PREDICTIONS OF PRODUCED WATER QUALITY AND QUANTITY
FOR SPATIALLY-DISTRIBUTED WELLS IN NIOBRARA FORMATION

Submitted by

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In partial fulfillment of the requirements
For the Degree of Master of Science
Colorado State University
Fort Collins, Colorado
Fall 2012

Master’s Committee:

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ABSTRACT

PREDICTIONS OF PRODUCED WATER QUALITY AND QUANTITY FOR SPATIALLY-DISTRIBUTED WELLS IN NIOBRARA FORMATION

Two main problems facing the oil and gas industry are the availability of water for well construction and disposal of the produced water. Produced water is typically only treated for a limited number of constituents, and common disposal options have been deep well injection, evaporation or discharge to wastewater treatment plants. However, because of factors such as regulations, local water shortage, and bans on disposal via deep well injection, the future will require much of the produced water be treated and eventually recycled and reused for future field development or other beneficial uses. Multiple cost effective produced water treatment methods have been developed but limited research has been done to understand produced water production volumes and quality from oil and gas fields. Accurate predictions of produced water volumes and quality over a period of time can be used to optimize design and siting of water handling and treatment facilities in a spatially heterogeneous shale oil and gas field. The information can also be used to model availability of water resources and plan long term recycling strategies for augmenting regional surface water supplies.

This study describes protocols to estimate and predict produced water quantity and quality from shale gas wells and applies these to a case study of Noble Energy Inc. wells in Yuma County, CO. Three different protocols of water production prediction were developed based on temporal and spatial variations of water quantity. Dissolution kinetics and geospatial data were used to develop a water quality prediction framework.
A Microsoft Excel based tool, which uses a combination of water quantity and quality protocols, was developed to predict water production and total dissolved solids (TDS) from Noble Energy Inc. wells in Yuma County for different field development scenarios. A framework for interactive web based applications based on developed protocols is also provided. This study also provides a framework for development of GIS based web applications, which can provide an analysis platform for producers and consulting firms to predict water production and/or water quality, optimize location of treatment facilities, truck routings and help make other decisions related to water management.

The study showed that using decline models to predict water production from shale gas fields will provide better long term predictions rather than using historical production average values. The case study and scenarios used for Noble Energy wells in Yuma County demonstrate that these prediction methods can be used in any other shale gas field by altering decline models and coefficients.

**Keywords:** Produced water volume prediction, produced water quality prediction, hydraulic fracturing, flow back water, shale gas, Niobrara, water resources, water management, produced water recycling, produced water reuse, produced water treatment.
ACKNOWLEDGMENT

This research project would not have been possible without the support of many people. I would like to thank all of the people that have helped and inspired me during my studies. First, I would like to express my gratitude to my adviser, Prof. Dr. Kenneth Carlson who was abundantly helpful and offered invaluable assistance, support and guidance. His belief in me and his mentoring have led me to opportunities that have exceeded my greatest expectations when I first came to CSU as an international student. I am very thankful for all he has done and it has been my honor to work with him.

I was delighted to work with Dr. Kimberly Catton on this project as my faculty committee member. All the statistical analysis of the work would not have been possible without her help and support. I appreciate her enthusiasm and kindness.

Dr. Sally Sutton deserves special thanks as my outside committee member and instructor without whose knowledge and assistance this study would not have been successful.

Special thanks also to all of my graduate friends, especially project members Stephen Goodwin, Huishu Li, Ashwin Dhanasekar, Bing Bai for sharing the literature, and offering invaluable assistance and support.

Dr. Mazdak Arabi, Dr. Sybil Sharvelle and Dr. Pinar Omur-Ozbek also deserve recognition for their inspiration and contributions to my education and my graduate school experience.

I would also like to convey great thanks to the Ministry of Education of Tatarstan for giving me an opportunity to study abroad and providing the financial means and support throughout my studies at CSU.

Finally, I wish to express my deepest gratitude to my family for their unconditional love and support throughout my life, for their understanding & endless love.
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1. INTRODUCTION

1.1 Origin of the problem

Produced water is the largest waste stream of the oil and gas industry. According to Clark and Veil (2009) approximately 20 billion barrels of produced water (PW) was generated from nearly one million onshore wells in 2007. Most of this water was managed through injection for enhanced oil recovery (10.7 billion barrels) or disposal (7 billion barrels) and 0.65% (139 million barrels) was discharged to water bodies (Clark et al., 2009). On the other hand, development of unconventional resources requires large amounts of fresh water, sometimes up to five million gallons of fresh water to complete a single well (Jason et al., 2012). Moreover, an average unconventional shale gas well might be completed several times over its lifetime in order to maintain hydrocarbon production. As the population grows, demand for hydrocarbons will increase, which will inevitably raise the rate of fresh water consumption by the oil and gas industry (Hutchings, 2010). Many of the new areas under consideration for shale oil and gas exploration are located in ecologically sensitive regions with semi-arid environments, remote or drought areas, where water availability for drilling and stimulation is critical (Jason et al., 2012). Expanding municipal and industrial demands will also intensify competition over water resources (Goodwin et al., 2012). Disposal options for produced water and water availability for drilling and stimulation are the two main barriers to the development of many shale gas plays (GE, 2011). However, there is a great opportunity in treating, reusing and recycling this waste stream of oil and gas operations and converting it into a valuable resource, which can be utilized for future field development, industry or other beneficial uses. The Colorado Oil and Gas Conservation Commission (COGCC) has also identified the need for an assessment of the water supply in Colorado for the oil and gas industry with the explicit need to identify the potential for
water reuse (STRONGER, 2011). Many factors including geological restrictions, local water scarcity, legislation, and PW disposal bans will drive producers to increase recycle and beneficial reuse of produced water.

Many cost effective PW recovery methods that have been developed and many PW pilot treatment facilities built across the nation in major oil and gas plays (Acharya et al. 2011; Das, 2012; Dores, 2012; Jason et al., 2012), but limited research has been done to understand produced water production volumes and quality with time from the shale oil and gas field. Accurate predictions of produced water volumes and the quality over a period of time are important as they can be used by producers and consulting firms to optimize design and siting of water handling and treatment facilities in a spatially heterogeneous gas field, as they are key factors for initial capital investments and operational costs (Muraleedaaran, 2009). The information can also be used to model availability of water resources and plan long term recycling strategies for augmenting regional surface water supplies.

This study is a part of research that is being conducted at Colorado State University for developing a GIS-based Optimized Fluids Management (OFM) tool. Fluids management is a key element to enhance safety and environmental protection during the development of domestic natural gas and other petroleum resources. Optimized management of fluids can minimize community impacts such as truck traffic, noise and road damage, reduce air quality concerns such as the release of air toxics, and influence well pad siting and density decisions that result in a reduction of disturbance to the landscape. In addition, a comprehensive tool that manages fluids can result in a smaller regional water footprint and through coordination of logistics minimize the risk of spills and leaks that could impact surface and ground water quality. This study provides protocols for estimating and predicting produced water quality and volumes as
they are the core elements of optimized fluid management. Analysis is conducted using information about wells in Yuma County, CO from all producers. Example predictions are made for Noble Energy wells located in Yuma County, one of the target areas for water management optimization in CSU’s research program.

1.2 Objectives

The main objectives of this thesis are as follows:

1. Develop protocols to estimate and predict produced water production from a shale gas field based on historical data. Apply the developed protocol to predict produced water production from existing Noble Energy Inc. wells in Yuma County.

2. Develop a framework for estimating and predicting water quality from existing shale gas wells.

3. Combine water quantity and quality protocols to estimate temporal and spatial trends for water quality and quantity for selected wells. Develop an interactive Excel based tool to predict water production and quality from Noble Energy Inc. wells in Yuma County for different development scenarios.

4. Provide a framework for a web-based tool that can implement these protocols.

1.3 Structure of Thesis

The thesis is divided into three sections: (i) an extensive review of existing literature about unconventional resources, water production and use from oil and gas operations, produced water quality, water management strategies and environmental issues related to the oil and gas industry, (ii) protocols for estimating produced water flow and framework for water quality estimation from a shale gas field, including different water production scenarios in case study of Noble Energy wells in Yuma County. This section is written in the form of a journal paper,
which will be submitted to SPE (Society of Petroleum Engineers) Journal (iii) application of
developed protocols in the form of a Microsoft Excel based tool and proposed online GIS based
web application.
2. LITERATURE REVIEW

2.1 Introduction

Hydrocarbons are the primary energy resource used worldwide. Natural gas is a naturally occurring hydrocarbon gas mixture, which has no color or smell, mainly consisting of methane (Encana, 2012). Compared to other fossils fuels, natural gas emits less carbon dioxide during combustion, while releasing significant amounts of energy. Natural gas is formed beneath the earth’s surface and trapped in porous sedimentary rock with impermeable layers on the top of it (Naturalgas.org, 2012). After extraction and purification, gas is delivered through the network of pipelines to end-users domestically and internationally. More than 90% of natural gas consumed in the US is produced domestically (EIA, 2011). According to US Energy Information Administration (EIA, 2011), consumption of natural gas is expected to increase, mostly due to gasification of coal-fired power plants. Most of technologically recoverable natural gas in the USA is in the form of shale gas, tight sands and coal bed methane, which are also known as unconventional resources. It is predicted (Figure 2.1) that unconventional natural gas will account for 77% of total domestic natural gas production by 2035 (EIA, 2012). Figure 2.2 provides a map of major shale gas plays in the US.

![Figure 2.1. U.S. natural gas production, 1990-2035 (trillion cubic feet) (EIA, 2011).](image-url)
Unlike conventional gas resources, development of shale gas is more complex and requires additional technology, resources and energy. The two most important components are horizontal drilling and hydraulic fracturing (Jones et al., 2011).

Hydraulic fracturing is the process of injecting fracturing fluid into the target source rock at high pressures in order to increase permeability of the formation by creating additional fractures through which hydrocarbons can flow to the wellbore (API, 2010). The process of hydraulic fracturing is a highly sophisticated engineering process which involves many stages. Fracturing fluid contains water, sand and chemical additives with different purposes. Each chemical has its own use such as reducing viscosity, preventing scaling, controlling bacterial growth, pH buffering and others. Horizontal drilling is a method where the wellbore is drilled vertically to...
the target formation and continues horizontally through it. This technique allows producers to consolidate many gas wells into one pad, which reduces the surface footprint by up to 90% (API, 2010).

2.2 Major environmental concerns of shale gas development.

Recent developments in hydraulic fracturing and horizontal drilling have unlocked large amounts of unconventional resources located throughout the USA and made them economically feasible to recover. However, these practices have aroused many concerns about the potential impact of shale gas development on water resources and the environment (Sakmar, 2011). Table 2.1 provides a list of environmental challenges of shale gas development and different mitigation strategies.

Table 2.1. Shale gas development major environmental issues and mitigation strategies.

