

THESIS

GIS BASED LOCATION OPTIMIZATION FOR MOBILE PRODUCED WATER
TREATMENT FACILITIES IN SHALE GAS OPERATIONS

Submitted by

Amol Hanmant Kitwadkar

Department of Civil & Environmental Engineering

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Spring 2014

Master's Committee:

Adviser: Kenneth H. Carlson

Kimberly Catton

Thomas Bradley

Copyright by Amol Hanmant Kitwadkar 2014

All Rights Reserved

ABSTRACT

GIS BASED LOCATION OPTIMIZATION FOR MOBILE PRODUCED WATER TREATMENT FACILITIES IN SHALE GAS OPERATIONS

Over 60% of the nation's total energy is supplied by oil and natural gas together and this demand for energy will continue to grow in the future (Radler et al. 2012). The growing demand is pushing the exploration and exploitation of onshore oil and natural gas reservoirs. Hydraulic fracturing has proven to not only create jobs and achieve economic growth, but also has proven to exert a lot of stress on natural resources—such as water. As water is one of the most important factors in the world of hydraulic fracturing, proper fluids management during the development of a field of operation is perhaps the key element to address a lot of these issues. Almost 30% of the water used during hydraulic fracturing comes out of the well in the form of flowback water during the first month after the well is fractured (Bai et. al. 2012). Handling this large amount of water coming out of the newly fractured wells is one of the major issues as the volume of the water after this period drops off and remains constant for a long time (Bai et. al. 2012) and permanent facilities can be constructed to take care of the water over a longer period. This paper illustrates development of a GIS based tool for optimizing the location of a mobile produced water treatment facility while development is still occurring.

A methodology was developed based on a multi criteria decision analysis (MCDA) to optimize the location of the mobile treatment facilities. The criteria for MCDA include well density, ease of access (from roads considering truck hauls) and piping minimization if piping is

used and water volume produced. The area of study is 72 square miles east of Greeley, CO in the Wattenberg Field in northeastern Colorado that will be developed for oil and gas production starting in the year 2014. A quarterly analysis is done so that we can observe the effect of future development plans and current circumstances on the location as we move from quarter to quarter. This will help the operators to make long-term decisions and also they can make decisions about the well pad siting and well densities. Three different scenarios—baseline, retroactive and proactive—were considered to see what could be the proper way to answer the question of optimal fluids management (OFM). Once the locations were obtained the results from different scenarios were compared for piping distances from each well going towards the facility, assuming the pipeline distance as the criteria to be minimized. The results obtained were pretty robust and observed to be fulfilling the intended purpose.

TABLE OF CONTENTS

ABSTRACT.....	ii
LIST OF TABLES	vi
LIST OF FIGURES	vii
CHAPTER 1: INTRODUCTION.....	1
CHAPTER 2: LITERATURE REVIEW	4
2.1. Area of Study	4
2.2. Water Usage.....	6
2.3. Produced Water and Flowback Volumes.....	6
2.4. Sources of Water Production	6
2.4.1. Frac-Flowback Water.....	7
2.4.2. Produced Water.....	7
2.5. Current Practices of Produced Water Management.....	7
2.5.1 Deep Well Injection	7
2.5.2. Evaporation in Pits and Ponds	8
2.5.3. Disposal to Publically Owned Treatment Works (POTWs).....	9
2.5.4. Direct Reuse for Fracturing	9
2.5.5. Treatment for Reuse or Surface Discharge.....	10
2.6. Environmental Impacts Associated with Hydraulic Fracturing.....	11
2.7. Geographic Information Systems (GIS)	15
2.8. Water Production Prediction.....	15
2.9. Potential MCDA Methods for the Analysis.....	18
2.10. Research Objectives.....	19

CHAPTER 3: GIS BASED LOCATION OPTIMIZATION TOOL FOR MOBILE PRODUCED WATER TREATMENT FACILITIES IN SHALE GAS OPERATIONS.....	20
3.1. Summary	20
3.2. Introduction.....	21
3.3. Methods.....	23
3.3.1. Studying the Development Plans	23
3.3.2. Preparation of the Basemap	24
3.3.3. Preparation of Shapefiles for Each Quarter	25
3.3.4. The Water Production Prediction Tool.....	26
3.3.5. Work Flow of the Model.....	27
3.4. Results and Discussion	34
3.5. Conclusions.....	42
3.6. Future Work.....	42
REFERENCES	44
A. APPENDICES	47
A1. Documentation of steps in ArcMap 10.1.	47
A2. The Fuzzication Process.....	87

LIST OF TABLES

Table 1: The simpler table of development plans	24
Table 2: The additional attributes of a shapefile and their types	25
Table 3: Pattern of reclassifying all the rasters after using Fuzzy Membership Tool	31
Table 4: Types of MCDAs.....	33

LIST OF FIGURES

Figure 1. Shale gas development in the state of Colorado.....	4
Figure 2. A map of the Wattenberg Field that indicates oil and gas wells	5
Figure 3. The extended parts of Wattenberg Field, along with the northeastern end of Wattenberg Field at the lower left hand corner of the map	5
Figure 4. A typical class II injection well	9
Figure 5. A typical treatment process of produced water for reuse as fracturing fluid	10
Figure 6. A typical produced water treatment train for surface discharge or agricultural reuse ..	11
Figure 7. Environmental issues associated with hydraulic fracturing	12
Figure 8. Decline curves from different ‘b’ values in Arps equation	16
Figure 9. ‘k1’ and ‘a’ of horizontal oil and gas wells in the Wattenberg field (Bai et al. 2012)..	18
Figure 10. The flowchart of the location optimization model	28
Figure 11. The area of study and the included DPs and their locations (Noble Energy Inc.)	34
Figure 12. The most significant to least significant optimal locations for a mobile treatment facility for the fourth quarter of 2013	36
Figure 13: The most significant to least significant optimal locations for a mobile treatment facility for the first quarter of the year 2014.....	37
Figure 14. Pipeline distances for the wells up until the fourth quarter of 2013 from the optimal facility locations obtained for analysis done for fourth quarter of 2013.....	38
Figure 15. Pipeline distances for the wells up till first quarter of 2014 from the optimal facility locations obtained for analysis done for fourth quarter of 2013	38
Figure 16: A map showing largest to smallest total pipeline distances for the most significant locations for all the four analyses for the fourth quarter of year 2013	40
Figure 17: A map showing largest to smallest total pipeline distances for the most significant locations for all the four analyses for the first quarter of year 2014.....	41
Figure 18. Screenshot of the ArcMap getting to start window	47

Figure 19. Screenshot of blank map document with other options available in toolbars present at the top.....	48
Figure 20. Screenshot of the dropdown menu for more toolbar options	49
Figure 21. Screenshot showing the location of the ArcGIS online menu.....	50
Figure 22. Screenshot showing all the maps available for use on ArcGIS online along with the PLSS map.....	51
Figure 23. Screenshot showing the display of the PLSS map and the geo-referencing toolbar ...	52
Figure 24. Screenshot showing the “Add Control Points” button and the geo-referencing points just beneath the geo-referencing toolbar.....	53
Figure 25. Screenshot showing the geo-referenced development plan image with the PLSS map ready for further analysis	54
Figure 26. Screenshot showing the dropdown menu of all the available toolbars	55
Figure 27. Screenshot showing the path to create a shapefile through ArcCatalog	56
Figure 28. Screenshot of the Create New Shapefile window	57
Figure 29. Screenshot showing the Editor Toolbar	58
Figure 30. Screenshot showing start editing window	59
Figure 31. Screenshot of Create Features window under an edit session.....	60
Figure 32. Screenshot showing the roads shapefile drawn on top of the boundary shapefile with create features window pinned to the right side.....	62
Figure 33. Screenshot showing drawn boundaries of development plan 11 using editor toolbar	63
Figure 34. Screenshot showing the location of Create Random Points toolbox in the Arc Toolbox	64
Figure 35. Screenshot showing the details of the Create Random Points tool	65
Figure 36. Screenshot showing the Environment Settings of the Create Random Points tool.....	66
Figure 37. Screenshot showing the points created after the Create Random Points tool	67
Figure 38. Screenshot showing the Add Field option in the Table Options of the Attribute Table of the wells shapefile	68
Figure 39. Screenshot showing the contents of the Add Field window.....	69

Figure 40. Screenshot showing the location of Add-In Manager in the menu bar	70
Figure 41. Screenshot showing the Add-In Manager window	71
Figure 42. Screenshot showing the GUI of the water prediction tool	73
Figure 43. Screenshot showing the location of the Feature to Raster tool in the Arc Toolbox	74
Figure 44. Screenshot showing the contents of the Feature to Raster tool window	75
Figure 45. Screenshot showing the Raster Analysis tab in the Environment Settings of the Feature to Raster tool	76
Figure 46. Screenshot showing the location of the Near Tool in Arc Toolbox	77
Figure 47. Screenshot showing the contents of the Near Tool window	78
Figure 48. Screenshot showing the location of the Kernel Density Tool in the Arc Toolbox.....	79
Figure 49. Screenshot showing the contents of the Kernel Density tool window	80
Figure 50. Screenshot showing the location of the Fuzzy Membership tool in Arc Toolbox	81
Figure 51. Screenshot showing the contents of the Fuzzy Membership tool window	82
Figure 52. Screenshot showing the location of the Reclassify tool in the Arc Toolbox.....	83
Figure 53. Screenshot showing the contents of the Reclassify Tool	84
Figure 54. Screenshot showing the location of the Weighted Overlay tool in the Arc Toolbox..	85
Figure 55. Screenshot showing the contents of the Weighted Overlay tool.....	86
Figure 56. A graph of values in a large type of fuzzy membership showing the spread and the crossover point	87
Figure 57. A graph of values in a small type of fuzzy membership showing the spread and the crossover point	88

CHAPTER 1: INTRODUCTION

The oil and gas industry is increasing oil and gas exploration in the United States to fulfill the US energy demand. In Colorado, there is a large field of operation in the northeastern part of the state recognized as the Wattenberg Field. Colorado has a semi-arid climate hence new oil and gas developments that are being done by using the technique of Hydraulic fracturing have high water supply needs are a growing concern. . The water supply is currently allocated to urban water use and agricultural use such that oil and gas development is changing the water usage in the state. In addition to water supply issues, an equally important issue is the disposal and treatment of the water produced during hydraulic fracturing. In addition to the pressure on water supply, hydraulic fracturing is associated with other community issues such as air quality, road damage, and noise pollution.

From an environmental perspective, one large issue associated with hydraulic fracturing is the treatment of water produced from the fractured wells and optimized handling and transportation of the same. The amount of water required for drilling and fracturing is dependent upon the type of well being drilled. Horizontal wells require larger volumes of water than vertical and directional wells due to the increased drilling length. Water usage varies depending on the type of well. For a typical vertical well, 65,000 to 600,000 gallons of water are needed, but a horizontal well requires an average of 4.5 million gallons of water per well. The fracturing water is mixed with other chemical components (e.g breaker, biocide, water gellant) (Frac Focus, accessed August 2013) and sand and then hydraulic fractured to release oil and gas from shale formations deep beneath the ground. This water is trucked to the well site before the drilling and the hydraulic fracturing is started, and is stored in a tank (Chesapeake Energy, 2013). Upon the completion of hydraulic fracturing, the fluid is allowed to flow back to the surface to relieve the

down-hole pressure and allow gas to migrate to the surface. The term “flowback water” typically refers to the fracturing fluid mixed with formation brine which flows at a high rate immediately following hydraulic fracturing but before the well is placed into production. “Produced water” then refers to the fluid that continues to be coproduced with the gas once the well is placed into production and may be present over the lifetime of the well (Barbot et al. 2013). For a normal length well the average flowback water volumes are around 14000 bbls and produced water volumes are around 4000 bbls. (Bing et al. unpublished) This water is usually trucked out of the site and then taken to deep well injection sites (Chesapeake Energy, 2013).

Increased truck traffic from hydraulic fracturing operations is a large public concern to the local communities in the Wattenberg field. Truck traffic is associated with an increase in accident potential, noise, and increased costs of road maintenance. The truck traffic involved with the transportation of water supply and water requiring disposal is estimated at 1,500 trucks trips (Fossinger et al. 2013). One method that could reduce the truck traffic would be to reuse the flowback and produced waters for drilling and fracturing of new wells in the area. The water coming out of wells after fracturing is very contaminated as it gets in contact with the formation down hole and interacts with it. The water required for fracturing needs to be cleaner than that. A treatment plant set up in the area would intake flowback and produced water from the hydraulically fractured wells and deliver cleaner water for the wells to be drilled later. The siting of mobile treatment plants is not a trivial undertaking as development can occur in multiple locations over distances of hundreds of square miles (Personal communication-Noble Energy Inc). The objective of this study is to provide an answer to this question of locating a mobile treatment plant in such area. The method developed uses a spatial multi-criteria decision analysis (MCDA) on an ESRI (Environmental Systems Research Institute) ArcGIS-based platform. The

data about the development area, location of the wells and the schedule for drilling and fracturing was obtained from a major operator in the Wattenberg Field. A quarterly analysis was done to see how the location of the treatment unit is affected by the change of the development plans. Four case studies were done for each quarter varying the weightage of the criteria to see what could best answer this problem.

CHAPTER 2: LITERATURE REVIEW

2.1. Area of Study

The map below shows the shale gas development in the state of Colorado.

