THESIS

DEVELOPMENT OF GRAPHICAL USER INTERFACE TOOLS FOR OPTIMAL FLUID MANAGEMENT IN SHALE OIL AND GAS OPERATIONS

Submitted by

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ABSTRACT

DEVELOPMENT OF GRAPHICAL USER INTERFACE TOOLS FOR OPTIMAL FLUID MANAGEMENT IN SHALE OIL AND GAS OPERATIONS

Oil and gas extraction is increasing in many parts of the country due to the use of hydraulic fracturing. Hydraulic fracturing is a technique to extract oil and gas from shale rock formations that is characterized by the input of large quantities of pressurized water into horizontal wells. The high pressure fluid generates cracks in the shale formation that release the gas, oil, and other constituents into the fluid. The fluid that returns to the surface is characterized as flowback or produced water. Flowback is defined as the water that returns to the surface prior to the initiation of oil or gas production and produced water refers to the post-production return water. There is widespread public and government agency interest in assessing the quantity and quality of water used in hydraulic fracturing to ensure environmental protection and public health.

Optimal water management in hydraulic fracturing has the potential to (1) reduce freshwater use, (2) increase produced water recycle, (3) reduce energy expenditures from water transport, and (4) enhance safety and environmental protection in the development of natural gas and other petroleum resources. Improved management of water can enhance safety and environmental protection by minimizing impacts such as road damage, truck traffic, noise, air pollution, water pollution and landscape disturbance. Interactive management tools allow operators to increase water reuse and minimize the environmental risks of hydraulic fracturing. This research entails developing graphical user tools to optimize water management in shale oil and gas operations. The tools that were developed include (1) a Water Production Modeling Tool, (2) a Water Use Calculator, and (3) a Water Quality Tool. The tools are MATLAB executable files that can run without a MATLAB license. The output of these tools will provide information for users to predict wastewater production, water demand needed for treatment, and analyze water quality components such as contaminant concentrations.

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1 Introduction

Development of unconventional natural gas has expanded rapidly to meet global energy demands. Technology improvements such as horizontal drilling and hydraulic fracturing have improved production of natural gas across the Unites States. (Gregory et al. 2011, Vidic et al. 2013) By 2035, production from unconventional natural gas is projected to increase to 21 trillion cubic feet per year and constitute 77% of natural gas production. (U.S. EIA 2012) However, these technologies pose a risk to the environment. For instance, regional water quantity and quality, gas migration, wastewater discharge and management, contaminant transport or spills are environmental concerns associated with development of hydraulic fracturing. (Cooley et al. 2012)

To optimize water management and implement new strategies, it is important to have accurate predictions of water quantity and quality. However, there is a need for reliable and comprehensive data on water-for-energy and energy-for-water activities both in public and private industry. (Murkowski 2014) In addition to the sparsity of data, the facility locations for water collection, water treatment and/or reuse for drilling and fracturing change while a field is developed. (Goodwin 2014) Therefore, water management tools must be useful for proprietary datasets and be able to generate rapid results with a user friendly interface.

The objective of this thesis is to model, quantify and visualize water information in a flexible platform to make assessments of water data faster for the shale oil and gas users within the rapidly changing and uncertain oil and gas field. This thesis introduces three Graphical User Interface (GUI) tools which were developed though MATLAB for optimal water management.

Each of them provides key information for users to assess water quantity and quality of any selected development plan for an oil and gas field. The flexibility in the GUIs allows the users to work with tools either by installing MATLAB software on their computer or as a stand-alone application without requiring any software on the computer. Users can instantly obtain necessary information on the GUI screen, observe the results on the plots and save the output data on the Excel file in order to compare different reports after each time of running the tool. The three tools are described in detail below:

1. The Water Production Modeling Tool uses well data to produce a water production equation that can be used to estimate produced water quantity at any time past the drill date.
2. The Water Use Calculator is used to assess the amount of water used in the process of hydraulic fracturing for any selected field. The information includes a histogram of water used per well, a histogram of water used per horizontal foot, a histogram of horizontal length per well, the average water used per well by year, the average horizontal length per well by year and water used per horizontal length by year.
3. The Water Quality GUI is a tool that calculates the chemical contaminant concentrations over the selected period of time by user. The output of this tool provides concentration of Ca, Na, Cl and TDS, plots concentrations at any point in time for a given development plan.

This thesis consists of 5 chapters. A review of literature with more emphasis on the relationship of water in hydraulic fracturing is provided in Chapter 2. Chapter 3 presents the methods which were utilized to develop the GUIs. Chapter 4 provides the results of case studies of using the developed tools and finally a discussion is presented in Chapter 5.

2 Literature Review

2.1 Water and Energy

Many aspects of industry related to water (e.g., transportation, wastewater treatment, desalination, water supply treatment) require large inputs of energy. Likewise, energy is water-intensive in terms of resource extractions (e.g. oil, gas, coal), converting the energy, processing, and power generation. This interdependence is often described as the water-energy nexus. The interdependencies between the two are clear and often tested during water stress, extreme temperature events, or long electricity outages. (Mielke et al. 2010)

By 2030, water consumption in the U.S. is projected to increase by 7% above the consumed level in 2005. The energy sector is expected to contribute 85% of this increase in water consumption from bioenergy, thermoelectric, and fossil fuel extraction. (Murkowski 2014) (Figure 2-1) Among different sectors, agriculture has the most significant amount of water consumption (71%). The energy sector is the second largest consumer at 14%, and public and domestic uses are third at 7%. Energy extraction from biofuels along with unconventional oil and gas production are anticipated to have an important role in increasing the water demand. (Carter 2013)

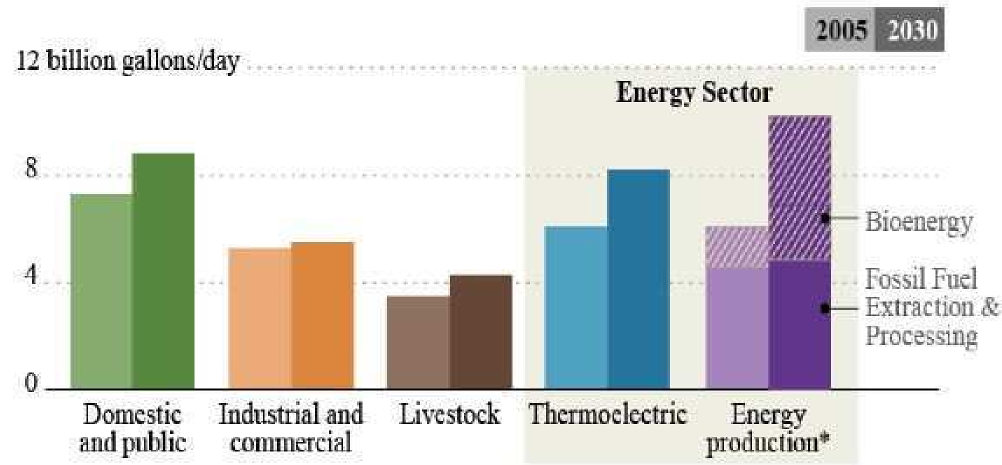

Figure 2-1 Estimated and projected water consumption for domestic and public, industrial and commercial, livestock, thermoelectric and energy production (Source: CRS, "Energy's Water Demand: Trends Vulnerabilities, and Management" (2010))

Water is necessary for fuel extraction and powering the economy. Estimations show that water intensity values (expressed as gallons per million British thermal units [MMBtu]) range from conventional natural gas (at less than one gallon per MMBtu); followed by coal, unconventional natural gas, uranium mining and enrichment (at 1 to 10 gallons per MMBtu); oil (at 10 to 100 gallons per MMBtu); to highest irrigated biofuels (at 100 to 1000 gallons per MMBtu). One of the interesting studies done in Wattenberg (Northeast Colorado) is considering the efficiency of water use. This study compared water intensity of unconventional shale in the Wattenberg to other source of energy including coal, natural gas, oil and nuclear. Water intensity for unconventional shale resources is estimated between 1.8 and 2.8 gal/MMBtu. The results show that only wind (0 gal/MMBtu), solar (0 gal/MMBtu), primary oil recovery (1.5 gal/MMBtu) and conventional natural gas (1.5 gal/MMBtu) had slightly lower water intensity in comparison with unconventional shale resources. Thus, large volumes of water are consumed in the production of fuels. (Murkowski 2014, Goodwin 2014)

On the other hand, energy is required for moving, treatment and distribution of the 410 billions of gallons of water in the daily needs of United of States. In 2000, 3.7 % of the United States electricity about 123 billion kilowatts per hour (kWh) was used for treating and transporting water and wastewater for residential and commercial demands. As an example, California uses 30% of natural gas and 88 billion gallons of diesel fuel every year for water sector. (Murkowski 2014)

As our energy demand grows, there will be more conflict over water among farmers, industrial sources, power suppliers and municipalities. Energy decisions must be evaluated for their impact on business, security and the environment. Decision makers must take into consideration both water availability and energy demands and find the appropriate balance among tradeoffs. (Glassman et al. 2011) There are several recommendations to evaluate the water energy relationship such as updating and improving the quality of data, creating cost analysis, identifying innovative technologies, promoting federal leadership, and publicizing best practices. (Mielke et al. 2010, Murkowski 2014)

2.2 Natural Gas Development

In 2014, the United States consumed approximately 26.79 trillion cubic feet of natural gas. 30 percent of the total consumption contributed to electricity, 20 percent to industrial uses, 19 percent to residential uses, and the remainder was used in commercial uses, plant fuel consumption, pipeline losses and vehicle fuel respectively. (EIA 2015) Moreover, global demand of natural gas is increasing. For example, in China 4% of the energy demand is natural gas and the demand is expected to increase to 8% by 2020. Availability of natural gas, easy transportation, clean combustion and efficiency are the main advantages that are cited. (Gregory 2011)

In 2013, the Potential Gas Committee published data that the United States possesses 2,384 trillion cubic feet (Tcf) of natural gas resources (as of the end of 2012). (Potential Gas Committee, 2013) This is the highest evaluation in 48 years history of the committee and this evaluation exceeded the previous assessment (2010) which was 486 Tcf. New evaluations consist of shale gas resources in the Atlantic, Mid-Continent, Rocky Mountain and Gulf Coast areas and conventional/tight gas resources in the Rockies and Mid-Continent. (Potential Gas Committee 2013)

2.2.1 Shale Gas

Natural gas production is typically classified as either conventional or unconventional based on the extraction technique. Unconventional natural gas resources include coalbed methane, tight sands and shale gas. (Figure 2-2) Shale gas is projected to be the fastest growing source of exploration of natural gas. (Gregory et al. 2011, Cooley et al. 2012) Shale gas is a natural gas present in shale rock formations. Shale rock, which is a fine-grained sedimentary rock composed of silt-sized particles, and may contain other minerals such as quartz, calcite, and pyrite has a lower permeability than sandstone and other conventional formations. (EIA 2010) (Gregory et al. 2011)

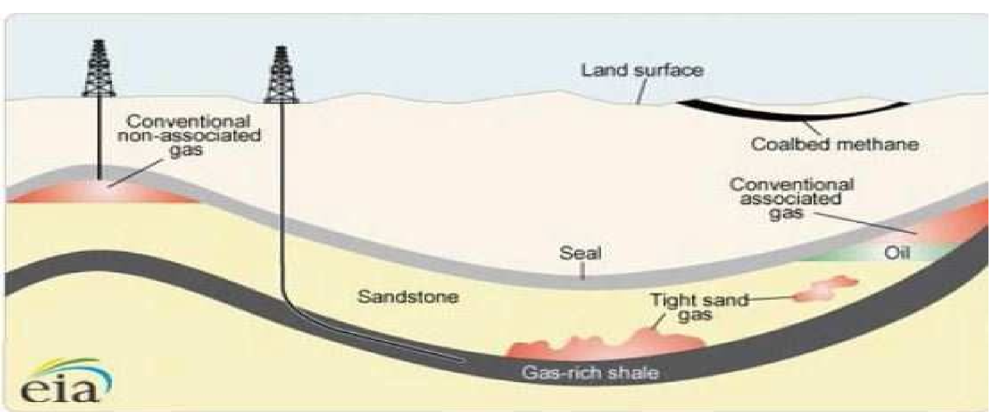

Figure 2-2 Types of natural gas, including non-associated gas, tight gas, associated gas, shale gas, and coalbed methane (Source: U.S. EIA 2011a)

Because of the low permeability of shale, developing and extracting unconventional natural gas resources is costly and complex, but advances in technology and new drilling followed by hydraulic fracturing has increased shale gas developments and made it economically viable. In 1990, 15% of total production of natural gases was attributed to the unconventional resources, at approximately 2.6 trillion cubic feet per year. (Cooley et al. 2012) However, EIA estimations have projected that unconventional natural gas production will increase to 77% by 2035 or 21 trillion cubic feet per year (Cooley et al. 2012). Figure 2-3 illustrates the EIA's projection of different natural gas resources development.

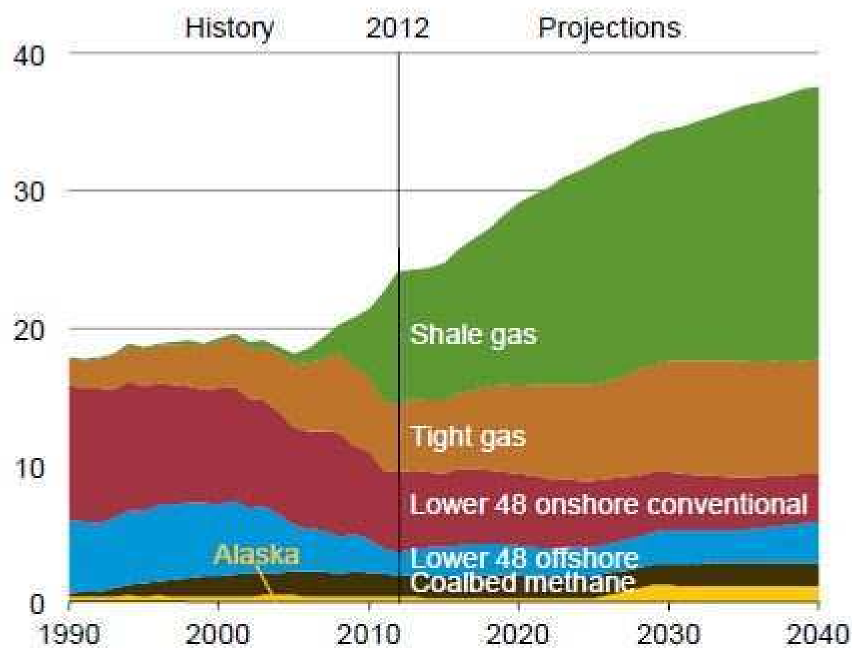

Figure 2-3 U.S. natural gas production (trillion cubic feet) by source, 1990-2040 (Source: U.S. EIA 2014)

There are several economic benefits of having an abundance of natural gas. According to an in-depth economic analysis by IHS Global Insight (2008) energy companies hired 622,000 Americans and 2.2 million additional jobs were sustained at the same time. ("US Natural Gas Benefits", n.d.) Previously in the 2000s, the United States was projected to import substantial quantities of natural gas due to declining domestic gas production and increasing demand for natural gas. However, because of higher domestic production, current importation of natural gas is unnecessary. The projections show that the United States will be a net exporter by 2016 and there will be added revenues, jobs, trades and less flaring with increasing exports. (Ratner et al. 2013) Figure 2-4 shows the projections of the natural gas production, consumption and trade by 2040. While natural gas is considered a cleaner energy in comparison with coal and oil due to a lower level of carbon dioxide release, (Chen et al. 2014) there are several social and environmental concerns associated with developing natural gas resources

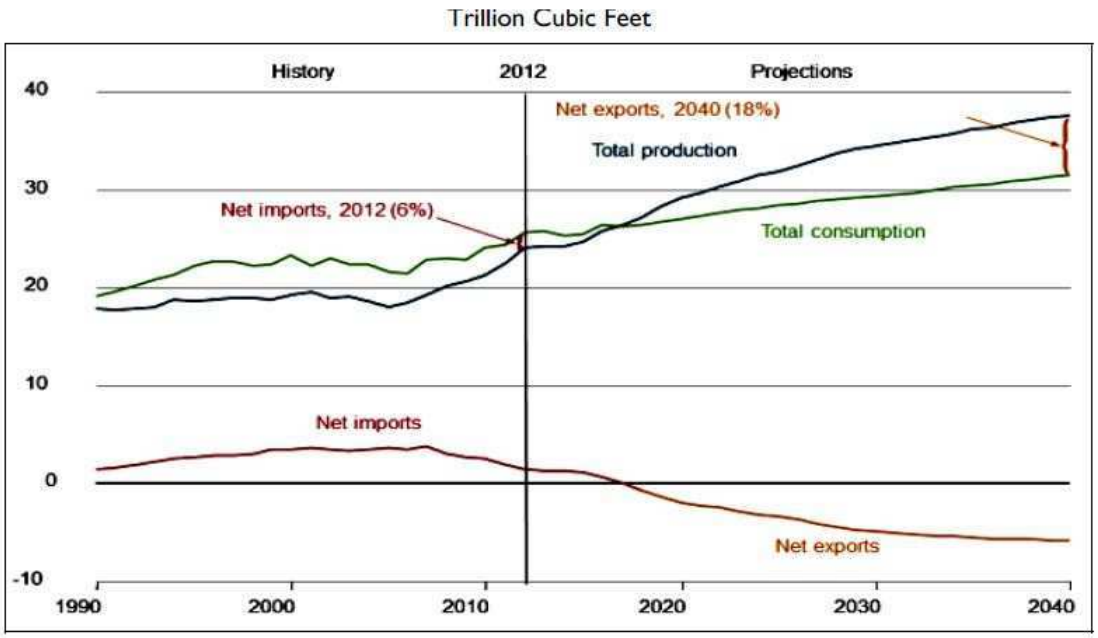

Figure 2-4 U.S. natural gas production, consumption, and trade
Source: Energy Information Administration, Annual Energy Outlook 2014, DOE/EIA-0383(2014), April 2014, MT-42, http://www.eia.gov/forecasts/aeo/mt_naturalgas.cfm.

2.2.2 Hydraulic Fracturing

Hydraulic fracturing is the process of producing fractures in the rocks by pumping large volumes of fluids consisting of water, proppant and chemical additives. The fluid is injected at high pressure down to the wellbore to open fractures to stimulate the flow of natural gas or oil. ("The Process of Hydraulic Fracturing", n.d.) Fracturing fluids consist of different chemical additives including sands, friction reducers, surfactants, gelling agents, scale inhibitors, acids, corrosion inhibits, antibacterial agents and clay stabilizers. (Jackson et al. 2011) The fluid that is brought back to the surface prior to production (typically, two to four weeks) is termed flowback. This water often contains fracturing fluid additives, brine, hydrocarbons, suspended solids and sometimes naturally radioactive material. When the well is in the production phase, the waste fluid (produced water) continuously returns to the surface over the lifetime of the well. (Mantell 2011) Generally, the amount of wastewater generated is greatly dependent to the geologic characteristics and the formation. (Haluszczak et al. 2013, Vidic et al. 2013)

2.2.3 Environmental Concerns of Hydraulic Fracturing

The main concerns related to hydraulic fracturing and the development of unconventional oil and gas resources include impacts to air quality (Litovitz et al. 2013, Colborn et al. 2014), water quantity and quality (Gregory et al. 2011, Cooley et al. 2012), wastewater management, as well as land and habitat fragmentation. (Vidic et al. 2013, Chen et al. 2014) In addition, lack of comprehensive data and information created challenges to implement a robust assessment of concerns associated with hydraulic fracturing. For example, most of energy sectors in the United States are private, hence, data accuracy and consistency are challenging. (Carter 2013)

2.2.4 Hydraulic Fracturing and Water Usage

2.2.4.1 Water Volume

Water volume highly depends on well type and its geological location. Generally, deeper wells with less permeable rock require more water for hydraulic fracturing. One study concluded that water requirement predictions should be based on the number of hydraulic fracturing stages rather than the number of wells. The number of hydraulic fracturing stages range from three to 45 and the total water use can vary from a few hundred thousand gallons up to nearly eight million gallons per well. It is not correct to assume all of the wells consume specific amount of water (Goodwin 2014)

Industry studies have postulated that the water used in fracturing is not significant in comparison with total annual water withdrawal in the United States. In 2005, approximately 149,650 billion gallons of water were withdrawn for various purposes in the United States. The largest two sectors were thermoelectric power generation (49%) and irrigation (31%). Alternatively, less than 1% was used for mining purposes which includes oil and gas extraction. (Chen et al. 2014) Although the water withdrawal for natural gas extraction is less than 1%, hydraulic fracturing water use is not evenly distributed in all states; therefore, locally there are higher fractions of water use that can have significant impact on water availability in areas prone to drought. For example, in Texas, water use for hydraulic fracturing has increased by about 125%, from 36,000 acre feet (AF) (0.04 cubic kilometers) in 2008 to about 81,500 AF (0.1 cubic kilometers) in 2011. Moreover, hydraulic fracturing is expanding to drier parts of Texas including southern and western areas which means that industry needs to adopt alternative ways to supply water, including recycling and water reuse. (Nicot et al. 2012)

A common estimation of water use is between one to seven million gallons per well (Vidic et al. 2013, Cooley et al. 2012, “Colorado Water Supply and Hydraulic Fracturing” n.d.) Table 2-1 shows water consumption per well in different shale oil and gas fields.

Table 2-1 Water consumption per well in different shale oil and gas fields

Author	Field	Water Consumption per Well
Vidic et al. 2013	Marcellus	2 million to 7 million gallons
Cooley et al. 2012	Eagle Ford Shale in Texas	up to 13 million gallons
Colorado Water Supply and Hydraulic Fracturing	Wettenberg basin in Colorado	two to five million gallons

Due to the risks associated with fracturing wells in arid regions, operators are transitioning toward alternative sources such as industrial wastewater, saltwater and brackish water. However, due to additional steps of preconditioning the water to meet desired influent water quality criteria it is costlier than procuring conventional sources such as groundwater or surface water. Depending on the water quality requirement, the cost of treatment can be less than \$1.00/bbl to high as \$5- \$6/bbl, and these costs do not include transportation costs. The ability of industry to implement alternative water sources will have significant impact on reducing freshwater demand in hydraulic fracturing operations. (Mehta 2014)

2.2.4.2 Water Quality

Water is blended with fracturing fluid additives to formulate fracture fluid. After the blending, the fracture fluid is injected with high pressure to induce the fracture. The additives do not comprise more than 1% of the fluid by volume. However, due to high volumes of water used in the fracturing, 1% additives concentration can represent significant volume of chemicals. They include gelling agents, proppant, breakers, friction reducer, corrosion inhibitor, scale inhibitor, biocides, cross-linkers and clay stabilizer. (Vidic et al. 2013, Gregory et al. 2011) Typically, the blended fluid is rich in organic and nitrogen along with high concentration of salts. These contaminant can pose serious environmental risks and health concerns if discharged into the environment.