<table>
<thead>
<tr>
<th>Environmental Issues</th>
<th>Description</th>
<th>Mitigation or management programs (Jones F, 2011).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential subsurface contamination of groundwater</td>
<td>Possibility of contaminant migration from target formation through (Broderick, 2011):</td>
<td>• Micro-seismic monitoring of hydraulic fracturing job (Only 3% of frac jobs are seismically monitored (Kent, 2010))</td>
</tr>
<tr>
<td></td>
<td>• fractures, created during hydraulic fracturing;</td>
<td>• API best practices and standards to ensure well integrity.</td>
</tr>
<tr>
<td></td>
<td>• naturally occurring faults and cracks;</td>
<td>• Disclosure of chemicals used for hydraulic fracturing.</td>
</tr>
<tr>
<td></td>
<td>• outside space of casing;</td>
<td>• Detailed geological and hydrogeological analysis of subsurface structures.</td>
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<td></td>
<td>• other casing failures related to corrosion, poor construction or improper plugging.</td>
<td>• Integrity testing of casing of the wells.</td>
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<tr>
<td></td>
<td>Failure or loss of integrity of the well casing (wellbore) during drilling, stimulation or operation (Broderick, 2011).</td>
<td>• Groundwater quality monitoring near hydraulic fracturing operations.</td>
</tr>
<tr>
<td>Potential soil and surface water or near surface groundwater impacts</td>
<td>Blowouts (Blowouts were reported in Pennsylvania and West Virginia during drilling operations (Zoback et al., 2010)). Spills, overflow or leaching from cuttings/mud pits (Broderick, 2011):</td>
<td>• Determination of accurate information about subsurface structure;</td>
</tr>
<tr>
<td></td>
<td>• storage capacity limitations;</td>
<td>• Personnel trained for unusual situations.</td>
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<td></td>
<td>• human error;</td>
<td>• Proper liquid management (Storage of frac water and flowback water in close containers)</td>
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<td></td>
<td>• heavy rain or storm;</td>
<td>• Detailed baseline monitoring before starting operations (soil, groundwater, methane, noise, wastewater, waste);</td>
</tr>
<tr>
<td></td>
<td>• pit liner failure;</td>
<td>• Application of spill prevention procedures;</td>
</tr>
<tr>
<td></td>
<td>Spill of fracturing chemicals during transportation and mixing (Broderick, 2011):</td>
<td></td>
</tr>
<tr>
<td><strong>Spill of flowback water while transferring to storage/disposal/treatment facility (Broderick, 2011):</strong></td>
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<tr>
<td>- Pipeline failure;</td>
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<td>- Insufficient storage capacity;</td>
<td></td>
<td></td>
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<tr>
<td>- Human error</td>
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<tr>
<td><strong>Other spillage of frac fluids and frac flowback fluids during transportation, storage or disposal.</strong></td>
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</table>

<table>
<thead>
<tr>
<th><strong>Water availability for field development can be an issue in:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Drought, remote, water shortage, environmentally sensitive areas</td>
</tr>
<tr>
<td><strong>Produced water disposal issues:</strong></td>
</tr>
<tr>
<td>- Bans on disposal wells;</td>
</tr>
<tr>
<td>- Regulations;</td>
</tr>
<tr>
<td>- Risk of formation plugging;</td>
</tr>
<tr>
<td>- Seismic activity;</td>
</tr>
<tr>
<td>- Social perception;</td>
</tr>
<tr>
<td>- Clean water act.</td>
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<table>
<thead>
<tr>
<th><strong>Optimized fluid management</strong></th>
</tr>
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<tbody>
<tr>
<td>- Develop detailed fluid management plans:</td>
</tr>
<tr>
<td>- GIS optimization</td>
</tr>
<tr>
<td>- Carefully select and audit contractors to avoid waste issues;</td>
</tr>
<tr>
<td>- Work with local communities regarding storage and transport of waste to offsite facilities.</td>
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<table>
<thead>
<tr>
<th><strong>Land disturbance (Lechtenbohmer, 2011):</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>- High well density (up to 6 wells/km²)</td>
</tr>
<tr>
<td>Road network</td>
</tr>
<tr>
<td>Pipeline network</td>
</tr>
<tr>
<td>Hauling</td>
</tr>
<tr>
<td><strong>Using multiwell pads;</strong></td>
</tr>
<tr>
<td><strong>Reduction of visual impacts by strategically placing operations with respect to natural barriers (forests, hills, etc.)</strong></td>
</tr>
<tr>
<td>- Flaring operations only during day light hours to minimize visual impacts; application of seismic techniques with minimum surface impact</td>
</tr>
<tr>
<td>- Land reclamation programs such as reseeding and erosion control of the well pad after stimulation and drilling operations.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Emission sources:</strong></th>
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<tbody>
<tr>
<td><strong>Well development (noise, particulate matter, SO₂, NOₓ, VOC, CO, CO₂) (Lechtenbohmer, 2011):</strong></td>
</tr>
<tr>
<td>- Drill rigs</td>
</tr>
<tr>
<td>- Truck traffic</td>
</tr>
<tr>
<td>- Frac pumps</td>
</tr>
<tr>
<td>- Frac ponds</td>
</tr>
<tr>
<td>- Completion venting</td>
</tr>
<tr>
<td>- Fugitives</td>
</tr>
<tr>
<td>- Valves and Pneumatics</td>
</tr>
<tr>
<td>- Other drilling equipment</td>
</tr>
<tr>
<td>- Flaring</td>
</tr>
<tr>
<td><strong>Detailed emission monitoring program for (air, wastewater, waste, noise, greenhouse gas)</strong></td>
</tr>
<tr>
<td><strong>Share monitoring data with agencies and stakeholders involved</strong></td>
</tr>
<tr>
<td><strong>Green completions</strong></td>
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<table>
<thead>
<tr>
<th><strong>Earthquakes</strong></th>
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<tbody>
<tr>
<td>Aduschkin, 2000; AGS, 2011; Michaels, 2010 and Lechtenbohmer, 2011 reported induced seismic activity due to oil and gas operations</td>
</tr>
<tr>
<td><strong>Treatment and recycling of produced water instead of disposal.</strong></td>
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</table>

<table>
<thead>
<tr>
<th><strong>Other issues:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Mobilization of naturally occurring radioactive elements</td>
</tr>
<tr>
<td>- Large consumption of resources</td>
</tr>
<tr>
<td>- Impact on biodiversity</td>
</tr>
</tbody>
</table>
2.3 Water use and water production in the development of unconventional resources

Large quantities of water are required for successful shale gas development. The majority of this water is used for drilling and completion operations. Water requirements for shale gas wells may vary widely, but typically require 1.7 - 4 million gallons of water over the lifetime of the well (INGAA, 2008). For example, the average water use per hydraulic fracturing in Colorado and Texas is 1.1 and 2.7 million gal per job according to FracFocus (Figures 6.7-6.10 in appendix A). As energy production decreases, the well can be restimulated several times during its lifespan to economically recover energy. Although the amount of water used for developing these unconventional resources might seem large, it represents a relatively minor volume of total water use in the exploration area compared to use by agriculture and municipalities (DOE, 2009).

Many sources of water are used for hydraulic fracturing such as surface water, municipal water supplies, irrigation water purchased from landowners, groundwater, wastewater from municipal waste water treatment plants, reused or recycled well construction and stimulation water and recycled produced water (COGCC, 2012). Table 2.2 shows the estimated water use for drilling and stimulation in different shale plays.

Table 2.2. Water use for well construction in different shale gas plays (Chesapeake Energy, 2008).

<table>
<thead>
<tr>
<th></th>
<th>Water used, bbls/well</th>
<th>Wells/year</th>
<th>Water used per year, MM bbls/year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Drilling Fracturing Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barnett</td>
<td>10000 70000 80000</td>
<td>600</td>
<td>48</td>
</tr>
<tr>
<td>Fayetteville</td>
<td>1500 70000 71500</td>
<td>250</td>
<td>18</td>
</tr>
<tr>
<td>Haynesville</td>
<td>25000 65000 90000</td>
<td>200</td>
<td>18</td>
</tr>
<tr>
<td>Marcellus</td>
<td>2000 90000 92000</td>
<td>600</td>
<td>55</td>
</tr>
</tbody>
</table>

When construction of the well is completed, along with oil and gas, it starts producing water, which is called produced water. The amount of this water varies significantly according to several factors. Three important factors are the type of hydrocarbon being produced, the
geographical location of the field and the method of production (Clark et al., 2009). The type of hydrocarbon will determine not only the volume but also the time when water is generated during the life of the well. The reason is that different hydrocarbons are found in different formations with different physical and chemical properties, which can greatly influence water production. For example, coal bed methane generates the majority of water in the beginning of well life, while conventional oil and gas wells start producing more water as they get more mature. With coal bed methane, water is pumped out from the formation in order to decrease pressure, so gas can flow to the surface. For conventional oil, on the other hand, less water is produced in the early stages of production, when pressure is high enough to let oil flow to the surface by itself. As the well matures, water production increases as oil pumped out of the reservoir replenishes with water from neighboring formations. Water flooding used to stimulate the production in conventional wells will increase the water to oil ratio even more (GOA, 2012).

Geographical location is another factor influencing water production. For example, according to the USGS (2000), the average water production per coal bed methane well in the Powder River Basin in Wyoming and Montano is more than 15 times larger than water production from San Juan Basin in Colorado and New Mexico. Wells located in the same field at some distance from each other will also have differences in water quantity.

The method of production is another key factor affecting the volumes of water produced. Wells that need stimulation such as waterflooding or hydraulic fracturing will produce significantly more water than wells that can produce under existing pressures. Produced water from hydraulically fractured wells will consist of naturally occurring formation water and the rest of the fracturing water.
According to Clark et al (2009) almost 21 billion barrels of produced water were generated from offshore (600 million bbl) and onshore (20.4 billion bbl) oil and gas wells in the United States in 2007. In Colorado, water produced from the oil and gas fields in 2011 was estimated at 330 million barrels according to the COGCC database (Figure 2.3). Eighty six percent (86%) of Colorado’s 47,871 active wells are located in 6 counties: Weld, Garfield, Yuma, La Plata, Las Animas, Rio Blanco.

![Figure 2.3. 2011 Oil, gas water production in Colorado (COGCC, 2012).](image)

However, counties that contribute the greatest amount of produced water are not necessarily those that have the greatest number of the wells. While Weld County has the highest number of active wells (40% of the total wells in Colorado, 17558 wells), it contributes only 3% (one million bbl) of total produced water generated in Colorado (Figure 2.4). Las Animas on the other hand, contributes 20% (70 million bbl) of produced water in Colorado, with only 6% (2885 wells) of active wells. This can be explained by the fact that the majority of wells in Las Animas
are coal bed methane wells (2299 wells), while most of the wells in Weld County are in shale formations.

![Map of Colorado showing produced water production distribution by Counties](image)

Figure 2.4. Produced water production distribution by Counties in Colorado. (Number of the wells in each County is provided in parenthesis. Data source: COGCC, 2012).

Yuma County, which is the target area of this research has 3892 (8.2% of total Colorado wells) active wells and all of them are classified as natural gas wells. Yuma county contributed 1.4% (5 million barrels) of Colorado’s produced water generated in 2011.