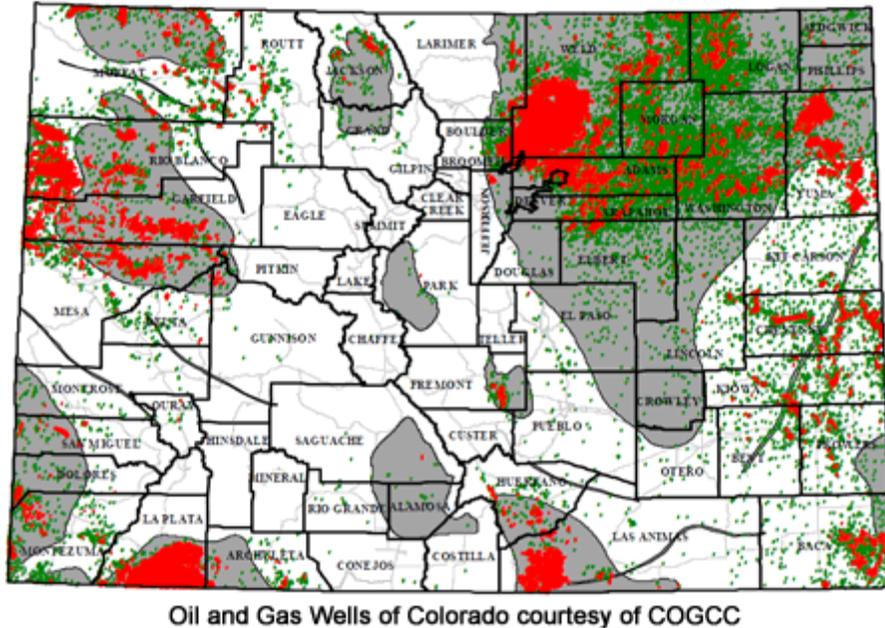
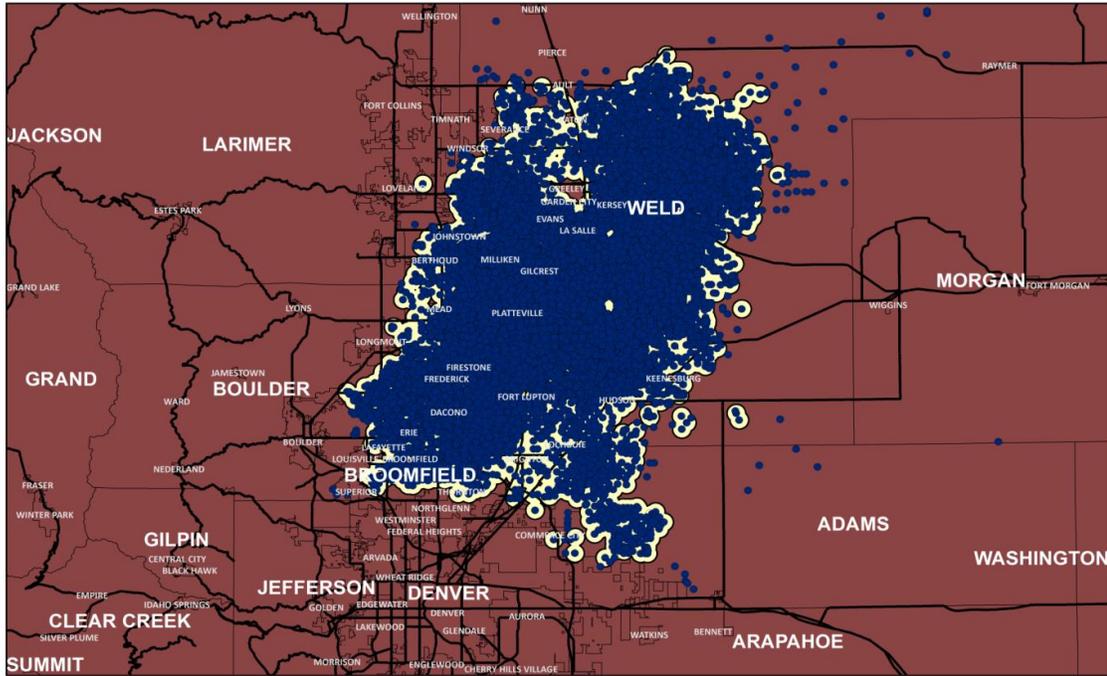


Figure 1. Natural gas development in the state of Colorado. Each dot represents the location of one well

The area marked in red on Figure 1 is the area where a large development is going on, while comparatively lesser developments are marked with green and gray. The development areas in the northeastern part of the state is the Wattenberg Field.

As the new exploration operations are taking place, the traditional area of the Wattenberg Field (Figure 2) has expanded. The area of current study is located northeast of the Wattenberg Field and is known as the Pony Wells area.

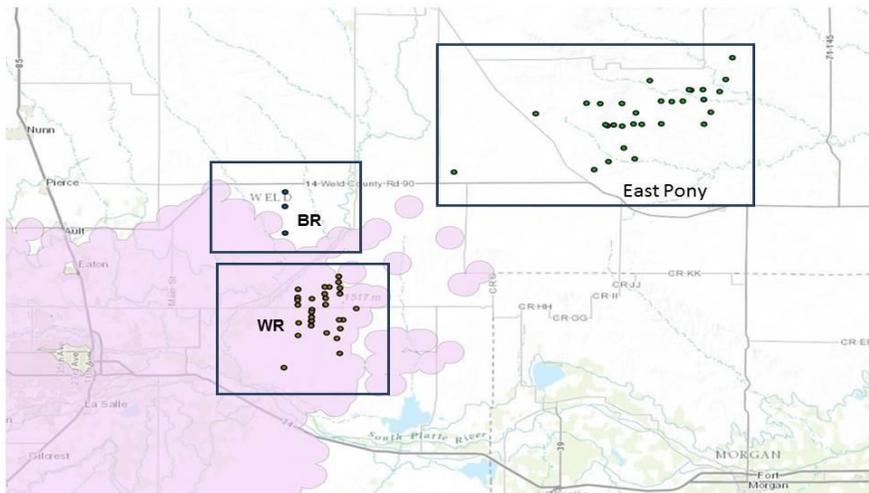


Legend

- Oil & Gas Wells
- Highways
- Wattenberg Field

Data Source: COGCC Database, Colorado State University

Figure 2. A map of the Wattenberg Field with its numerous oil and gas wells. Each blue dot represents the location of the well



Legend:

- BR- Ball Ranch
- WR- Wells Ranch

Figure 3. The extended parts of Wattenberg Field, along with the northeastern end of Wattenberg Field at the lower left hand corner of the map.

2.2. Water Usage

The amount of water required for drilling and fracturing usually depends upon the type of well being drilled. Horizontal wells need much larger volumes of water than vertical and directional wells due to the larger drilling length. For each stage of a hydraulic fracture, an average of anywhere from 5,000 gallons (119 bbl; diluted acid stage) up to 50,000 gallons (1190 bbl; prop stages) of fracturing (frac) fluid is needed, which means that the entire fracturing operation would require approximately 2-4 million gallons of water, 3 million gallons (71,428 bbl) being most common (Satterfield et al. 2008). A typical horizontal shale well requires a maximum of approximately 600,000 gallons (14,000 bbl.) for drilling and 2-5 million gallons of water for hydraulic fracturing. For vertical and directional wells, the water needed for fracturing is between 100,000 and 1,000,000 gallons (2,300-23,000 bbl.). Also, a substantial amount of water is needed for hydraulic fracturing, usually several times more than for drilling. (US Department of Energy, Office of Fossil Energy, 2009)

2.3. Produced Water and Flowback Volumes

The water production from all the hydraulically fractured wells is the root cause of all the environmental, social and also the economic problems associated with the process of hydraulic fracturing. According to estimates prepared after a few years of observations, 8 barrels of water are generated while producing one barrel of oil. The economic cost of handling and disposing of produced water is from 5 to 10 billion dollars every year in the United States (Neil et al. 2004).

2.4. Sources of Water Production

The sources of produced water include injected water (frac water), formation water and sometimes aquifers. The injected hydraulic fracturing water is usually the major source of water from oil and gas wells.

2.4.1. Frac-Flowback Water

Frac flowback water mostly consists of fracturing fluid used for the fracturing of oil and gas wells which returns to the surface. This water contains chemicals, metals, and other components that are used for hydraulic fracturing. The usual frac load recovery is from 15%-40% of the fracturing fluid injected down the well, and it flows back over a period of 3-4 weeks after fracturing, most of which is within 7-10 days(Radler et al. 2012).

2.4.2. Produced Water

Produced water is basically the water that naturally occurs in the shale formation beds that are traversed by the wellbore. Produced water flows throughout the lifecycle of the well along with oil and gas production. The volume and production rate of produced water over time is still not clear and more studies need to be done in that area.

2.5. Current Practices of Produced Water Management

The EPA regulates the disposal of produced water, as most of its components are considered to be potentially hazardous like heavy metals, dissolved formation materials, Naturally occurring radio-active materials (Environmental Protection Agency website; 2013) The following are the ways by which flowback and produced water is managed currently.

2.5.1 Deep Well Injection

This method basically allows management of produced water by injecting it in deep underground wells (Railroad Commission of Texas; accessed May 29th 2012). Class II types of injection wells are used for such disposal as it is the specified type for this purpose by USEPA (Produced Water Management Information System, U.S. Federal Regulations). It is required that

an injection well has three layers of casings to protect the underground source of drinking water (USDW) from contamination.

Although it is the most commonly used method for disposal of the produced water, its use is still debatable as it has many problems associated with it. It is considered unsafe as it contaminates the ground water during injection, if all the three layers fail at the same time, and it migrates to streams and contaminates them as well. Another important concern is the induced seismicity. Many earthquakes were reported in Texas and Ohio where a lot of oil and gas development was going on. Seismologists have reported that those earthquakes were not the result of hydraulic fracturing but were caused due to the deep well injection activity. Also, due to limited capacity (1200 to 3000 bpd) and considerably large capital investment (1 to 2 million dollars) required for a very limited life span, the injection wells probably won't prove to be a good way of disposing produced water.

2.5.2. Evaporation in Pits and Ponds

Although evaporation could be the cheapest way to handle frac flow back and produced water, there are a lot of other environmental issues associated with its usage, and these are a hindrance for the use of this method for disposal. For example this method can only be used in really dry areas where the evaporation rate is more than the precipitation rate. Also the evaporation rate will be very low since the salinity and TDS are really high, which will increase the osmotic pressure for fluid being stored (Vidic, 2010).

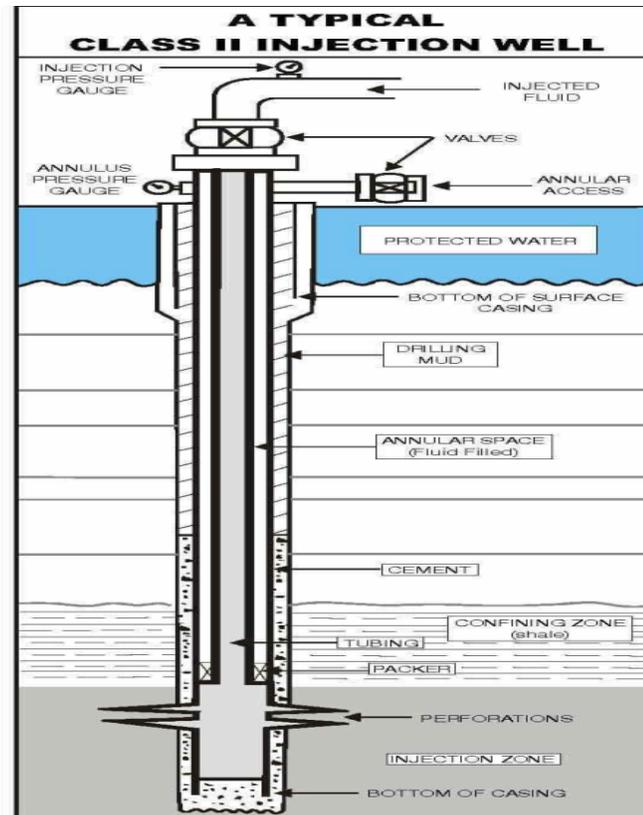


Figure 4. A typical class II injection well (USEPA)

2.5.3. Disposal to Publically Owned Treatment Works (POTWs)

Disposal to POTWs was one of the options used a few years back to handle the frac flowback and produced water. But the common biological processes used in POTWs and the high salinity of the produced water make it impossible to remove the high TDS of the produced water. Also, this water then can't be disposed of to the surface waters due to regulatory limitations (Vidic 2010).

2.5.4. Direct Reuse for Fracturing

A considerable number of operators consider reusing produced water directly for fracturing new wells due to its high salinity and viscosity. A lot of energy and money can be saved by direct reuse of the produced water for hydraulic fracturing, as the TDS need not be

decreased and the chemical additives in the produced water can be recycled. This being said, there are some other components of produced water, such as chlorides and bacteria, which need to be taken care of for safety issues. Chlorides need to be removed as they might cause corrosion of the metal components used during the fracturing process (Vidic, 2010). A typical treatment train for fracturing reuse is represented in figure 5 (Kimball 2010).

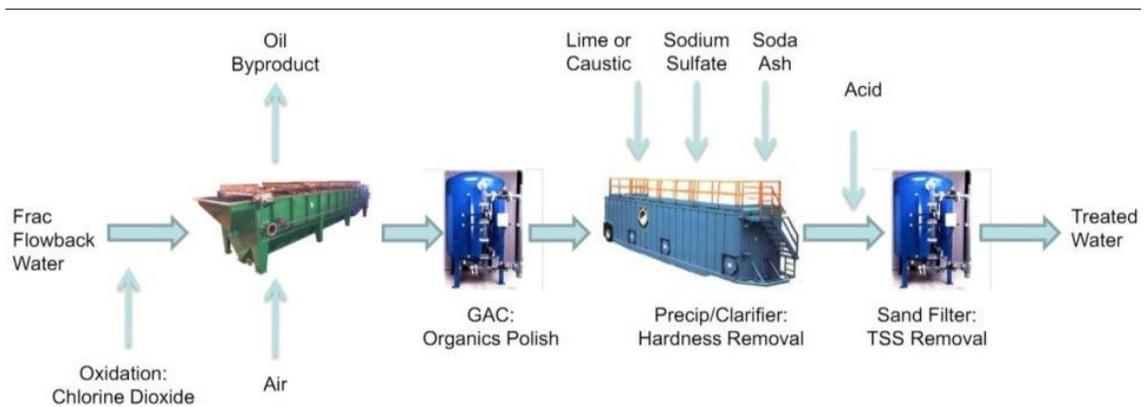


Figure 5. A typical treatment process of produced water for reuse as fracturing fluid (Kimball, 2010)

2.5.5. Treatment for Reuse or Surface Discharge

For reuse of produced water other than hydraulic fracturing a more refined treatment is required. As the TDS standard for agricultural reuse is less than 2000 mg/L and 500 mg/L for surface discharge, TDS reduction of produced water is very important. According to the type of reuse intended the treatment refinement varies. Usually a reverse osmosis (RO) treatment is opted for TDS reduction. A typical treatment train for this kind of reuse is represented in figure 6 (Kimball 2010).

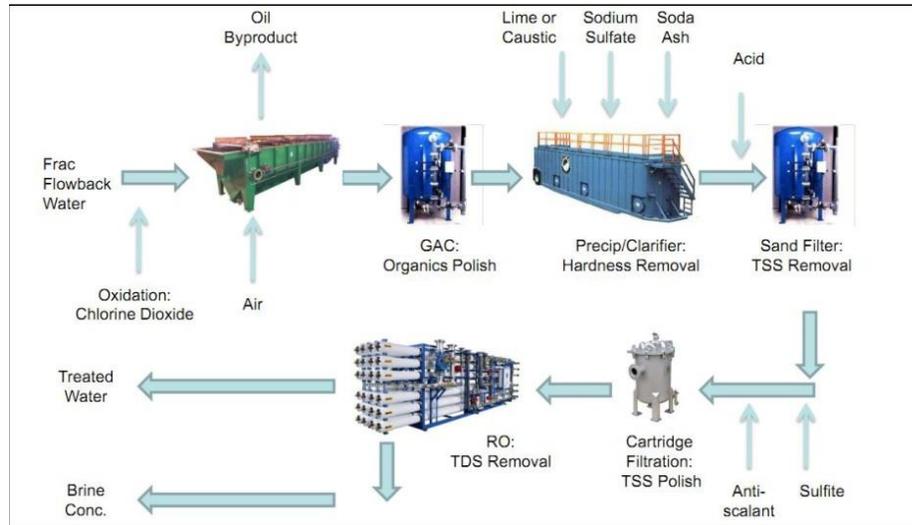


Figure 6. A typical produced water treatment train for surface discharge or agricultural reuse (Kimball, 2010)

Although this seems to be the best option of reuse the costs associated with RO treatment are very high and vary according to the input and desired output quality of water (Howarth et al. 2012).

2.6. Environmental Impacts Associated with Hydraulic Fracturing

As discussed before, the process of hydraulic fracturing is very water intensive. Along with that there are a lot of other environmental issues associated with the process of hydraulic fracturing which can be summarized in the following paragraphs.

The crux of most of the environmental issues associated with hydraulic fracturing is the necessity of hauling water over large distances.