One of the most common problems with well construction is a fault in sealing the annular space around casings to prevent gas leakage from a well into the water body. (Gorody 2012) Gas leakage in wells is associated with increased methane levels. With the low solubility of methane (26 mg/L at 1 atm, 20°C), it is not regulated in drinking water and is not considered a hazard with. But methane can be oxidized by bacteria and result in the depletion of oxygen. Water with low oxygen concentrations increases the solubility of chemical elements such as arsenic and iron. In addition, anaerobic bacteria can change sulfide to sulfate and create water and air quality issues. (Harrison et al. 1983) Methane is also an explosion hazard in the volatile form. Therefore, there are immediate actions to ventilate when methane concentration in produced water is higher than 28 mg/l and remediation should be performed to reduce the concentration to less than 10 mg/l. (Jackson et al. 2011)

Currently, there is a great amount of public concern to gas leakage in wells. In a methane distribution and origin study, in the Wattenberg, the results show that neither distance to oil and gas wells nor density of oil and gas wells had impact on methane concentrations. More than 98 percent of dissolved methane had microbial origin rather than aquifer contamination because of oil and gas activities. (Li and Carlson 2014) A study of 48 water wells in Pennsylvania, investigated 2010 and 2011, indicated there were no differences in dissolved CH_4 concentration before and after drilling and there were no differences related to distance to active wells. However, there was one well which methane concentration increased after drilling, which is consistent with average rate of casing problems of 3 percent. (Vidic et al. 2013) Regardless of the origin of methane contamination, energy companies are responsible for methane contamination of water wells from shale gas developments.

Another concern is the contamination of produced water due to the rock and shale formations. Minerals and organics present in the formation dissolve into the fracturing water and create a brine solution including the metals, salts, oil, greases, organic compounds, sodium, chloride, bromide, and other inorganic constituents such as arsenic, barium, and radionuclides. There is widespread variation in different areas depending to the characteristics and geological formations. (Soeder and Kappel 2009, Kimball 2011, Gregory et al. 2011)

Table 2-2 shows wide variation in fracturing flowback chemistry. (Kimball 2011) In Table 2-2 calcium concentration varies between 683 mg/L to 14,100 mg/L and TDS varies between 6220 to 283,428 mg/L. In addition, interactions between various fracture additives result in high molecular weight polymeric compounds that not only are toxic but also make the water prone to biological attack. (Mehta 2014)

Table 2-2 Wide variation in fracturing flowback chemistry
Ref: ProChem Tech International, Inc

Parameter(mg/L)	Frac 1	Frac 2	Frac 3	Frac 4
Barium	7.75	2,300	3,310	4,300
Calcium	683	5,140	14,100	31,300
Iron	211	11.2	52.5	134.1
Magnesium	31.2	438	938	1,630
Manganese	16.2	1.9	5.17	7.0
Strontium	4.96	1,390	6,830	2,000
TDS	6,220	69,640	175,268	248,428
TSS	490	48	416	330
COD	1,814	567	600	2,272

In addition, spills and leaks from hydraulic flow can run into to surface water or seep into the ground water. Spills can occur in any stage of hydraulic fracturing. For example, chemicals are hauled to the site where they are mixed to form the fracturing fluids. Equipment failure may occur during the mixing or the storage tanks may fail during the drillings and release the chemicals into the environment. Although there are several reports of spills associated with hydraulic fracturing, the extent of the problem is not considered well known. Additional research is needed to study the cause, frequency, severity and impact of spills associated with hydraulic fracturing. (Cooley et al. 2012)

2.2.4.3 Wastewater Management

Managing wastewater and treatment strategies are constrained by economics of implementation, regulations, geology setting, and technology performance. (Gregory et al. 2011) Most of the produced water in the United States is disposed in deep underground injection wells, called Class II wells. (Gregory et al. 2011) However, availability of deep well disposal is an important constraint for shale gas development. For example, the state of Pennsylvania has only seven disposal wells. In contrast, Texas had more than 11,000 Class II disposal well in 2008. (Gregory et al. 2011) Thus, due to lack of wells, the produced water in Pennsylvania is hauled to Ohio and West Virginia. However, disposal is limited by high transportation costs. Moreover, the constructions of new disposal wells are costly, complex and time consuming. (Gregory et al. 2011, Vidic et al. 2013) Also, long term disposal to deep well injection will remove water from fresh water cycle and could lead water scarcity. (Hickenbottom et al. 2013) Therefore, deep well injection is not acknowledged to be a sustainable solution. (Gregory et al. 2011, Vidic et al. 2013)

Wastewater reuse is becoming more common in the areas that deep well disposal is challenging. Reuse reduces the total water use that must be treated or disposed and helps to minimize environmental costs and enhances the economic feasibility of shale oil and gas operations. Wastewater is impounded in the surface and reused either directly or after dilution or pretreatment. However, reusing the wastewater only works when there is net water consumption in the field. Once the well field matures and rate of hydraulic fracturing diminishes, the field becomes a net water producer and produced water volume exceeds the water required for hydraulic fracturing. (Vidic et al. 2013)

Moreover, not all of the produced water from hydraulic is suitable for reuse. For example, the produced water from Fayetteville Shale is considered a great potential for reuse since it has low levels of TDS, chloride and less scaling tendency. On the other hand, Haynesville Shale is considered less attractive due to high levels of TDS, chloride, TSS and high scaling tendency. Therefore TDS, TSS and brines in produced water highly depends on the nature of the formation. (Jackson et al. 2011, Gregory et al. 2011, Vidic et al. 2013)

In the early stages of the Marcellus Shale development, flowback/produced water was discharged to publicly owned treatment works (POTWs). Since the POTWs were not designed to treat total TDS, the majority of TDS passed directly into the watershed and resulted in increasing salt loads in Pennsylvania rivers. (Vidic et al. 2013) Therefore, this is not considered a sustainable approach for managing the flowback. Currently, the amount of TDS accepted by POTWs is regulated. For example, in Pennsylvania the amount of oil and gas wastewater must not exceed the 1% of the average daily volume of waste handles by POTW. On the other hand, the amount of waste that is produced is much higher than the amount of flowback water that can be sent. (Gregory et al. 2011, Vidic et al. 2013, Mehta 2014)

2.2.5 Air Issues

Potential sources of air pollution from natural gas operations include volatile chemicals introduced during drilling and hydraulic fracturing, combustion byproducts from mobile and stationary equipment, chemicals used during maintenance of the well pad and equipment, and numerous non-methane hydrocarbons (NMHCs). (Colborn et al. 2014) Colborn et al. (2014) conducted an exploratory study to assess air quality in rural western Colorado area where residences and gas wells co-exist. They conducted weekly sampling for a year before, during, and after drilling and hydraulic fracturing of a natural gas well pad. Their study revealed that the concentration of (NMHCs) were highest during the initial drilling phase and did not increase during hydraulic fracturing. Moreover, they showed that selected polycyclic aromatic hydrocarbons (PAHs) were at concentrations greater than those at which prenatally exposed children in urban studies had lower developmental and IQ scores. (Colborn et al. 2014)

In another study, the Colorado School of Public Health studied human health risks from air emissions from development of unconventional natural gas resources in Garfield County, Colorado. They conducted a health impact assessment (HIA) to assess how the project may impact public health. They utilized EPA guidance to assess chronic and sub-chronic non-cancer hazard indices (HI) and cancer risks in two groups: 1) resident living more than half mile from wells and 2) residents living less than half mile from wells. The results showed that cumulative cancer risks were 10 in a 1,000,000 for residents living less than half mile from wells and 6 in a 1,000,000 for residents living more than half mile from wells. (McKenzie et al. 2012) Also, chronic HIs were 1 and 0.4 for residents less than half mile from wells and more than half mile from wells, respectively. Hence, the residents living more than half mile were in a greater risk of exposure to development of natural gas. (McKenzie et al. 2012)

Another study which compared the Greenhouse Gas Emission (GHG) footprint of coal, conventional gas and unconventional gas, concluded that due to high sensitivity of methane footprint, shale gas has a higher GHG footprint compared to conventional gas. Table 2-3 summarizes the Global Warming Potential (GWP) estimations of coal, conventional gas and unconventional gas. (Jenner and Lamadrid 2013) Also, coal emits more NO_2, SO_2, CO, black carbon and mercury, at a mass per energy base, than conventional and shale gas lifecycles. Therefore, use of natural gas reduces the overall health problems associated to nervous system, inner organs and the brain. (Jenner and Lamadrid 2013)

Table 2-3 GWP estimates.
Source: NETL (2011b).

GWP estimate	Avg. coal	Avg. conv. gas	Avg. unconv. gas
20-years horizon (Ib CO_2-e/MWh)	2661	1483	1613
100-years horizon (Ib CO2-e/MWh)	2453	1140	1179

2.3 Water Management Tools for Unconventional Oil and Gas Development

The five tools which are described below were designed to help users obtain necessary information for water treatment and planning.

First, the tool developed by Colorado School of Mines (CSM) in collaboration with Kennedy/Jenks Consultants, and Argonne National Laboratory is referred to as the CBM (Coalbed Methane) Produced Water Management Tool. The tool consists of 4 modules: a Water Quality Module (WQM), a Treatment Selection Module (TSM), a Beneficial Use Screening Module (BSM) and a Beneficial Use Economic Module (BEM). Each has a Microsoft Excel-based interface that seeks to help gas producers, water utilities and public to gain information about the produced water characteristics, costs, technology and environmental issues associated with the production of water for beneficial use from coalbed methane produced water.

("Produced Water Treatment and Beneficial Use Information Center", n.d.) CSM's Water Quality Module (WQM) is the first module that predicts water quality at a location based, by incorporating known water quality information from a combination of public and private sources. The advantage of this module is that it provides wide range of produced water quality information. However, the module does not consider water quality changes during different stages of hydraulic fracturing. The Treatment Selection Module (TSM) seeks to recommend various treatment methods based on inputs of water quantity, water quality and the desired recovery rate. The advantage of this module is that it considers 40 unique treatment technologies. However, the water quantity input is not based on a time-dependent water production model or development plan. The Beneficial Use Screening Module (BSM) requires that the user inputs including water quality, supply timing and duration of supply so that the module can identify the top 2 or 3 beneficial use by ranking them qualitatively. Finally, the Beneficial Use Economic Module (BEM) estimates the economic and non-economic costs of project scenarios. Users can compare multiple beneficial uses on a project scenario based on user inputs and results from WQM and TSM. ("Produced Water Treatment and Beneficial Use Information Center", n.d.)

Three tools were designed by Stephen Goodwin, at Colorado State University including Fixed/Mobile Treatment Site Optimization, Water Volume Prediction Tool and Treatment Facility Siting Tool. First, the Fixed/Mobile Treatment Site Optimization helps the user to site the best location for treatment facility. The user inputs the near-future well pad development, the near-future flowback/produced water, sensitive areas and distance from existing treatment facilities. The tool uses the Multi-Criteria Decision Analysis (MCDA) method and weights each criteria based on the value from the user. It provides a relative score of 0-100, where 100 is the best location for treatment facility. This tool allows the user to change weighing of each criteria and the start/end date to better identify the best location that is impacted by important factors. Finally, the result is plotted in the GUI with a pseudocolor (checkerboard) plot. (Goodwin 2014)

Second, the Water Volume Prediction Tool allows the user to predict water volume within a development plan. The user inputs the development plan as a number of wells per month and the average time it takes to develop a well. The user also inputs the start and end date of the prediction window. The output of the model includes the fresh water demand, total wastewater, flowback, transition, and produced water. (Goodwin 2014)

Finally, the Treatment Facility Siting Tool allows the users to place freshwater, injection wells, and treatment facilities in the GUI. The geodesic distance between the fresh water source, the well pad, and the treatment facility/injection is calculated. By using the distance and water volume, the number of truck trips can be calculated. The user can adjust the cost of both trucking and injection for better estimation in the case of price changes. The outputs include trucking cost, disposal cost, road damage, kg of CO_2, truck trips, miles driven. (Goodwin 2014)

Another Water Production Prediction Tool designed at CSU uses a breakdown of horizontal and vertical drilling for predicting the volume of water production. The tool can also be used to predict water production for future proposed development from given oil and gas fields based on the historical data. The model requires inputting the number of existing wells, the types of wells, and the production dates and associated water volumes. After the models are developed from existing wells, they can be applied for predictions of future water production. (Bai et al. 2013)

2.3.1 Arp's Decline Curve

An Arp's decline analysis is used to assess well production and predict well performance based on real production data. (Arp's 1945) Arp's decline curves were proposed nearly sixty years ago and many studies are based on this empirical method. (Lie and Home 2003) The empirical Arp's decline equation represents the relationship between production rate and time for oil and gas wells and is shown below.

$$q(t) = \frac{q_i}{(1+bD_it)^{\frac{1}{b}}} \qquad (2.1)$$

Where q(t) is the oil production rate at time t ,qi is the initial oil production rate, b and D_i are two empirical constants. Equation 2.1 is a more general equation and two other curves including exponential and harmonic are generated from that in two special cases when b=0 and b=1.

b=0 represents an exponential decline in oil and gas production, which is expressed as follow:

$$q(t)= q_i\, e^{D_it} \qquad (2.2)$$

b=1 represents a harmonic decline oil and gas production that can be expressed as follow:

$$q(t) = \frac{q_i}{(1+D_it)} \qquad (2.3)$$

Other values for b represent a hyperbolic decline in oil and gas production. The Arp's equation is still used frequently for production decline analysis. (Lie and Home 2003, Goodwin 2014, Bai et al 2013)

3 Methods

3.1 Data Sources

3.1.1 Northern Colorado Data

Northern Colorado data was provided from one of the energy companies working as a field developer in the Wattenberg field. The water production data used in the Water Production Modeling Tool to calculate the water production equation. The dataset consists of daily produced water data for 25 wells. (Figure 3-1)

	A	B	C	D	E	F	G
1	Well No.1	Well No.2	Well No.3	Well No.4	Well No.5	Well No.6	Well No.7
2	210	696	730	147	589	677	799
3	420	549	1200	100	336	438	471
4	373	484	542	100	633	345	354
5	317	342	698	100	352	329	252
6	321	473	728	50	506	280	0
7	344	353	540	40	938	111	0

Figure 3-1 Northern Colorado data used in Water Production Modeling Tool

Another data set of Northern Colorado drilling data was used in the Water Quality Tool to predict chemical concentration in the field. The dataset is an Excel file and consists of Na, Ca, Cl and TDS concentration equations in time. Chemical concentration equations, as well as development plan spreadsheet and water production equation were used in Water Quality Tool.

3.1.2 Texas Data

A similar dataset was developed to describe water use in the Eagle Ford in Texas. The Texas data was extracted from the *FracFocus* website (fracfocus.org) as an Excel file consisting of drilling date per well, horizontal feet drilling per well, water used per well for 1177 horizontal wells. Texas data was used in Water Use Calculator Tool for analyzing the amount of water used in hydraulic fracturing located in Texas. Wells drilling dates are in the duration of 2011 to 2014. (Figure 3-2)

1	latitude	longitude	datu	true_verti	total_wate	wu_bbls	wellbore_p	horizont	bbls/ft
124	28.265890	-99.031937	NAD27	9205	698502	16631.33	Horizontal	3672.00	4.53
130	30.671173	-96.599838	WGS84	0	822570	19585.39	Horizontal	5304.00	3.69
139	28.438178	-98.612848	NAD27	11153	886998	21119	Horizontal		
156	30.648880	-96.503980	NAD27	7445	1060122	25242	Horizontal		
160	28.394630	-98.500530	NAD83	11919	1098846	26163.52	Horizontal	4157.00	6.29

Figure 3-2 Texas data used in Water Use Calculator Tool including 1177 horizontal wells

3.2 Water Production Modeling Tool

One way to reduce water consumption in hydraulic fracturing is to reuse or recycle produced water. Thus, it is important to calculate the quantity of produced water to predict future production. The objective of the Water Production Modeling Tool is to help users calculate water production rates for different oil and gas wells rapidly with their own data to assist with water management and planning.

A Graphical User Interface (GUI) was developed in MATLAB for this tool to allow interaction with the user (Figure 3-3). The tool allows users to (1) import data from Excel spreadsheets, (2) generate the coefficient values for the prediction equation (Arp's constants, RMSE, R^2), and (3) plot the results with uncertainty percentiles. The tool is also an executable file that does not require the users to have MATLAB software on their computer.

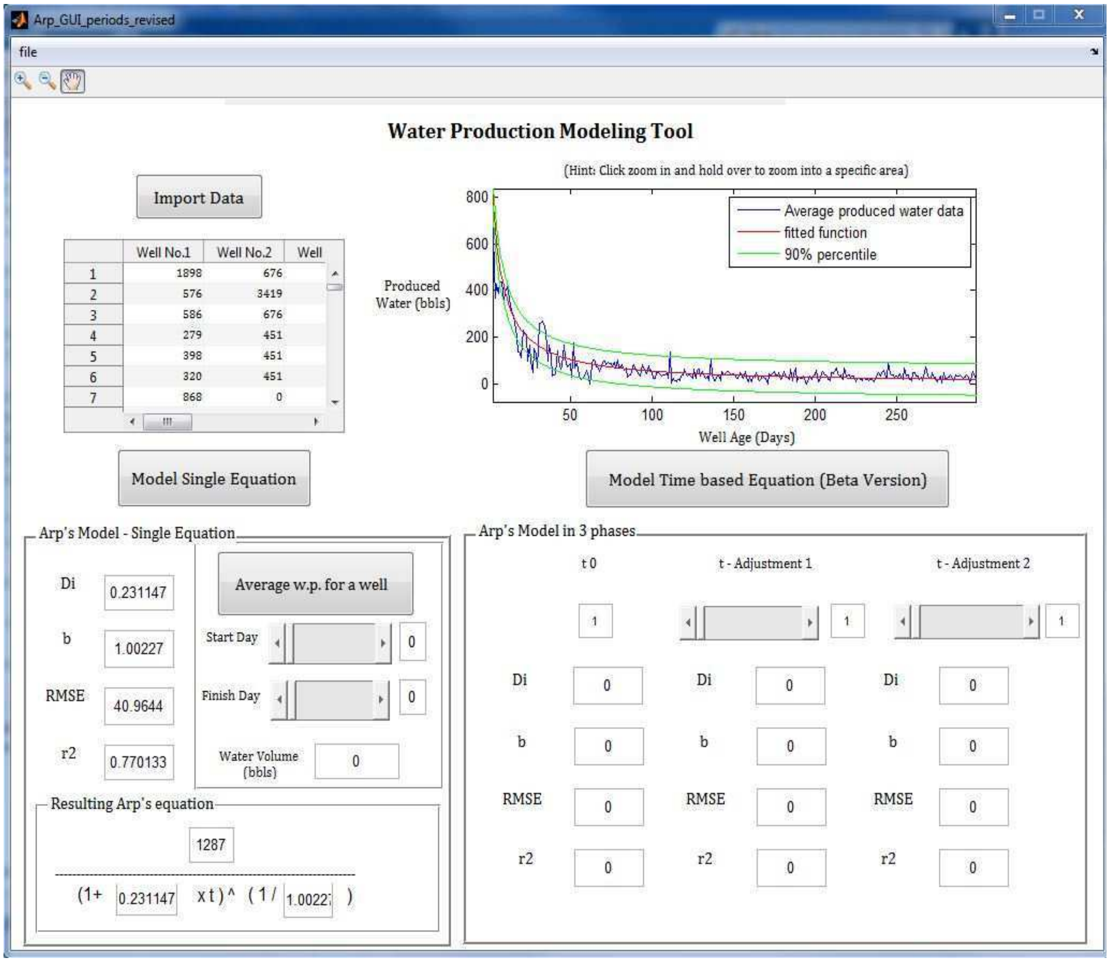

Figure 3-3 Water Production Modeling Tool

3.2.1 Importing and Reading the Excel file

The user imports the Excel file in the GUI using the import data button on the GUI and selecting the appropriate .xls or .xlsx file.