2.4 Produced water quality

Just as no two water sources are the same, no two identical oil and gas wells exist. Each well has its own individual physical-chemical and geological properties. Produced water quality varies widely depending on the target geological formation, geographical location, the depth of the formation, production stimulation methods, type of hydrocarbon, chemicals used during
drilling and stimulation and maturity of the field (Clark et al., 2009). Average and maximum TDS values from different shale plays are shown in table 2.3.

Table 2.3. Flowback water TDS from different shales (Acharya et al. 2011).

<table>
<thead>
<tr>
<th>Shale</th>
<th>Average TDS, mg/l</th>
<th>Maximum TDS, mg/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fayetteville</td>
<td>13000</td>
<td>20000</td>
</tr>
<tr>
<td>Woodford</td>
<td>30000</td>
<td>40000</td>
</tr>
<tr>
<td>Barnett</td>
<td>80000</td>
<td>150000</td>
</tr>
<tr>
<td>Marcellus</td>
<td>120000</td>
<td>280000</td>
</tr>
<tr>
<td>Haynesville</td>
<td>110000</td>
<td>200000</td>
</tr>
</tbody>
</table>

Salts, scaling metals, oil and grease, suspended solids, formation organic compounds and radioactive elements are constituents found in produced water (Clark et al., 2004). In addition to naturally occurring constituents, produced water also contains chemicals added during drilling, completion and the oil/water separation processes. Exposure to many of these components is hazardous, toxic or harmful to human health and the environment. Hence, proper management of this largest oil and gas waste stream in an environmentally friendly manner is vital to protect human health, ground and surface water, minimize environmental impacts and decrease future fresh water use (DOE, 2009).

Main water characteristics that will dictate treatment processes needed are: oil/and grease, hardness/metals (Ba, Ca, Fe, Mg, Mn, Sr), bacteria, TDS (mainly Cl and Na), and total suspended solids. Concentrations of all of these constituents are mainly dictated by the formation rocks and secondarily the feed water used for stimulation or drilling. As seen in Tables 2.4 and 2.5, fracturing fluid constituents are a relatively small fraction when compared with water quality after 30 days of flow back.
Table 2.4. Change in flowback water constituents over time. Location 1, Marcellus shale. (McElreath, 2011).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hydraulic fracturing fluid</th>
<th>Concentration in produced formation water following hydraulic fracturing (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>6 hours</td>
</tr>
<tr>
<td>TKN</td>
<td>41.3</td>
<td>523</td>
</tr>
<tr>
<td>Ammonia</td>
<td>38.5</td>
<td>110</td>
</tr>
<tr>
<td>Chloride</td>
<td>126</td>
<td>16500</td>
</tr>
<tr>
<td>Sulfate</td>
<td>165</td>
<td>91.6</td>
</tr>
<tr>
<td>TDS</td>
<td>1500</td>
<td>39300</td>
</tr>
<tr>
<td>Sodium</td>
<td>94.9</td>
<td>7260</td>
</tr>
<tr>
<td>Boron</td>
<td>0.0785</td>
<td>0.075</td>
</tr>
<tr>
<td>Benzene</td>
<td>&lt;1</td>
<td>4.15</td>
</tr>
<tr>
<td>Toluene</td>
<td>1.44</td>
<td>1.01</td>
</tr>
</tbody>
</table>

Table 2.5. Change in flowback water constituents with time. Location 2, Marcellus shale (McElreath, 2011).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hydraulic fracturing fluid</th>
<th>Concentration in produced formation water following hydraulic fracturing (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>6 hours</td>
</tr>
<tr>
<td>Sulfate</td>
<td>35.3</td>
<td>86</td>
</tr>
<tr>
<td>TKN</td>
<td>97.2</td>
<td>112</td>
</tr>
<tr>
<td>Ammonia</td>
<td>9.62</td>
<td>39.3</td>
</tr>
<tr>
<td>Chloride</td>
<td>2790</td>
<td>31200</td>
</tr>
<tr>
<td>TDS</td>
<td>7700</td>
<td>39400</td>
</tr>
<tr>
<td>Sodium</td>
<td>793</td>
<td>7940</td>
</tr>
<tr>
<td>Benzene</td>
<td>77</td>
<td>64.7</td>
</tr>
<tr>
<td>Toluene</td>
<td>198</td>
<td>62.6</td>
</tr>
</tbody>
</table>

Oil and grease and suspended solids are removed by well-known treatment methods such as clarification, media filtration and adsorption (Acharya et al. 2011). TDS (salinity) and hardness/metal removal requires methods such as membrane desalination and softening and can account for the majority of the capital cost of a produced water treatment system (Kimbal, 2011). It is therefore important to understand current and predict future concentrations of these constituents (TDS, hardness and metals) to design a treatment plant. Key contaminants of produced water, their impact on reuse and treatment options are shown in Table 2.6.
Table 2.6. Produced (flowback water) water key contaminants and impact for reuse (Acharya et al. 2011)

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Impact for reuse</th>
<th>Treatment options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particulates</td>
<td>Plugging</td>
<td>Clarification: coagulation, flocculation, settling and filtration</td>
</tr>
<tr>
<td>Suspended solids</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil and grease</td>
<td>Fluid stability</td>
<td>Adsorption: activated carbon, walnut shells or other sorbents Electrocoagulation</td>
</tr>
<tr>
<td>Dissolved organics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volatile organics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total dissolved solids</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chlorides</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfates</td>
<td>Scaling</td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardness (Ca, Mg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strontium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silica</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biological counts</td>
<td>Bacterial growth</td>
<td>UV, biocides</td>
</tr>
<tr>
<td>Naturally occurring Radioactive Materials (NORM)</td>
<td>Radioactivity</td>
<td>Dissolution and extraction</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

With recent concerns of unconventional gas development and its potential impact to groundwater supply, the USGS and other government agencies (e.g. COGCC) started conducting temporal and spatial analysis of surface and groundwater supply to reveal potential impact. However, there has been no research done to model produced water quality change over the lifetime of the well. Some studies such as Acharya, 2011, McElreath, 2011, Vidic, 2010 provide TDS and other constituent’s kinetics for flow back water quality, but most of the data is limited to 30 days of sampling. Figure 2.5 shows the variation of main water quality parameters such as TDS, calcium, sodium and chloride with time.
2.5 Summary

The development of the shale gas industry provides economic benefits including direct and indirect jobs, contributes additional government revenues and increases energy security. However environmental and social concerns still surround shale gas development. Recycling of produced water is one of the key water management strategies that can address water availability, water disposal and some environmental issues. Installation of a central treatment facility or an onsite treatment system is a key component of a successful recycling strategy. Accurate predictions of produced water quantity and the quality from shale gas wells over a period of time can be used in optimization of design and siting of water handling and treatment facilities in a spatially heterogeneous shale gas field. The information can also be used to model
the availability of water resources and plan long term recycling strategies for augmenting regional surface water supplies.

The oil and gas industry has more than a century of history in the United States, and there is a lot of research that has been done in this field. Many methods and models have been built and developed around forecasting hydrocarbon production, but there is a lack of research done to predict water quality and quantity from shale gas wells. The goal of this study is to increase the understanding of produced water quantity and quality from shale gas wells and to propose a protocol for predicting future trends. A user interface for the proposed protocol is developed in the MS Excel and a framework for migration to GIS based web tools is described.
3. DEVELOPMENT OF PROTOCOLS FOR PREDICTING PRODUCED WATER FLOW AND QUALITY FROM NIOBRARA FORMATION

Summary

Two main problems facing the oil and gas industry are the availability of water for well construction and disposal of the produced water. Produced water is typically only treated for a limited amount of constituents, and common disposal options have been deep well injection, evaporation or discharge to wastewater treatment plants. However, because of factors such as regulations, local water shortage, and bans on disposal via deep well injection, the future produced water treatment methods have been developed but limited research has been done to understand produced water production volumes and quality from oil and gas fields. Accurate predictions of produced water volumes and quality over a period of time can be used to optimize design and siting of water handling and treatment facilities in a spatially heterogeneous shale oil and gas field. The information can also be used to model availability of water resources and plan long term recycling strategies for augmenting regional surface water supplies. The ability to aggregate this information for a group of wells and predict how this might change with continued field development is also important for designing reuse strategies.

This study describes protocols to estimate and predict produced water quantity and quality from shale gas wells. In addition, the protocols are applied to Noble Energy wells in Yuma County, CO. Three different protocols for water production prediction have been developed based on temporal and spatial variations of water quantity. Dissolution kinetics and geospatial data were used to propose a water quality prediction framework. Both water quantity and quality protocols were applied to Noble Energy wells in Yuma County as a case study.

The study showed that using decline models to estimate water production from shale gas fields will provide better long term prediction than using historical production average values.
The case study and scenarios used for Noble Energy wells in Yuma County demonstrates that these prediction methods can be used in other shale gas fields by altering decline models and coefficients.

**Keywords:** Produced water volume prediction, produced water quality prediction, hydraulic fracturing, flowback water, shale gas, Niobrara, water resources, water management, produced water recycling, produced water reuse, produced water treatment.
3.1 Introduction

Produced water (PW) is the largest waste stream of the oil and gas industry. According to Clark and Veil (2009), approximately 20 billion barrels of PW was generated from nearly one million onshore wells in 2007. The majority, 95.2%, of this water was managed through injection for enhanced oil recovery (55.4% of injected PW or 8.6 billion barrels) or disposal (38.9% of injected PW or 6 billion barrels), with 4.4% discharged to water bodies (Clark et al., 2009). However, many factors such as geological restrictions, local water scarcity, legislation, PW disposal bans will drive producers to recycle and beneficially reuse their waste PW for future field development or other industry uses (Dores et al., 2012). There are many cost effective PW recovery methods that have been developed and multiple PW pilot treatment studies that have been conducted across the nation in major oil and gas plays (Das, 2012; Dores, 2012; Jason et al., 2012; Acharya et al. 2011), but very limited research has been done to understand PW production volumes and quality from the shale oil and gas field. Accurate predictions of PW volumes and PW quality for a life of the well will allow producers to optimize design and siting of water handling and treatment facilities in a spatially heterogeneous gas field. The information can also be used to model availability of water resources and plan long term recycling strategies for augmenting regional surface water supplies.

In this study protocols were developed to estimate PW quantity and quality from shale gas wells. The decline curve analysis is commonly used in the oil and gas industry to estimate hydrocarbons recovery rate in time. Water production decline curve analysis is used to develop protocols for estimation and prediction of PW production from shale gas wells in Yuma County Colorado. Example predictions are made for Noble Energy wells located in Yuma County, as
Yuma County is one of the target areas for water management optimization in studies conducted by Colorado State University.

A conceptual methodology for estimating and predicting PW quality has been developed using dissolution kinetics and geospatial data. This methodology was also applied to Noble Energy wells in Yuma County.