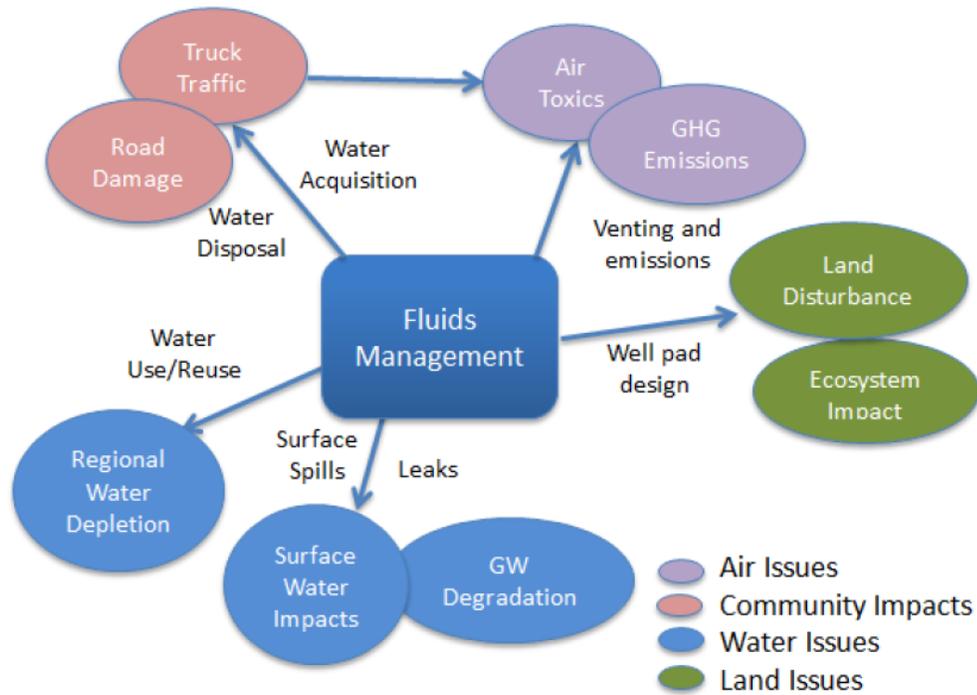


Figure 7. Environmental issues associated with hydraulic fracturing

In light of the need to haul such a large amount of water, it is obvious that huge truck traffic to and from the well site is an inevitable problem. Texas department of transportation reports that 1,184 loaded trucks are necessary to ‘bring one gas well into production,’ plus 353 loaded trucks per year for maintenance and 997 loaded trucks every five years to re-frac a well (Fossinger et al. 2013). Of course not all this traffic is for water alone—some of this traffic would be to haul equipment for set-up, to transport fluids (water, oil, gas), and to take down each piece of equipment when the well is completed. These high volumes of truck traffic has led to many different problems in the areas where drilling is located. Many wells are being drilled in rural areas like farms and ranches where there is generally not very much traffic from day to day. Higher numbers of trucks have led to increased traffic accidents and, in some cases, increased fatalities. Pollution from the trucks is also a concern. Because of the high volumes of trucks

going to and from the well, there will be a large increase in CO2 emissions. Noise pollution is also increased because of the many vehicles going to and from the well site each day. Also, many wells are drilled on agricultural land which means they are in the middle of fields or pastures. Sometimes the well companies have to create their own paths to the well site, and in that process they destroy earth ditches and other infrastructure. Most of this traffic is industrial trucks, with some individual trucks weighing, as much as 80,000 to 100,000 lbs when fully loaded (Marcellus-Shale.us 2013). This kind of infrastructure damage is also done on roadways to the well site. The New York Department of Transportation reports that pavement structural damage done by the passage of a single large truck is equivalent to that done by about 9,000 automobiles (Fossinger et al. 2013). This of course increases the cost of road repair and decreases the amount of time the roads are drivable. In 2010, Pennsylvania estimated \$265 million would be needed to repair damaged roads in the Marcellus Shale region. Environment America Research and Policy Center, 2012 Texas, has approved \$40 million in funding for road repairs in the Barnett Shale region. If the development is going on near a neighborhood, the value of the land and houses in the particular neighborhood goes down due to the issues mentioned above.

A considerable amount of these issues can be addressed by OFM (Optimized Fluids Management). The most effective way would be to reuse and recycle the flowback and produced water in the field itself, which would reduce the overall truck hauls in the developing fields. As these fields are usually very large and development might happen in different parts of the field at different points of time, a mobile treatment plant seems to be a viable option for treatment and reuse within the field itself.

There have been a few studies done for choosing the appropriate technology for a decentralized treatment plant, done by MCDA. The technologies were weighted based on different criteria such as treatment efficiency, operational complexity, maintenance required, capital investment, energy input and energy output (Gallagher et al. 2010). But developing technology for the treatment is out of the scope of this paper. Rather it is more of a spatial issue as to the placement of the mobile treatment facility. This paper will address the logistics such as strategies for defining the location of a mobile treatment plant as the development plans continue over the development field. Such an analysis has been done before for the optimization of the regional wastewater system planning where sewers, possible pump stations and the location of the treatment plants were the governing factors of the MCDA. The sewers were analyzed by giving various constraint equations. The treatment plants' placement was governed by the water quality requirements at the point where the treated wastewater stream met the river, as well as by the change in the river flow. The pump stations, however, were determined by considering the constraints provided by the local geography (Zeferino et al. 2012). This has also been done for the optimal siting of fire stations. The different objectives used to obtain the optimal sites include: minimizing response time to fire, minimizing total mileage for fighting rural or county fires, and maximizing protection per dollar's worth of burnable property (Liu et al. 2006). This analysis is more complex than the objective fulfilled by this paper, as the road network and traffic would have to be considered in order to come up with the location of fire stations to minimize the response time and at the same time serve a larger area.

To solve the current problem of locating an optimal site for a mobile treatment plant the points to be considered are as follows: where the water is coming from, how much water is coming, where the water is going and how many well sites can be served with the chosen site for

the treatment facility. Also a suitable platform to perform this kind of spatial MCDA should be chosen where the results can be seen visually and at the same time all the criteria mentioned above can be included in the analysis.

2.7. Geographic Information Systems (GIS)

GIS integrates hardware, software and real world data for record keeping, managing, analyzing, and displaying all forms of geographically referenced information. GIS allow one to easily view, understand and interpret data in many ways that reveal relationships and trends in the form of maps, reports, and charts (ESRI ArcGIS resources 2013). That is why GIS are gaining a lot of interest these days in different research areas where geography is involved (Singh et al. 2003). A lot of systems, such as water resource systems, can be easily represented spatially using GIS. Traditional water resources data can be easily viewed in GIS along with social, economic and environmental factors using different analyses available within GIS. GIS allow the user to control and manipulate data input with the help of convenient user dictated applications so that the user can decide how features will respond to changes to the environment, and to create rules to supervise the modeling process (McKinney et al. 2002). Due to all these user-oriented amenities available within GIS, ESRI ArcGIS 10.1 software was chosen to prepare the model and perform the analysis.

2.8. Water Production Prediction

In order to reuse or recycle the water, to site the facility location and also to size the facility, it's very important to understand how much water is produced. Since the analysis was to be a done in an area where the development has just started, the water production data was not available. So there was need for a tool that could predict the water production over a period of time.

The Arps equation (equation 1) has been used traditionally for calculating the production rate of oil and gas and therefore can be used as a first approximation for modeling water production decline rates. In the Arps equation, $q(t)$ is the production rate at t , q_i is the initial production rate, $D_{(i)}$ is the decline rate constant, t is time and b is the degree of curvature (Arps 1944).

$$q(t) = \frac{q_i}{(1+D_i t)^{1/b}} \quad (1)$$

In the Arps equation (1), b value changes from 0 to 1. When $b=0$, the Arps equation changes to the form of $Q=Ae^{-kt}$, which is exponential decline, and when $b=1$, the equation changes to harmonic decline.

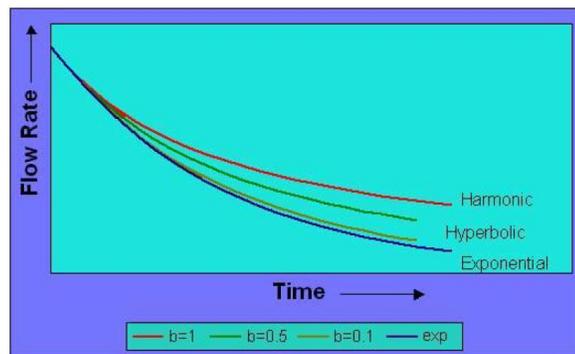


Figure 8. Decline curves from different 'b' values in Arps equation

A sample of eighty-six horizontal wells was studied. Daily frac flowback and produced water data was acquired from Noble Energy Inc. Based on that data, predictions of water production were made. Raw data analysis uses the flowback report from Noble Energy as the flowback period, and uses the day after the period as the first day of produced water generation (Bai et al. 2012). After the raw data was analyzed, it was found that the average flowback time for a horizontal well was a month, transition water flowed from the 31st day until the 163rd day,

and produced water flowed after that until the end of the life of well. Using the frac flowback analysis and produced water production curves for the eighty-six wells, the average curve was plotted and a prediction of future water production was made. Based on the average A1 and k1 for all eighty-six horizontal wells, the equation of frac flowback water production for horizontal wells is as follows:

$$q = \frac{1516}{(1+0.06138t)^{1/0.478}} \quad (2)$$

The equation for transition water is as follows:

$$q = \frac{176.33}{(1+0.03738t)^{1/0.994}} \quad (3)$$

However, for produced water, production rate was modeled with harmonic function for peak flow condition. The equation of harmonic decay is $= \frac{c}{1+at}$, in which c is the initial water production rate and ‘ a ’ is the initial decay rate. After applying harmonic function to each horizontal well, the average c and a value of eighty-six wells was calculated and the equation of produced water production for horizontal wells is

$$q = \frac{29.3919}{(1+0.00341t)^{1/0.899}} \quad (4)$$

ArcGIS interpolated maps are used to estimate the spatially-defined ‘ $k1$ ’ value (frac flowback decay rate constant) and ‘ a ’ value (produced water decay rate constant). Like the decay rate of vertical wells (k), the distribution of ‘ $k1$ ’ and ‘ a ’ are not homogeneous. Therefore, in the analysis of all horizontal wells in the Wattenberg Field, an average $k1$ value of 0.043 (half-life of 16.12 days) and average a value of 0.04469 (half-life of 15.51 years) was used.

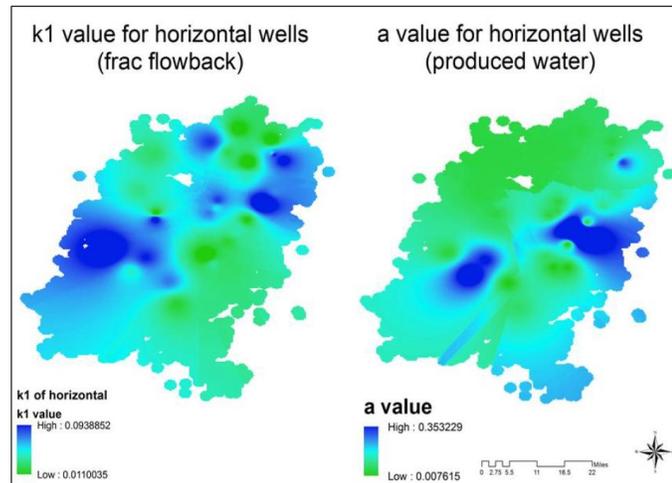


Figure 9. ‘k1’ and ‘a’ of horizontal oil and gas wells in the Wattenberg field (Bai et al. 2012)

2.9. Potential MCDA Methods for the Analysis

The problem we are trying to solve is a multi-objective (MO) one, which adds to the complexity of the problem. Many spatial and location problems inherently possess multiple conflicting objectives and for this reason the resultant MO optimization problem opts for trade-off optimal solutions (Pareto-optimal). Pareto-optimal solutions for MO problems can typically be addressed by three methods: the weighted method, the constraint method and the weighted minimax method. The simplest of all is the weighted method which uses different values to weight the criteria given by the analyst. In the constraint method, a constraint value is applied to each criterion that is under consideration, and a decision is then made based on the value provided by the objective function. In the weighted minimax method, all the values of each criterion—from minimum to maximum—are alternated until the best possible solution is found out of the worst possible solutions (Li et al. 1999).

Looking at these alternatives, the weighted minimax method was out of the question. The constraint method seemed a little too demanding, as we would have to provide the constraints for each criterion and simultaneous objective function. Integrating all of this into ArcMAP would make the database very large and complicated to prepare, which would make the model far too complex for no reason. Therefore, the simple weighted method was chosen.

2.10. Research Objectives

- To define criteria, those will affect the siting of mobile treatment plant.
- To develop a model within ArcGIS to site the optimal location of mobile treatment plant as the development plans progress over a period of time.
- To incorporate the water prediction tool into the analysis.
- To automate the entire model as a tool that can be published online for the industry use.

CHAPTER 3: GIS BASED LOCATION OPTIMIZATION TOOL FOR MOBILE PRODUCED WATER TREATMENT FACILITIES IN SHALE GAS OPERATIONS.¹

3.1. Summary

Over 60% of the nation's total energy is supplied by oil and natural gas together and this demand for energy will continue to grow in the future (Radler et al. 2012). The growing demand is pushing the exploration and exploitation of onshore oil and natural gas reservoirs. Hydraulic fracturing has proven to not only create jobs and achieve economic growth, but also has proven to exert a lot of stress on natural resources—such as water. As water is one of the most important factors in the world of hydraulic fracturing, proper fluids management during the development of a field of operation is perhaps the key element to address a lot of these issues. Almost 30% of the water used during hydraulic fracturing comes out of the well in the form of flowback water during the first month after the well is fractured (Bai et. al. 2012). Handling this large amount of water coming out of the newly fractured wells is one of the major issues as the volume of the water after this period drops off and remains constant for a long time (Bai et. al. 2012) and permanent facilities can be constructed to take care of the water over a longer period. This paper illustrates development of a GIS based tool for optimizing the location of a mobile produced water treatment facility while development is still occurring.

A methodology was developed based on a multi criteria decision analysis (MCDA) to optimize the location of the mobile treatment facilities. The criteria for MCDA include well density, ease of access (from roads considering truck hauls) and piping minimization if piping is used and water volume produced. The area of study is 72 square miles east of Greeley, CO in the

¹ Authors: Amol H. Kitwadkar, *Colorado State University*, Ken Carlson, *Colorado State*

Wattenberg Field in northeastern Colorado that will be developed for oil and gas production starting in the year 2014. A quarterly analysis is done so that we can observe the effect of future development plans and current circumstances on the location as we move from quarter to quarter. This will help the operators to make long-term decisions and also they can make decisions about the well pad siting and well densities. Three different scenarios—baseline, retroactive and proactive—were considered to see what could be the proper way to answer the question of optimal fluids management (OFM). Once the locations were obtained the results from different scenarios were compared for piping distances from each well going towards the facility, assuming the pipeline distance as the criteria to be minimized. The results obtained were pretty robust and observed to be fulfilling the intended purpose.

3.2. Introduction

The oil and gas industry is using innovative new practices for fulfilling the growing energy demands, including horizontal drilling and hydraulic fracturing (Radler et al. 2012). In northeastern Colorado, both of these technologies are being utilized in the Wattenberg Field. The state of Colorado has a semi-arid environment with low rainfall; hence new oil and gas developments are becoming a concern, as they demand a very large quantity of water—to a degree of billions of barrels. This is bound to exert pressure on the water as well as some other natural resources.

A horizontal well requires an average of 4.5 million gallons of water per well (US Department of Energy, Office of Fossil Energy, 2009). This water is mixed with other chemical components and sand and then used for hydraulic fracturing to release oil and gas from shale formations deep beneath the ground. This water is trucked to the well site before the drilling and hydraulic fracturing is started and stored in tanks (Chesapeake Energy, Accessed May 2013).