The Excel file must contain columns with the water production data for each well in a field. Each column refers to one well produced water data. (Figure 3-4) The MATLAB command lines for receiving and reading the file are `Uigetfile` to receive the Excel file and `xlsread` to read it. [See: Appendix A.1]

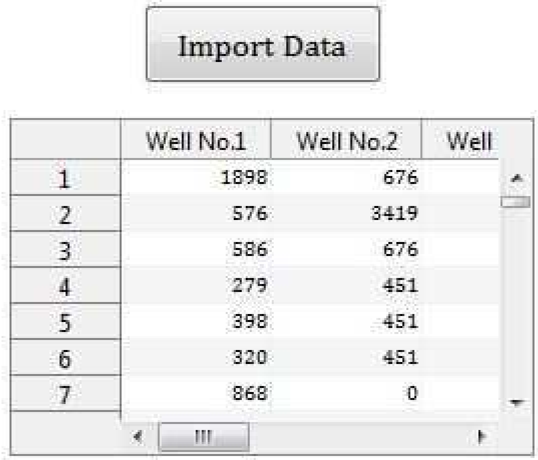

Figure 3-4 Imported Excel file in the Water Production Modeling Tool

3.2.2 Water Production Equation

After reading the Excel file, the daily average water production (bbl.) is calculated and saved in one variable (p). The Arp's decline equation was used to represent the relationship between production rate and time for oil wells in the pseudo-steady state period and is shown as follow:

$$q(t) = \frac{q_i}{(1+bD_it)^{\frac{1}{b}}} \qquad (3.1)$$

Where q(t) is the oil production rate at time t, qi is the initial oil production rate, and *b* and *Di* are two constants that are specific to each set of data . (Li and Home, 2003) To find the constants *b* and *D* the *fit* function in MATLAB was used with the average produced water variable (p), produced water days variable (days), custom Arp's equation and start points for the two constants of b and Di. Since the initial flow (q0) is numeric, first it needs to be changed to string variable to put it in the f (fitted equation) command line. The custom equation fit uses the nonlinear least-squares fitting procedures to find the b and D constants. ("Selecting a custom equation fit at command line", n.d.) (Figure 3-5) [See Appendix: A.2]

Figure 3-5 Constants for Arp's equation in the Water Production Modeling Tool

3.2.3 Plotting Produced Water Data

The plot of the water production data consists of the fitted equation (red line), 90 percent percentile (green line) and average produced water (blue line) (Figure 3-6). The user can visualize the Arp's result on the plot instantly after pressing Model Single Equation button. [See: Appendix A.3]

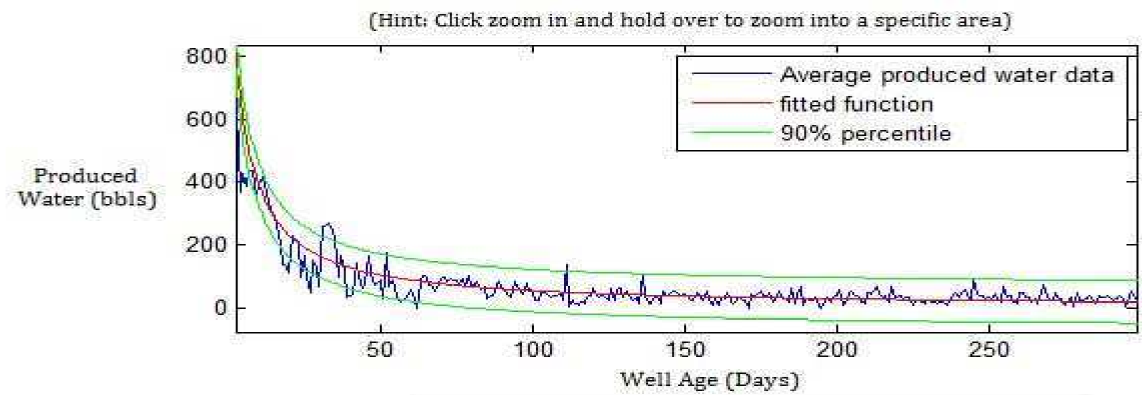

Figure 3-6 Plot of average produced water, fitted model and 90 percent percentile in the Water Production Modeling Tool

3.2.4 Calculating RMSE and R^2

To measure the accuracy of the fitted equation; the root mean square error (RMSE) and coefficient of determination (R^2) is calculated in the GUI. RMSE measures the difference between observed produced water values and fitted produced water equation model and R^2 provides a measure of how well observed data are replicated by the model. P is the observed average produced water and f (days) is the produced water model which these two are used as inputs for calculating R^2 and RMSE. [See: Appendix A.4]

The result includes D and b, which are Arp's constants and accuracy measurements including RMSE and R^2. (Figure 3-7) [See: Appendix A.5]

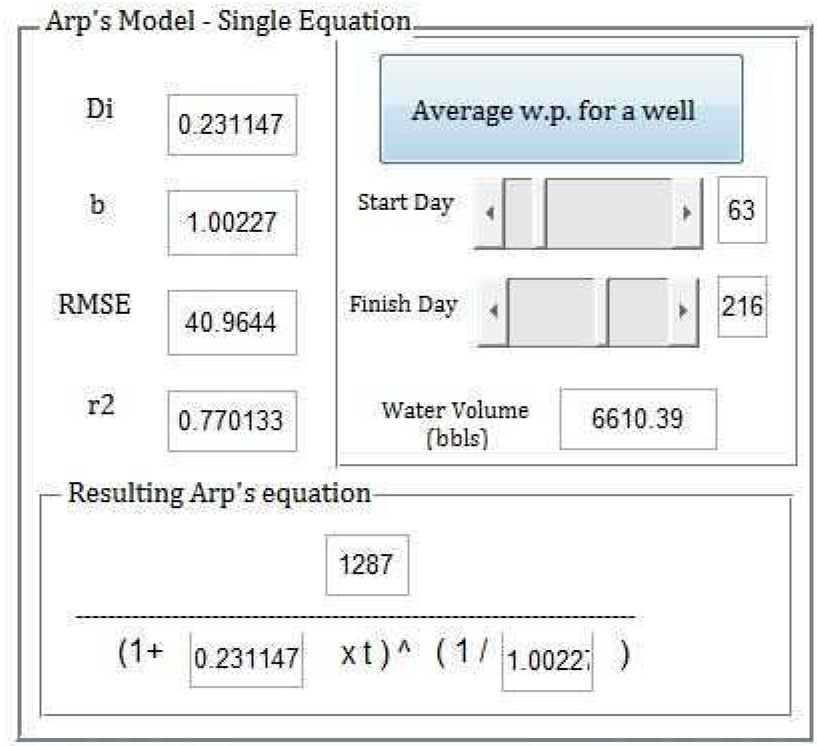

Figure 3-7 Arp's result in the Water Production Modeling Tool

3.2.5 Storing the Results

The GUI has a menu at the top left corner with the command "file" and there is a sub menu with a "save" function. The user is able to save the result of Arp's equation in MATLAB and Excel file types. Once the results are displayed on the GUI screen, user can press the file button and then the save button. [See: Appendix A.6]

3.2.6 Summary

The Water Production Modeling Tool allows the users to obtain water production equation of any arbitrary development plan. The tool calculates a custom equation and the amount of variance captured in the water production model (R^2). The observed and modeled data is then plotted in the tool. In addition, the user can save the result and compare different report instantly. Moreover, the Water Production Modeling Tool can be used either through MATLAB software or as an application outside of MATLAB to increase accessibility to the tool.

3.3 Water Use Calculator Tool

The amount of water used in drilling and hydraulic fracturing is an important variable to optimize water management. The Water Used Calculator Tool allows users to visualize water use with a variety of statistical analyses. It helps the user to identify water use change or horizontal length change in a field level and also the annual change of those parameters by illustrating different statistical figures. Therefore, the user can obtain valuable data to predict and plan for water reuse and recycling in a field.

The Water Use Calculator was developed in MATLAB and is accessible as a separate executable file outside of MATLAB similar to the previous tool. This GUI requires one Excel file input containing water use volume per well, horizontal length per well, and drilling dates. The outputs for the tool are a histogram of water used per well, a histogram of horizontal length per well, a histogram of water used per horizontal foot, the amount of water used versus horizontal foot, the average water used per well by year, the average horizontal length per well by year, the average water used per horizontal length per year and the total number of horizontal wells which were studied for all of the calculations. In addition, the mean and standard deviation is calculated for the histogram plots. (Figure 3-8)

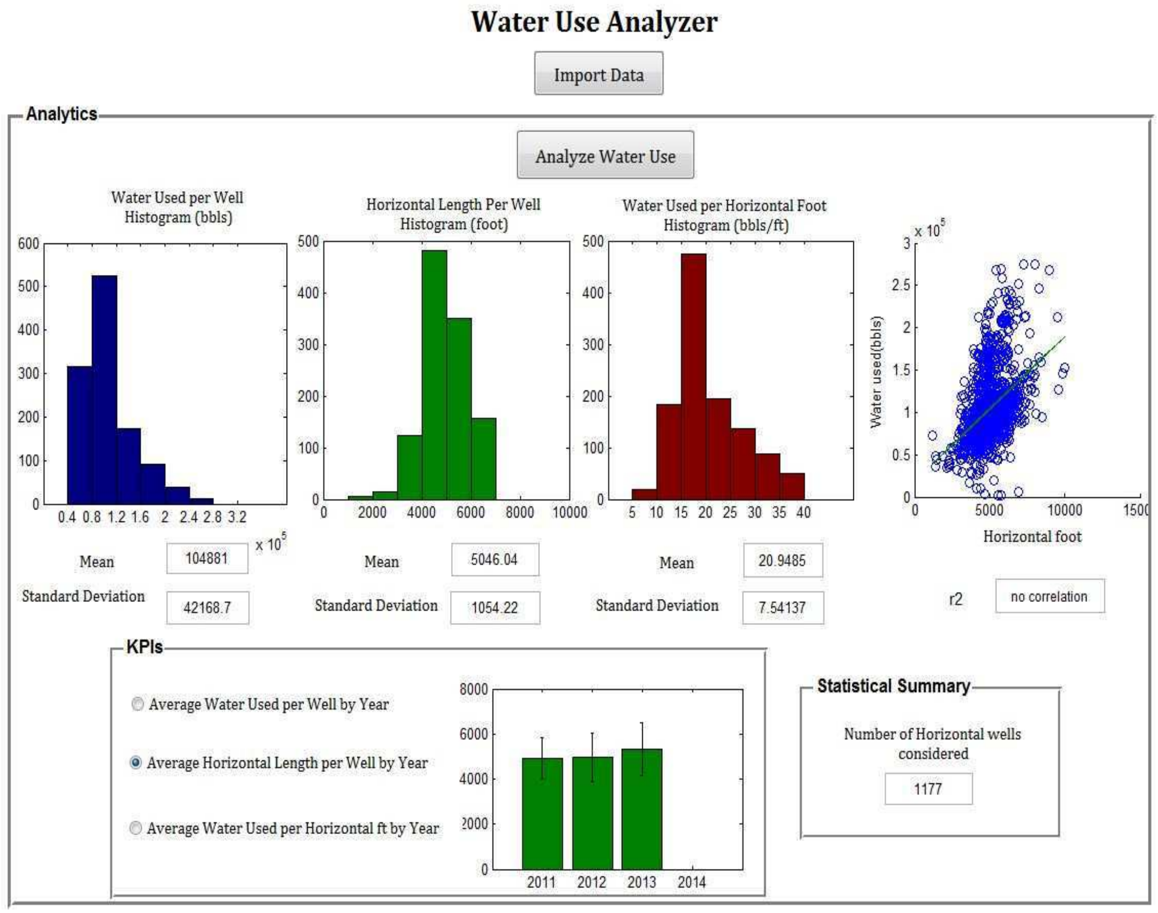

Figure 3-8 Water Use Calculator

3.3.1 Histogram of Water Used per Well

A histogram of water used per well is a graphical representation of the number of wells using specified amounts of water for drilling. The histogram of water used per well indicates how the consumed water is distributed within the wells. (Figure 3-9)

To construct the histogram, a "bin" was created, which divides the entire range of values into a series of small intervals. Then, a number of values fall into each interval and the frequency of each bin is recorded and plotted. Standard deviation and mean are set in the part of calculations. [See: Appendix B.1]

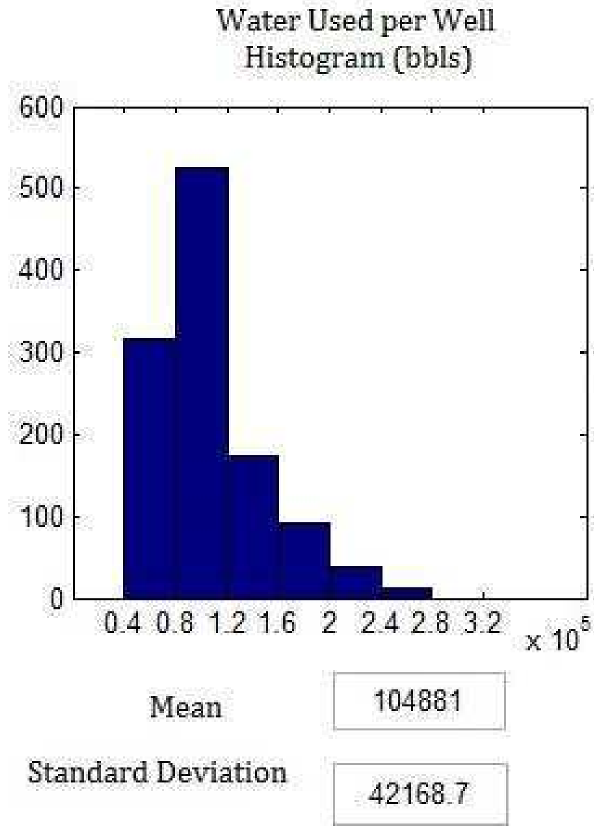

Figure 3-9 Histogram of water used per well

3.3.2 Histogram of Horizontal Length per Well

The histogram of the horizontal length per well indicates distribution of horizontal drilling length within the wells. (Figure 3-10) A histogram counts the frequency of occurrence of well length in labeled bins within certain intervals. In addition to the histogram, the mean and standard deviation are calculated and displayed [See: Appendix B.2].

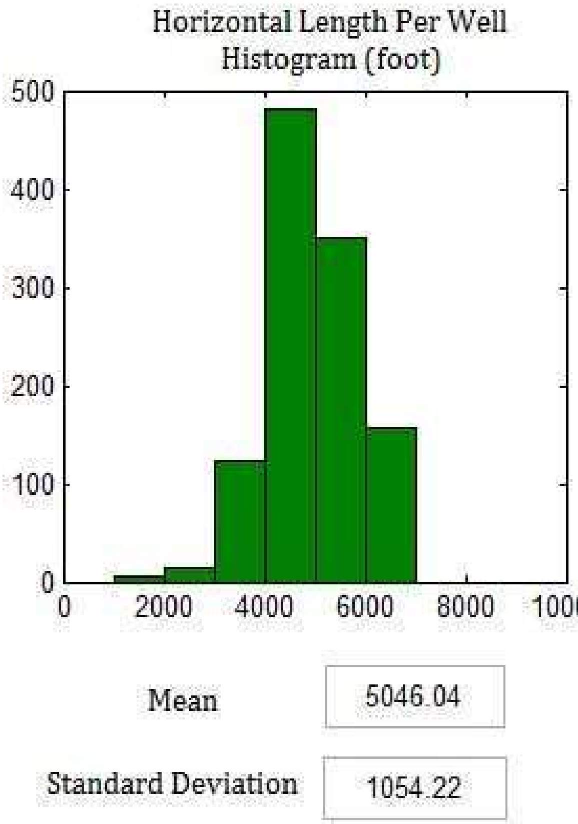

Figure 3-10 Histogram of horizontal length per well

3.3.3 Histogram of Water Used per Horizontal Length

The Water Use Calculator GUI assesses the water used per horizontal length from the Excel file to construct a histogram of water use per horizontal length. [See: Appendix B.3] Figure 3-11 shows water used per horizontal length histogram of a sample data using Water Use Calculator GUI.

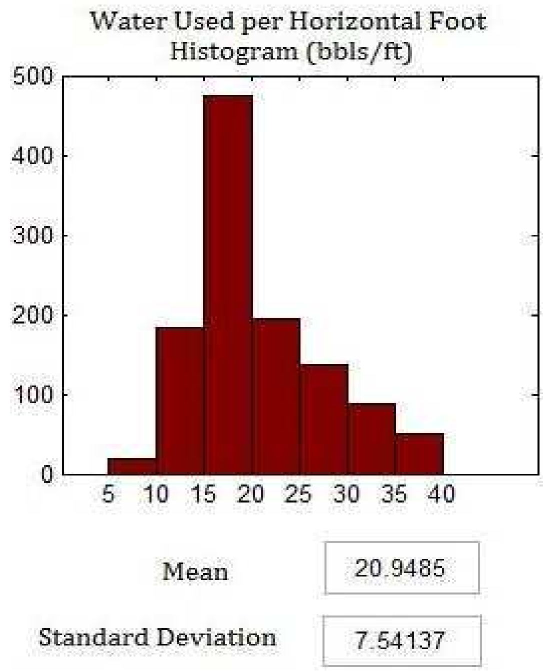

Figure 3-11 Histogram of water use per horizontal length

3.3.4 Average Water Used per Well by Year

The data file in Excel is uploaded by the user and contains the drilling dates of the wells. The Water Use Calculator GUI has access to this data and changes the dates to numerical variables within MATLAB. The water use data is categorized into separate groups based on year of drilling and the GUI calculates the average water use for each year. [See: Appendix B.4] Once the user clicks on the *Average Water Used per Well by Year* button, the result is displayed on the GUI screen. (Figure 3-12)

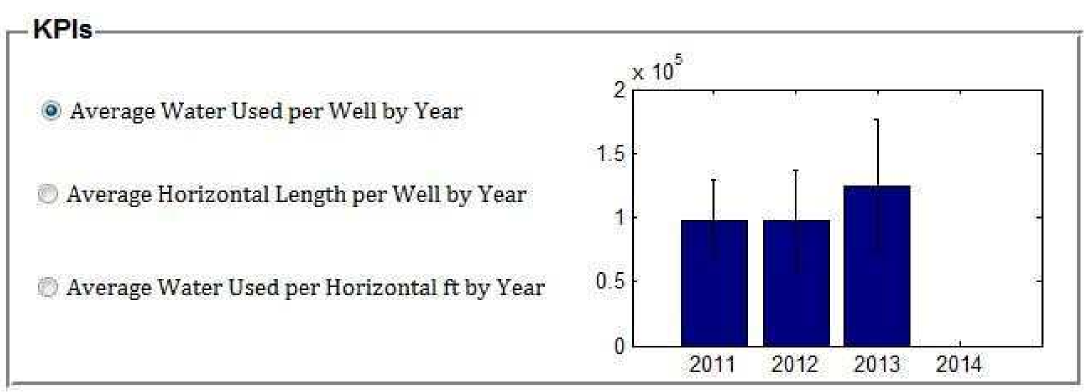

Figure 3-12 The selection and plot display for the average water used per well for a given year.

3.3.5 Average Horizontal Length per Well by Year

As in the previous section, the Water Use Calculator GUI categorizes horizontal length data in separate group variables based on the year of drilling. It calculates the average of horizontal length for each year. The steps are the same as in the previous section. [See: Appendix B.5] Once the user presses the *Average Horizontal Length per Well by Year* button, the bar graphs which consists of error bars and average horizontal foot per year are displayed. (Figure 3-13)

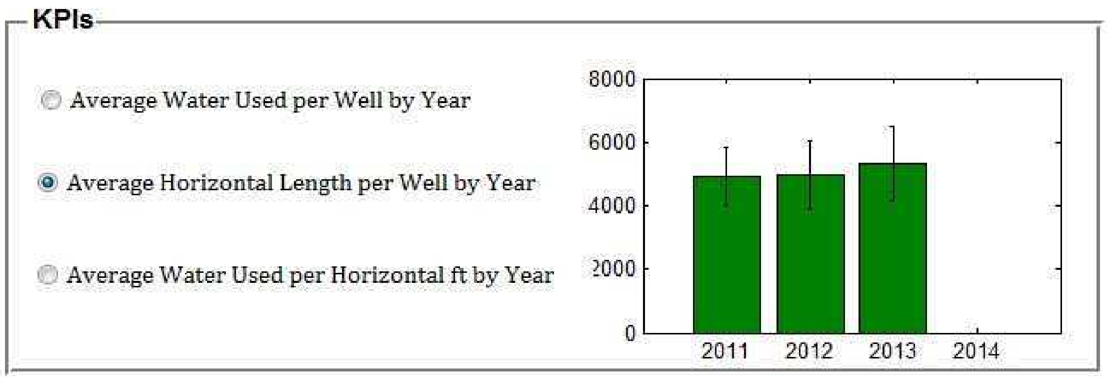

Figure 3-13 The selection and plot display for the average horizontal length per well for a given year.

3.3.6 Average Water Use per Horizontal Length by Year

This part displays the average water use per horizontal length by year using bar charts. It has valuable information which helps the user to understand how average water used per horizontal length is changing each year. (Figure 3-14) [See: Appendix B.6]

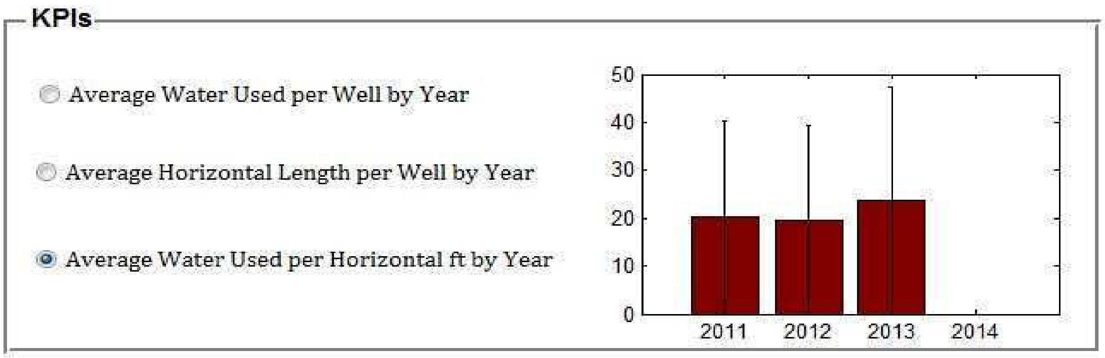

Figure 3-14 The selection and plot display for the average water used per horizontal length for a given year.

3.3.7 Summary

The Water Use Calculator GUI is a flexible tool that helps users instantly visualize the water use volume analysis for a single development plan. The output of the Water Use Calculator helps the users to predict and plan for water reuse and recycling in a field and enhances the speed of calculations. The Water Use Calculator GUI is specifically designed for horizontal wells and is accessible either by MATLAB software or as an application outside of MATLAB.

3.4 Water Quality Tool

To reduce the water contamination associated with development of natural gas development, it is important to predict how water contamination concentration changes with time. The Water Quality Tool predicts how chemical contaminants concentrations including sodium, chloride, calcium and total dissolved solids are changing in the desired time period selected by user. One of the greatest capabilities of Water Quality Tool is that it synthesizes groups of data and gives a field level prediction which helps the user to plan for future months or even years.

The Water Quality Tool generates plots of chemical concentrations versus time for calcium, sodium, chloride and TDS. The tool can also extract the concentration of selected contaminant in the specified date and displays it in the result panel. In addition, there is a pop-up menu in the result panel that the user can access to understand water volume information.

The user is required to input different parameters including the Arp's model, development plan, chemical concentration equations and prediction period. The user is able to adjust characteristics including water per foot, well lifespan, and average lateral lengths. The user can save the concentration results in an Excel file. This GUI is accessible within the application or through MATLAB software. Figure 3-15 shows the main screen of the Water Quality Tool.