3.2 Drivers for produced water reuse or recycling

Historically considered a waste stream, PW is becoming a valuable resource for energy extraction. Many environmental, economic, regulatory, and social factors will cause the petroleum industry to change the way it deals with PW in the future (Dores et al., 2012). Table 3.1 summarizes the main driving factors in treating, recycling and reusing PW from oil and gas operations.

3.3 Study area location and description

Yuma County is located in the northeastern corner of Colorado. The county shares a border with both Nebraska and Kansas. According to the 2010 census, the population of the county is just over 10,000 people, with a population density of 4 people per square mile. Nineteen operators have over 3600 wells with annual gas production of 37 billion cubic feet, predominantly from the Niobrara shale formation (COGCC, 2011). Most of the wells produce dry gas with a negligible amount of oil.

Yuma County (Fig. 3.1) is one of the target areas for water management optimization in a larger study being conducted by CSU in collaboration with Noble Energy, Inc. Optimization includes developing long term water recycling and reuse strategies, as well as treatment options and optimal siting of water treatment facilities.
Table 3.1. Important factors driving PW treatment, reuse and recycling (Dores et al., 2012; Das, 2012).

<table>
<thead>
<tr>
<th>Factor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local water availability/scarcity</td>
<td>Many of the new areas under consideration for shale oil and gas exploration are located in ecologically sensitive regions with semi-arid environment, remote or drought areas, where water availability for drilling and stimulation is critical (Jason et al., 2012). Moreover, expanding municipal and industrial demands can create conflicts over water resources (Goodwin et al., 2012).</td>
</tr>
<tr>
<td>Increased regulatory/legislation scrutiny</td>
<td>Regulations related to PW disposal will continue to be stringent. Bans on disposal wells are already common in several regions of the US. Zero liquid discharge is imposed by local authorities in many areas of the US and Canada. It is expected that other regions will adopt stringent regulations.</td>
</tr>
<tr>
<td>Clean water act</td>
<td>Produced water cannot be discharged into open water bodies.</td>
</tr>
<tr>
<td>Risk associated with formation plugging or limited disposal capacity</td>
<td>Risk of formation plugging increases with time. Produced water from thousands of wells is brought and disposed of in a limited number of disposal wells. Disposal formations that intake PW might reach their capacity, which might result in production being stopped.</td>
</tr>
<tr>
<td>Cost of disposal via injection</td>
<td>Some wells are located in remote areas with no available nearby disposal wells. Long distance hauling of the PW can significantly increase operational costs in addition to disposal costs; therefore, onsite treatment and reuse is an option considered by operators.</td>
</tr>
<tr>
<td>Water allocation for drilling and stimulation</td>
<td>Development of unconventional resources requires large amounts of fresh water, sometimes up to five million gallons of fresh water to complete a single well (Jason et al., 2012). As the population grows, demand for hydrocarbons increases, which will inevitably raise the rate of fresh water consumption by the oil and gas industry (Hutchings et al., 2010). With proper treatment, PW can be the source water for production operations.</td>
</tr>
<tr>
<td>Well injection has the potential to contaminate fresh water aquifers</td>
<td>Continued injection under high pressure of vast amounts of PW can lead to migration of PW to fresh water aquifers through natural faults, cracks or along casings. Corrosion or other factors can lead to the failure of casings in aged wells, which can also pose the risk of contamination.</td>
</tr>
<tr>
<td>Social perception</td>
<td>In water shortage regions, use of large volumes of water for oil and gas operations is not socially responsible. In some areas where fresh water is not readily available, disposal of PW instead of seeking beneficial uses for it might be socially unacceptable.</td>
</tr>
<tr>
<td>Induced seismic activity</td>
<td>Aduschkin, 2000; AGS 2011; Michaels 2010 and Lechtenbohmer 2011 have reported induced seismic due to excessive injection during oil and gas operations</td>
</tr>
</tbody>
</table>
Figure 3.1. Map of the study area. Natural gas producing wells are represented as circles; Noble Energy wells are shown in red, and other producers are white.
3.4 Data collection

Information about PW annual production volumes, gas production, production days and first production dates from 1999 to 2011, and well location ESRI ArcGIS shapefiles were obtained from the publicly available Colorado Oil and Gas Conservation Commission database (COGCC, 2012b). Fig. 3.2 shows the distribution of wells by age. Information about completion, recompletion dates, as well as water used for stimulation and frac flowback volumes were provided by Noble Energy, Inc. as a separate MS Excel spreadsheet for each well. All data from the COGCC database and Noble Energy data were downloaded in February 2012.

3.5 Water production model

3.5.1 Prediction basis

The empirical Arp’s equation is a traditional decline curve analysis which was first proposed nearly sixty years ago to predict hydrocarbon production rate (Arps, 1944; Baihly et al., 2010; Kewen et al., 2003). This equation relates production rate and time for oil wells during a pseudo steady-state period and can be written as:

\[ q(t) = \frac{q_i}{(1 + bD(t))^{\frac{1}{b}}} \]  

(1)
where $q(t)$ - production rate at $t$, $q_i$ - initial rate, $D_i$ – decline rate, $b$ - degree of curvature.

Even though there have been other prediction approaches proposed since that time, the Arp’s equation is still widely used by industry because of its simplicity and applicability in almost any situation (Ebrahimi, 2010). Exponential and harmonic decline functions are special cases of Arp’s equation when $b$ is equal to 0 and 1, respectively. The hyperbolic decline function uses both parameters $D_i$ and $b$, where $0 < b < 1$. Most of the time all three functions can be well fitted to historical water production data, however each results in significantly different long term forecasts as shown in Fig. 3.3.

![Figure 3.3](image)

Figure 3.3. Representation of special cases of Arp’s equation: harmonic ($b=1$), hyperbolic ($0<b<1$) and exponential ($b=0$) (Lee, 1996).

The exponential decline curve has the highest decline rate and will lead to the most conservative forecast when predicting oil production, while the harmonic function has a smaller decline rate, providing less aggressive decline predictions. In this study a decline curve analysis
(DCA) was performed using harmonic \((b=1)\) and exponential \((b=0)\) decline functions to demonstrate the expected range of results.

3.5.2 Average field decline function (FDF)

Annual water production (AWP) data and production days (PD) from 2859 wells, the majority vertical with a few directional were downloaded and placed in a database. The annual water production rate was then converted to the equivalent average daily water production rate (DWPR) based on AWP and PD. Wells drilled prior to 2005 were eliminated to account for only recent technology and completion techniques. Wells with missing or incomplete water production information were also eliminated from analysis. The average daily water production data for each year from the all wells were classified from the first to seventh year of operation, so that the production data could all use the same start date, based on the production days information. For example, when one well began production in 2005 and another began in 2010, the data would be organized by first, second etc. year of production regardless of the drilling year. After that, quality control of the data was performed for DWPR values of each year of operation by excluding values above the 99th percentile and below the first percentile to remove outliers (Some wells had DWPR values over a few orders of magnitude

![Figure 3.4. Distribution of average daily water production for the operational year 2 (\(\alpha = 1.1064, \beta = 12.945\)). Field data presented as columns, Weibull distribution fitted to the data is shown as solid line. Coefficients: year 1 (\(\alpha = 0.9264, \beta = 13.72\)), year 2 (\(\alpha = 1.1064, \beta = 12.945\)), year 3 (\(\alpha = 1.087, \beta = 9.696\)), year 4 (\(\alpha = 1.12, \beta = 8.5676\)), year 5 (\(\alpha = 1.2074, \beta = 7.1794\)), year 6 (\(\alpha = 1.3335, \beta = 6.9312\)), year 6 (\(\alpha = 1.3695, \beta = 6.137\)).]
from the average). Next, mean and 95th percentile of DWPR values and distributions were calculated for each operating year (Fig. 3.5). Weibull distribution (Fig. 3.4) was found to be best at describing each operational year distribution of DWPR.

A decline curve analysis (DCA) was performed using harmonic and exponential functions by least square error (LSE) fitting to the mean values of DWPR (Table 3.2- 3.3 and Fig. 3.6) to model average field water production decline over time.

Figure 3.5. Daily water production histogram for each operational year is color coded; mean and 95th percentile are shown with black lines, columns are number of production data records available for each year.
Unlike conventional oil and gas reservoirs, Fig. 3.5 shows that average water production declines for shale gas wells. Production in the beginning of the well life is high due to flowback of mainly fracturing water used during stimulation and high initial formation pressures. Water production declines over time and formation water replaces fracturing fluid.

Correlation coefficients, obtained from fitting water production data to harmonic and exponential decline functions are 0.981 and 0.979 respectively (Table 3.2). Both of these decline curves can be used for water production modeling; however, exponential decline function might underestimate water production when used for long term predictions, potentially leading to building an undersized treatment plant. For this reason, the authors decided to use the harmonic decline function to model water production from wells in the study area, which will provide less aggressive decline predictions. The harmonic decline function in general can be shown as:

\[ y = \frac{19.74}{1 + 0.35 \cdot x} \]

* Correlation coefficient found using squared CORREL function in MS Excel
where $q(t)$ production rate at year $t$, bbl day$^{-1}$ well$^{-1}$; $D_t$ – decline rate (year$^{-1}$), $q_i$ – initial water production rate, bbl day$^{-1}$ well$^{-1}$. For Yuma County field data $D_i = 0.35$, $q_i = 19.74$ bbl day$^{-1}$ well$^{-1}$ (Table 3.2 and Fig. 3.6).

The field decline function (FDF) is a function, which describes decline in average water production rate in the field. From this function, one can get obtain information about how water production declines over time from an average well in the field. Equation 3 is a FDF which is generated for Yuma County wells. This function is further used to model water production from shale gas wells in Yuma field.

$$q(t) = \frac{q_i}{1 + D_i t} \quad (2)$$

$$q(t) = \frac{19.74}{1 + 0.35 \cdot t} \quad (3)$$
where \( q(t) \) is a production rate for any corresponding operational year, 19.74 \( \frac{bbl}{day} \) is a water production rate at the initial time, and 0.35 \( year^{-1} \) is the calculated decline rate for the Yuma County field. In the following sections \( t = 1 \) is considered as a new well (first operational year), \( t \geq 2 \) is considered as a well operated 2 years or more, i.e. if a prediction is made for 2011 based on data prior to and including 2010, wells drilled in 2011 have \( t = 1 \), wells drilled in 2010 or earlier have \( t = 2 \) or more.

3.5.3 Prediction methods

The field decline function is used to develop three different water production prediction methods. For each method \( D_i \) (decline rate), \( q_i \) (initial production rate) and \( t \) (operational year of a well) are model parameters. Table 3.4 and Figure 3.7 show parameters used in different prediction methods.

Table 3.4. Parameters used in different prediction methods.