Upon the completion of hydraulic fracturing, the fluid is allowed to flow back to the surface to relieve the down-hole pressure and allow gas migration to the surface. This water is usually trucked out of the site and then taken to deep well injection sites. Considering the amount of water to be trucked back and forth, the truck traffic involved in the process is huge. It takes around 1,500 trucks trips per year to hydraulically fracture a well and maintain it (Fossinger et al. 2013).

One feasible solution for reducing the truck hauls in and out of these areas would be to reuse the flowback and produced waters for drilling and fracturing new wells in the area. For that to happen there should be a treatment plant set up in the area. Different treatment options are available according to what degree the water is to be treated (Kimball 2010). Usually the development areas are quite large—up to hundreds of square miles—and development is going on at multiple sections located far away from each other within those areas (personal communication). The objective of this study is to provide an answer to this question of locating a mobile treatment plant in such an area. As the siting of the plant is to be based on different conflicting criteria to be satisfied, it was a multi objective problem. This kind of analysis has been done before for the optimization of the regional wastewater system planning—for these analyses, sewers, possible pump stations and the location of the treatment plants were the governing factors of the MCDA (Zeferino et al. 2012). Generally the methods used to solve such problems are: the weighted method, the constraint method and the weighted minimax method (Li et al. 1999). As this was more of a spatial problem and visual results were required, and also looking at the variety of the tools available in different platforms, ESRI ArcGIS was chosen to perform the analysis. Studying the feasibility of the use of the three methods stated above with ArcGIS, the simple weighted method was chosen to lessen the complexity of the analysis. The

method developed uses a spatial MCDA on ESRI ArcGIS based platform. The data about the development area, location of the wells and schedule for drilling and fracturing was obtained from a major operator in the Wattenberg Field. A quarterly analysis was done to see how the location of the treatment unit is affected by the change of the development plans. Four case studies were done for each quarter varying the weightage of the criteria to see what could best answer this problem.

3.3. Methods

3.3.1. Studying the Development Plans

The development plans (DPs) for new oil and gas development for years 2014, 2015, 2016 and 2017 for a field situated east of Greeley, CO were obtained from Noble Energy Inc. The maps showed the exact location of DPs marked in different colors and the legend of the maps provided the names and numbers of different plans. A Gantt chart described the exact start and end date of each DP and the exact location of the development for a particular stretch of a DP by denoting the number of the one square mile sections where the development will be going on, according to the PLSS (Public Land and Survey System) divisions and total development period of a DP and the number of wells to be drilled under the particular DP. Studying all these together a simpler table (Table 1) was prepared where the overlapping of all the DPs and number of wells drilled under a particular DP in a particular quarter of the year and the start and end date of each DP under the particular quarter could be seen easily.

The first column of the Table 1 is the year and the quarter of the year. Second, third and fourth columns represent the DPs in the particular quarter. The numbers in the brackets represent the PLSS section numbers where the development is happening under each DP. The numbers

below that are the start and end date in mm/dd format of the particular DP in the quarter under consideration separated by a colon and the number below the dates is the number of wells to be drilled during that quarter of the year under a particular DP.

Table 1: The simpler table of development plans

Year	Start and end date	Number of wells to be drilled	Number of the PLSS section where development is going on	
2013_3	DP1 6/16 : 9/18	10	DP 2 (4,3) 9/8 : 9/29 6	
2013_4	DP1 9/29 : 12/22	10	DP2(4,3,9,10) 10/1 : 12/31 25	
2014_1	DP1 1/1 : 2/2	3	DP2(9,10) 1/1 : 2/15 13	DP 3(25) 2/17 : 3/31 15
2014_2			DP2(15) 6/8 : 6/30 6	DP3(25,26) 4/1 : 6/30 15

3.3.2. Preparation of the Basemap

As the DP maps obtained were in the pdf format they were converted to jpeg format and imported to ArcMap. This development plan image was then geo referenced using a PLSS map of USA, which was imported from ArcGIS online and then the image map was geo-referenced according to the townships mentioned in the development plan. This also helped with preparing

the extent of shapefiles for the DPs in each quarter. The roads are assumed to be lying along the grid lines of the PLSS sections.

3.3.3. Preparation of Shapefiles for Each Quarter

For placing the wells as points on a map in ESRI ArcMap a tool named “Create Random Points” is used. This tool can be found under the Data Management section of the ArcToolbox. This tool basically uses the polygon partitioning algorithm to randomly plot the points (ESRI ArcGIS resources 2013). In order for the tool to work one has to provide the extent in which the points are to be plotted and the number of points to be plotted. We had the extents and the number of points from the DP maps and the table mentioned above. Once the points were plotted, the fields mentioned in Table 2 were added to the attribute tables of each shapefile.

Table 2: The additional attributes of a shapefile and their types

Field	Type
Latitude	Float
Longitude	Float
DRILL_DATE	String
Days	Integer
WaterProdu	Double
WaterCuml	Double

The latitude and longitude of each point is obtained using the “Calculate Geometry” option available in attribute options. The rest of the attributes are for the use of Water Production Prediction Tool. The “DRILL_DATE” is the drilling date for each well. “Days” is the number of days past between the drilling date of the well and the end date selected for the analysis in the prediction tool, which will be explained further. “WaterProdu” is the water production per day at

that point in the life of the well, while the “WaterCuml” is the total water produced till that point of time. The types of the fields have to be specific as mentioned in Table 2 in order for the tool to accept the input and provide proper outputs.

3.3.4. The Water Production Prediction Tool

The water production tool uses the Arps equation to calculate daily water production and cumulative water production. Eighty-six wells were sampled in the area of study and the water volume curves were fitted to the equation. The equations used are as follows (Bai et al. unpublished):

$$\text{Frac flowback} \quad q = \frac{1516}{(1+0.06138t)^{1/0.478}} \quad (5)$$

$$\text{Transition water} \quad q = \frac{176.33}{(1+0.03738t)^{1/0.994}} \quad (6)$$

$$\text{Produced water} \quad q = \frac{29.3919}{(1+0.00341t)^{1/0.899}} \quad (7)$$

All these equations were programmed into ArcGIS using C# platform and then a GUI (Graphical User Interface) was prepared using Microsoft Visual Studio platform. The GUI contains a calendar. The calendar allows one to choose the date for the end of the analysis. This basically allows the tool to have the number of days (t) for the water production (q) calculations.

When the tool is run, the number of days is calculated using the “DRILL_DATE” column and the “Days” column is filled up first. The number of days is used to decide which equation will be used to calculate the water production. For the first 30 days it is considered frac flowback. After those 30 days and until 163 days it is considered transition water and after 163 days until the end of the life of the well everything is considered produced water. This

differentiation basically enables the tool to decide which equation to use for a particular well depending upon which stage of production it lies in. Once this is done the shapefile is ready for further analysis.

3.3.5. Work Flow of the Model

3.3.5.1. Working of the Model

The shapefiles required to run an analysis as depicted in the model in Figure 10 are the wells' shapefile with the water production data already obtained from the prediction tool, the well's shapefile from the previous quarter of the year, the wells' shapefile from the next quarter of the year and the roads' shapefile. All the shapefiles are imported into ArcMap.

“Near Tool” was then used on the shapefiles from the current quarter, twice. This tool adds a column of the distances (in linear unit of the input's coordinate system) of all the elements in the input shapefile from the input near features. The two near features used at two different times were the roads and the wells from the previous quarter so that the attribute table of the wells shapefile from current quarter would have columns of the distances from these two.

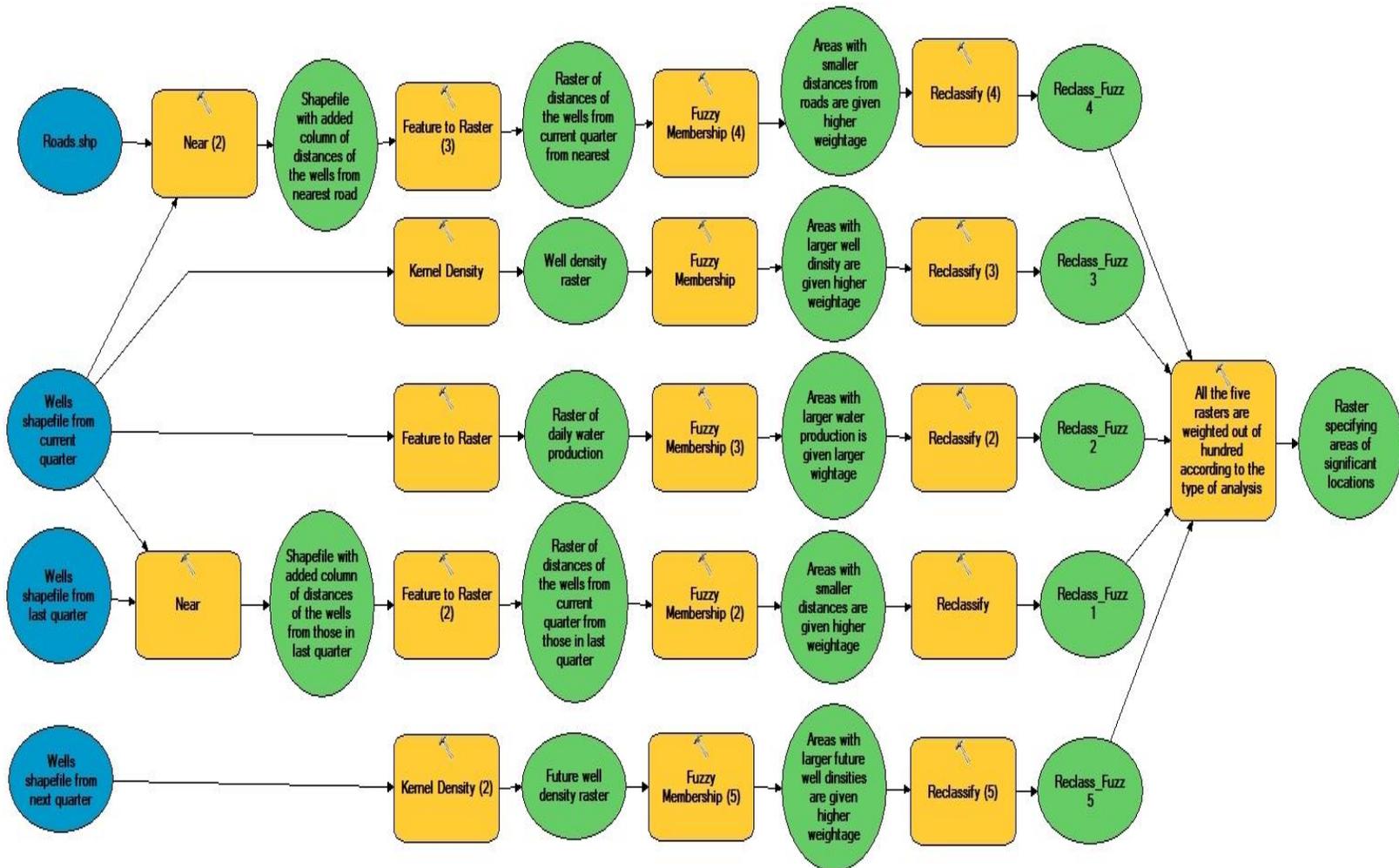


Figure 10. The flowchart of the location optimization model

Once this was done, rasters were prepared using the “Feature to Raster” tool based on the values of the near distances. This tool converts a feature to a raster. One can specify any of the attributes in the attribute table of the shapefile on which the raster should be based. Once the cell size, the processing extent and the number of cells is defined by the tool, the center value is used to decide the value of the particular raster pixel. . We obtained two rasters, one based on the near distances from roads and other based on near distances from the wells in previous quarter. Also a raster based on daily water production values was obtained.

A raster of density of the wells in the current quarter and as well as of the ones in the next quarter was obtained using the “Kernel Density” tool. This tool calculates the density of features in a neighborhood around those features. This tool is based on the Kernel density quadratic function and that’s why the search radius has a significant effect on the output raster. The concept behind the tool is a smoothly curved surface fitted over each point. The surface value is highest at the location of the point and diminishes with increasing distance from the point, reaching zero at the search radius distance from the point. The density at each output raster cell is calculated by adding the values of all the kernel surfaces where they overlay the raster cell center.

All these rasters were then subjected to the “Fuzzy Membership Tool.” This tool is used to classify all the values on a 0 to 1 scale, in the raster dataset according the convenience. Zero is assigned to those locations that are definitely not a member of the specified set, 1 is assigned to those values that are definitely a member of the specified set. And the entire range of possibilities between 0 and 1 are assigned to some level of possible membership (the larger the number, the greater the possibility). The input values can be transformed by any number of functions and operators available in the ArcGIS Spatial Analyst extension that can reclassify the

values to the 0 to 1 possibility scale. However, the Fuzzy Membership Tool allows you to transform continuous input data based on a series of specific functions that are common to the fuzzification process (ESRI ArcGIS resources 2013). The fuzzification functions that are used in the analysis are as follows:

- Large: The Fuzzy Large transformation function is used when the larger input values are more likely to be a member of the set.
- Small: The Fuzzy Small transformation function is used when the smaller input values are more likely to be a member of the set.

The following logics were used for the different rasters obtained:

- a) Well density rasters: Large
- b) Distance rasters (from roads and wells in previous quarter): Small
- c) Water production raster: Large

All of these rasters were then reclassified to integer values using the “Reclassify” tool. The tool changes the values of a raster as one wants. This tool is basically used to bridge up the gap between the Fuzzy Membership Tool and Weighted Overlay Tool. As mentioned before the output values from Fuzzy Membership tool are decimal values while the Weighted Overlay Tool can only work with integer values. The classification pattern for the rasters is mentioned in Table 3.

What Table 3 means is all the values ranging between 0 to 0.1 will be classified as 1 and so on. Once all the rasters are reclassified to integer values as mentioned above, they are imported to the “Weighed Overlay.” This tool overlays several rasters using a common measurement scale and weights each one of them according to the importance provided to the

tool. It basically multiplies the cell values of each input raster by the rasters' weight of importance and adds the resulting cell values together to produce the output raster. Different rasters imported in the tool are given the weightage out of 100 according to what analysis is being done. The different analyses performed and the weights for different criteria will be mentioned later. The raster obtained using this tool will give the least significant to most significant locations for the placement of the treatment facility by color variation.

Table 3: Pattern of reclassifying all the rasters after using Fuzzy Membership Tool

0 - 0.1	1
0.1 - 0.2	2
0.2 - 0.3	3
0.3 - 0.4	4
0.4 - 0.5	5
0.5 - 0.6	6
0.6 - 0.7	7
0.7 - 0.8	8
0.8 - 0.9	9
0.9 - 1	10

3.3.5.2. Assumptions of the Model

- All the wells considered for preparing the water prediction tool actually belong to a different field very close by and the wells in the area under consideration are assumed to behave in the same way.
- As the area under consideration is not a developed area, it has no constructed roads in it. So the roads assumed are along the lateral and longitudinal lines which form the one square mile sections.

- The exact location of the wells wasn't available, so the accuracy of areas of development is only limited to the one square mile section. And we had to rely on the points provided by the "Create Random Points" tool for the exact location of the wells.
- To transport the water from the well locations to the treatment facility collapsible piping is assumed. And that's why the straight line distance between the existing well sites and the new well sites is considered in order to incorporate the piping distance in the analysis.