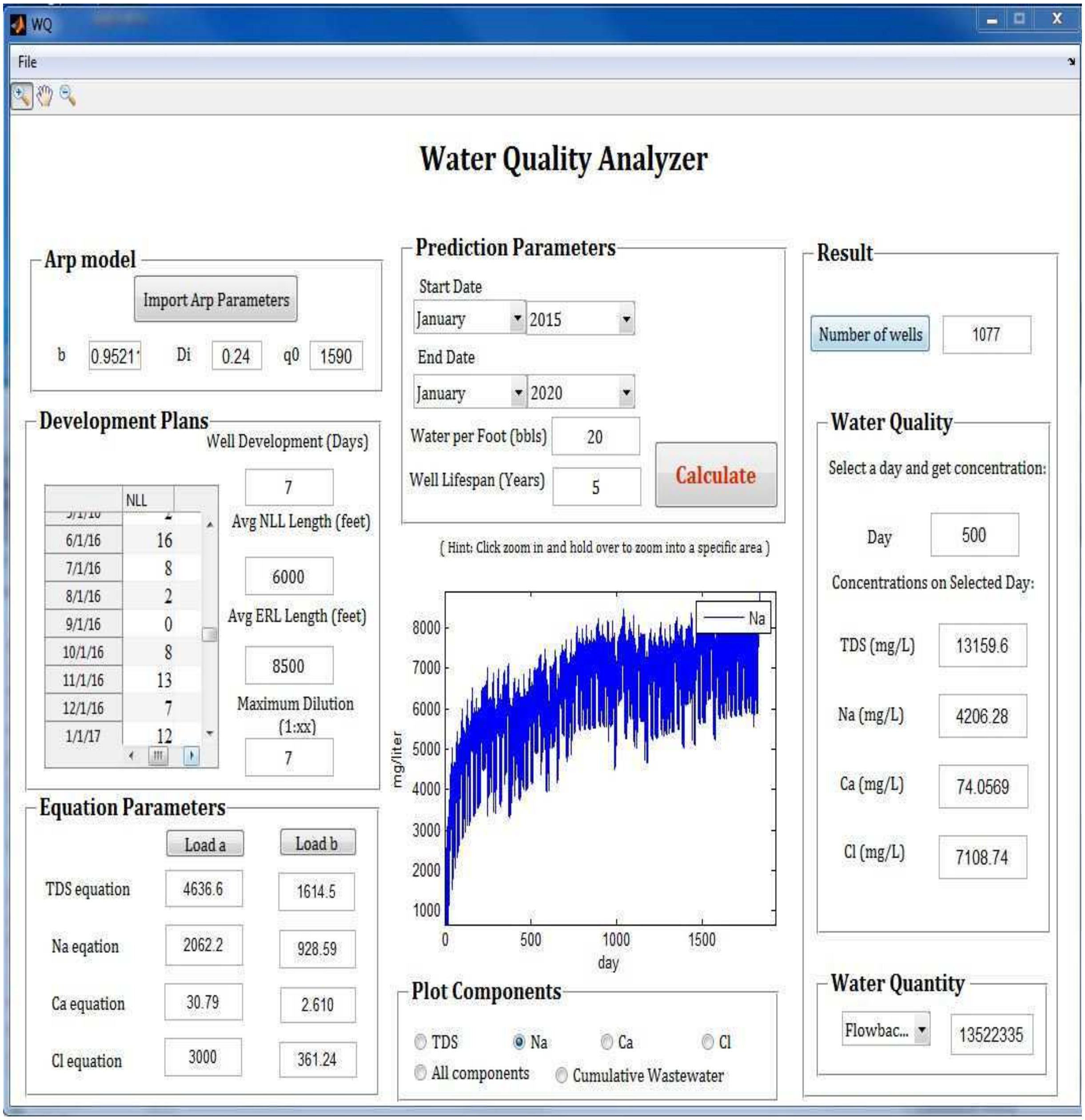

Figure 3-15 The entire display panel for the Water Quality Tool.

3.4.1 Arp's Equation Input

To predict contaminant concentrations, it is necessary to have a water production equation associated with the development plan to calculate water volume. The Arp's equation parameters are uploaded as an Excel file format in the Arp's Model panel. (Figure 3-16) Once the user imports the Arp's parameters, they are passed from the GUI into MATLAB and the water production equation is created. In general, the user can obtain the Arp's equation parameters from the Water Production Modeling Tool. [See: Appendix.C.1]

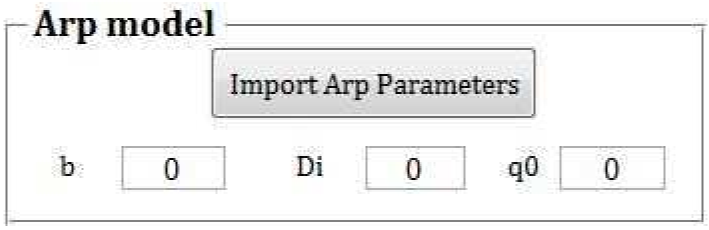

Figure 3-16 The display to import the parameters for the Arp's equations.

3.4.2 Development Plan Input

The Water Quality Tool allows the users to input any development plans into the GUI as a spreadsheet, and adjust the average length of laterals including Normal (NLL) and Extended (ELL) and number of days for developing each well. (Figure 3-17) The following code was used in MATLAB to input data in the development plan spreadsheet:

```
DP=get(handles.Table, 'Data');
```

Figure 3-17 The display panel for the development plan in the Water Quality Tool. The number of wells and the drilling data are entered into the Excel spreadsheet by the user. The normal lateral length (NLL) and extended length (ERL) are entered by the user into the tool.

3.4.3 Concentration Equations Parameters Input

Another input that is needed for the prediction process is the concentration equations for the water chemicals. The chemical equation consists of two coefficients referred to *a* and *b*. The user inputs *a* and *b* parameters in the Equation Parameter panel for all of the chemical contaminant parameters. (Figure 3-18) After the parameters are uploaded, they are passed from GUI into the MATLAB and the concentration equations of Ca, Na, Cl, and TDS are created. [See: Appendix: C.2]

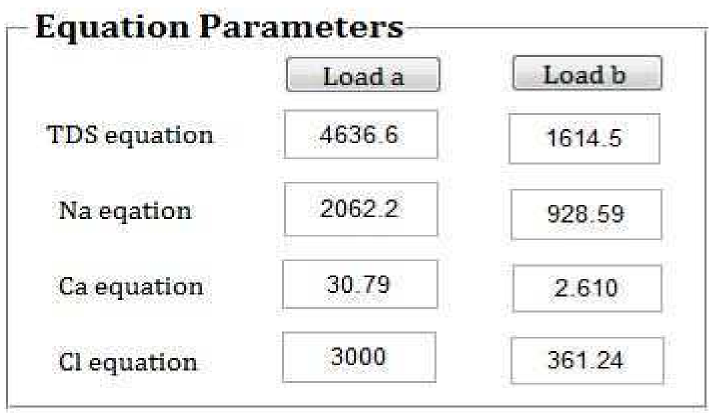

Figure 3-18 The user-defined equation parameters that relate concentration to days past production in the Water Quality Tool.

3.4.4 Prediction Parameters

To define the start date and end date of the prediction period, there is a panel referred to as the Prediction Parameters panel, in which the user selects the start and end month/year of the prediction period from a drop down menu. (Figure 3-19) The start month/year and end month/year are used to define which rows of the development plan are used for calculating water volume. The following equations were used to convert start month/year and end month/year to the corresponding row of the development plan spreadsheet. (See: Appendix: C3)

$$S=12 * (start\_year-1) + start\_month \quad (3.1)$$

$$E=12 * (23-end\_year) + end\_month-1 \quad (3.2)$$

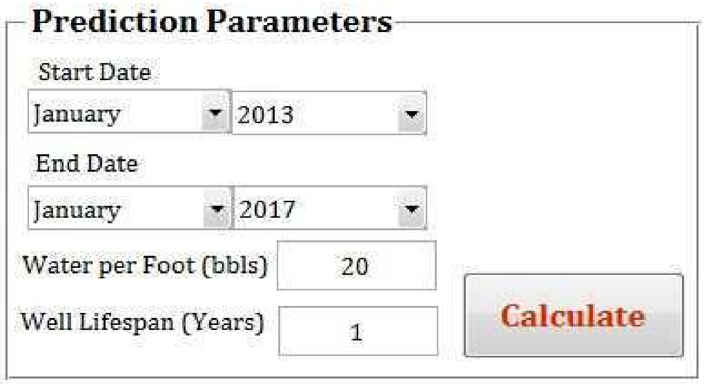

Figure 3-19 The display for the prediction parameters in the Water Quality Tool.

3.4.5 Calculating Chemical Concentration Prediction

After the user inputs all the required data including Arp's equation parameters, chemical equation parameters, development plan spreadsheet and the prediction period, the user can press the calculate button. The Water Quality Modeling Tool predicts daily produced water for each well using the development plan spreadsheet and equation (3.1) and stores them in a matrix variable (*flow).* This variable has columns referring to wells and rows referring to each day of drilling. The GUI does the same steps to store daily chemical concentration prediction for each well, separately for TDS, Ca, Na, and Cl using (3.4), (3.5), (3.6) and (3.7) equations. The GUI then multiplies flow and concentration matrices to calculate daily mass prediction for each well. Next, the GUI calculates daily mass by summing the mass values of all the wells (summing columns values) and storing it in a variable (sum_mass). The GUI does the same process for the produced water values of all wells in each day and stores it in a variable (sum_flow). The GUI finally divides the daily mass variable by the daily produced water variable to obtain the daily concentrations. The following equations were used for predicting chemical concentrations and produced water quantity: [See: Appendix C4]

$$Q: \frac{1590}{(1+0.24* t)^{\frac{1}{(0.95)}}} \quad \text{(bbl.)} \qquad (3.3)$$

$$C_{(TDS)}: \; 4636.6 \ln(t) + 1614.5 \quad \text{(mg/L)} \qquad (3.4)$$

$$C_{(Na)}: \; 2063.2 \ln(t) - 928.59 \quad \text{(mg/L)} \qquad (3.5)$$

$$C_{(Cl)}: \; 3000 \ln(t) - 361.24 \quad \text{(mg/L)} \qquad (3.6)$$

$$C_{(Ca)}: \; 30.79 \ln(t) - 2.61 \quad \text{(mg/L)} \qquad (3.7)$$

3.4.6 Plotting the Chemical Concentration Prediction

In the plotting panel, there are chemical elements including Cl, Na, Ca and TDS that the user can select for plotting. The GUI displays the desired concentrations at any point in time. (Figure 3-20)

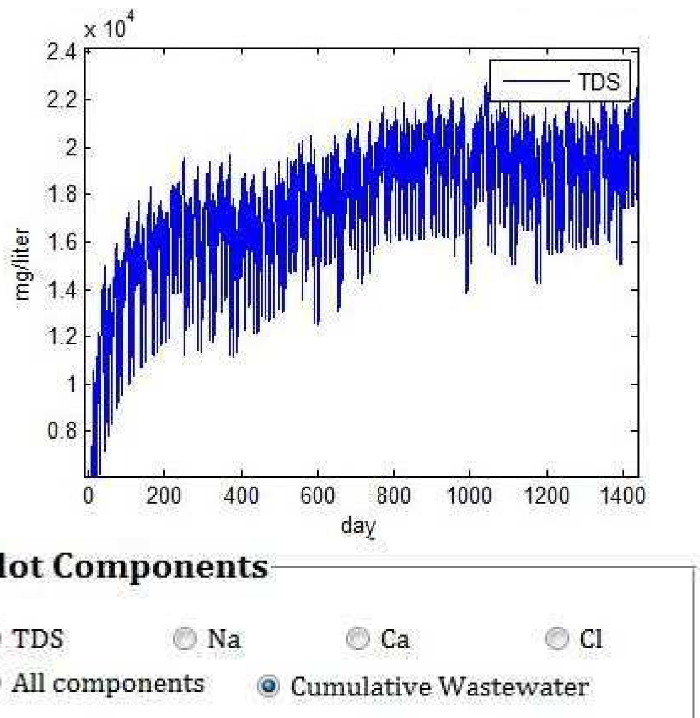

Figure 3-20 An adjustable display plot of chemical concentrations by day for produced water including total dissolved solids (TDS), sodium (Na), calcium (Ca), and chloride(Cl) for the Water Quality Tool.

3.4.7 Result Panel in Water Quality GUI

The result panel displays water quality, water quanitity, and the number of wells. In the water quantity section, the user can specify a date and can obtain the related concentration data for all the contaminants. In the water quantity section, there is a pop-up menu of water volume data including total fresh water, average fresh water, peak fresh water, total wastewater, flowback, transition and produced water. In addition, the total number of the wells used for calculation in the model can be calculated by pressing the number of wells button in result panel. (Figure 3-21)

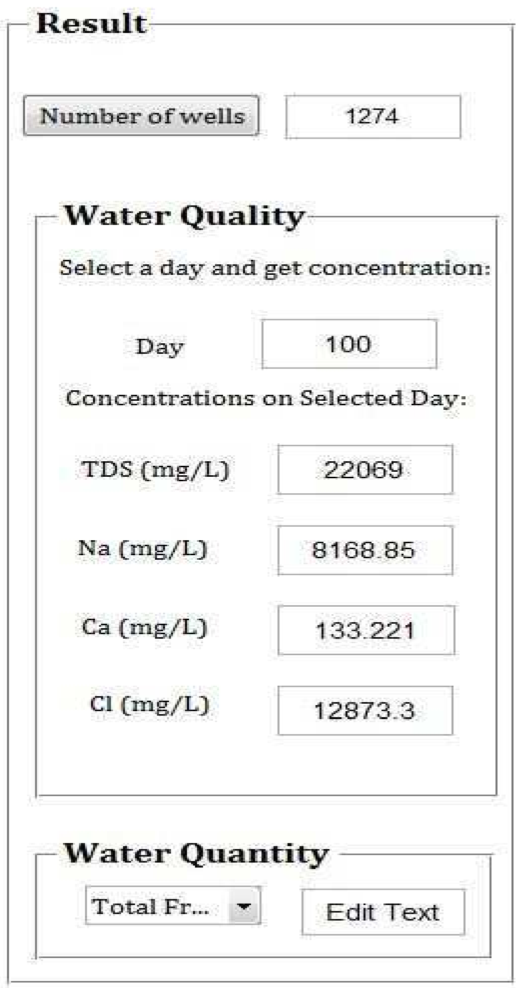

Figure 3-21 The result panel for Water Quality Tool that displays the chemical concentrations on a entered day.

4 Results of Case Studies

4.1 Water Production Modeling Tool in Northern Colorado

The Water Prediction Modeling Tool is used to calculate the water production equation for the Northern Colorado area. For this study, 25 wells were used. After running the GUI, The Arp's constants of *D* and *b* and accuracy parameteres including R^2 and RMSE were caclulated. The fitted function model (red), daily avaerage produced water (blue) and 90 percent percentile (greeen) are shown in the Figure 4-1. The highest level of average daily produced water change is observed in the period of 0 to 30 days of water production (flowback) and gradually after flowback period, produced water values fall close to a constant value.

The results of running the model are as below:

$$Di: 0.143$$
$$b: 0.95$$
$$R^2: 0.95$$
$$RMSE: 8.19$$
$$Arp's\ Equation = \frac{549.71}{(1+0.143*t)^{\frac{1}{0.9521}}}$$

Given the high value of R^2 (0.95), the calculated Arp's equation is proposed to function as an effective prediction of variance in produced water. Thus, it can be used for predicting the produced wastewater and demand water for treatment.

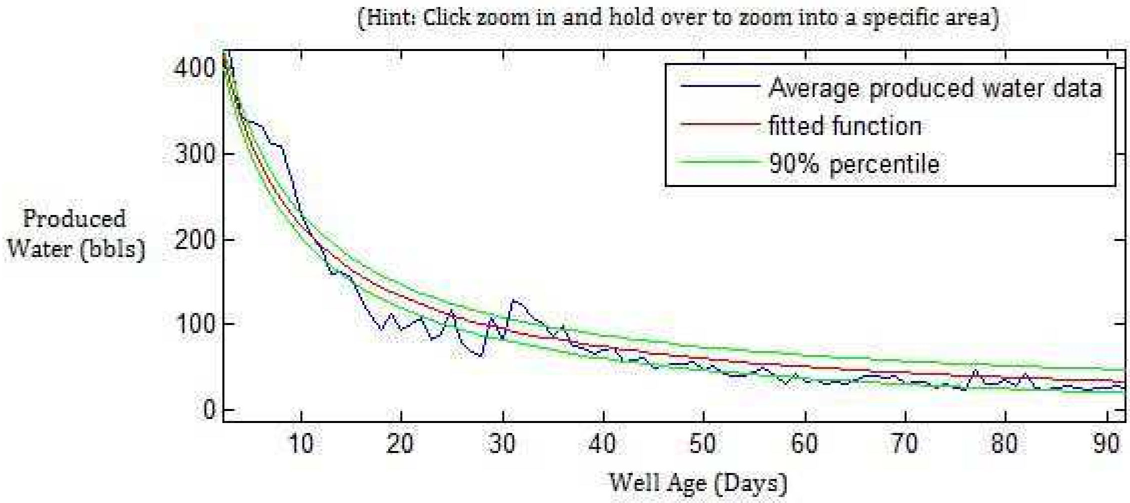

Figure 4-1 Chart of water production for days past production including average produced water data (blue line), fitted water production (red line), and the 90 percent confidence intervals (green line).

The Water Production Modeling Tool allows the users to calculate a water production equation for any development plan. The main application of water production equation is that it allows the user to predict wastewater production and the amount of water demand for treatment in the field. Therefore, the user can use water quantity information for water management and planning in developing oil and gas operations.

4.2 Water Use Calculator Tool for Texas Dataset

In this section, the Water Use Calculator Tool is used to analyze the amount of water used in drilling and hydraulic fracturing for the Texas area. For this study, 1177 horizontal wells were used. After running the tool, the tool generates the histogram of water used per well (Figure 4-2), the histogram of horizontal length per well (Figure 4-3), the histogram of water used per horizontal foot (Figure 4-4), the average water used per well by year (Figure 4-5), the average horizontal length per well by year (Figure 4-6), and the average water used per horizontal length by year. (Figure 4-7)

The water used per well histogram shows that the peak value of water used per well is in the range of 80,000 to 120,000 barrels. More than 500 wells fall in this range and the average water use value is 104,881 barrels. (Figure 4-2) The horizontal length per well histogram has a peak value between 3,000 to 4,000 feet. About 480 wells fall in this range and the average value of horizontal length is 5,046.6 feet. (Figure 4-3) The water use per horizontal foot peak value is in the range of 15-20 bbl/ft and the average value is 20.94 bbl /ft. (Figure 4-4)

The average water use per well by year graph shows that water use is increasing yearly from 100,000 barrels in 2011 to 125,000 barrels in 2013. (Figure 4-5) The average horizontal length per well by year graph shows that horizontal length drilling is increasing from 5000 feet in 2011 to 5500 feet in 2013. (Figure 4-6) The average water used per horizontal foot by year graph shows that water use per horizontal length is increasing from 20 bbl/ft in 2011 to 24 bbl/ft in 2013. (Figure 4-7)

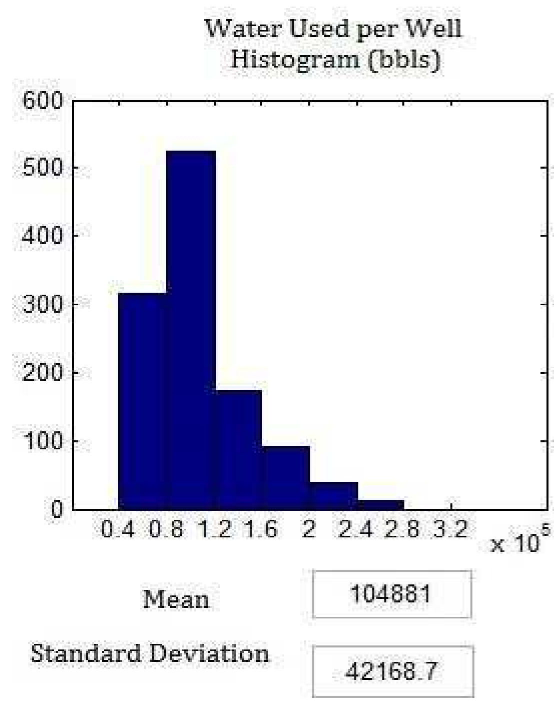

Figure 4-2 The histogram of water used per well for 1177 wells in Texas. The drilling dates range from 2011 to 2014.

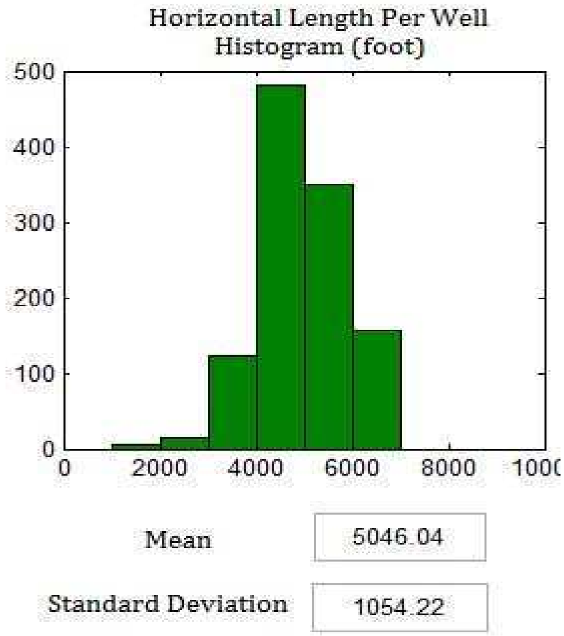

Figure 4-3 The histogram of the horizontal length per well for 1177 wells in Texas. The drilling dates range from 2011 to 2014.

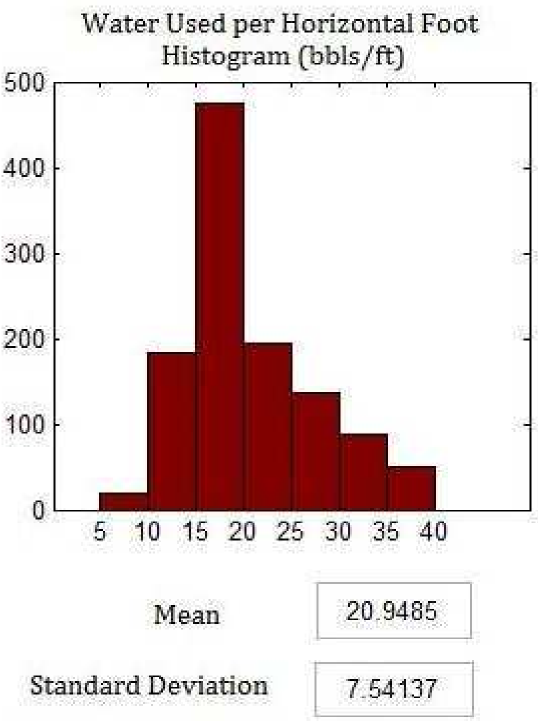

Figure 4-4 The histogram of water used per horizontal foot for 1177 wells in Texas. The drilling dates range from 2011 to 2014.

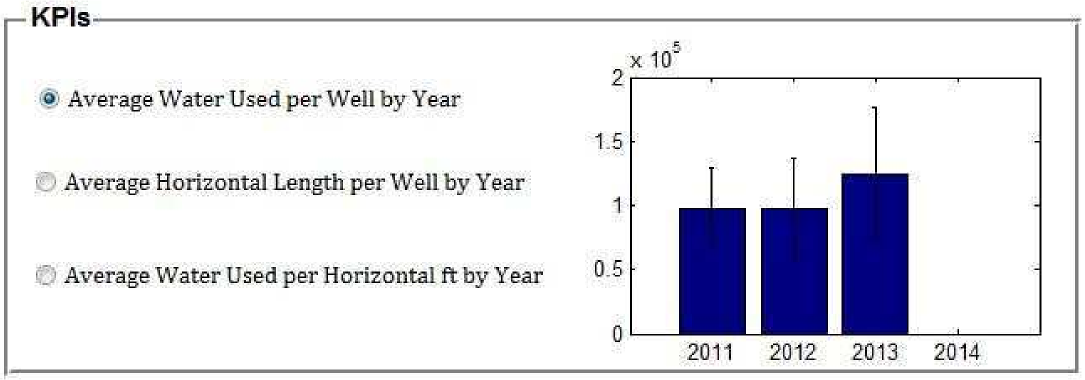

Figure 4-5 Average water used per well by year for Texas sample data for 1177 wells. The drilling date ranges from 2011 to 2014.