<table>
<thead>
<tr>
<th>Prediction method</th>
<th>( q_i )</th>
<th>( D_i )</th>
<th>( t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method 1</td>
<td>Fixed</td>
<td>Fixed</td>
<td>Variable</td>
</tr>
<tr>
<td>Method 2</td>
<td>Variable</td>
<td>Fixed</td>
<td>Variable</td>
</tr>
<tr>
<td>Method 3</td>
<td>Variable</td>
<td>Variable</td>
<td>Variable</td>
</tr>
</tbody>
</table>

Figure 3.7. a) Method 1, \( t \) as a variable, b) Method 2, \( t \) and \( q_i \) as a variable, c) Method 3, \( t, q_i \) and \( D_i \) as a variable.
3.5.3.1 Method (1) of water production prediction based on FDF and age of the wells.

In this method, age of the wells and the FDF is used to model water production. Individual water production behavior (Example: fracturing) is not accounted for in this method of prediction. All wells that have the same age \( t \) will have the same predicted daily and annual water production. To calculate annual water production from a well, daily water production is multiplied by the average for field production days in a year. Equation 4 is an equation that can be used to calculate water production from selected wells.

\[
WP = \sum_{i=1}^{n} \left( \frac{19.74}{1+t_{ni}^{0.35}} \right) \cdot N_a + \sum_{i=1}^{m} \left( \frac{19.74}{1+t_{ni}^{0.35}} \right) \cdot N_n
\]

where, \( n \) is number of wells with operational year \( t \geq 2 \), \( m \) number of proposed new or refractured wells \( t = 1 \), \( t_n \) – age of each \( t \geq 2 \) well by the year of prediction, \( N_n \) – field average operation days for a first operational year (when \( t = 1 \)), \( N_a \) – average annual operational days after first operational year (when \( t \geq 2 \)). For Yuma County wells: \( N_a = 362 \text{ days} \), and \( N_n = 184 \text{ days} \), found averaging production days from historical data.

This method can be used for quick estimation of water production from a field with a large number of wells and can be implemented to predict future water production by changing (increasing) the age of the well for each additional future year.

Table 3.5 shows a calculation example of total water production for 2011 from Noble Energy, Inc. wells in Yuma County. First, age of the wells has to be determined (wells count column shows how many wells have different ages \( t \) by 2011). Thirty-one wells were drilled in 2010 \( t = 2 \), so they were 2 years old in 2011; therefore, the water production rate for a 2-year-old well from the field decline curve is 11.6 \( \text{bbl/day-well} \) from equation 2 when \( t = 2 \). In 2011, these

\[
Q = 31 \text{ wells} \cdot 11.6 \frac{\text{bbl}}{\text{day-well}} \cdot 362 \frac{\text{days}}{\text{year}} = 129914 \frac{\text{bbl}}{\text{year}}
\]

Similar
calculations were made for all wells, except that the wells drilled in 2011 have 184 production days instead of 362 days. To predict water quantity for 2012, the corresponding production rate has to be changed for each group of wells.

Table 3.5. Example water production prediction calculation for the year 2011 based on data before 2010

<table>
<thead>
<tr>
<th>Operational year, t</th>
<th>Well drilled</th>
<th>Well count, n</th>
<th>Field decline curve</th>
<th>Sum, bbl</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2011</td>
<td>0</td>
<td>14.6</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2010</td>
<td>31</td>
<td>11.6</td>
<td>129914</td>
</tr>
<tr>
<td>3</td>
<td>2009</td>
<td>0</td>
<td>9.6</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>2008</td>
<td>4</td>
<td>8.2</td>
<td>11857</td>
</tr>
<tr>
<td>5</td>
<td>2007</td>
<td>27</td>
<td>7.1</td>
<td>69821</td>
</tr>
<tr>
<td>6</td>
<td>2006</td>
<td>32</td>
<td>6.3</td>
<td>73383</td>
</tr>
<tr>
<td>7</td>
<td>2005</td>
<td>138</td>
<td>5.7</td>
<td>284285</td>
</tr>
<tr>
<td>8</td>
<td>2004</td>
<td>12</td>
<td>5.2</td>
<td>22439</td>
</tr>
<tr>
<td>9</td>
<td>2003</td>
<td>12</td>
<td>4.7</td>
<td>20543</td>
</tr>
<tr>
<td>10</td>
<td>2002</td>
<td>27</td>
<td>4.4</td>
<td>42619</td>
</tr>
<tr>
<td>11</td>
<td>2001</td>
<td>28</td>
<td>4.0</td>
<td>41003</td>
</tr>
<tr>
<td>12</td>
<td>2000</td>
<td>0</td>
<td>3.8</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>1999 and older</td>
<td>152</td>
<td>3.5</td>
<td>194473</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>890337</td>
</tr>
</tbody>
</table>

For existing Noble Energy wells, this method over-predicts 2011 water production values by 13%. This is related to the fact that all of the wells in last group (1999 and older) were assumed to be 13 years old, while in reality most of them are much older.

3.5.3.2 Method (2) of water production prediction based on individual initial production modeling with constant field decline rate.

In this method of prediction it is assumed that water production from all existing wells decline with the same rate. Therefore, decline rate is taken as a field decline rate when decline curve fitted to the data. All proposed new or refractured wells are assumed to have the same decline rate as FDF and variable initial water production.

To determine the production rate decline for each existing well, a harmonic decline curve is fitted to historical daily production data with a least square method for wells older than $t \geq 2$,.
solving for \( q_i \) (initial water production) as it is assumed that decline rate \( D_t \) is constant throughout the field. Wells could be fractured multiple times over their lifetime to maintain hydrocarbon production, therefore it is important to locate the last fracturing job for older wells and fit the curve from the fracturing year. An Excel based filter was developed to find the fracturing year using multiple criteria. After location of the fracturing year, curve fitting is conducted for each well and correlation coefficients are calculated. An example flowchart of the methodology is shown in Figure 6.14 – 6.15 in the supplementary appendix A. New or refractured wells \((t = 1)\) are modeled using FDF described by equation 3.

To calculate overall water production for a particular year, equation (5) can be used:

\[
WP = \sum_{i=1}^{i} \frac{q_i}{1+0.35 t_i} \cdot N_a + \sum_{j=1}^{j} \frac{19.74}{1+0.35 i} \cdot N_n
\]

where \( q_i, t_i \) are initial flow rate and operational year for each older than 1 year \((t \geq 2)\) \( i \) well. \( q_i \) is found by LSE fitting the data to the function. \( j \) – number of proposed new or refractured wells \((t = 1)\), \( N_n \) – first year average production days, \( N_a \) – average operational days after first year.

3.5.3.3 Method (3) of water production prediction based on individual decline model.

To predict water quantity from the selected area, wells are divided into three categories based on operational year: wells with \( t > 2 \), \( t = 2 \) and \( t = 1 \) (proposed new or refractured wells). A harmonic decline curve fitting with least square method is used to model each existing well with \( t > 2 \) by solving for \( D_t \) and \( q_i \) (three data points are assumed to be enough for curve fitting). If fractured multiple times, a curve fitting is used from the last fractured year. For each dataset curve fit, the correlation coefficients are calculated and compared with those found in the model using decline rate only (Method 2). Curves with the highest correlation coefficients are selected to describe flow from a particular well. For wells with \( t = 2 \), the fitting curve is found by solving
for $q_i$ only, as in the previous section. New or fractured wells ($t = 1$) are assumed to have the same production behavior as FDF. Therefore, initial and decline rate is the same as FDF.

To calculate overall water production from selected wells, equation (6) is used:

$$WP = \sum_{i=1}^{t} \frac{q_i}{1 + D_i \cdot t_i} \cdot N_a + \sum_{k=1}^{k} \frac{q_k}{1 + 0.35 \cdot t_k} \cdot N_a + \sum_{j=1}^{j} \frac{19.74}{1 + 0.35 \cdot 1} \cdot N_n$$

(6)

where $q_i, D_i, t_i$ are initial flow rate, decline rate and operational year for each $t > 2$ well. $q_k, t_k$ are initial flow rate and operational year for each $t = 2$ well. $D_i, q_i, q_k$ are found by LSE fitting the data to the function. $j$ – number of proposed new or refractured wells ($t = 1$), $N_n$ – first year average production days, $N_a$ – average operational days after first year.

3.5 Summary for water production prediction protocols

Three water production prediction protocols are summarized in Table 3.4. Example of prediction methods modeling for single well is shown in figure 3.8.

![Figure 3.8. Example of prediction modeling for the well 05-125-02382.](image-url)
Table 3.4 Summary table of prediction methods.

<table>
<thead>
<tr>
<th>Prediction methods</th>
<th>Prediction from wells operated more than 2 years ((t &gt; 2))</th>
<th>Prediction from wells operated more than 1 year and less or equal to 2 years ((t = 2))</th>
<th>Prediction from new or refractured wells ((t = 1))</th>
<th>Advantages and disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method (1) of prediction based on field production decline curve</td>
<td>Age of the wells and FWPDC is used to determine production rate for particular year.</td>
<td>Number of production days for new wells or refractured wells is 184 days. Water production rate is taken from FDF.</td>
<td>Based on production rate and production days, overall water production is calculated.</td>
<td>P: Quick prediction of water production from entire field. Low complexity, easy to automate. C: Prediction not accounting for individual well behavior (Each well with same age has same production rate)</td>
</tr>
<tr>
<td>Method (2) of prediction based on individual water production decline with constant field decline rate</td>
<td>LSE harmonic decline curve is fitted solving for initial production rate ((q_i)), decline rate constant, (D_t = \text{conts.})</td>
<td>Number of production days for new wells or refractured wells is 184 days. Water production rate is taken from FDF.</td>
<td></td>
<td>P: Accounts for variation in initial water production from different wells. More accurate long term predictions. C: Assumes that the decline rate is the same for all wells. Complex in terms of calculation</td>
</tr>
<tr>
<td>Method (3) of prediction based on individual decline model for a field</td>
<td>LSE harmonic decline curve is fitted solving for initial production rate ((q_i)) and decline rate ((D_t)).</td>
<td>LSE harmonic decline curve is fitted solving for initial production rate ((q_i)), decline rate constant, (D_t = \text{conts.}).</td>
<td>Number of production days for new wells or refractured wells is 184 days. Water production rate is taken from FDF.</td>
<td>P: Accounts for variation in initial water production and decline rates from different wells. More accurate long term predictions. Compares correlation coefficients from method (2) and chooses highest one. C: Complex calculations.</td>
</tr>
</tbody>
</table>

The first method does not account for spatial variation and temporal variation of water production. It uses the same initial production rates and same decline rate for all wells with the
same age/operational year. Therefore, use of this method should be limited to quick estimations of water production in the near future from existing wells.

Figure 3.5 (water production distribution for a first year) shows that initial water production is highly variable. The second method accounts for variation in initial water production from existing wells, but the average decline rate for the field is used for each individual well. The decline rate may fluctuate from one well to another, therefore, there can be differences in water production.

The third method also accounts for variation in initial production and decline rates for all existing wells. The field decline curve is used for all new or refractured wells. Therefore it is believed that this method will give the most accurate forecasts. However, use of this method requires the most complex calculations and modeling.

3.5.4 Prediction scenarios

This section shows three scenarios using the prediction methods described above. Predictions made are based on data prior to and including 2010. Prediction methods include:

- Prediction using average 2010 production data;
- Prediction based on method (1);
- Prediction based on method (2);
- Prediction based on method (3).