3.3.5.3. Criteria for the Analysis

- Minimum distance from roads: The lesser distance from roads means easy accessibility of the facility for the trucks, should the water need to be trucked somewhere else. The lesser this distance is, the better the location for the treatment facility.
- Minimum distance from the wells in previous quarter: The lesser distance from the wells in previous quarter means lesser piping length for transporting water to the facility. The lesser this distance is, the better the location for the treatment facility.
- Well density of the wells in current quarter: Larger well density locations are preferred locations for the location of the treatment facilities, as it will serve larger number of wells.
- Well density of the wells in next quarter: Larger future well density locations are preferred because this consideration in the analysis will bring the pro-active aspect to it and it will save on the costs for the moving of the facility after every quarter.
- Daily water production: The location of the facility closer to the wells that produce more water is preferable, as it would reduce the costs for transporting the water to the facility.

3.3.5.4. Different Analysis Performed

A set of different analyses were performed by varying weightages of all these criteria discussed above. The different types of analyses done and the weights for different criteria in each one of the analyses are mentioned in Table 4.

Table 4: Types of MCDAs

Type of Analysis	Existing well density	Water production	Future well density	Distance from the wells in previous quarter	Distance from roads
Baseline I	25%	25%	40%	5%	5%
Baseline II	--	50%	40%	5%	5%
Retroactive	45%	45%	--	5%	5%
Proactive	--	--	90%	5%	5%

Baseline I study is neutral study which assigns equal weights to the current as well as future development. Baseline II study is very similar to Baseline I except for the fact that all of the weightage for the existing well density is given to the daily water production just to see if the well density and water production are interchangeable. Retroactive study was performed to see if we can satisfy site the facility for the wells fractured before along with the ongoing development by giving a considerable weightage to total water production instead of daily water production. The proactive study is performed to see if there is any need to move the facility every quarter and if we can retain the facility for multiple quarters depending upon the development plans. The weightage for the distance from the wells in previous quarter remains the same for all the studies because there might be some wells which might be in their flow back or transition period and if

the facility is moved at the end of the quarter those wells still need to be considered for the siting of the facility. All of the weightages were discussed with the industry according to their needs.

3.4. Results and Discussion

The last quarter of the year 2013 and first quarter of the year 2014 were selected for demonstration as there is quite a bit variation in the location of DPs. Figure 11 depicts the extent of the case study and the DPs under consideration as mentioned in Table 1.

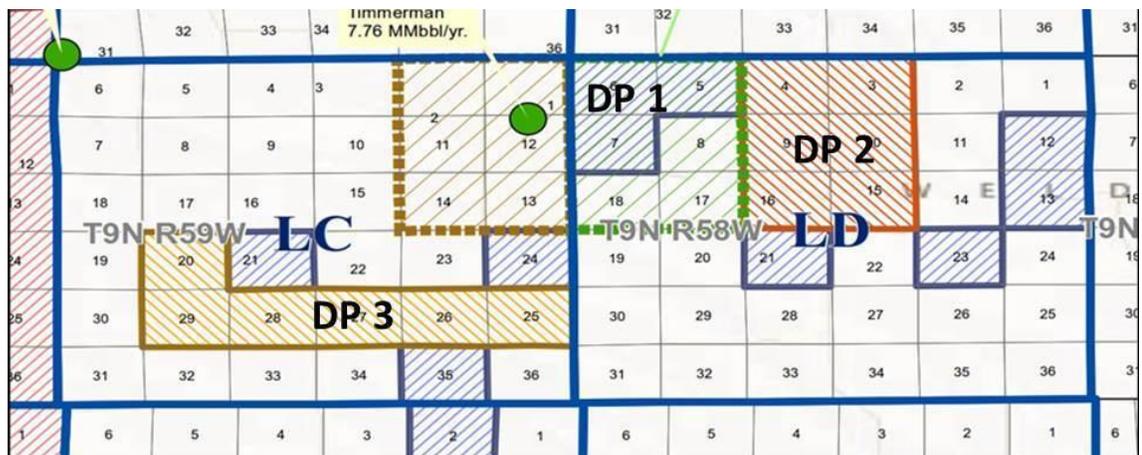


Figure 11. The area of study and the included DPs and their locations (Noble Energy Inc.)

If we consider the Baseline I analyses of both the cases, the location variation is considerable because the development is shifted to the southern part of the field and hence the most important criteria, such as well density and water production, are inclined towards that part of the field. For the Baseline II analyses for both cases, the results are pretty similar. If the comparison between Baseline I and Baseline II analyses is done, it is observed that the results are pretty similar. Except for the fourth quarter of year 2013 (Figure 14), it gives a few extra locations in Baseline II analysis as compared to the Baseline I. This could be due to the fact that

because there is more weightage for water production and no weightage for the existing well density, the results are skewed towards the recent wells as water production from those is more.

The results for Proactive analysis in each case look almost similar to those of the Baseline studies. This might be because the development stays in almost the same area although there is some development happening in the southern part, as we can infer from the DPs in table 1. However the results of the proactive analyses of both the cases are very different from each other as the development in the southern part is much more than that in northern part in second quarter of the year 2014.

On the other hand the results of Retroactive analyses are interesting. In both the cases they remain almost the same as a lot of weightage is given to existing well density and water production. However there are some extra locations in the southern part of the field as the development is happening in the southern part in the first quarter of the year 2014.

If the pipeline distance is assumed as the function to be minimized and if the results for all the different analyses are compared with each other, they seem to be fulfilling the purpose. This is done by selecting one site out of all the significant locations obtained for every study and then calculating total straight-line pipeline distances from all the wells to the location.

As we can see clearly in figure 14, the pipeline distances for all the wells up until the fourth quarter of 2013 from the optimal facility locations obtained under Baseline I, Baseline II and Retroactive analyses are lesser than those obtained under the proactive analysis. The location obtained under proactive analysis is going to be closer to the new wells drilled in first quarter of 2014 and the distances from those wells to that location is definitely lesser, as seen in figure 15.

Year 2013, Fourth Quarter

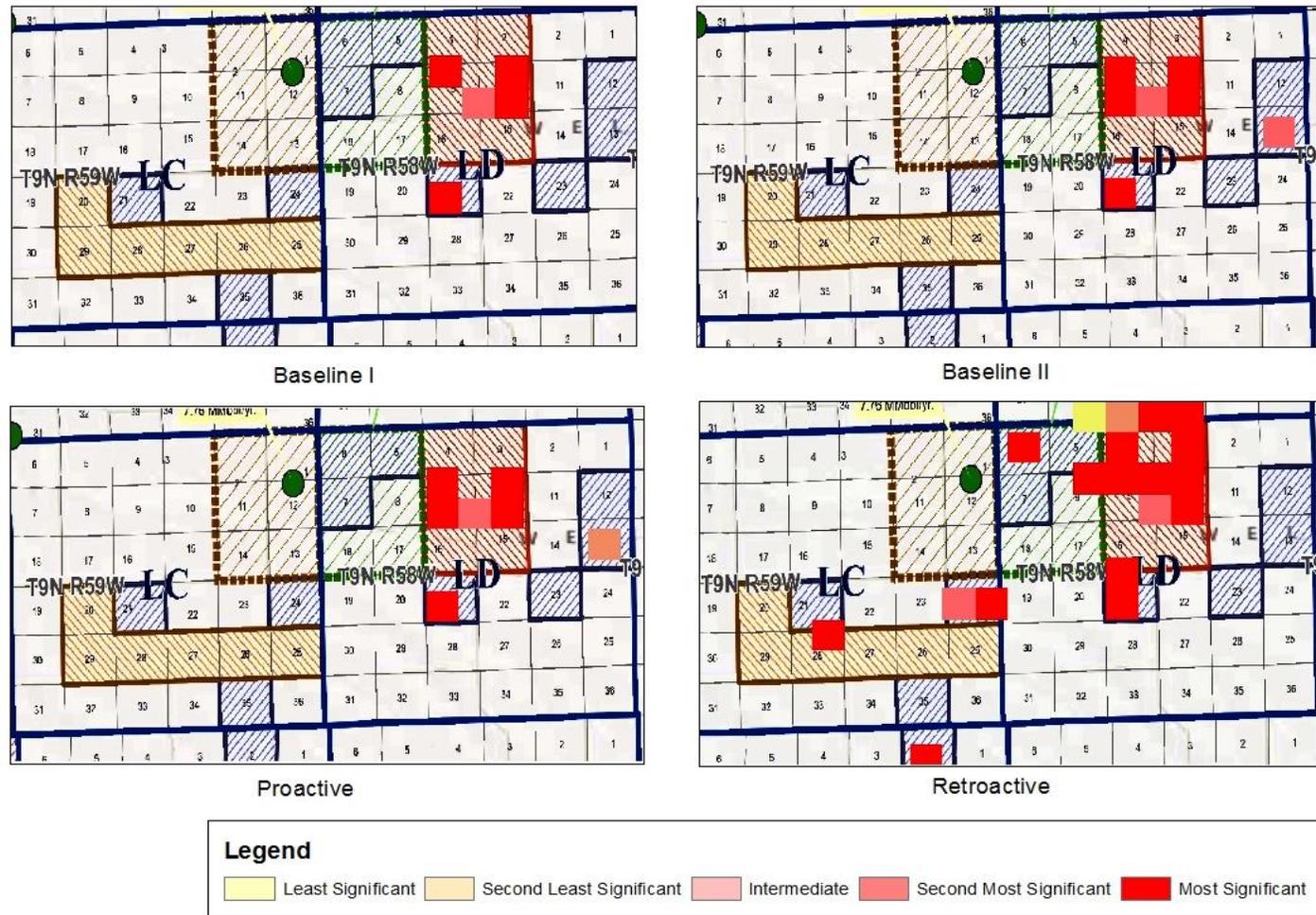


Figure 12. The most significant to least significant optimal locations for a mobile treatment facility for the fourth quarter of 2013

Year 2014, First Quarter

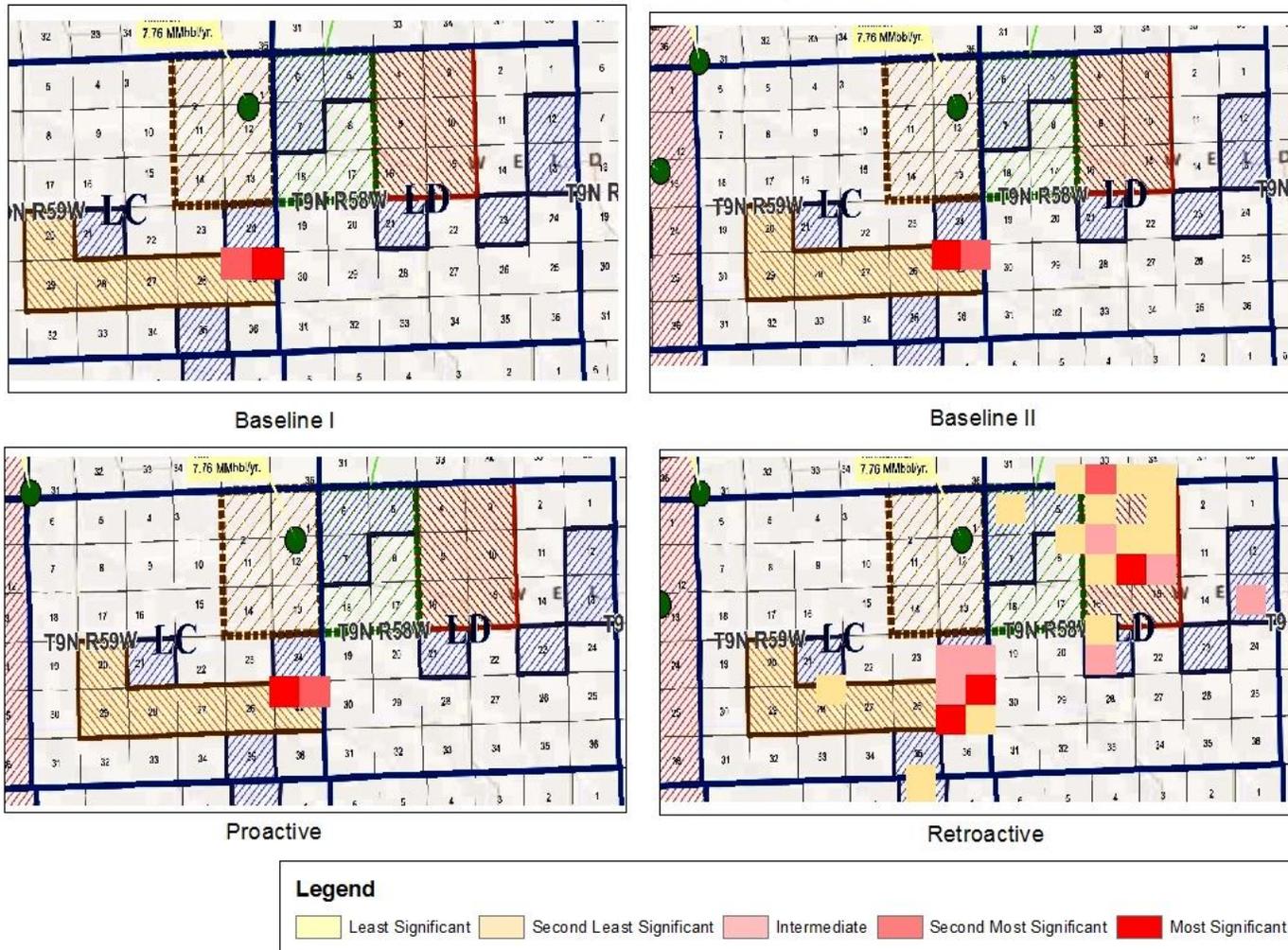


Figure 13: The most significant to least significant optimal locations for a mobile treatment facility for the first quarter of the year 2014.

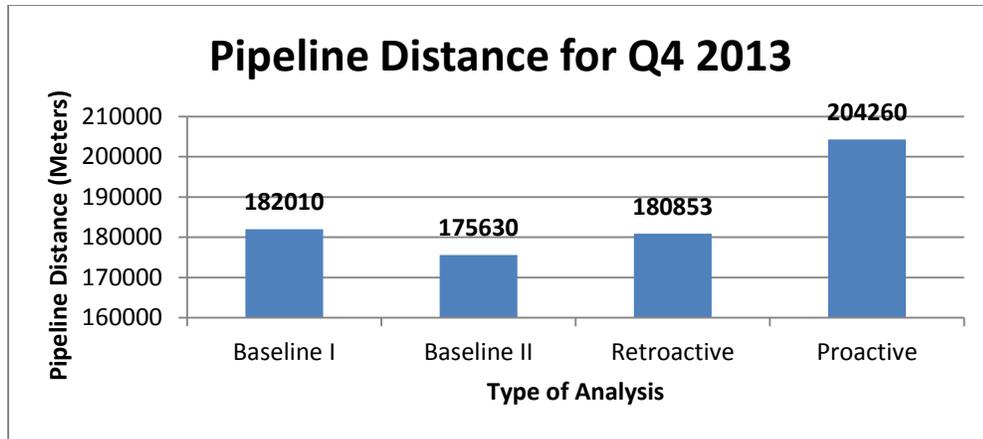


Figure 14. Pipeline distances for the wells up until the fourth quarter of 2013 from the optimal facility locations obtained for analysis done for fourth quarter of 2013

However, the distances for Baseline I and Baseline II analyses appear to be much different from each other. All of this variation is because of the difference in selection of the one single location out of all. These distances are definitely subject to change depending upon which of the locations is chosen out of all the significant locations obtained. And many such analyses can be done to decide which location out of all locations obtained gives the minimum pipeline distance.