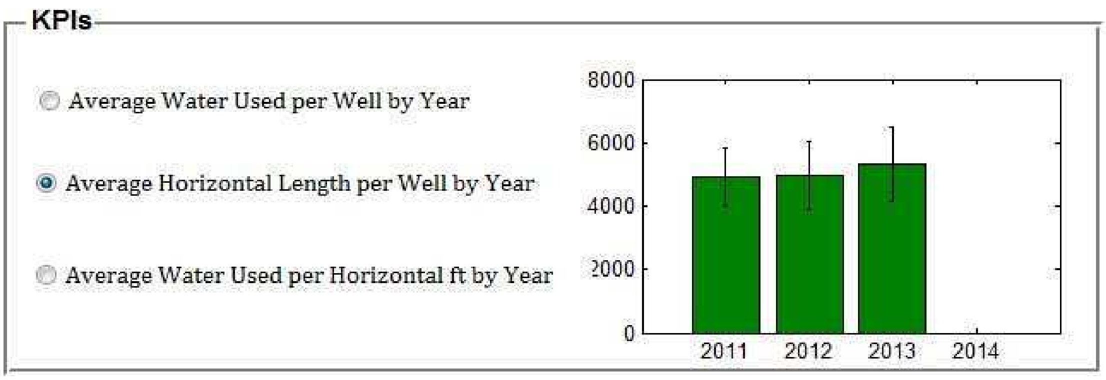

Figure 4-6 Average horizontal length per well by year for Texas sample data for 1177 wells The drilling dates range from 2011 to 2014.

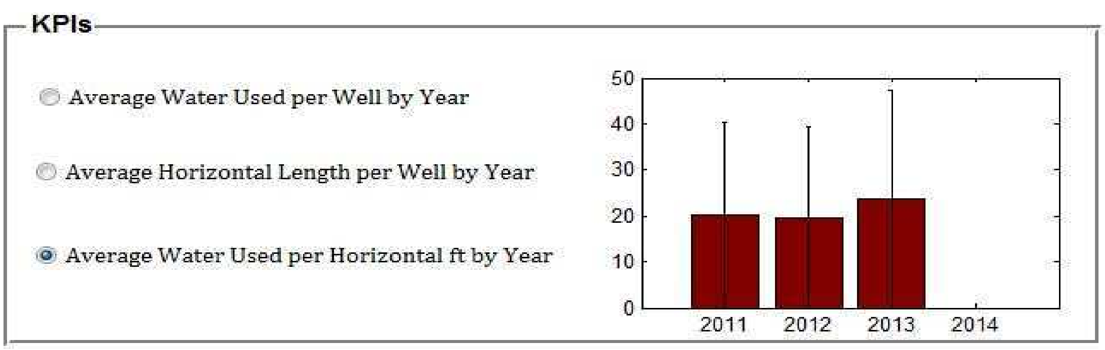

Figure 4-7 Average water used per horizontal foot per year for Texas sample data for 1177 wells. The drilling dates range from 2011 to 2014.

The Water Use Calculator allows the user to visualize water use analysis in a field. Not only this tool helps the user to identify how different parameters are changing in the field, but also it illustrates annual change of those parameters.

4.3 Water Quality Tool in Northern Colorado from 2015 to 2020

The Water Quality Tool is used to predict concentration of Na, Ca, Cl and TDS for the desired development plan field in the Northern Colorado area. The Arp's equation is uploaded by the user and can be obtained from Water Production Modeling Tool. The GUI allows the user to input the development plan as a spreadsheet into the GUI. The spreadsheet is a theoretical development plan based on real data in Northern Colorado. Prediction period starts in January 2015 and ends in January 2020. This model assumes a one year well lifespan and 20 barrels of water per foot of well length. The chemical concentration equations of the Northern Colorado wells are uploaded by user.

The results of running the tool demonstrate that the TDS concentration increases with time and varies between 12,000 to 20,000 mg/liter during the prediction period. (Figure 4-8) Na concentration also increases with time and varies in the range of 4500 to 7500 mg/L. (Figure 4-9) Ca concentration also changes in the range of 75 to 120 mg/L. (Figure 4-10) Cl concentration changes in the range of 7000 to 1100 mg/L. (Figure 4-11) All four chemical concentration plots show that concentration increases with time and after a period of time it decreases to a constant value. However, one of the greatest achievements of using this tool is that the range of chemical concentration change is instantly visualized and user can plan treatment of each contaminant based on the obtained result.

The Water Quality Tool helps the user to predict chemical contaminant as a function of time. It synthesizes different inputs and gives a field level prediction of chemical concentrations that help user to plan for future water quality changes.

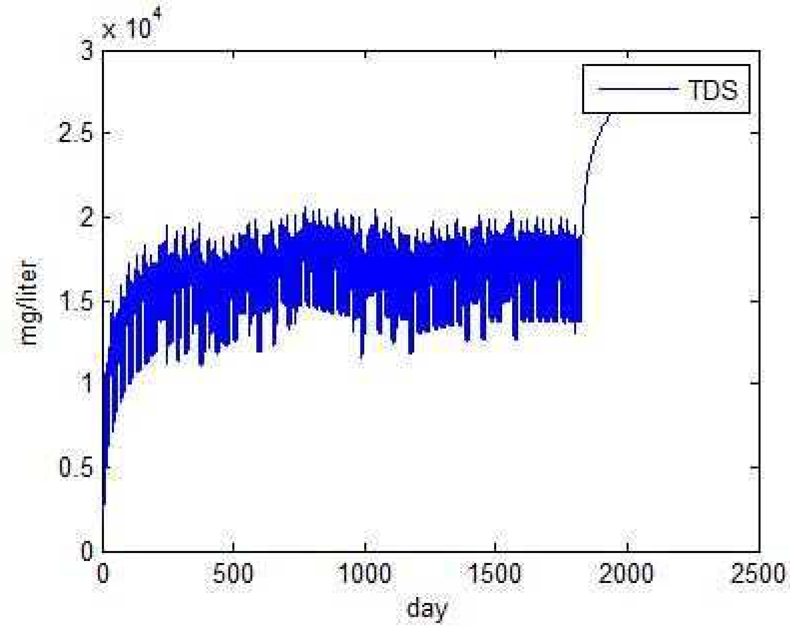

Figure 4-8 TDS concentration prediction (mg/L) in the Wattenberg field in Northern Colorado for 1077 wells. Drilling date from Jan 2015 to Jan 2020.

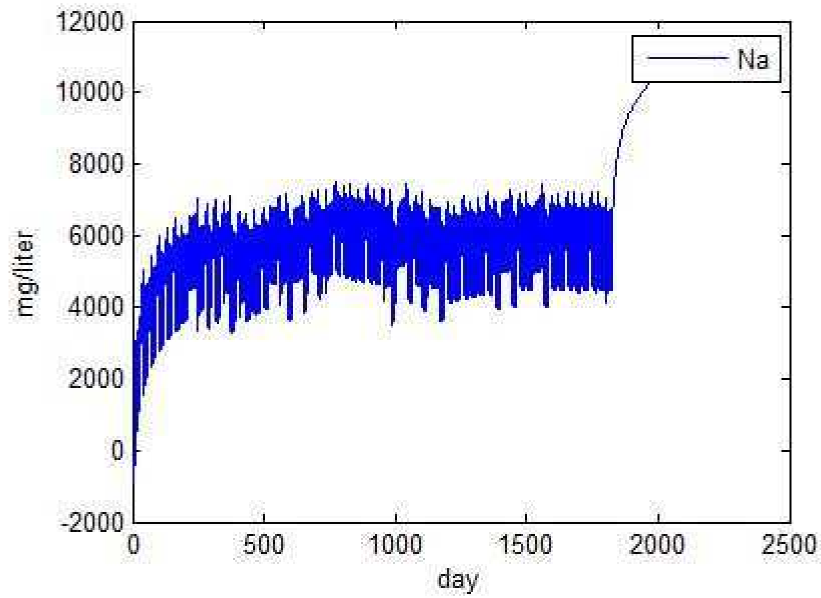

Figure 4-9 Na concentration prediction (mg/L) in the Wattenberg field in Northern Colorado for 1077 wells. The drilling dates range from Jan 2015 to Jan 2020.

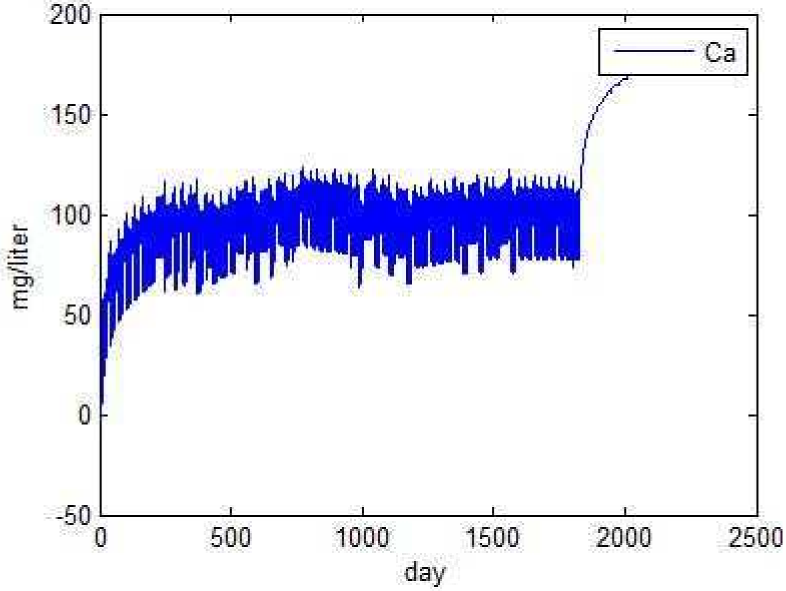

Figure 4-10 Ca concentration prediction (mg/L) in the Wattenberg field in Northern Colorado for 1077 wells. The drilling dates range from Jan 2015 to Jan 2020.

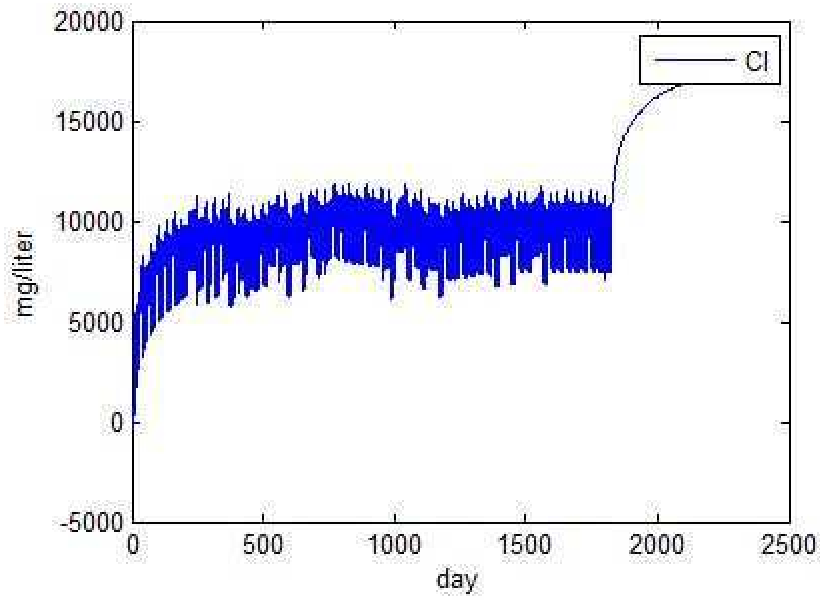

Figure 4-11 Cl concentration prediction (mg/L) in the Wattenberg field in Northern Colorado for 1077 wells. The drilling dates range from Jan 2015 to Jan 2020.

5 Conclusions

Because there are many interdependent variables that determine the methods for water management in an unconventional natural gas field (e.g., facilities location for water collection, water treatment and/or reuse for drilling, water quantity, and water quality), it is important to develop interactive management tools that can assess water data and perform calculations with a user-friendly interface to assist in water management and planning. The objective of this thesis has been to model, quantify, and visualize water information using a flexible software platform that makes the assessment of water data faster for shale oil and gas users in rapidly changing and uncertain oil and gas field. A set of software tools were designed for water management in the development of unconventional natural oil and gas field.

Previous tools have been developed by universities (e.g., Colorado School of Mines) and private companies (e.g., ALL Consulting). One of the tools designed by Colorado School of Mines is referred to CBM (Coalbed Methane) Produced Water Management Tool. ("Produced Water Treatment and Beneficial Use Information Center", n.d.) This tool has an Excel file interface which provides information about produced water characteristics, costs, technology and environmental issues associated with the production of water for beneficial use from coalbed methane produced water. Additionally, researchers at Colorado State University have designed Excel and MATLAB interfaces for fixed/mobile treatment site optimization, water volume prediction, treatment facility siting and water production prediction tool. (Goodwin 2014, Bai et al. 2013, "Center for Energy and Water Sustainability", n.d.). Water Table 5-1 summarizes the benefits and inadequacies of the mentioned above tools and Table 5-2 summarizes the beneficial features of the designed tools in this thesis.

Table 5-1 Current tools benefits and inadequacies

Tool	Benefits of the tool	Inadequacies of the tool
CSM	- Tool Provides produced water quality for coalbed methane sites - Tool provides beneficial use assessments for coalbed methane produced water	Tool is not programmable for customized data
Fixed/Mobile Treatment	Tool optimizes the best location for treatment facility	Tool is limited in number of environmental impacts
Water Volume Prediction	Tool predicts water volume in time based on development plan and water production equation for Northern Colorado	- Tool is not programmable to customize different oil and gas areas - Tool is not programmed for water quality assessments
Treatment Facility Siting	Tool provides trucking costs, disposal cost, road damage, and ruck trips for Northern Colorado	Tool is not customized for different oil and gas fields
Water Production Prediction	Tool predicts future produced water in the field	Tool is not integrated to GIS or decision support analysis for water assessments
Treatment Technology Decision by All Consulting	Tool provides treatment technologies, cost, regulatory considerations	Tool does not provide integrated assessment of water quality and water resources analysis

Table 5-2 Designed tools benefits

Tool	Benefits of the tool
Water Production Modeling Tool	Tool provides water production equation to predict produced water for any field and it is integrated to Water Quality Tool
Water Use Calculator Tool	Tool provides visual water use analysis with statistical calculations in the field level
Water Quality Tool	Tool predicts chemical concentration in the field level for any desired development plan in time

The primary contributions of this thesis are:

- A set of software tools have been developed to provide decision support for the development of water management plans to support oil and gas development.
- The utility of these tools were demonstrated using proprietary and public datasets from a variety of locations in the US. The tools provide value to the user through visualization of data, through synthesis of large datasets, and through prediction of future water quantity and quality characteristics.

As a future work, the tools that were developed herein can be extended in the following ways to be more beneficial for the water management and treatment planning purposes:

1. A new GUI should be developed which has access to all three tools that were developed here. By doing so, the user will have a better accessibility to data through a single major tool.

2. A Water Quality Tool with integrated water treatment methods. Moreover, cost analysis is needed to add to this tool to determine which water treatment method is more efficient and economical.
3. The Water Use Calculator tool should be enhanced by adding suggested water reducing methods.
4. The Water Quality Tool can be extended to cover more chemical components such as Iron.
5. The current tools can be extended to calculate other environmental concerns such as CO_2, NO_2 , and O_3 emissions, landscape, and habitat fragmentation.

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Appendix A: MATLAB codes for Water Production Modeling

A.1

```
[filename,pathname]=uigetfile('*.xlsx;*.xls','Select your file');
handles.Excelfile=fullfile([pathname, filename]);
a=xlsread(handles.Excelfile);
```

A.2

```
q0_str=num2str(p(1));
str=[q0_str,'./((1+Di.*x)).^(1./bi)'];
 f=fit(days,p,str,'StartPoint',[0.01,0.5]);
```

A.3

```
ph1=plot(handles.axes1,days,p);
hold on;
 ph2=plot(handles.axes1,days,f(days),'r');
hold on;
 ph3=plot(handles.axes1,days,p11,'g');
hold on;
```

A.4

```
[r2_whole ,rmse_whole]=rsquare(p,f(days));
```

A.5

```
set(handles.rmse_whole_box,'String',rmse_whole)
```

```
set(handles.r2_whole_box,'String',r2_whole)

set(handles.Di_whole_box,'String',handles.Di_whole)

set(handles.b_whole_box,'String',handles.b_whole)
```

A.6

```
f=handles.f;

Di_whole=handles.Di_whole;

b_whole=handles.b_whole;

q0=handles.q0;

%days=handles.days;

m={'Di_global','b_global','q0';Di_whole,b_whole,q0};

 [filename, pathname] = uiputfile({'*.xls';'*.xlsx*'},'save as to excel');

if isequal([filename,pathname],[0,0])

        return

    else

        % Construct the full path and save

        outname = fullfile(pathname,filename);

        %save(handles.fil,'Di_whole','b_whole','f')

        xlswrite(outname,m);

        guidata(hObject,handles)
```

Appendix B: MATLAB codes for Water Use Calculator

B.1

```
handles.wu_bbls_filter=wu_bbls(handles.logArray);
binranges1=40000:40000:320000;
[bincounts]=histc(handles.wu_bbls_filter,binranges1);
bh1=bar(handles.axes1,binranges1,bincounts,'histc');
set(bh1,'FaceColor',[0 0 0.5]);
```

Calculating mean and standard deviation:

```
handles.mean_wu=nanmean(handles.wu_bbls_filter);
set(handles.bbl_well_box,'String',handles.mean_wu);
handles.STD_bbls_well=std(handles.wu_bbls_filter);
set(handles.STD_bbls_per_well_box,'String',handles.STD_bbls_well);
```

B.2

```
handles.horizontal_filtered=horizontal(handles.logArray);
binranges2=10^.3:1000:8*10.^3;
[bincounts]=histc(handles.horizontal_filtered,binranges2);
bh2=bar(handles.axes2,binranges2,bincounts,'histc');
set(bh2,'FaceColor',[0 0.5 0]);
```

Calculating mean and standard deviation:

```
handles.mean_H=nanmean(handles.horizontal_filtered);
```

```
set(handles.hotizontal_ft_box,'String',handles.mean_H);

handles.STD_horizontal_well=std(handles.horizontal_filtered);

set(handles.STD_horizontal_per_well_box,'String',handles.STD_horizontal_well)
```

B.3

```
handles.bblsft_filter=bblsft(handles.logArray);

binranges3=5:5:40;

[bincounts]=histc(handles.bblsft_filter,binranges3);

bh3=bar(handles.axes3,binranges3,bincounts,'histc');

set(bh3,'FaceColor',[0.5 0 0]);
```

- Calculating mean and standard deviation:

```
handles.mean_H=nanmean(handles.horizontal_filtered);

set(handles.hotizontal_ft_box,'String',handles.mean_H);

handles.STD_horizontal_well=std(handles.horizontal_filtered);

set(handles.STD_horizontal_per_well_box,'String',handles.STD_horizontal_well)
```

B.4

- Defining the years of drilling and converting to numbers:

```
fracture_d =a(:,3);

exdate2matdate = 693960;

fracture_d = fracture_d + exdate2matdate;

DateString= {'01/01/2011';'12/31/2011';'01/01/2012';'12/31/2012';'01/01/2013';

'12/31/201 3';'01/01/2014';'12/31/2014'};
```

```
formatIn='mm/dd/yyyy';

date_num=datenum(DateString,formatIn);
```

- Categorizing values of each year in separate groups:

```
handles.logp1=fracture_d_filter>=date_num(1) & fracture_d_filter<date_num(2);

handles.logp2=fracture_d_filter>=date_num(3) & fracture_d_filter<date_num(4);

handles.logp3=fracture_d_filter>=date_num(5) & fracture_d_filter<date_num(6);

handles.logp4=fracture_d_filter>=date_num(7) & fracture_d_filter<date_num(8);
```

- Average water used and standard deviation calculations:

```
water_2011=handles.wu_bbls_filter(handles.logp1);

water_2012=handles.wu_bbls_filter(handles.logp2);

water_2013=handles.wu_bbls_filter(handles.logp3);

water_2014=handles.wu_bbls_filter(handles.logp4);

 mean_W_2011=mean(water_2011);

std_W_2011=std(water_2011);

mean_W_2012=mean(water_2012);

std_W_2012=std(water_2012);

mean_W_2013=mean(water_2013);

std_W_2013=std(water_2013);

mean_W_2014=mean(water_2014);

std_W_2014=std(water_2014);
```

- Bar graphs of average water use by year and related error bars:

```
x=2011:1:2014;

y=[mean_W_2011,mean_W_2012,mean_W_2013,mean_W_2014];
```

```
e=[std_W_2011,std_W_2012,std_W_2013,std_W_2014];
bh5=bar(handles.axes6,x,y);
set(bh5,'FaceColor',[0 0 0.5]);
hold on;
h=errorbar(handles.axes6,x,y,e,'c'); set(h,'linestyle','none','Color','black')
hold off
guidata(hObject,handles)
```

B.5

```
horizontal_well_2011=handles.horizontal_filtered(handles.logp1);
horizontal_well_2012=handles.horizontal_filtered(handles.logp2);
horizontal_well_2013=handles.horizontal_filtered(handles.logp3);
horizontal_well_2014=handles.horizontal_filtered(handles.logp4);
 mean_feet_2011=mean(horizontal_well_2011);
std_feet_2011=std(horizontal_well_2011);
mean_feet_2012=mean(horizontal_well_2012);
std_feet_2012=std(horizontal_well_2012);
mean_feet_2013=mean(horizontal_well_2013);
std_feet_2013=std(horizontal_well_2013);
mean_feet_2014=mean(horizontal_well_2014);
std_feet_2014=std(horizontal_well_2014);
 x=2011:1:2014;
y=[mean_feet_2011,mean_feet_2012,mean_feet_2013,mean_feet_2014];
```

```
e= [std_feet_2011,std_feet_2012,std_feet_2013,std_feet_2014];
bh6=bar(handles.axes6,x,y);
set(bh6,'FaceColor',[0 0.5 0]);
hold on;
h=errorbar(handles.axes6,x,y,e,'c'); set(h,'linestyle','none','Color','black')
hold off
guidata(hObject,handles)
```