Fig. 3.9 shows *scenario one*, which assumes no field development for the next 10 years (no drilling in 2011-2020, just existing wells). Fig 3.10 shows *scenario two*, which assumes constant field development (20 new wells or refracs per year) for the same period. Figure 3.11 shows *scenario three*, which assumes constant aggressive field development (100 new wells or frac jobs each year) for 10 year forecast.
Figure 3.9. Scenario 1. No field development for the next 10 years. Predictions made are based on data prior to and including 2010 wells.

Predictions with all three of the methods were compared with estimations made using average production data from 2010. To predict produced water production using average 2010 data, for the same set of wells average annual water production was calculated (1776 bbl/well-year). The number of wells in each year was multiplied by the 2010 average to estimate total water production for that year.
It can be seen from all three scenarios that under the assumptions made (zero, constant and aggressive field development), there is a significant difference in estimated volumes between prediction methods accounting for water production decline and prediction methods using only historical average values. Actual 2011 water production was 790000 bbl from 469 selected wells, 9 of them were refractured. Prediction using average 2010 overestimated water production by 5% (830000 bbl), method (1) overestimated by 16% (910000 bbl), method (2) underestimated by 6% (770000 bbl) and method 1 underestimated by 7% (730000 bbl). Prediction methods 2 and 3 were close for near future predictions as well as long term predictions. Predictions differences using average 2010 and prediction method 3 were 500000 and 340000 bbl for scenario 1 and 2 respectively over a 10 year forecast.
Scenario 3: Aggressive field development scenario

Figure 3.11. Scenario 3. Constant aggressive field development of 100 new wells or frac jobs per year (20% of existing wells). Predictions made are based on data prior to and including 2010.

From provided scenarios, it is clear that water production prediction using only historical average values can lead to overestimation in slow development years (Scenarios 1 and 2) and underestimation in aggressive development periods (scenario 3).

Accurate well-based water prediction is important when dealing with small groups of wells or when siting a treatment plant (water handling facility). Flows from each well can be accounted for to minimize pumping costs. As method 3 uses water production rate decline modeling for each existing well, resulting water production prediction is accurate for individual wells and small group of wells. All the proposed new wells or refractured wells are modeled using FDF. Use of individual well based modeling water production from proposed wells drilled after the
last known water production data and before the predicting year has to be cumulatively accounted as well.

3.6 Assumptions and limitations

In reality, many factors affect water production. Some wells are drilled and have just started producing, some wells are plugged or abandoned, and some wells are closed for maintenance.

When predicting water production, some assumptions have to be made:

a. Water production volumes available from the COGCC database are assumed to be accurate. The database contained many missing or zero values for annual water production, while gas production and production days were present. Noble Energy specialists confirmed that some production information was not uploaded completely to the COGCC database as it was reported to them. Therefore, missing or unavailable water production data is ignored during calculations and analysis.

b. The field decline curve used to describe water production from wells is based on the statistical average field water production values. This curve gives only a general idea or trend of water production within a particular field. Well stimulation and drilling is done differently by different operators or service providers. Therefore, water decline might be different for different wells.

c. When a well is plugged or abandoned, it is assumed to be very old in well age, and has very small water production according to the decline curve; therefore, the impact on total water production from closed or abandoned wells is assumed to be negligible.

d. Refractured wells are assumed to have the same impact on water production as new, just completed wells.
3.7 Water quality model

Produced water quality varies widely depending on many factors such as the geological formation, the geographical location, the depth of the formation, production stimulation methods, type of hydrocarbon, chemicals used during drilling and stimulation, and maturity of the field (Clark C.E. et al., 2009). Salts, scaling metals, oil and grease, suspended solids, formation organic and inorganic compounds, and radioactive elements are the major constituents of produced water (Clark C.E. et al., 2004). In addition to naturally occurring constituents, produced water also contains chemicals added during drilling, completion and oil/water separation processes. Concentrations of all of these constituents are mainly dictated by formation rocks and formation water with a very minor effect of the feed water used for stimulation or drilling. Oil and grease and suspended solids are removed by treatment methods such as clarification, media filtration and adsorption (Acharya R., et al. 2011). TDS (salinity) is decreased by membrane desalination or thermal distillation, hardness/metals removed by softening. Desalination and softening can account for the majority of capital cost of a produced water treatment system (Kimbal, B. 2011). Knowledge of current and predicted water quality parameters can aid in optimal design of a produced water treatment facility. This study shows a framework for predicting water quality parameters contributed mainly by formation rocks such as TDS, Ca, Mg and other metals. A water quality parameter (WQP), which is used further in the text, is any measurable constituent (element or group of elements like Ca, Mg, Sr, TDS etc) in produced water which is dissolved directly from formation rocks surrounding produced water.

3.7.1 Concept background

The water-rock interaction is a complicated process, and more information can be obtained about it from the work of Brantley et al. (2008). For ease of use, simplifications and assumptions are made for the dissolution process in this study.
Initially, water in the formation is in chemical equilibrium with host rocks, minerals and hydrocarbons. Hydraulic fracturing introduces bulk quantities of relatively fresh water, which dilutes the formation water. As any chemical system needs some time to reach its equilibrium, water in the formation will dissolve formation rocks or precipitate solids until it reaches equilibrium for given conditions. In other words, the quality of the water will change with time as it gets exposed to formation rocks. Kinetics of dissolution is driven by many factors such as the activity of the constituent, temperature, pH, pressure, and the presence of other elements. For formation water, all of these factors are mainly dependent on the geology (characteristics) of the formation and the depth of the well.

Kinetics of dissolution can be derived from Fick’s First Law of diffusion (Eq. 7) and the integrated form is equivalent to the equation of first order reaction kinetics (Eq. 8) (Smith, 2004):

$$\frac{dn}{ds} = -DS \frac{dc}{dx}$$  \hspace{1cm} (7)

where: $dn$ [mol] - the amount of the dissolved substance within time interval $dt$ [s], $D \frac{m}{s}$ - diffusion coefficient; $S$ [$m^2$] - the total surface of the dissolved solid substance; $\frac{dc}{dx}$ - concentration gradient;

$$C = C_s(1 - e^{-kt})$$  \hspace{1cm} (8)

where: $k$ – reaction rate, $C_s$ – maximum concentration of substance or concentration at equilibrium.

For the case of PW quality from oil and gas wells, one more term has to be added to account for concentration of WQP in the initial water (Eq. 9):

$$WQP = C_s \cdot (1 - e^{-kt}) + C_i$$  \hspace{1cm} (9)

where $t$ is age of well, $WQP$ is water quality parameter, $C_i$ is the initial concentration of water quality parameter, $k$ is reaction rate and $C_s$ is saturation concentration of WQP.
There is limited reported research on temporal variation of water quality during the lifecycle of a well, but examples of TDS and other constituents’ kinetics provided for flowback water by Acharya, et al. (2011) are found to be a close to first order reaction kinetics. Therefore, it is assumed that the change of WQP with time can be modeled using first order kinetics. Reaction rates for different WQPs can be determined by back solving equation (9) using a series of actual measurements of WQPs at constant time intervals.

Any real world phenomena like elevation, characteristics of the formation (geology), as well as the depth of formation gradually change spatially and can be modeled using classical interpolation techniques. For this reason, it is expected that reaction rate \( (k) \) and the maximum concentration \( (C_s) \) for a particular WQP should gradually vary spatially for wells producing from the same formation. If \( k \) and \( C_s \) values for a WQP are given for a set of points (wells) in the field, then spatial interpolation can be implemented to build a surface of \( k \) and \( C_s \) values. With this interpolation map, each well in the field can be given its own \( k \) and \( C_s \) values extracted from the surface using the location of the well. Finally, each well will have its own water quality estimation curve.

3.8 Combined water quality and production model

Concentration of particular WQPs for a selected area can be estimated using the individual water production and water quality models described earlier. In order to determine the concentration of WQPs from selected wells, a simple mass balance has to be done using the following equation (Eq. 10):

\[
C(WQP) = \frac{\sum_{i=1}^{l} WQP_i \cdot WP_i}{\sum_{i=1}^{l} WP_i} \tag{10}
\]

where \( WPQ_i, WP_i \) – water quality parameter and water production for particular well.

An example of combined model implementation is described in the next section.
3.8.1 Example of water quality model use.

This section provides implementation of combined water quality and production methods in a case study of Noble Energy wells in Yuma County. Fig. 3.12 shows the Noble Energy, Inc. well age distribution in Yuma County.

Dissolution of the formation is one of the reasons why produced water from the wells deteriorates with well age. Initially, the produced water has a high quality (low concentration of metals, salts and other constituents), but as production continues, concentration of constituents, directly impacted by formation rocks, will increase until it reaches the saturation point. For the Yuma case study, it is assumed that produced water total dissolved solids (TDS) is one of the water quality parameters of interest. Instead of TDS, metals or other formation dependent constituents can also be modeled using a first order reaction rate (graphical representation shown in Fig. 3.13) by applying Equation 9.
Figure 3.13. Example of temporal TDS increase in produced water for well with $C_s=35000$ and $k=0.5$.

For this case study, it was assumed that a temporal water quality analysis of 6 wells across the shale gas field was conducted (at least 3 sample points, age of the well and initial water quality $(C_i)$ are needed to determine $C_s$ and $k$ values) and $C_s$ and $k$ values were determined. Table 3.6 shows assumed values.

Table 3.6. Wells with known k and Cs values.

<table>
<thead>
<tr>
<th>API</th>
<th>Well name</th>
<th>X, m</th>
<th>Y, m</th>
<th>TDS, mg/L</th>
<th>$k$, year$^{-1}$</th>
<th>$C_s$, mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>05-125-06132</td>
<td>1-4 SCHAFER</td>
<td>729370</td>
<td>4430677</td>
<td>34027</td>
<td>0.59</td>
<td>30000</td>
</tr>
<tr>
<td>05-125-08315</td>
<td>13-12 PARISET</td>
<td>714801</td>
<td>4428667</td>
<td>37090</td>
<td>0.60</td>
<td>32000</td>
</tr>
<tr>
<td>05-125-09492</td>
<td>23-14 STATE 243</td>
<td>742909</td>
<td>4418542</td>
<td>39118</td>
<td>0.72</td>
<td>38000</td>
</tr>
<tr>
<td>05-125-10044</td>
<td>31-32 STONE</td>
<td>719583</td>
<td>4442423</td>
<td>27802</td>
<td>0.55</td>
<td>27000</td>
</tr>
<tr>
<td>05-125-10144</td>
<td>12-2 VONDERWAHL</td>
<td>704304</td>
<td>4439859</td>
<td>19883</td>
<td>0.50</td>
<td>25000</td>
</tr>
<tr>
<td>05-125-10711</td>
<td>34-12 ALLEN</td>
<td>735702</td>
<td>4409796</td>
<td>39109</td>
<td>0.75</td>
<td>37000</td>
</tr>
</tbody>
</table>

X and Y coordinates of the wells are in UTM 13N, NAD 1983

After using kriging or an inverse weighted spatial interpolation technique (in ESRI ArcGIS a spatial analysis toolbox can be used (Childs, 2004)) $C_s$ and $k$ values can be predicted for the entire field using values provided in table 3.4. Results of interpolation are shown in fig. 3.14-3.15.
Figure 3.14. Interpolated $k$ (dissolution rate) values across the field using 6 known points.
Figure 3.15. Interpolated $C_s$ (maximum concentration) values across the field using 6 known points.