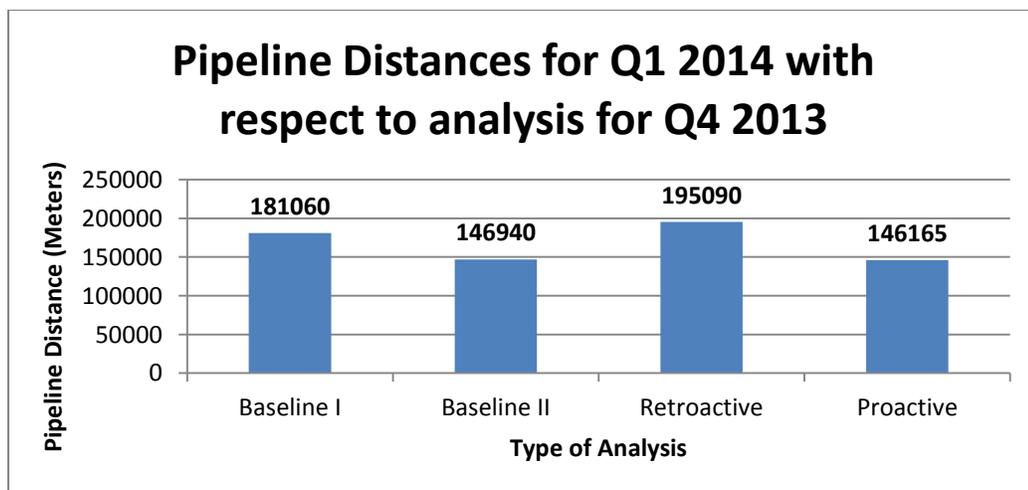


Figure 15. Pipeline distances for the wells up till first quarter of 2014 from the optimal facility locations obtained for analysis done for fourth quarter of 2013

Overall the results look pretty robust and the different analyses seem to fulfill the respective purpose. However there are some questions that are still unanswered. If we take a look at the results provided by both the Baseline studies, they look very similar. So the question is: does the well density and water production contribute a similar aspect to the analysis? The answer seems to be yes as per the results of the baseline studies. But the results of the Retroactive analyses say otherwise. Many of the most significant locations provided by the analysis for the first quarter of the year 2014 contain the areas of the developments that had happened during the fourth quarter of the year 2013, although the daily water production of the wells fractured during the first quarter of the year 2014 would be much more than those in the fourth quarter of the year 2013.

Another analysis was performed by selecting some of the most significant locations and then calculating straight line pipeline distances from the wells to the facility locations and the results were put on a map to see which locations have the minimum total pipeline distances out of all the selected most significant locations. The results are as follows (figure 16 and figure 17)

Some of the decisions regarding selection of one location out of all the significant should be left to the operators' consideration while using this model to get the results as it is highly dependent upon the whether the operator chooses to serve more wells or just the ones with higher water production rate and what modes will be used to transport the water to and from the mobile treatment facility to be put in the place.

Year 2013, Fourth Quarter



Figure 16: A map showing largest to smallest total pipeline distances for the most significant locations for all the four analyses for the fourth quarter of year 2013

Year 2014, First Quarter



Figure 17: A map showing largest to smallest total pipeline distances for the most significant locations for all the four analyses for the first quarter of year 2014

3.5. Conclusions

1. The well density and the water production are the governing criteria for the placement of the treatment facility.

2. When it comes to the question of using the well density and the water production interchangeably, the area under the consideration plays a major role. If the area is large enough and the DPs are spread all over the area at a considerable distance from each other, the well density and the water production are not interchangeable. When it comes to really small areas-to a degree of few square miles-they can be interchanged and either one of them can be used for an analysis.

3. From the comparison of the results between the Retroactive and Proactive studies, it is clearly seen that both, the place where the water is coming from to the facility and the place to which water is going from the facility play a major role. Both the criteria cannot be fully satisfied at the same time. There has to be a trade-off between the solutions in order to find one optimal solution.

4. Calculating the pipeline distances for all the most significant locations is necessary in order to choose one location out of all the ones obtained when it comes to minimizing the pipeline distance for the area to be served.

3.6. Future Work

1. To incorporate some other criteria like on-field water sources and optimal pipeline route in the analysis.
2. To consider some geographical difficulties like slope and natural barriers in the analysis.
3. To automate the model and publish it online.

4. To incorporate operator friendliness in the automated model so that one can do the different kind of analyses more easily.
5. To reduce work on the preparation work of shapefiles by incorporating the water prediction tool in the model.
6. To incorporate some cost aspects to the analysis as well as the results.

REFERENCES

1. Arps, J. J. 1944. Analysis of Decline Curves, Trans. *AIME* 160:228-47.
2. Asif, M., and T. Muneer. 2007. Energy supply, its demand and security issues for developed and emerging economies. *Renewable and Sustainable Energy Reviews* 11.7:1388-1413.
3. Barbot, Elise, et al. 2013. Spatial and temporal correlation of water quality parameters of produced waters from Devonian-age shale following hydraulic fracturing. *Environmental Science & Technology* 47.6:2562-2569.
4. Bernier, N. 2011. Earthquake in south Texas: Fracking fluid at fault? *KUT News*. Oct 20th 2011
5. Bai Bing, Caleb Douglas, Ken Knox and Ken Carlson. 2013. Development of protocols and tools for predicting frac flowback and produced water volume from Wattenberg oil and gas field, *Journal of Petroleum Science and Engineering, Volume 108*.
6. Bai Bing, Ken Carlson, Adam Prior, Caleb Douglas. Unpublished. Sources of variability in flowback and produced water volumes from shale oil and gas wells, *Journal of Petroleum Science and Engineering*.
7. ESRI ARcGIS resources (Accessed June 2013)
8. F.A.S.T.RTA. Advanced Production Decline Analysis (Accessed March 3rd 2013)
<http://www.fekete.com/software/rta/media/webhelp/c-te-analysis.htm>
9. Fossinger, Megan, Karyna Lemus, and Keira Havens. 2013. The economics of hydraulic fracturing, *Case Western Reserve, Law Review, Volume 63, Issue 4*.
10. Howarth, R. W., R. Santoro, and A. Ingraffea, 2012. Fracking wastewater disposal induced a dozen earthquakes in Ohio. *NY Daily News*
11. 2012. Methane and the greenhouse-gas footprint of natural gas from shale formations. *Climatic Change* DOI 10.1007/s10584-011-0061-5.
12. Hydraulic fracturing facts, Chesapeake Energy. (Accessed May 17th 2013)
<http://www.hydraulicfracturing.com/Pages/information.aspx>
13. Kimball, B., CDM. 2010. Water treatment technologies for global unconventional gas plays. U.S.-China Industry Oil and Gas Forum. Fort Worth, TX.
14. Liu, Nan, Bo Huang and Magesh Chandramouli. 2006. Optimal siting of fire stations using GIS and ANT algorithm. *Journal of Computing in Civil Engineering* 20.5: 361-369.
15. Marcellus-Shale.us (Accessed May 25th 2013)

16. McKinney, D. C. and X. Cai. 2002. Linking GIS and water resources management models: an object-oriented method. *Environmental Modelling & Software* 17(5): 413-425.
17. Modern shale gas development in the United States: A primer. U.S. Department of Energy, Office of Fossil Energy, 2009.
18. Veil J. A., Puder M. G. and Elcock D., 2004. A white paper describing produced water from production of crude oil, natural gas, and coal bed methane, *Argonne National Laboratory report under DOE (NETL), Contract W-31-109-Eng-38*.
19. Produced Water Management Information System, Federal Regulations. U.S. Environmental Protection Agency (Accessed May 7th 2013)
20. Radler, M. and L. Bell. 2012. U.S. energy demand to stay weak in 2012 amid strong oil, gas production. *Oil & Gas Journal* 110:24-31.
21. Railroad Commission of Texas Website. (Accessed May 29th 2013)
<http://www.rrc.state.tx.us/about/faqs/saltwaterwells.php>
22. Satterfield J., M. Mantell, D. Kathol, F. Hiebert, K. Patterson, and R. Lee. 2008. Managing water resources' challenges in select natural gas shale plays. Chesapeake Energy Corp. Presented at the GWPC Annual Meeting.
23. Singh, V. P. and R. N. Yadava. 2003. Watershed hydrology: Proceedings of the international conference on water and environment (WE-2003). Allied Publishers, Bhopal, India,.
24. The costs of fracking. Released by: Environment America Research and Policy Center Release date: Thursday, September 20, 2012.
25. Gallagher, Neal Thomas. 2010. An advanced decentralized wastewater management planning study and demonstration project for the CSU foothills campus. Master's thesis, Colorado State University. Advised by Dr. Sybil Sharvelle.
26. US EPA Water: Underground injection control. (Accessed May 18th 2013).
27. Vidic, Radisav D., Ph.D., PE, 2010, "Sustainable Water Management for Marcellus Shale Development", Department of Civil and Environmental Engineering, University of Pittsburgh, (Accessed May 21st 2013)
http://www.temple.edu/environment/NRDP_pics/shale/presentations_TUsummit/Vidic-Temple-2010.pdf
28. WikiMarcellus Website. (Accessed June 4th 2013)
http://www.wikimarcellus.com/wiki/Main_Page

29. Zeferino, João A., Maria C. Cunha, and António P. Antunes. 2012. Robust optimization approach to regional wastewater system planning. *Journal of Environmental Management* 109:113-122.

A. APPENDICES

A1. Documentation of steps in ArcMap 10.1.

1. Once you open the ArcMap this window will show up. Here you have to open a blank map as shown in the figure 17 by clicking on OK button at the bottom of the dialogue box.

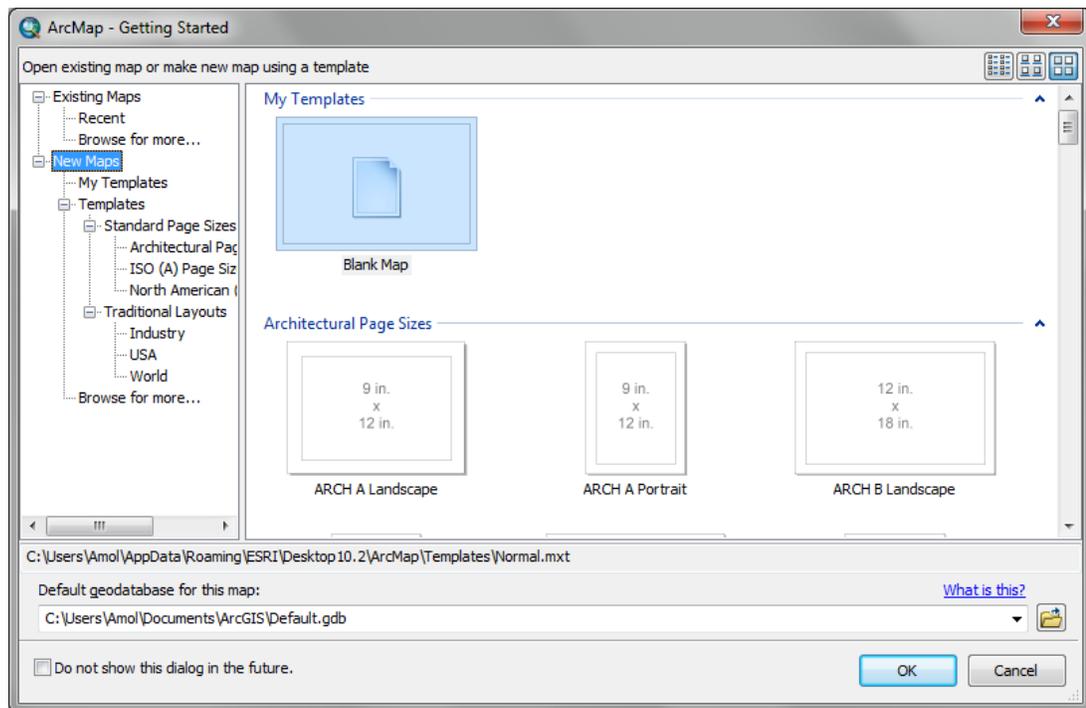


Figure 18. Screenshot of the ArcMap getting to start window

2. By clicking on the add data button, add the development plan data provided.

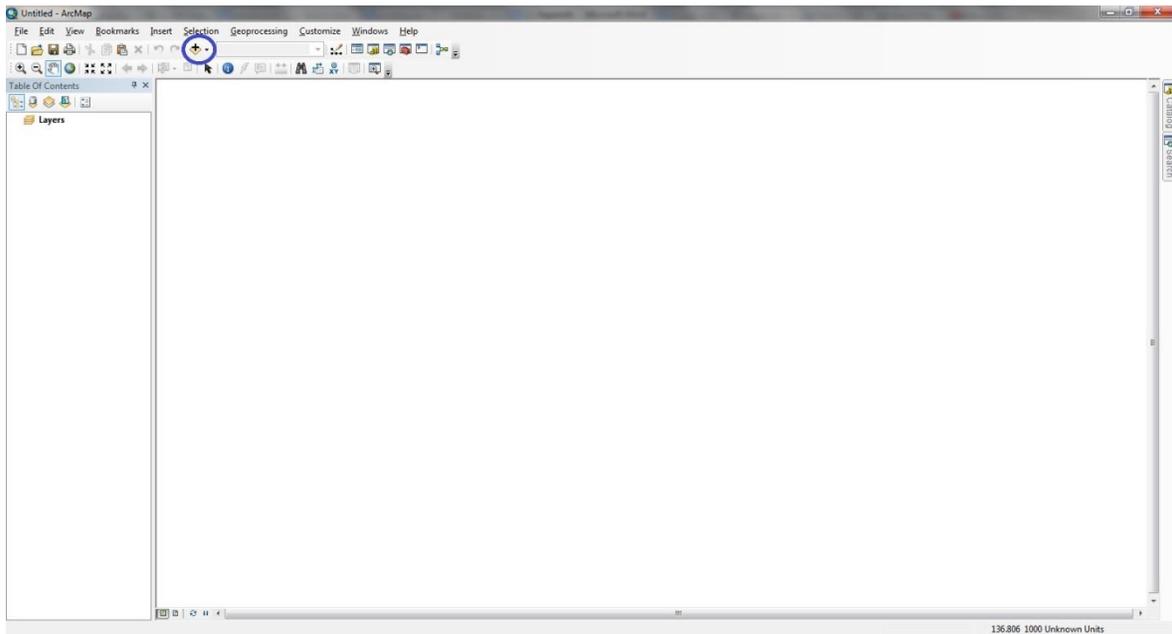


Figure 19. Screenshot of blank map document with other options available in toolbars present at the top

3. Once the development plan is loaded in ArcMap it will look something like shown in the figure. But as it is just an image it will not have any spatial reference. So to geo-reference the image the geo-referencing tool bar is selected by right clicking on the toolbar area beneath the Menu bar of the software window as shown in figure 19.