B.6

```
a=xlsread(handles.filename);
 fracture_d =a(:,3);
exdate2matdate = 693960;
fracture_d = fracture_d + exdate2matdate;
 DateString={'01/01/2011';'12/31/2011';'01/01/2012';'12/31/2012';'01/01/2013';
'12/31/2013';'01/01/2014';'12/31/2014'};
formatIn='mm/dd/yyyy';
date_num=datenum(DateString,formatIn);
fracture_d_filter=fracture_d(handles.logArray);
 handles.logp1=fracture_d_filter>=date_num(1) & fracture_d_filter<date_num(2);
handles.logp2=fracture_d_filter>=date_num(3) & fracture_d_filter<date_num(4);
handles.logp3=fracture_d_filter>=date_num(5) & fracture_d_filter<date_num(6);
handles.logp4=fracture_d_filter>=date_num(7) & fracture_d_filter<date_num(8);
bbls_feet_2011=handles.bblsft_filter(handles.logp1);
```

```
bbls_feet_2012=handles.bblsft_filter(handles.logp2);
bbls_feet_2013=handles.bblsft_filter(handles.logp3);
bbls_feet_2014=handles.bblsft_filter(handles.logp4);
 mean_bbls_feet_2011=mean(bbls_feet_2011);
std_bbls_feet_2011=mean(bbls_feet_2011);
mean_bbls_feet_2012=mean(bbls_feet_2012);
std_bbls_feet_2012=mean(bbls_feet_2012);
mean_bbls_feet_2013=mean(bbls_feet_2013);
std_bbls_feet_2013=mean(bbls_feet_2013);
mean_bbls_feet_2014=mean(bbls_feet_2014);
std_bbls_feet_2014=mean(bbls_feet_2014);
 x=2011:1:2014;
y=[mean_bbls_feet_2011,mean_bbls_feet_2012,mean_bbls_feet_2013,
mean_bbls_feet_2014];
e=[std_bbls_feet_2011,std_bbls_feet_2012,std_bbls_feet_2013,std_bbls_feet_2014];
bh7=bar(handles.axes6,x,y);
set(bh7,'FaceColor',[0.5 0 0]);
hold on;
h=errorbar(handles.axes6,x,y,e,'c'); set(h,'linestyle','none','Color','black')
hold off
guidata(hObject,handles)
```

Appendix C: MATLAB codes for Water Quality

C.1

```
[filename,pathname]=uigetfile('*.xlsx;*.xls','Select your file');

handles.filename=fullfile([pathname, filename]);

a=xlsread(handles.filename);

handles.Di_whole=a(1,1);

handles.b_whole=a(1,2);

handles.q0=a(1,3);

set(handles.Di_global,'String',handles.Di_whole);

set(handles.b_global,'String',handles.b_whole);

set(handles.q0_global,'String',handles.q0);

guidata(hObject,handles)
```

C.2

```
a_TDS=str2num(get(handles.TDS_a,'String'));

b_TDS=str2num(get(handles.TDS_b,'String'));

a_Na=str2num(get(handles.Na_a,'String'));

b_Na=str2num(get(handles.Na_b,'String'));

a_Ca=str2num(get(handles.Ca_a,'String'));

b_Ca=str2num(get(handles.Ca_b,'String'));

a_Cl=str2num(get(handles.Cl_a,'String'));

b_Cl=str2num(get(handles.Cl_b,'String'));
```

C.3

```
start_month=get(handles.StartMonth,'Value');

start_year=get(handles.StartYear,'Value');

end_month=get(handles.EndMonth,'Value');

end_year=get(handles.EndYear,'Value');

 S=12*(start_year-1)+start_month; % month started

E=(23-end_year)*12+end_month-1;   % month finished

s=datenum([start_year+2012,start_month, 1]);   % date start

e=datenum([23-end_year+2013,end_month, 1]);     % date finished
```

C.4

```
for i=1:length(dp)

   month=[];

   NLL=dp(i,1);

   ERL=dp(i,2);

   TOT=NLL+ERL;

   ms=datenum([start_year+2012,start_month+i-1, 1]);

   me=datenum([start_year+2012,start_month+i, 1]);

   month=zeros(1,me-ms);

   rem_ERL=rem(Dev*ERL,me-ms);

   rem_NLL=rem(Dev*NLL,me-ms);

   rig_ERL=ceil(Dev*ERL/(me-ms));

   rig_NLL=ceil(Dev*NLL/(me-ms));
```

```
    rig_TOT=ceil(Dev*TOT/(me-ms));
    for j=1:floor((me-ms)/Dev)
        month(j*Dev)=1*rig_TOT;
    end
    sm=sum(month);
    month(Dev)=month(Dev)+TOT-sm;
    eERL=ERL*.5;
    for j=1:(me-ms)
        if month(j)~=0
            if eERL>month(j)*LRatio
                initial=month(j);
                month(j)=month(j)+LRatio*month(j);
                eERL=eERL-initial*LRatio;
            elseif eERL>0
                initial=month(j);
                month(j)=month(j)+eERL;
                eERL=eERL-initial*LRatio;
            end
        end
    end
    wellcount=cat(2,wellcount,month);
end
 waterfoot=str2num(get(handles.wfoot,'String'));
```

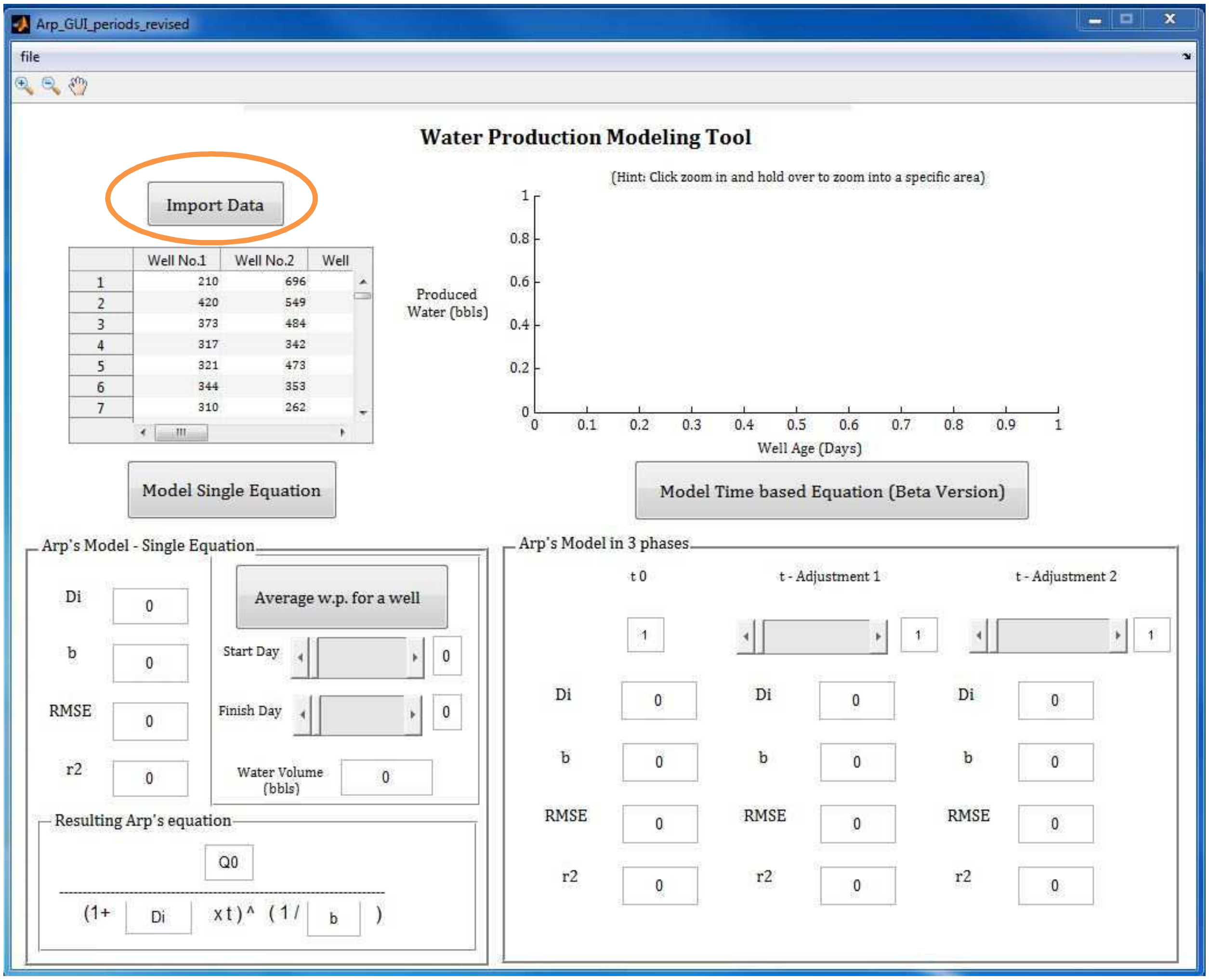
```
handles.Freshwater=wellcount*waterfoot*NLLlength;
 t=e-s;
length(handles.Freshwater);
%t=datevec(s:e)
 for i=1:(e-s)
    td(i)=datenum([start_year+2012,start_month, i]);
end
 tdv=datevec(td);
tyear=tdv(:,1);
 if E>85
    E=85;
end
 lifespan=str2num(get(handles.lifespan,'String'));
 a_TDS=str2num(get(handles.TDS_a,'String'));
b_TDS=str2num(get(handles.TDS_b,'String'));
a_Na=str2num(get(handles.Na_a,'String'));
b_Na=str2num(get(handles.Na_b,'String'));
a_Ca=str2num(get(handles.Ca_a,'String'));
b_Ca=str2num(get(handles.Ca_b,'String'));
a_Cl=str2num(get(handles.Cl_a,'String'));
b_Cl=str2num(get(handles.Cl_b,'String'));
  k=1;
 for i=1:length(wellcount)
```

```
    if wellcount(i)~=0
     k=k+1;
         for j=1:lifespan*365
             Flow(i+j-1,k-1)=wellcount(i)*handles.q0/
             ((1+handles.Di_whole*j)^(1/handles.b_whole))*159;
             TDS(i+j-1,k-1)=(a_TDS.*log(j)+b_TDS);
             Ca(i+j-1,k-1)=(a_Ca.*log(j)-b_Ca);
             Na(i+j-1,k-1)=(a_Na.*log(j)-b_Na);
             Cl(i+j-1,k-1)=(a_Cl.*log(j)-b_Cl);
             mass_TDS(i+j-1,k-1)=TDS(i+j-1,k-1)*Flow(i+j-1,k-1);
             mass_Ca(i+j-1,k-1)=Ca(i+j-1,k-1)*Flow(i+j-1,k-1);
             mass_Na(i+j-1,k-1)=Na(i+j-1,k-1)*Flow(i+j-1,k-1);
             mass_Cl(i+j-1,k-1)=Cl(i+j-1,k-1)*Flow(i+j-1,k-1);
      end
     end
end
sum_flow=sum(Flow,2);
xl=size(sum_flow);
handles.days=(1:xl);
sum_mass_TDS=sum(mass_TDS,2);
sum_mass_Ca=sum(mass_Ca,2);
sum_mass_Na=sum(mass_Na,2);
sum_mass_Cl=sum(mass_Cl,2);
```

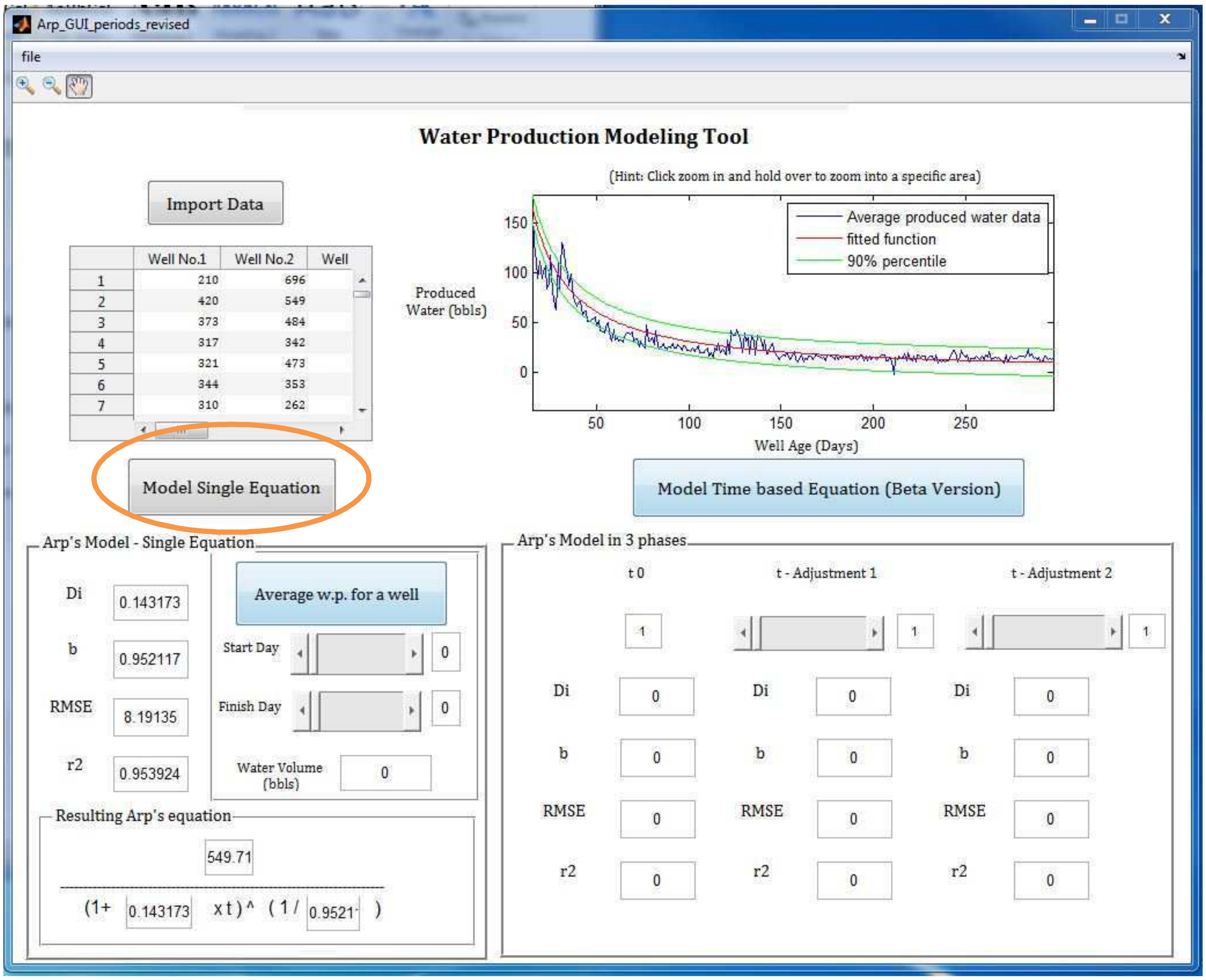
```
handles.conc_TDS=sum_mass_TDS./sum_flow;

handles.conc_Ca=sum_mass_Ca./sum_flow;

handles.conc_Na=sum_mass_Na./sum_flow;

handles.conc_Cl=sum_mass_Cl./sum_flow;

 handles.Flow=Flow;

handles.sum_flow=sum_flow;
```

Appendix D: Water Production Modeling Manual

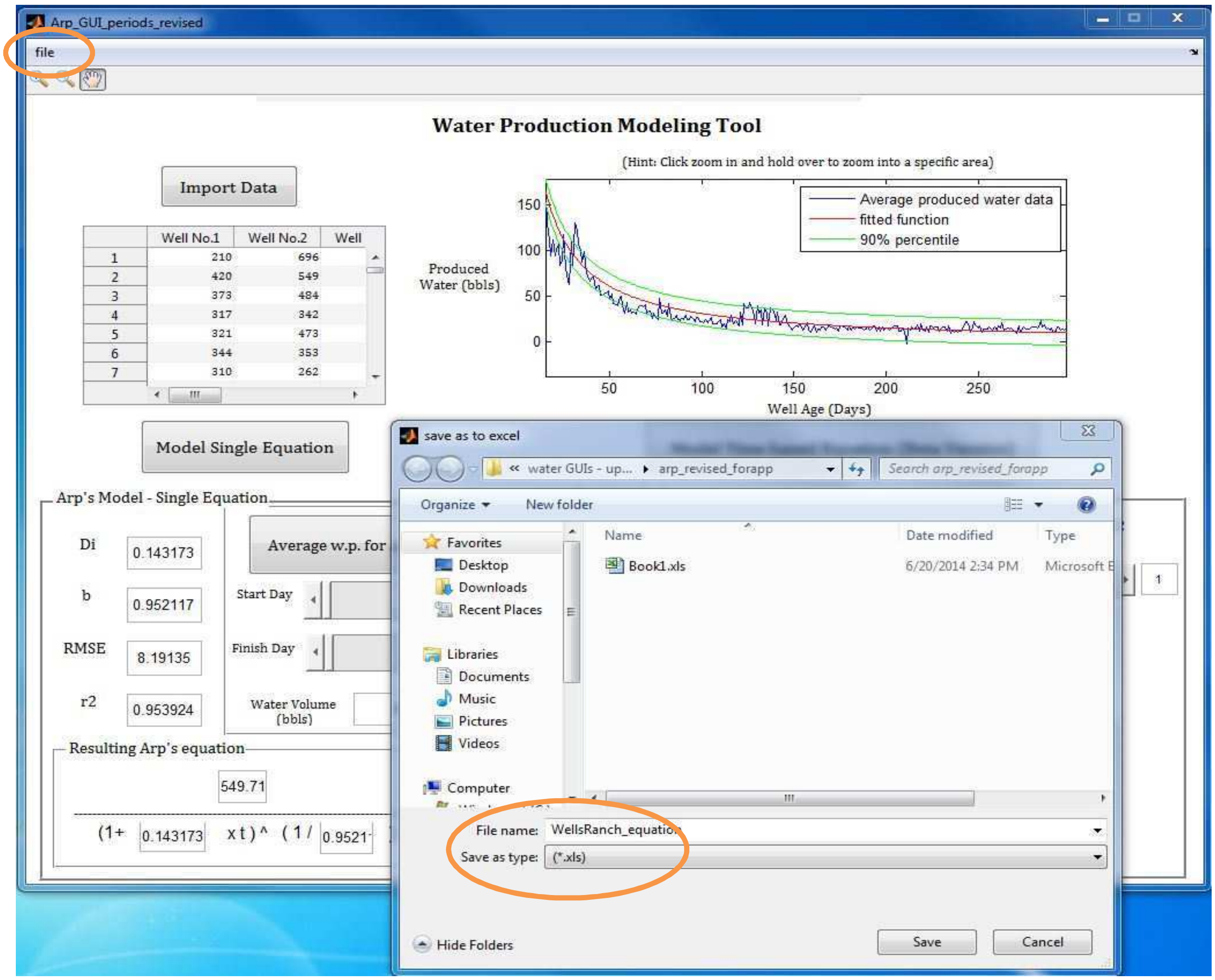
1) Click on the Import Data button to upload daily water production for desired development plan



2) Click on Model Single Equation to calculate Arp's equation

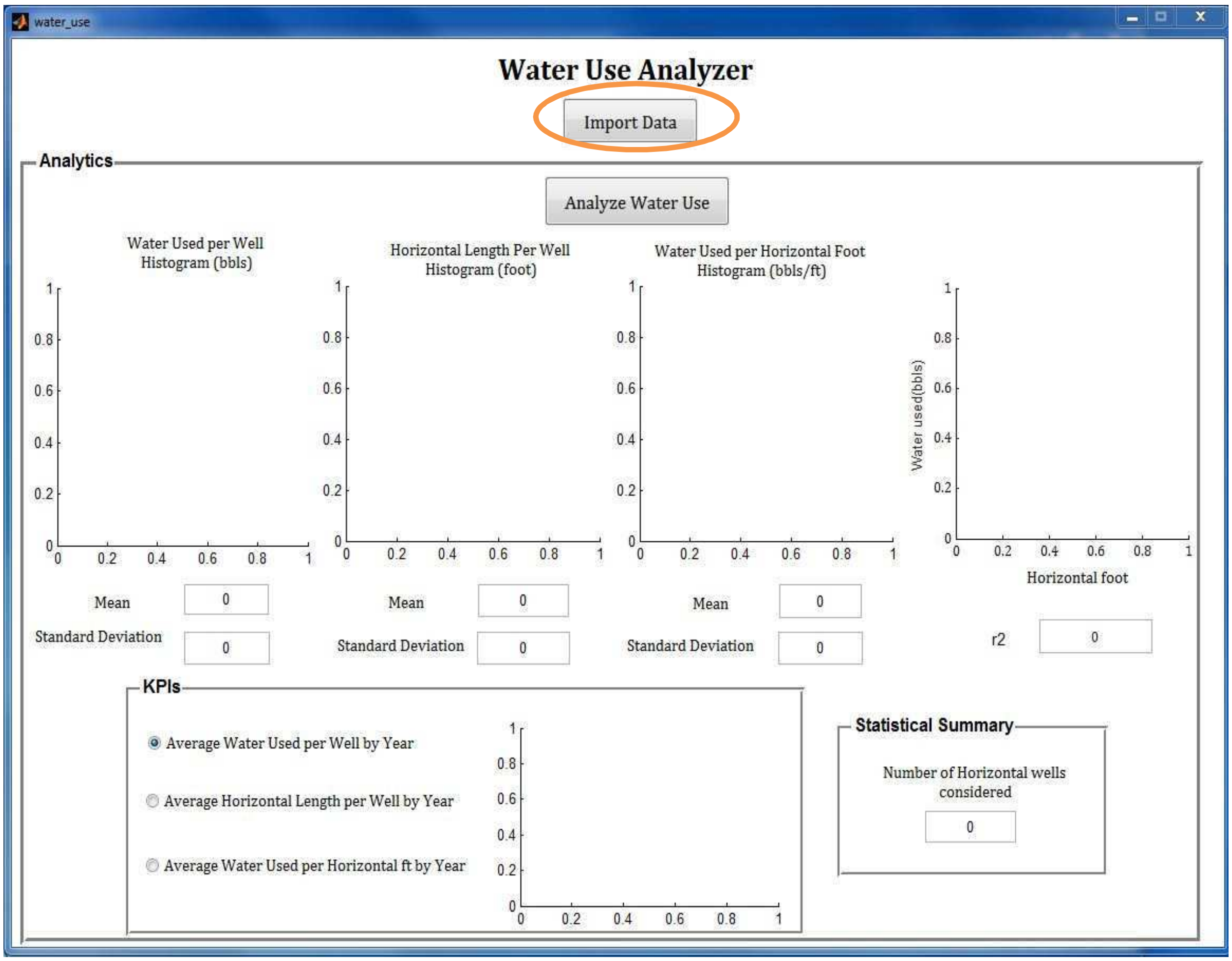


3) Click on file on the top left corner, and then click on Save as Excel to save the calculated Arp's equation result.

