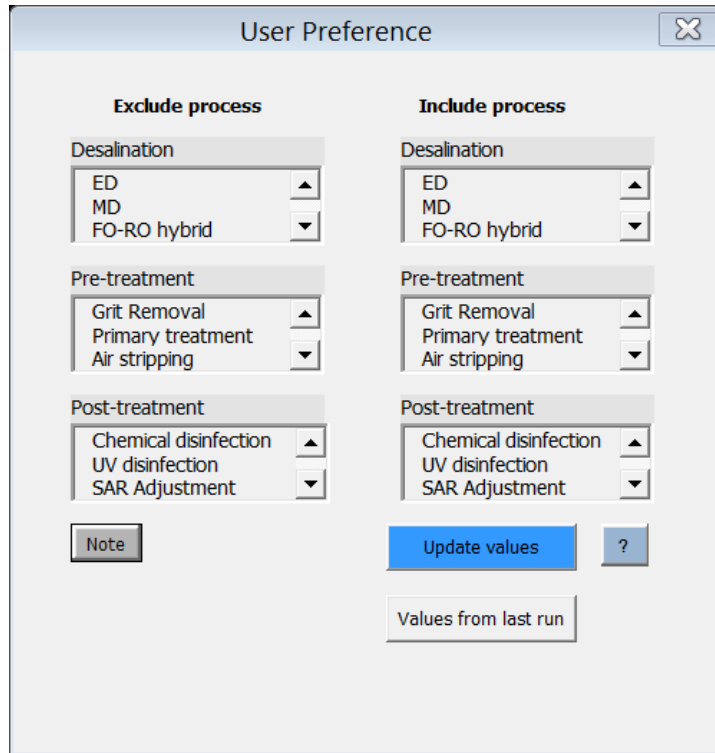


Figure F4 User preference interface.

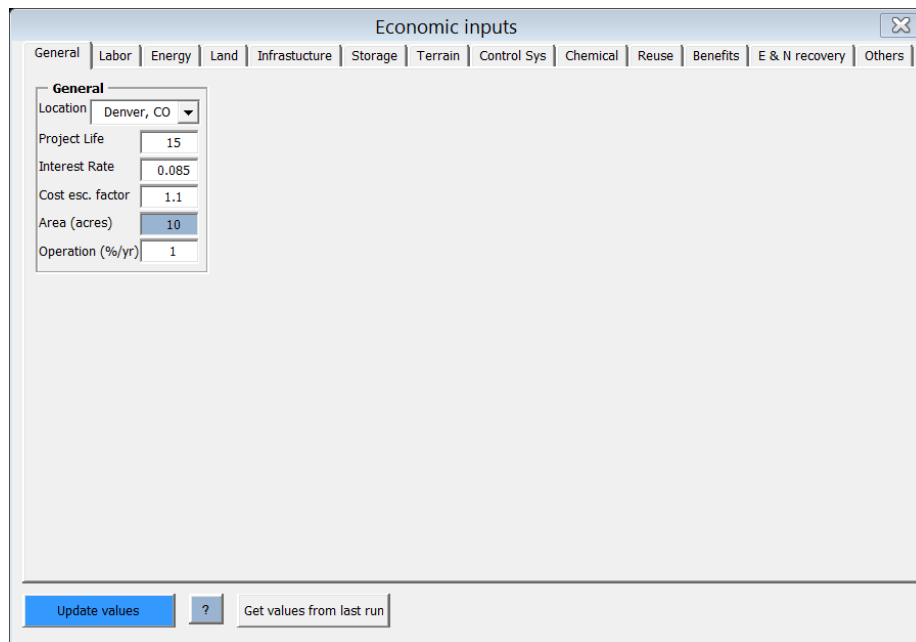


Figure F5 Economic inputs interface.

TSM

TSM Inputs | Output

Show treatment train | Go to outputs summary

CTP							
1	Air stripping	Acid Carbon IX (H)	Media filter	Tight NF	Chemical disinfection	Evap ponds/	Br
2	Air stripping	Acid Carbon IX (H)	Media filter	ED	Chemical disinfection	Evap ponds/	Br
3	Air stripping	(Ba) precipitation - Media filter	ED	Chemical disinfection	Evap ponds/	Brine disposal	--
TP1							
1	--	--	--	--	--	--	--
2	--	--	--	--	--	--	--
3	--	--	--	--	--	--	--
TP2							
1	--	--	--	--	--	--	--

Cost & Energy demand | Energy

CTP	Capital Cost Total	Annualized Capital Cost (\$)	Total Annual O & M cost (\$)	Total annualized cost (\$)	Annual O & M (\$/gal)	Tot. ann
1	25,178,700	2,907,400	1,156,700	4,064,100	0.0032	0.0111
2	25,782,200	2,980,300	1,417,100	4,397,400	0.0039	0.0120
3	21,832,300	2,523,900	1,175,600	3,699,500	0.0032	0.0101
TP1						
1	--	--	--	--	--	--
2	--	--	--	--	--	--
3	--	--	--	--	--	--
TP2						
1	--	--	--	--	--	--

Constituents requiring treatment

Benzene	Chloride	Fluoride	Iron (II)	Manganese	Rd 226+222+	TDS (calc)	Toluene

Figure F6 DST output interface.