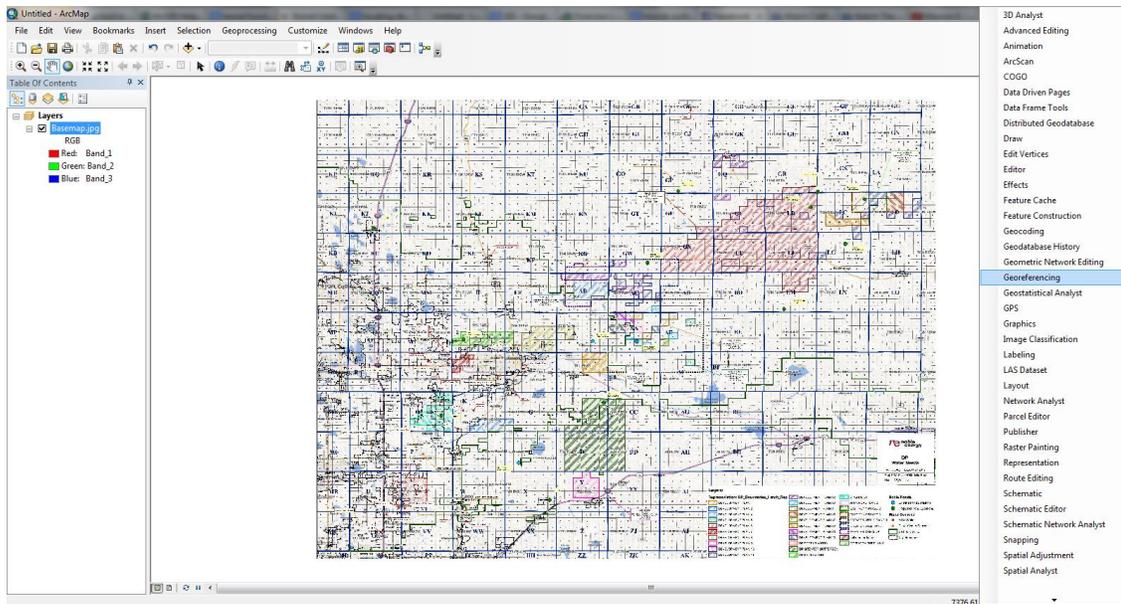


Figure 20. Screenshot of the dropdown menu for more toolbar options

4. Now to geo-reference the image there has to be spatially referenced background. As the development plans are prepared using the PLSS (Public Land and Survey System) grids, the PLSS map available on ArcGIS Online is used.

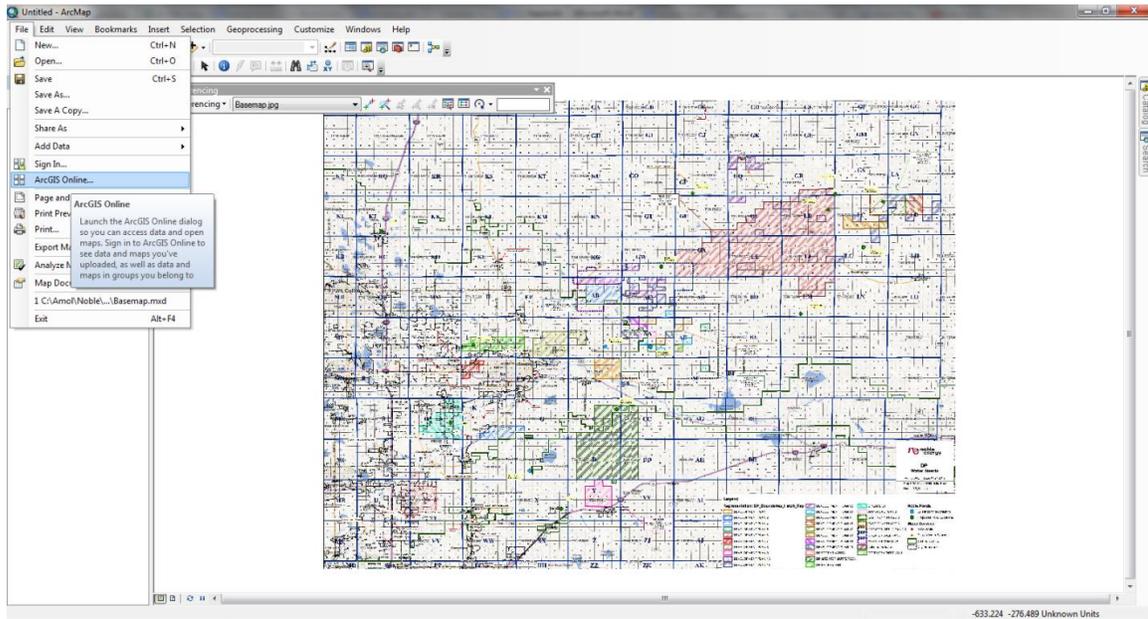


Figure 21. Screenshot showing the location of the ArcGIS online menu

6. Double click on the PLSS map thumbnail in the ArcGIS online window to load the map into your map document.

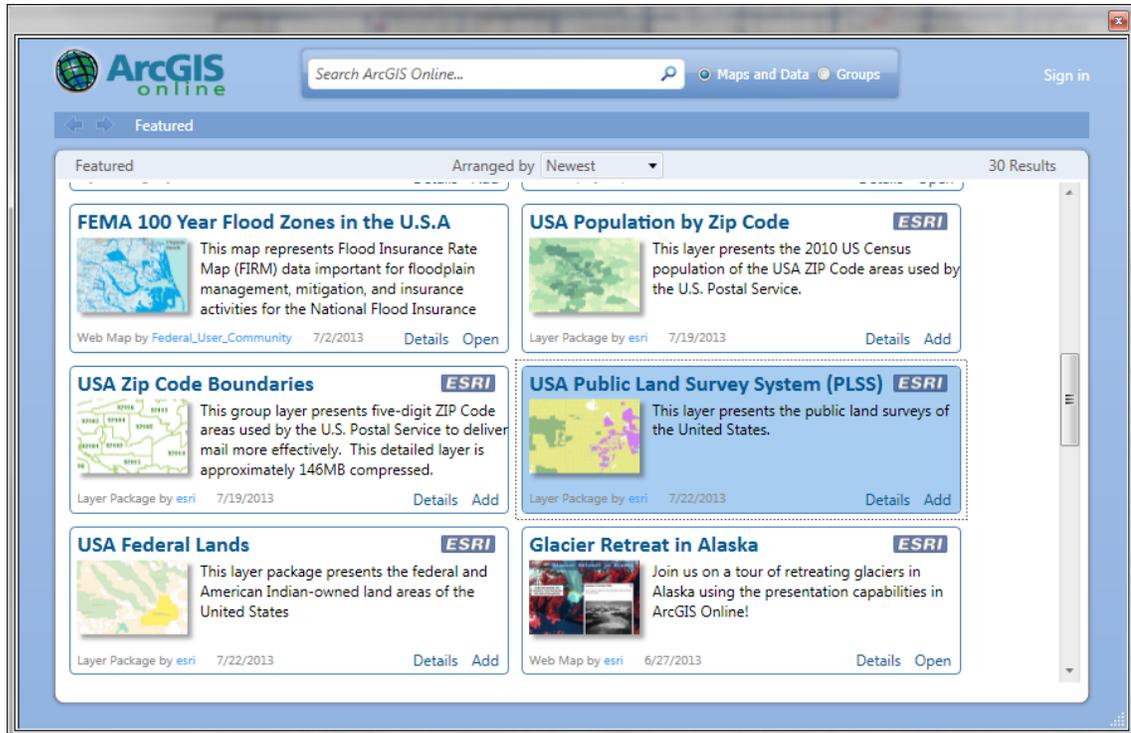


Figure 22. Screenshot showing all the maps available for use on ArcGIS online along with the PLSS map

7. Once the PLSS map is loaded, the display will appear something like as shown in figure 22. Now select the image of the development plan from the dropdown menu in the geo-referencing toolbar and identify the grids in the PLSS map which are present in the area of interest to geo-reference the image properly.

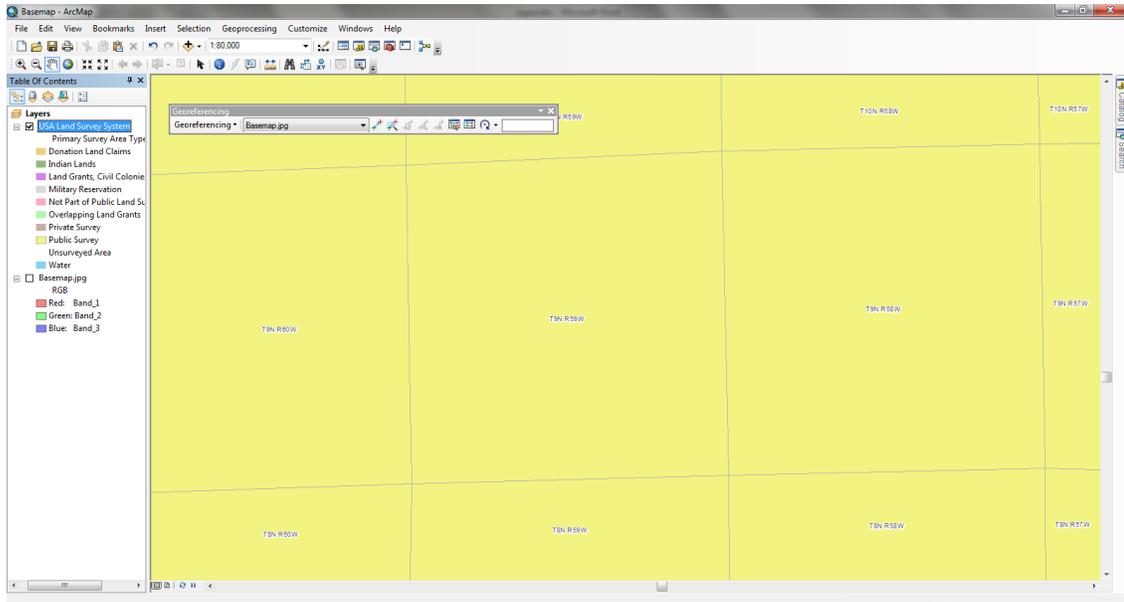


Figure 23. Screenshot showing the display of the PLSS map and the geo-referencing toolbar

- Click on the Add Control Points button on the geo-referencing tool bar and then click on the convenient points on the image and then click on the corresponding points on the PLSS map. The more the number of points, more is the accuracy of the referencing.

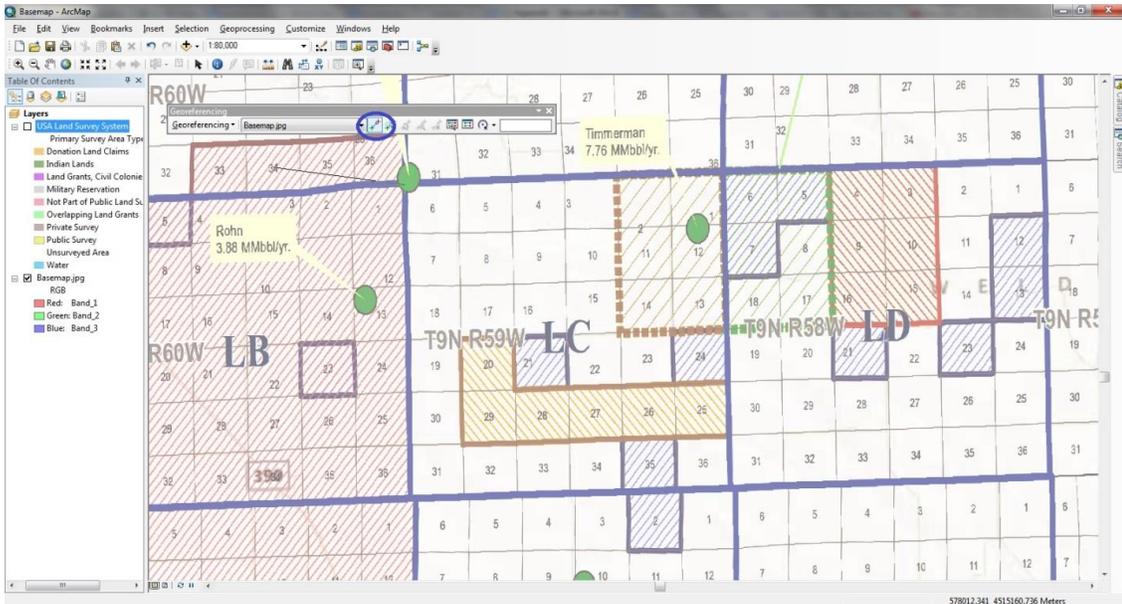


Figure 24. Screenshot showing the “Add Control Points” button and the geo-referencing points just beneath the geo-referencing toolbar

9. The edges in the geo-referenced image should approximately match with the ones in the PLSS map as shown in figure 24.

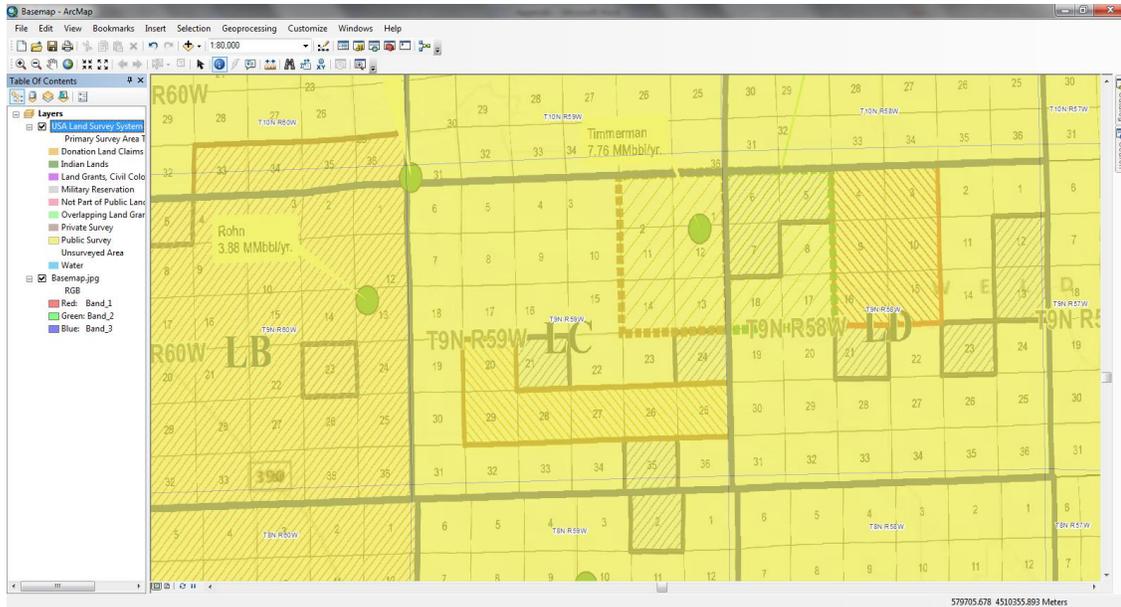


Figure 25. Screenshot showing the geo-referenced development plan image with the PLSS map ready for further analysis

10. Now again right click on the area beneath the menu bar in the software window, select the Editor Toolbar to draw the boundaries of the area of interest for the further analysis.