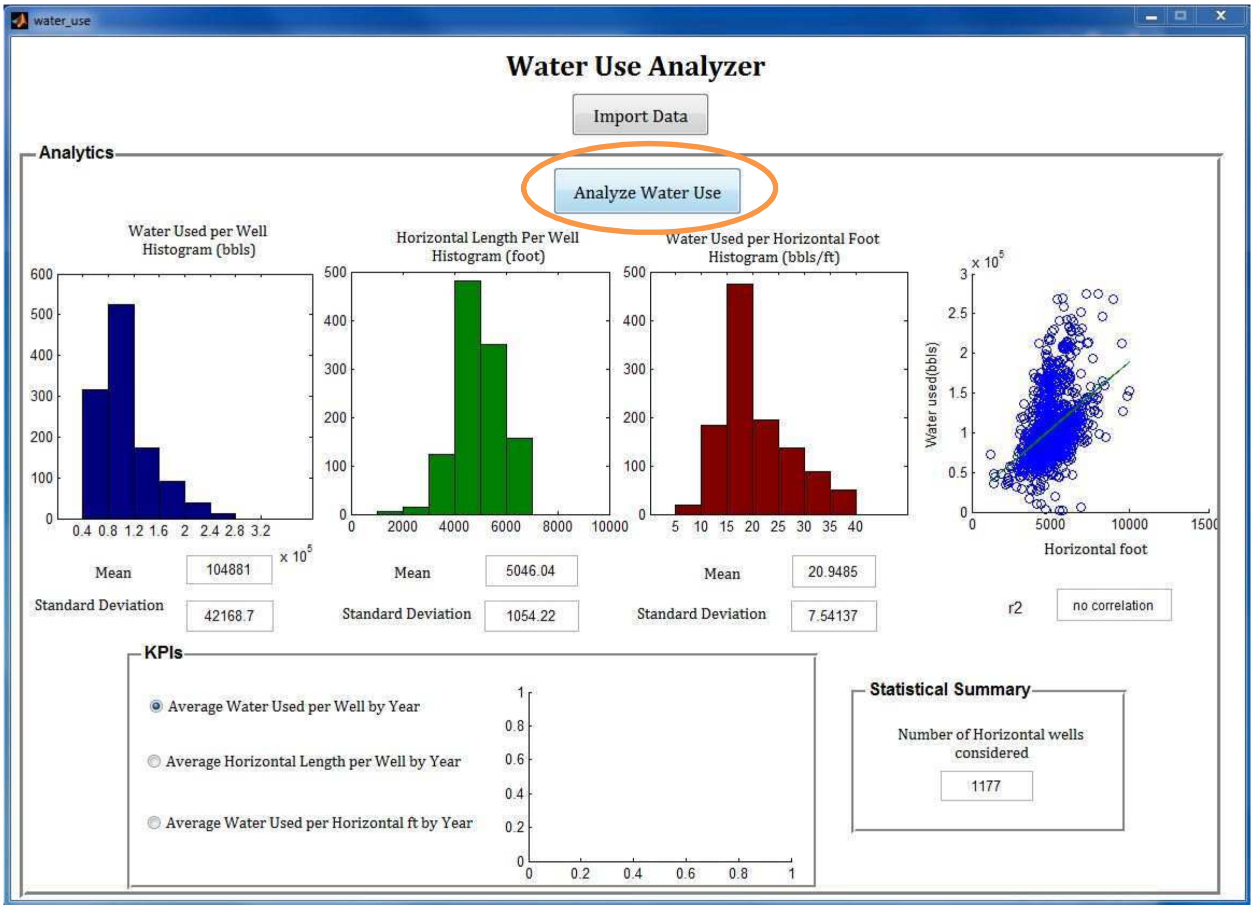


Appendix E: Water Use Calculator Manual

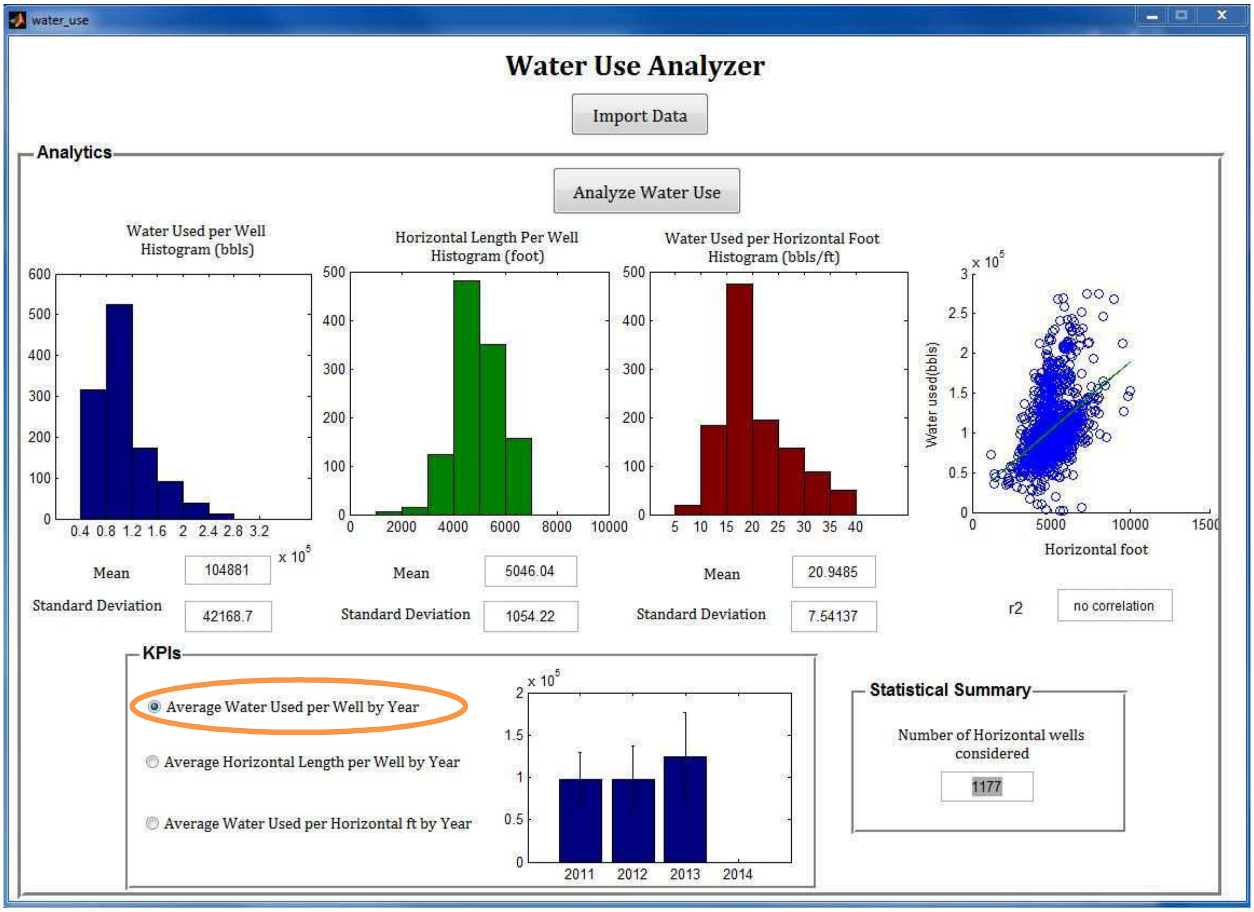
1) Click on Import Data button to upload water used data of your desired development plan



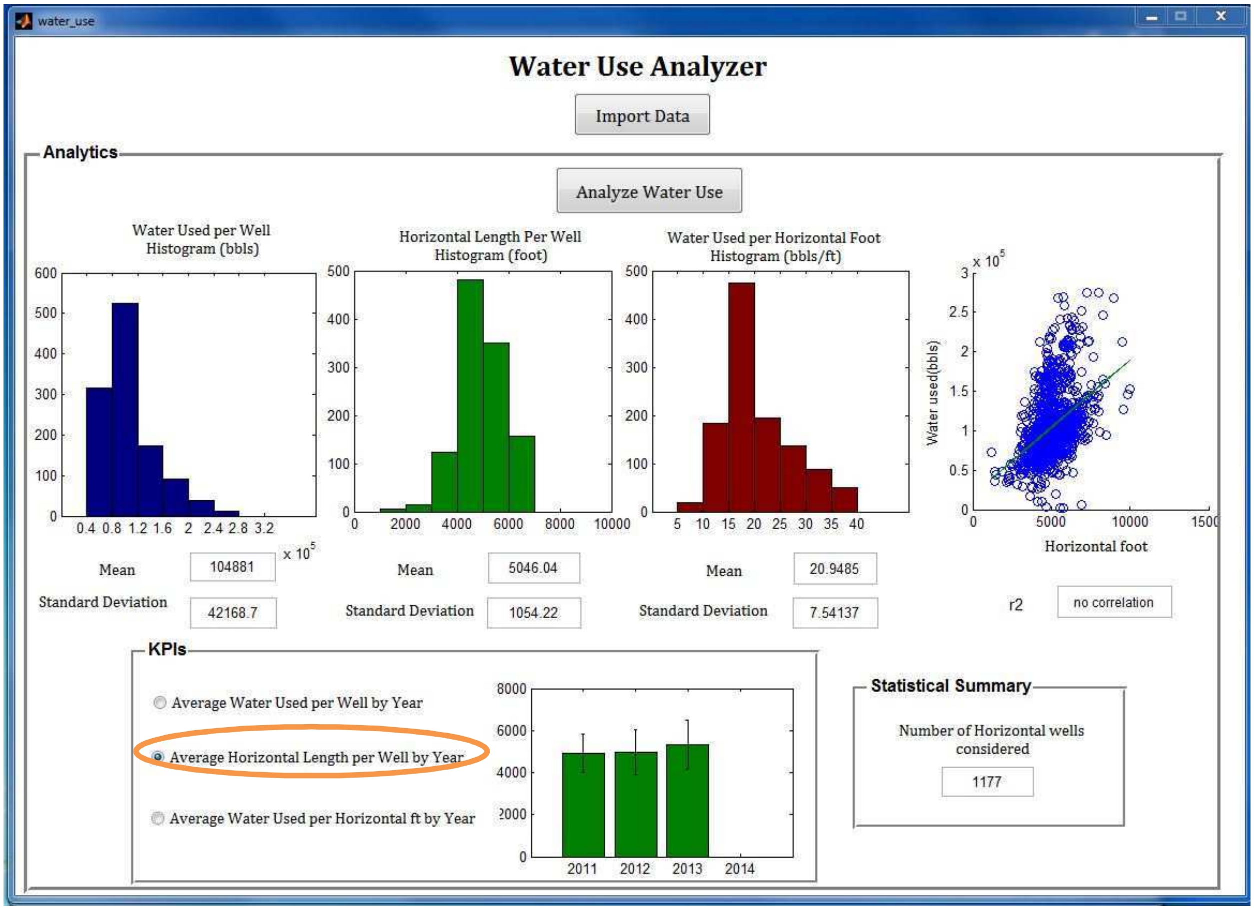
2) Click on Analyze Water Use to calculate the water used per well histogram, horizontal length per well histogram, water used per horizontal foot histogram, water used vs. horizontal foot and number of horizontal wells considered



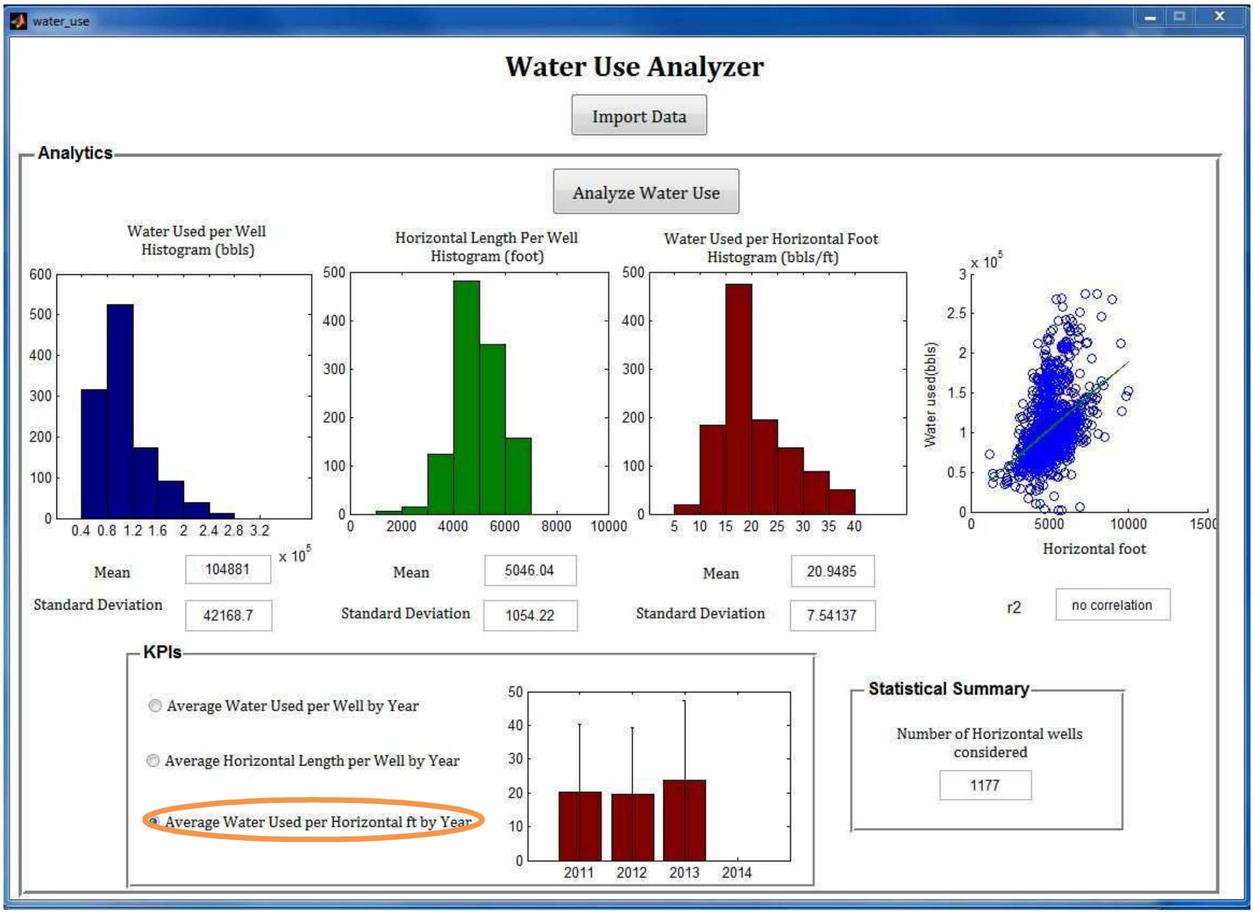
3) Click on Average Water Used per Well by year