After creating “$k$” and “$C_s$” surfaces, each well in the study area can be given $k$ and $C_s$ values based on spatial location (extract point values tool was used from ESRI ArcMap). Predicted and current water quality can be estimated using found $k$, $C_s$ values, age of the well and $C_i$ using eq. 9 (Table 3.7).

Table 3.7. Random 8 wells with determined k and Cs values.

<table>
<thead>
<tr>
<th>API</th>
<th>Well name</th>
<th>X, m</th>
<th>Y, m</th>
<th>TDS, mg/L</th>
<th>$C_s$, mg/L</th>
<th>$k$, year$^{-1}$</th>
<th>Age by 2011</th>
<th>Drilled/ fractured</th>
</tr>
</thead>
<tbody>
<tr>
<td>05-125-02379</td>
<td>12-28 WILTFANG</td>
<td>729435</td>
<td>4424854</td>
<td>34082</td>
<td>32895</td>
<td>0.44</td>
<td>8</td>
<td>2004</td>
</tr>
</tbody>
</table>
Using the discussed water quality framework and method of water quantity prediction (3) discussed in previous sections, two development scenarios are shown for Noble Energy wells in Yuma County. For the scenario (1) of no field development, prediction of water quality for area of study is shown in fig. 3.16.

![Graph showing water production and TDS values over years](image_url)

Figure 3.16. Scenario 1. Interpolated $C_s$ and $k$ values are used to predict water quality in combination with water production from existing wells (scenario 1).
To predict water quality for a scenario of constant field development, some assumptions should be made. As seen from spatial distribution of well ages (fig. 3.14), most recent wells were developed a little bit south of the middle of the map. So we can assume that for next years, drilling will take place in that area. From Fig. 3.14-15 we can assume $k=0.5$ and $C_a=32000$ for new drilled wells.

For scenario (2) of constant field development, prediction of water quality for the area of study is shown in Fig. 3.17.

![Graph showing water production and quality predictions](image)

Figure 3.17. Scenario 2. Constant field development. Interpolated $C_a$ and $k$ values are used to predict water quality from existing wells, $k=0.5$ and $C_a=32000$ are used to predict water quality from new drilled wells.

Water produced and water quality could be estimated and predicted for a range of future development options. Based on proposed spatial location, water quality kinetic parameters can be
estimated and historical water production data from nearby fields can be used to generate a
decline model for a well. This information is valuable to make better water management
decisions, hence provide more accurate information about water production and quality, greatly
improving the ability to treat and reuse PW.

3.8.2 Limitations

This is only a conceptual method of predicting and estimating water quality from shale gas
wells producing from one formation. Further validation of this procedure is needed to prove the
methodology. Produced water quality from shale gas wells in Yuma County has relatively low
TDS, below 30000; therefore, predicted water quality temporal changes are not significant. For
the scenario of no field development, water quality changes only by 10%. For Marcellus shale,
where TDS values as high as 200000 mg/L, results might be significantly different. This
conceptual methodology assumes that geology varies gradually spatially, however this might not
be a case in some instances. Local changes might be due to different events that happened locally
millions of years ago. For example, if a lake evaporated it could have left a formation with much
higher TDS or other constituents.

Another limitation is that this methodology assumes that the majority of constituents dissolve
from the producing shale formation. However, in some cases fractures can propagate near
formations or create connections to other aquifers, which could dictate water quality.

3.9 Conclusions

Spatial and temporal understanding of produced water production and quality from shale gas
is important to plan long term recycling strategies and optimize design and siting of water
handling and treatment facilities. Three different protocols of water production prediction have
been developed based on decline curve analysis for a field. A water quality prediction framework
was proposed based on dissolution kinetics and geospatial data. Among three different methods, it is recommended using the produced water prediction method based on individual well water decline modeling (method 3) because it accounts for all the spatial, temporal and stimulation variations in water production, leading to more accurate well-based predictions in a small or large field. From provided scenarios, it is clear that water production prediction using only historical average values can lead to overestimation in slow development years and underestimation in aggressive development periods. Dissolution kinetics and the spatial relationships used in water quality modeling account for temporal and spatial variations in water quality and are therefore believed to be more accurate. Further validation of the method is required. The case study and scenarios used for Noble Energy wells in Yuma County demonstrates that these prediction methods can be used in any other shale gas fields by altering decline models and coefficients.

Information on how current and future development of oil and gas fields will affect water quality and production can help make better decisions about water treatment, disposal, transportation, and the efficacy of pursuing development in a given field.
4. APPLICATION OF PREDICTION TOOLS

4.1 Excel based tool for predicting water production and quality from Noble Energy shale gas vertical wells in Yuma County.

4.1.1 Introduction to the tool

Water production and quality prediction protocols described in chapter 3 as the foundation for a MS Excel-based tool to predict produced water volumes and TDS from Noble Energy Inc. vertical shale gas wells located in Yuma County. The tool can be used by stakeholders to predict future water production and TDS for different field development scenarios. Predictions are based on existing wells historical production data and an assigned schedule of well development for future years. Water quantity predictions from existing wells are based on method (3) (individual well decline modeling) using historical data, new or refractured wells modeled using method (1) described in chapter 3. Water quality (TDS) prediction uses assumed values from section 3.7. Water production and TDS prediction from proposed wells are based on FDF development (section 3.1) and TDS kinetic coefficients (section 3.8). Screen shots of the tool can be seen in Fig. 4.1. This tool can also be used to forecast water production and water quality from any other shale gas field with vertical wells by altering the field decline model, water kinetics coefficients and historical data.

4.1.2 Inputs and outputs of the tool

The number of new or refractured wells for each future year, field water decline model and TDS kinetics coefficients are the main inputs of the tool. The user can input new wells that are planned in each future years starting from 2012. A water production decline and quality model for Yuma County wells that is developed in chapter 3 (equations 3 and 7) is used in this tool to predict water production and TDS.
Outputs of the tool:

- Water production from existing wells (W Pew, wells drilled before predicted years - 2011 included).
- Calculation based on historical data using method (3);
Predictions are made using developed decline curves for each well.

- Water production from wells drilled or refractured in predicted years during first operational year (WPnw).
  - Calculation is based on FDF. Number of new wells multiplied by the average water production rate and average production days in first operational year.
  - For example, if 5 wells were drilled in 2015, then fraction of water produced in 2015 by this new wells is
    $$Q = 5 \text{ wells} \cdot \left( \frac{19.74}{1+1.035} \right) \frac{\text{bbl}}{\text{day\cdot well}} \cdot \frac{184 \text{ days}}{\text{year}} = 13450 \frac{\text{bbl}}{\text{year}}.$$

- Water production from wells drilled or refractured in predicted years in second or above operational years (WPda).
  - Calculation based on FDF. This output shows water produced by wells which is drilled in predicted years, but not in first operational year. For example, if in 2012, 2013 and 2014 were drilled 10 wells in each, then in 2015 water production from this wells (30 wells drilled in 2012-2014) will be
    $$Q_{2015} = 10 \text{ wells}^{2012} \cdot \left( \frac{19.74}{1+4.035} \right) \frac{\text{bbl}}{\text{day\cdot well}} \cdot \frac{362 \text{ days}}{\text{year}} + 10 \text{ wells}^{2013} \cdot \left( \frac{19.74}{1+3.035} \right) \frac{\text{bbl}}{\text{day\cdot well}} \cdot \frac{362 \text{ days}}{\text{year}} + 10 \text{ wells}^{2014} \cdot \left( \frac{19.74}{1+2.035} \right) \frac{\text{bbl}}{\text{day\cdot well}} \cdot \frac{362 \text{ days}}{\text{year}} = 106681 \frac{\text{bbl}}{\text{year}}.$$

- Total water production for predicted year (TWP).
  - Sum of water production from existing and proposed new or refractured wells.

- TDS from existing wells
✓ TDS for each existing well is predicted for 2012-2020 using water quality prediction protocol described in section 3.

✓ Using predicted water production and simple mass balance, TDS from all wells is calculated: \( C_n = \frac{\sum_{i=1}^{l} WP_i TDS_i}{\sum_{i=1}^{l} WP_i} \), where \( WP_i \) is a predicted annual water production from \( i \) well in year \( n \), \( TDS_i \) is a predicted TDS values from \( i \) well in year \( n \), \( C_n \) is a TDS in year \( n \) from existing wells.

- TDS from wells drilled or refractured in predicted years during first operational year
  ✓ Same mass balance applied for this wells using corresponding water production information.

- TDS from wells drilled or refractured in predicted years in second or above operational years
  ✓ Same mass balance applied for this wells using corresponding water production information.

- Graphs of water production and TDS values.

4.2 GIS based web application

4.2.1 Overview

GIS is used to visualize, interpret and analyze spatial data in many ways that reveal trends, relationships, patterns in the form of maps, reports and charts (ESRI, 2012). This section provides a framework for a GIS based web application that can provide an analysis platform to producers and consulting firms to predict water production and/or water quality, optimize location of treatment facilities, truck routings and help make other decisions related to water management using their own uploaded information. The application can serve public and
government agencies by providing information about well locations, production, regulations, violations and others.

Protocols for produced water production and quality predictions that have been developed in Chapter 3 are quite complex and require a lot of effort to implement. These protocols can be integrated as one of the modules into a web application. Development of a web application can be done using different open source and commercial resources. The author recommends developing an application using commercial software from ESRI (Environmental Systems Research Institute) – ArcGIS for Server. ESRI is one of the world’s leading GIS service software company and offers a powerful framework for creating rich Internet based web applications. ArcGIS for Server is one of the ESRI products which can provide GIS functionality to any web server. GIS functionality can include web mapping, different spatial analysis tools like siting of treatment facility, minimizing piping distance, spatial interpolation and many other geo-processing tools. Figure 4.2 shows a brief data flow chart and interaction between different components of web application. Figure 4.3 shows possibilities of application and outputs.

4.2.2 Components of web application

- User interface
  
  ✓ Web browser interface, where user can interact with application: Import data, see prediction graphs, locate treatment facility etc.

  ✓ Based on MS Silverlight interface.

- Calculation engine

  ✓ Calculates FDF based imported production data.

  ✓ Calculates predicted values of water production for existing wells based on FDF.

  ✓ Predicts water quality parameter based on $k$ and $C_s$ values for existing wells.
Figure 4.2. Flow chart of web based GIS application.
Figure 4.3. Outputs of web application.
✓ Predicts water quality parameter based on $k$ and $C_s$ values inputted by user for proposed wells.