4) Click on Average Horizontal Length per Well by Year

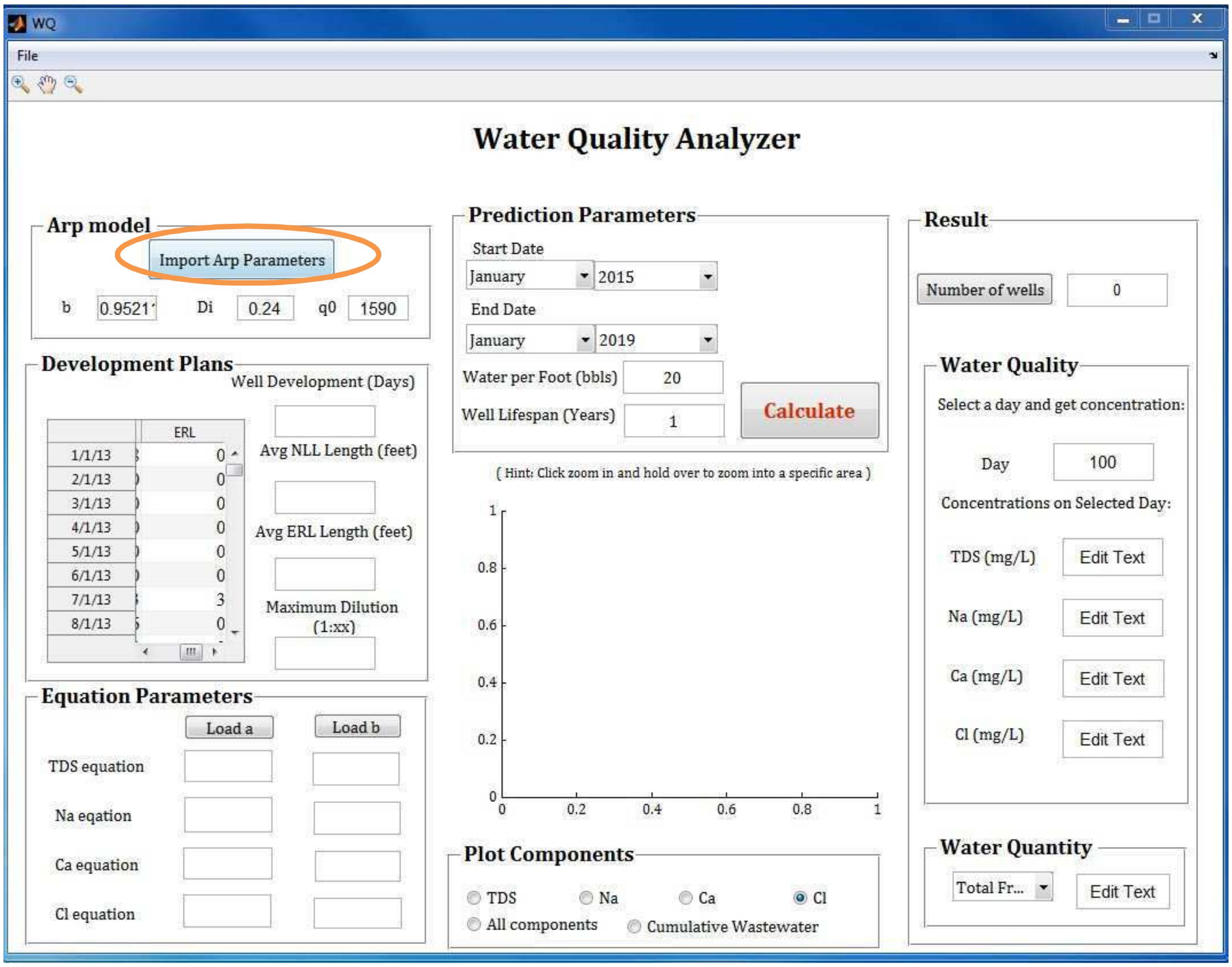


5) Click on Average Water Used per Horizontal foot by Year

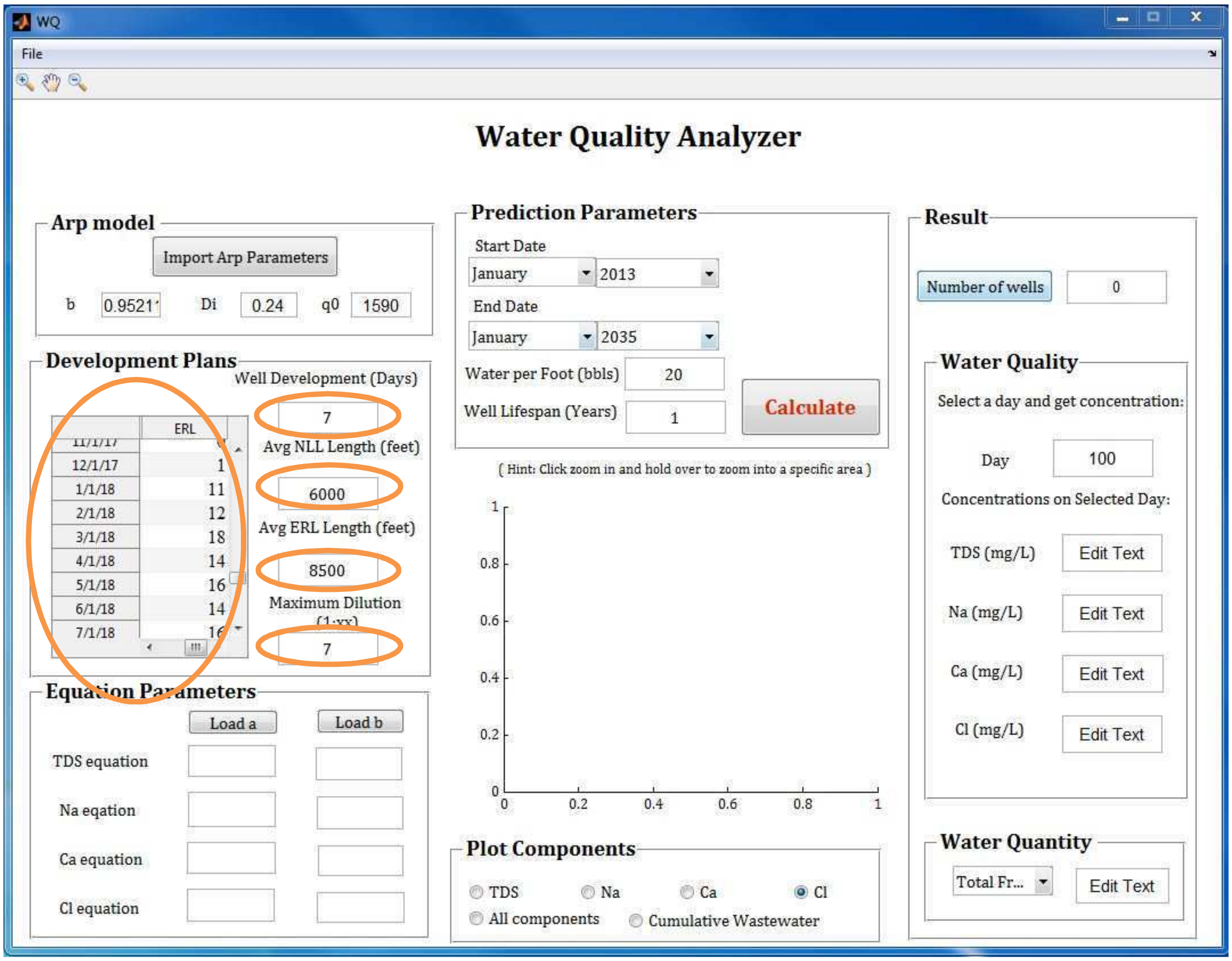


Appendix F: Water Quality Manual

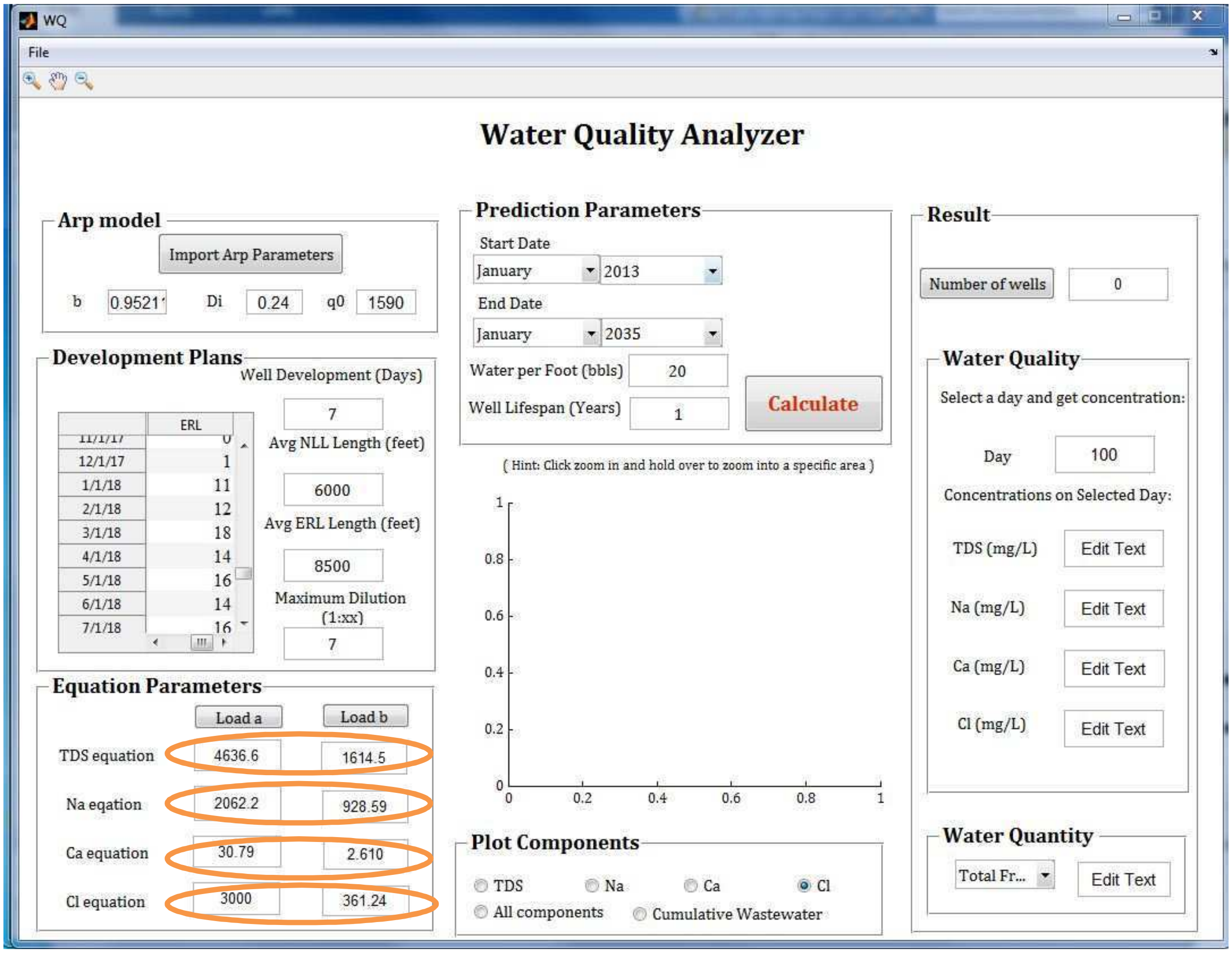
1) Click on Import Arp Parameters



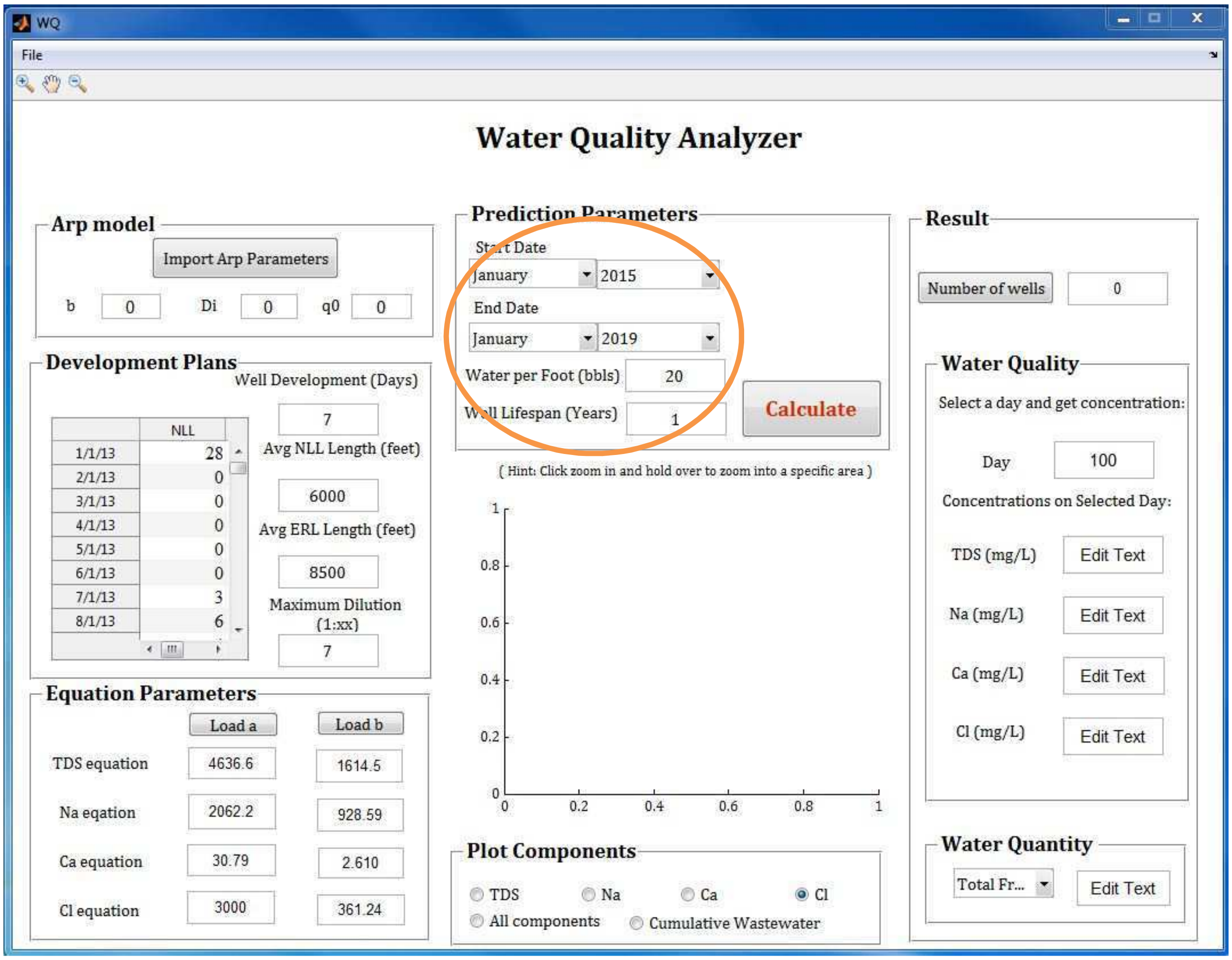
2) Enter development plan data in the spreadsheet in development plan Panel, input Wells Development (Days), Avg NLL Length (feet), Avg ERL Length (feet) and Maximum Dilution



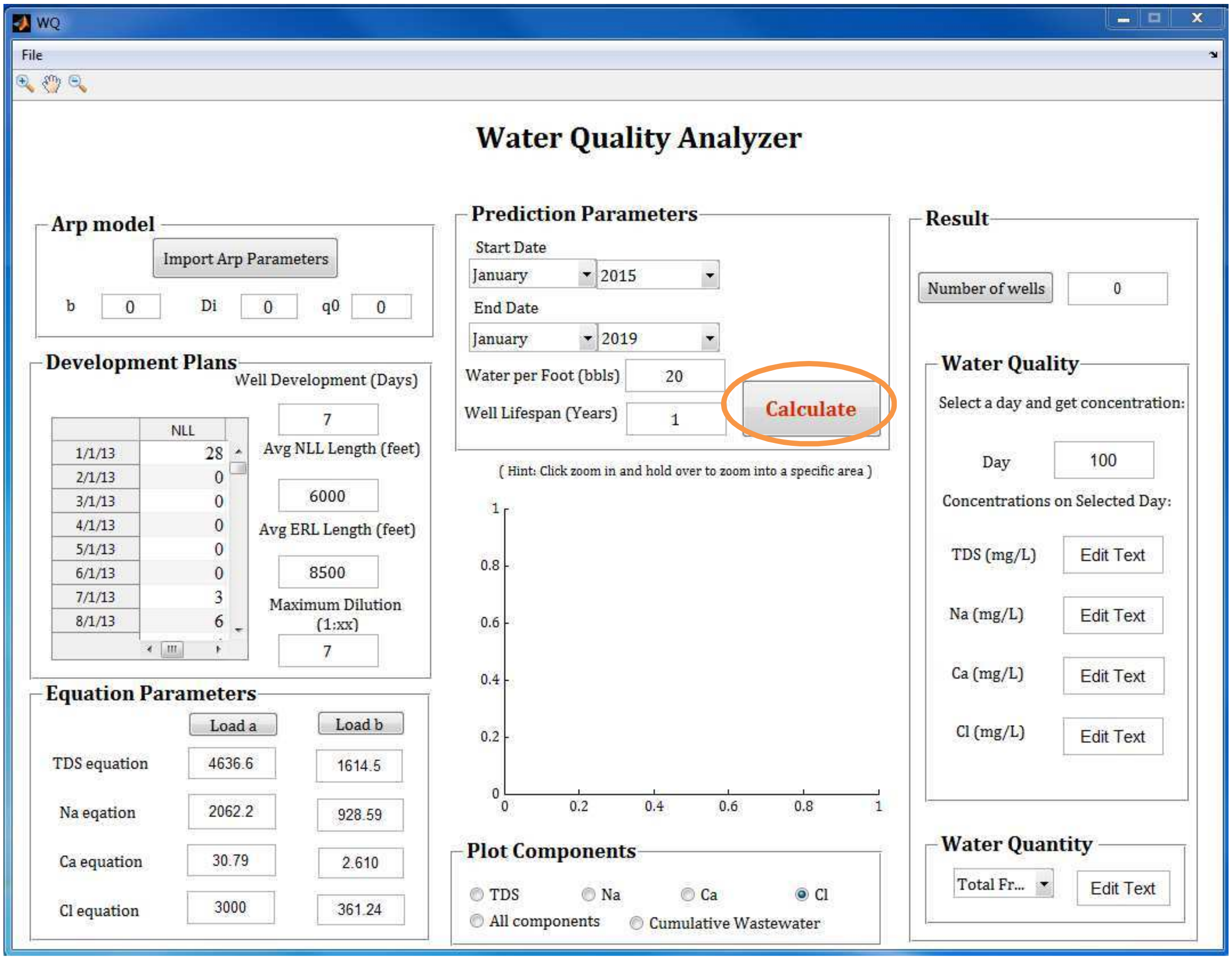
3) Enter Equation Parameters for TDS, Na, Ca, Cl



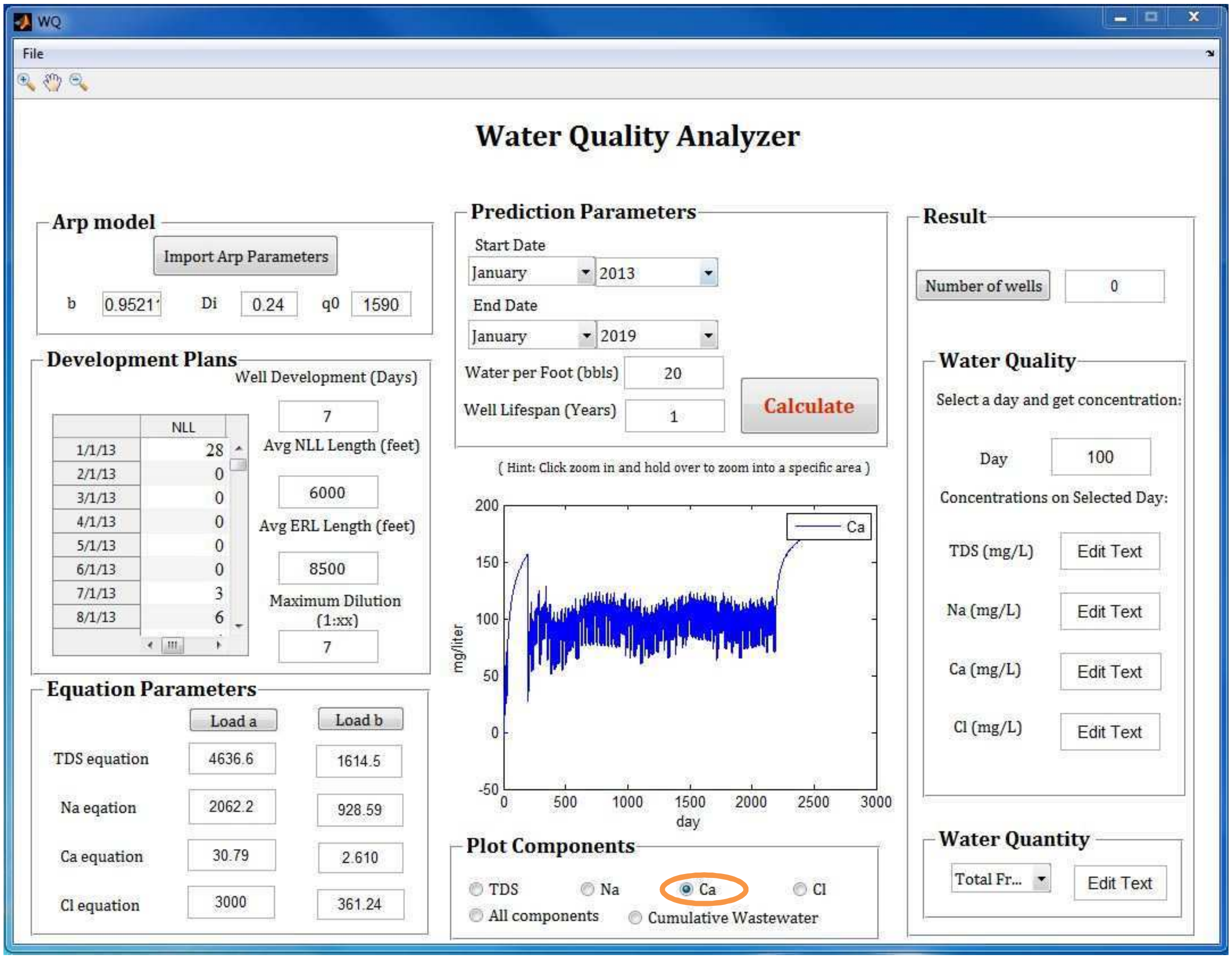
4) Input Prediction Parameters, including Start Date, End Date, Water per Foot, Well Lifespan



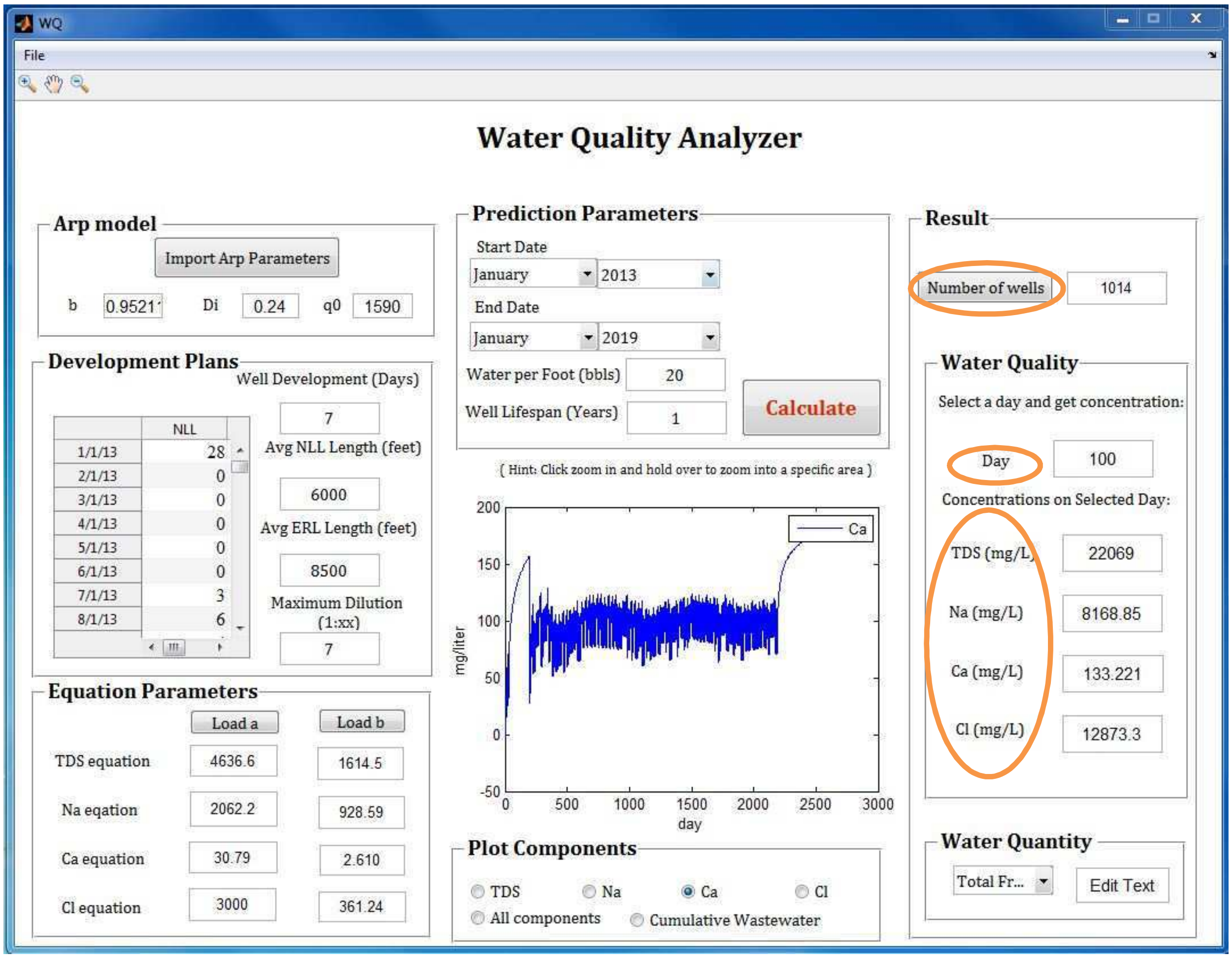
5) Click Calculate



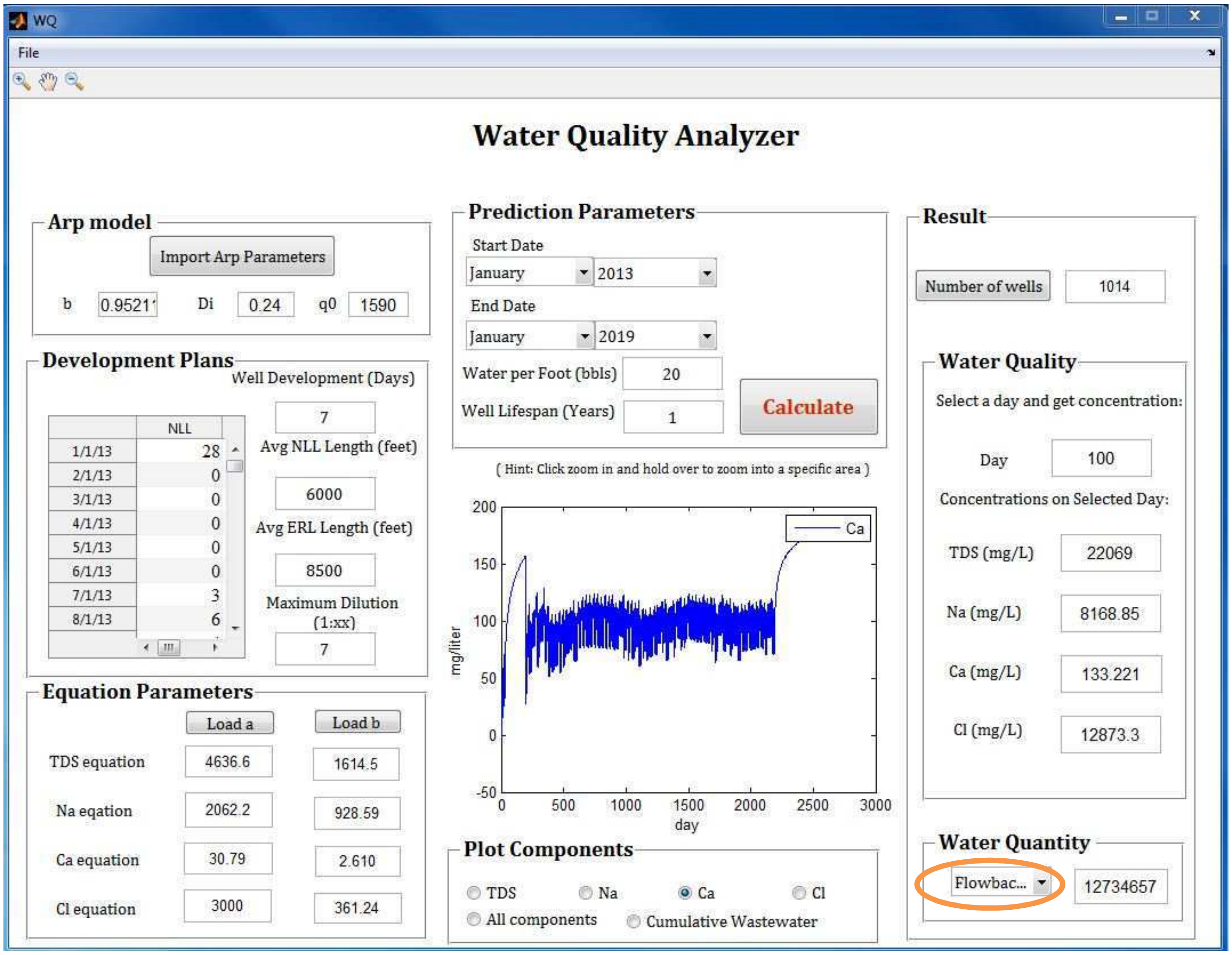
6) Select desired chemical component to be displayed in the plotting panel



7) Click on the Number of wells button, to obtain number of wells considered for that model running. In Water Quality panel, select a day and obtain the all chemical concentrations



8) Click on the pop up menu to calculate water quantity



9) Click on the file, then save to Excel button, to save the result