- **ArcGIS for Server**
  ✓ Provides mapping
  ✓ Provides interpolation service
  ✓ Provides tool and means for location optimization
  ✓ Other GIS services

- **Database Management System**
  ✓ Controls creation, maintenance and use of database
  ✓ Stores data

4.2.3 Clients of web application

Main clients of the web application:

- Oil and gas producers
- Oil and gas service companies
- Consulting firms
- Public
- Government agencies

4.2.4 Data input and outputs

Input for a web tool can be different databases including publicly available databases or internal industry databases. All the information should be standardized in order to upload. A standardized form of an upload file should be decided during programming stage.
Producers and consulting firms can use the application to analyze their well data to make better decisions. Table 4.1 shows outputs of the application depending on what data is uploaded for analyses.

Table 4.1. Information provided and outputs of the tools from wells location, production and quality data.

<table>
<thead>
<tr>
<th>Information</th>
<th>Tool outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well name(API)*</td>
<td>Basic treatment facility locator, mapping</td>
</tr>
<tr>
<td>Latitude/Longitude*</td>
<td>Water quantity prediction. Advance treatment facility locator (incorporates water production).</td>
</tr>
<tr>
<td>Oil/Gas/Water production data</td>
<td>Water quantity and quality prediction from existing wells, treatment facility siting optimization</td>
</tr>
<tr>
<td>Production days</td>
<td></td>
</tr>
<tr>
<td>$k$ and $C_s$ values for number of wells</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2. Information that can be on the web site for public availability.

<table>
<thead>
<tr>
<th>Feature type</th>
<th>Name</th>
<th>What information contains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point feature</td>
<td>Wells</td>
<td>• Name</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Geo-location</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Operator</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Producing formation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Water used for drilling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Water used for stimulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Oil/gas/water production data</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Water quality</td>
</tr>
<tr>
<td>Violation zones/points*</td>
<td></td>
<td>• Information about violations in oil and gas industry.</td>
</tr>
<tr>
<td>Polygon</td>
<td>Oil and gas fields</td>
<td>• Information about main oil and gas fields.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Description of main producing zones/formations and other relevant information about oil and gas fields.</td>
</tr>
<tr>
<td></td>
<td>States/County</td>
<td>• Information about oil and gas regulations in each state.</td>
</tr>
</tbody>
</table>

*Violation zones can be point or polygon feature

Figures 4.4-4.6 shows possible user interface of the GIS based web application
Figure 4.4. Possible user interface of web tool: layers tab
Figure 4.5. Possible user interface of web tool: legends tab
Figure 4.6. Possible user interface of web tool: tools tab
5. CONCLUSIONS

Produced water production and quality from vertical shale gas wells were studied to better understand spatial and temporal changes in these parameters. A literature review showed that the water management is a key element to enhance safety and environmental protection during the development of domestic natural gas and other petroleum resources. In addition, since water is an operations material, its availability is critical to meeting production goals. Large amounts of water are used and produced during the development of unconventional resources and most of produced water is deep well injected for disposal.

Many factors, such as geological restrictions, local water availability, policies and regulations, environmental risks, public perception and others provide an incentive to operators to treat and recycle their produced water. Research on treatment processes is fairly developed but studies related to management of water in a spatially and temporally distributed environment are limited. The objective of this study was to fill this gap and provide a framework for future research.

Three different protocols for water production prediction have been developed based on decline curve analysis in the Yuma field. A water quality prediction framework was proposed based on dissolution kinetics and geospatial data. Among the three different methods, it is recommended using a produced water prediction method based on individual well water decline modeling (method 3). This method accounts for all the spatial, temporal and geological variations in water production, which will lead to more accurate well based predictions in a small or large (field) scale. However, complex calculation required for this method is a downside of it. From all scenarios, it is clear that water production prediction using only historical average values can lead to overestimation in slow development years and possibly underestimation in aggressive development periods. For the scenario of zero field development, ten-year forecast
results were 2.5 times higher for predictions made using average historical data in comparison with method (3) which accounts for water production decline in each existing well. For the same prediction methods, in case of aggressive field development scenario of 100 new wells each year (20% of existing wells), use of prediction based on average historical data might under predict water production already for second year forecast. Dissolution kinetics and spatial data were used in water quality modeling to account for temporal and spatial variations in water quality. Further validation of the method is required. The case study and scenarios used for Noble Energy wells in Yuma County demonstrates that these prediction methods can be used in other shale gas fields by altering decline models and coefficients.

An Excel-based tool, which incorporates water quantity and quality protocols, was developed to predict water production and TDS from Noble Energy Inc. wells in Yuma County for different field development scenarios. Stakeholders can make better water management decisions and plan long term recycling strategies using the outputs of this tool.

GIS based web applications can provide analysis platforms to producers and consulting firms to predict water production and/or water quality, optimize location of treatment facilities, truck routings and help make other decisions related to water management, while public and government agencies can acquire valuable information about wells, production, regulations, violations and others. This study provided a framework for development of GIS based application.
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APPENDIX A: SUPPLEMENTARY INFORMATION

A.1 Information about gas wells in Colorado and Yuma County.

Figure A.1.1. Spatial distribution of Noble Energy wells in Colorado
Table A.1.1. Oil, gas and water production from different counties in Colorado.

<table>
<thead>
<tr>
<th>County</th>
<th>Number of gas wells</th>
<th>Number of oil wells</th>
<th>Water production, Bbl/year</th>
<th>Oil Production, Bbl/year</th>
<th>Gas production, Bbl/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>RIO BLANCO</td>
<td>1541</td>
<td>562</td>
<td>107204240</td>
<td>4815314</td>
<td>93689736</td>
</tr>
<tr>
<td>LAS ANIMAS</td>
<td>2881</td>
<td>4</td>
<td>70402032</td>
<td>1024</td>
<td>119595317</td>
</tr>
<tr>
<td>GARFIELD</td>
<td>8828</td>
<td>17</td>
<td>40378465</td>
<td>2300854</td>
<td>639160668</td>
</tr>
<tr>
<td>WASHINGTON</td>
<td>166</td>
<td>236</td>
<td>27330317</td>
<td>483137</td>
<td>1530083</td>
</tr>
<tr>
<td>LA PLATA</td>
<td>3004</td>
<td>77</td>
<td>23174294</td>
<td>33396</td>
<td>422008661</td>
</tr>
<tr>
<td>MOFFAT</td>
<td>352</td>
<td>84</td>
<td>12480348</td>
<td>318364</td>
<td>19436387</td>
</tr>
<tr>
<td>WELD</td>
<td>7663</td>
<td>9895</td>
<td>9945703</td>
<td>20715892</td>
<td>218395822</td>
</tr>
<tr>
<td>CHEYENNE</td>
<td>53</td>
<td>248</td>
<td>6734296</td>
<td>1342134</td>
<td>6156049</td>
</tr>
<tr>
<td>LOGAN</td>
<td>10</td>
<td>98</td>
<td>6122754</td>
<td>195599</td>
<td>335799</td>
</tr>
<tr>
<td>YUMA</td>
<td>3692</td>
<td>0</td>
<td>4913286</td>
<td>3391</td>
<td>39297634</td>
</tr>
<tr>
<td>27 Others</td>
<td>2175</td>
<td>1232</td>
<td>22068923</td>
<td>2251747</td>
<td>339722532</td>
</tr>
</tbody>
</table>
A.2 Water used for fracturing

Figure A.2.1. Water and sand used for hydraulic fracturing. 934 Noble Energy Inc. wells stimulated in 2011 (Noble Energy Inc.).

Figure A.2.2. Water used for hydraulic fracturing by formation. Noble Energy Inc. 934 wells hydraulically fractured in 2011. (Noble Energy Inc.).
Figure A.2.3. Distribution of water use for hydraulic fracturing in Colorado (FracFocus.org, 2454 wells)

Figure A.2.4. Distribution of water use for hydraulic fracturing in Texas (FracFocus.org, 2243 wells)
Figure A.2.5. Density distribution of water use for hydraulic fracturing in Texas (FracFocus.org).

Statistics of data:
1661-Oil wells, 581-Gas wells
Max: 15 million gal
Min: 1000 gal
95%: 7 million gal
Average: 2.7 million gal per well

Figure A.2.6. Density distribution of water use for hydraulic fracturing in Colorado (FracFocus.org).

Statistics of data:
2427-Gas wells, 26-Oil wells
Max: 24 million gal
Min: 10367 gal
95%: 4 million gal
A.3 VBA code to automate curve fitting

Below the VBA code for MS Excel to automate curve fitting process.

```vba
Sub Individual_Curve_fitting()
Dim R As Long
Dim Target
Dim ChgCells
//'Solver settings
SolverOptions AssumeLinear:=True
SolverOptions AssumeNonNeg:=True
For R = 3 To 480 'Row 1 to 480
SolverReset
Target = Cells(R, 116).Address 'Choosing target cells
ChgCells = Cells(R, 114).Resize(1, 1).Address 'Choosing changeable cells
SolverOk SetCell:=Target, MaxMinVal:=2, ByChange:=ChgCells 'Minimizing target cell by changing ChgCells
SolverSolve True
Next R
End Sub
```

A.4 Determination of treatment facility location minimizing total pipeline distance

One of the factors for optimal siting of treatment or water handling facilities is minimization of pipeline length. ArcGIS provides an easy spatial tool, which can find a location of facility minimizing sum of the distances from all wells to facility. Additional factors for optimum siting can account for:

1. Land use
   a. Land use should be accounted when routing a pipe. Some territories have limited access and routing should avoid it. Examples of limited access are private lands, restricted areas (National parks etc), water bodies (lakes, rivers, ponds) and other.

2. Slope
   a. Construction of a pipe is cheaper on flat than on steep surface. Therefore, slope is another factor, which should be accounted while routing a pipelines.
Figure A.4.1. Treatment facility location minimizing pipeline distance (Proposed location 720898, 4435216 UTM 13).
Figure A.4.2. Colorado TDS map from oil and gas wells (USGS, 2011)
Figure A.4.3. Fractured and producing Noble Energy Inc. wells in 2011
Figure A.4.4. Well selection methodology for sampling. Method 1: Random sampling
Figure A.4.5. Well selection methodology for sampling. Method 1: Random sampling and 5 random wells from each age group.
Figure A.4.6. Filtering for fracturing year and curve fitting for wells older than 2 years.
Figure A.4.7. Harmonic decline curve fitting solving for B only for wells which has 1 or 2 year water production information (Used in prediction method 2 and 3)
LIST OF ABBREVIATIONS

AWP - Annual water production
COGCC – Colorado Oil and Gas Conservation Commission
DCA – Decline curve analysis
DWPR – Daily water production rate
EIA – Energy Information Administration
FDF – Field decline function
FWPDC – Field water production decline curve
GHG – Greenhouse Gases
GIS – Geographic Information Systems
LSE – Least square error
PD – Production days
PW – Produced water
TDS – Total Dissolved Solids
WP – Water production
WQP – Water quality parameter