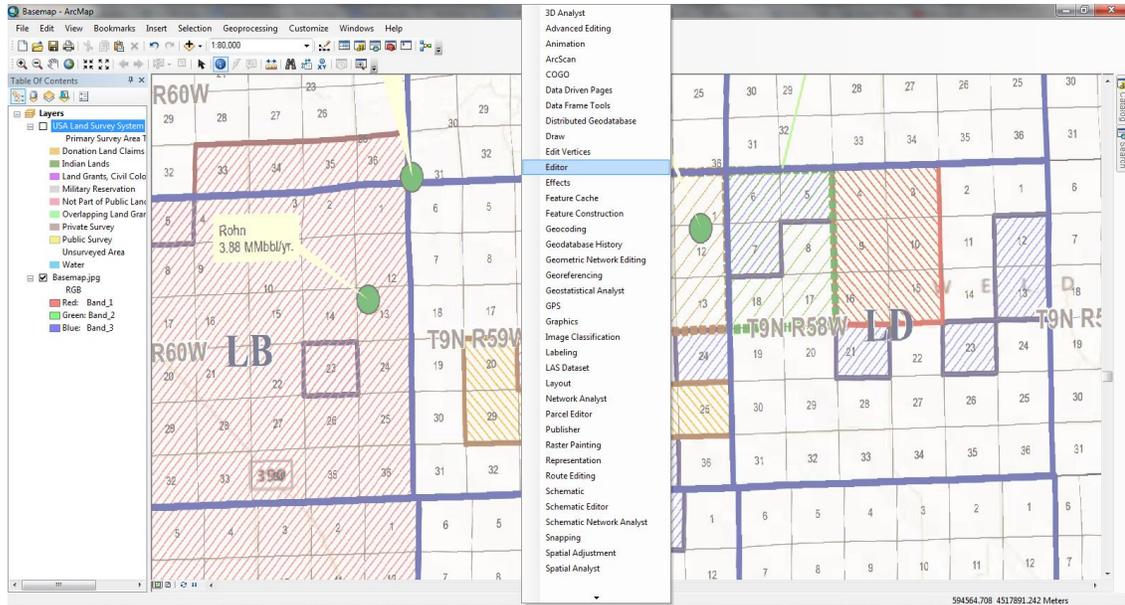


Figure 26. Screenshot showing the dropdown menu of all the available toolbars

11. Now click on the ArcCatalog pinned to the upper right hand side of the software window and go to a desirable path where you want to store your desirable data. Then right click on the folder and select new and then select Shapefile as shown in the figure 26.

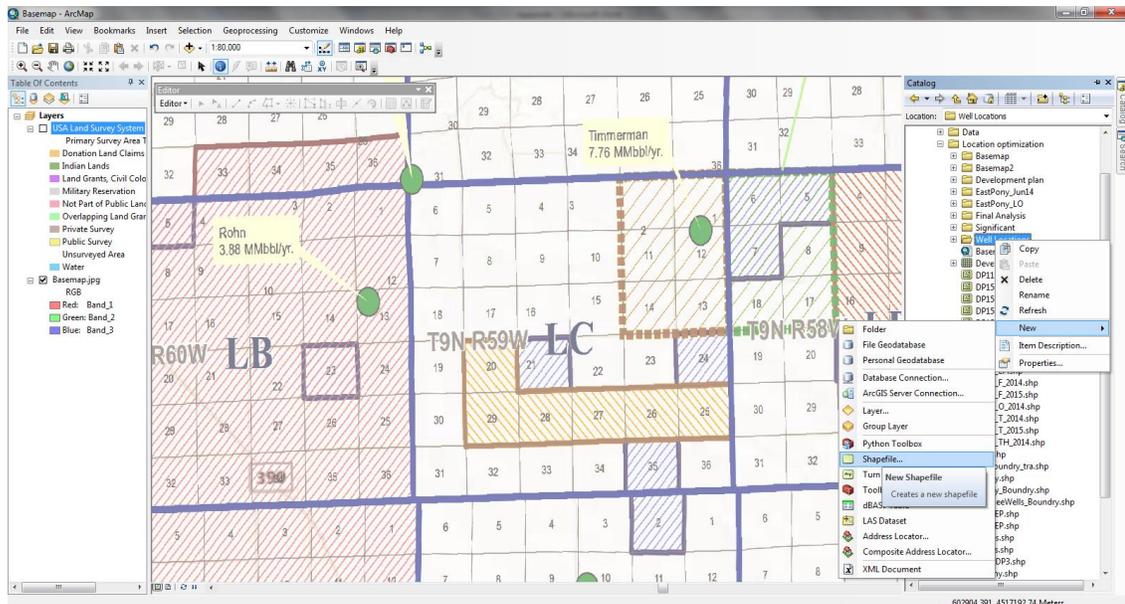


Figure 27. Screenshot showing the path to create a shapefile through ArcCatalog

12. Once you click on the shapefile option a window named “Create New Shapefile” will pop up. Name the shapefile in the name field and specify the type under the feature type. For boundary shapefile the type is going to be a polygon. Then select the same coordinate system as the layer’s coordinate system by clicking on the edit button present in the lower right corner of the description area. Once this is done click on the OK button and then drag the newly created shapefile into the table of contents window of the ArcMap which basically will add the blank shapefile to the map document.

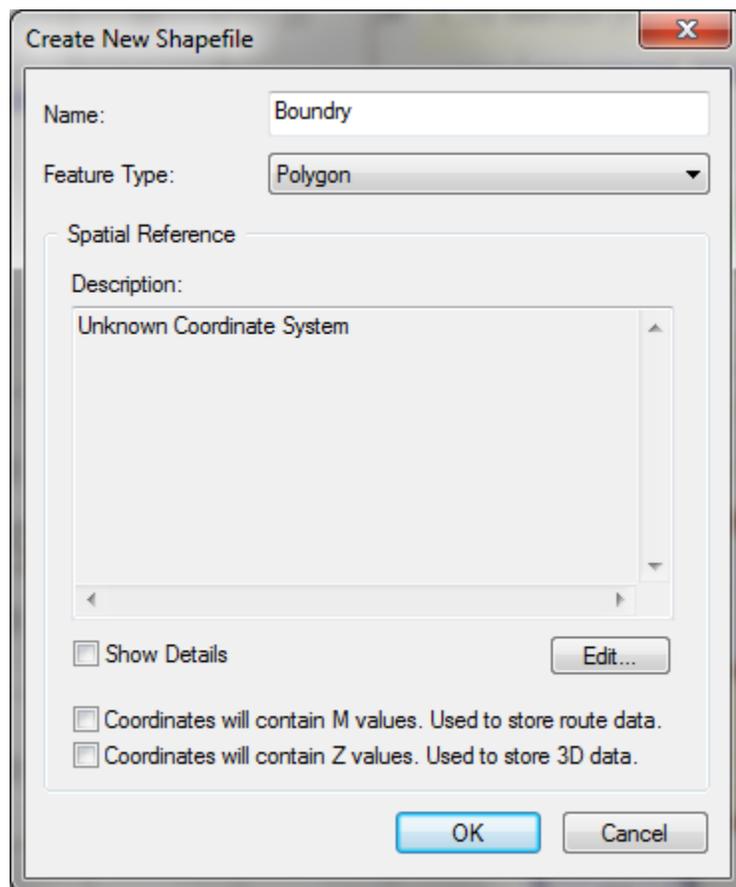


Figure 28. Screenshot of the Create New Shapefile window

13. Now click on the editor button present on the left side of the editor toolbar and click on “Enable Editing” in the dropdown menu which pops out.

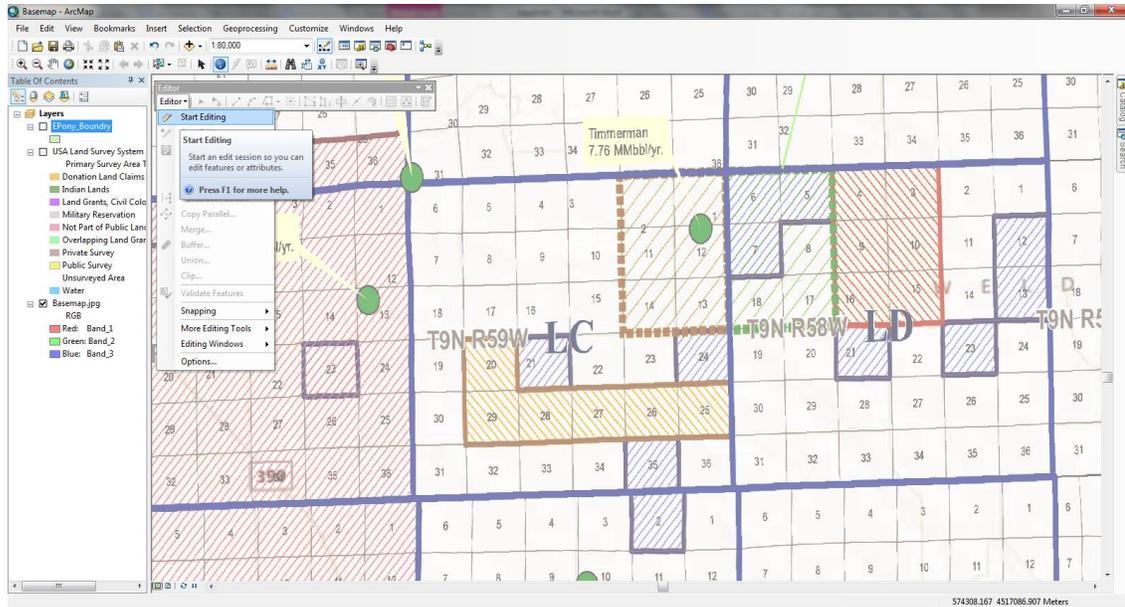


Figure 29. Screenshot showing the Editor Toolbar

14. Once you click on start editing button a new window will pop up which will ask you to choose between the layers present in the table of contents of the map document to edit. Here you chose the newly created shapefile and click on OK.

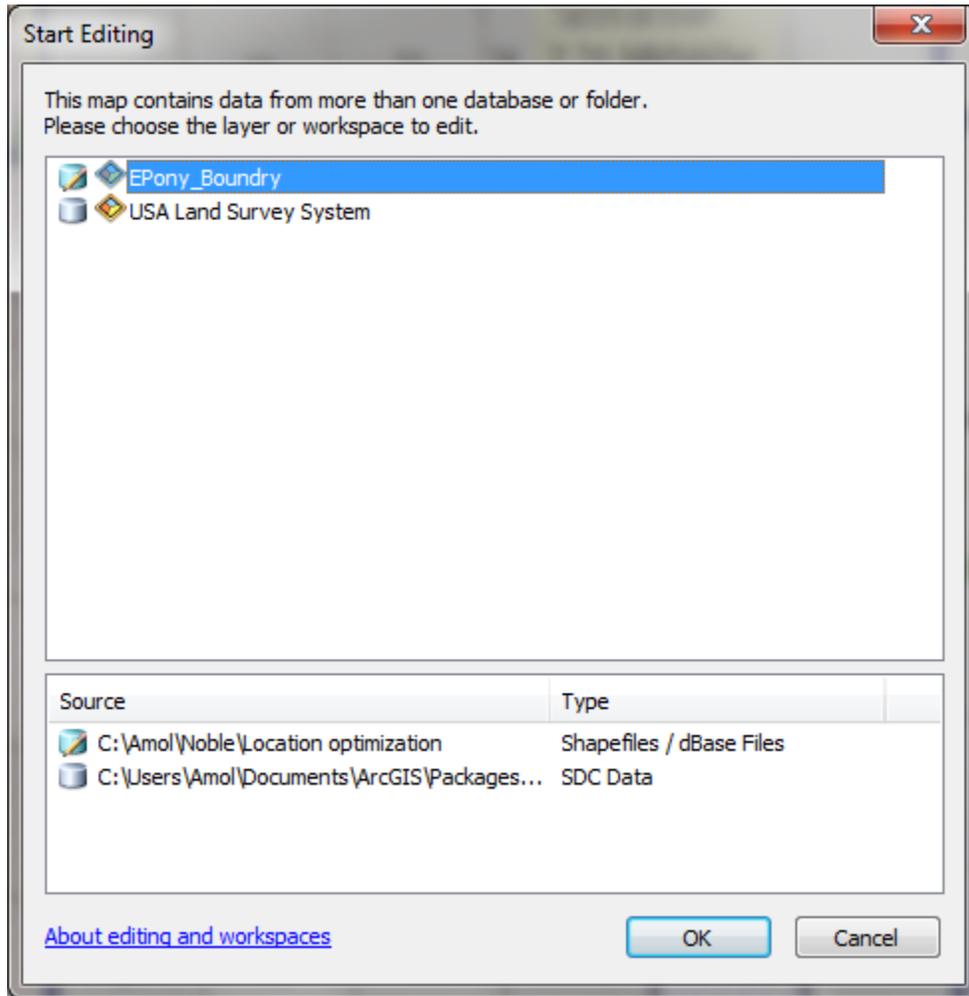


Figure 30. Screenshot showing start editing window

15. Once you click on OK, there will be a Create Features window pinned to the right hand side which will show all the editable features available for the current editing session. So now select the shapefile you just created and you will see a list of construction tools in the bottom of the Create Features Window. Then select the Polygon tool to draw the boundary of the desired area.

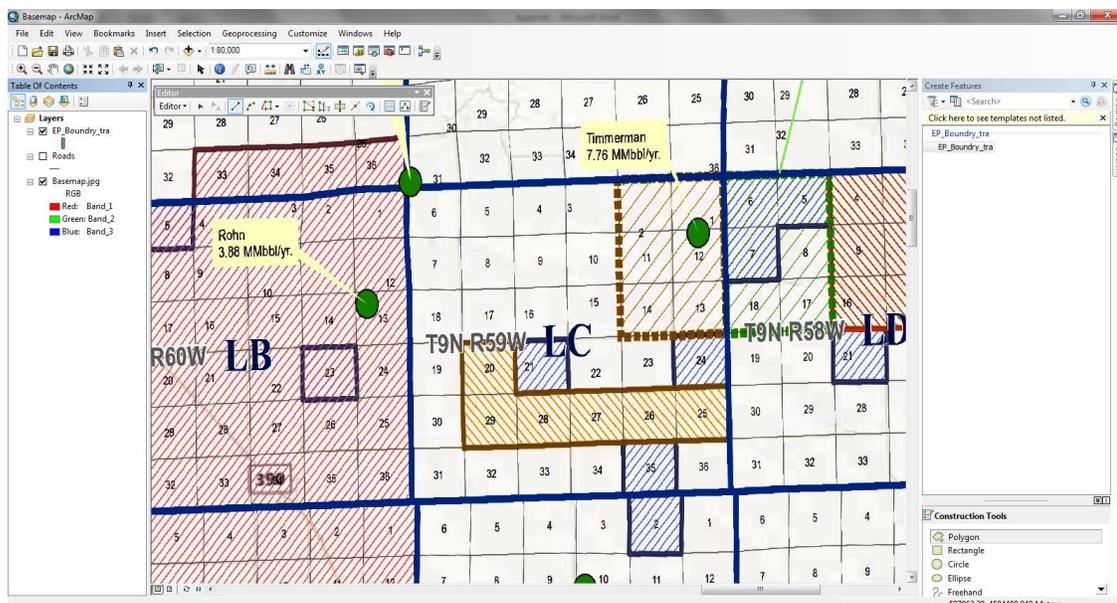


Figure 31. Screenshot of Create Features window under an edit session

16. Once this is done, you will see a cross marked cursor on the screen. Now start by clicking on one of the vertex of the boundaries and then trace along the line of the boundary as seen in the development and click on the vertices or the points where you want to change the direction of the line and start tracing again. Once you reach the same point where you started double click on the point. By double clicking you specify the closing point of the boundary. Now again click on the editing Editor button on the Editor toolbar ad click on Save Edits and then click on Stop Editing.

17. Similarly create another new shapefile in ArcCatalog for the roads which are assumed along the one square mile grids using the same procedure mentioned before and import that into ArcMap. Now click on Editor button on Editor toolbar and start editing. Now click on the shapefile created for roads in the start editing window. Now you will have the Create Features window pinned to the right side where you will see the roads shapefile selected and down below there is list of construction tools. Here you select the line tool as the roads are gonna be drawn in the form of lines. The roads are assumed to be along the one square mile grids. So just draw the lines along the lines already present in the development plan image by right clicking on starting point and then double clicking on the end of the line, both of which are going to be lying on the boundary of the area under consideration. The end result looks as shown in figure 31.

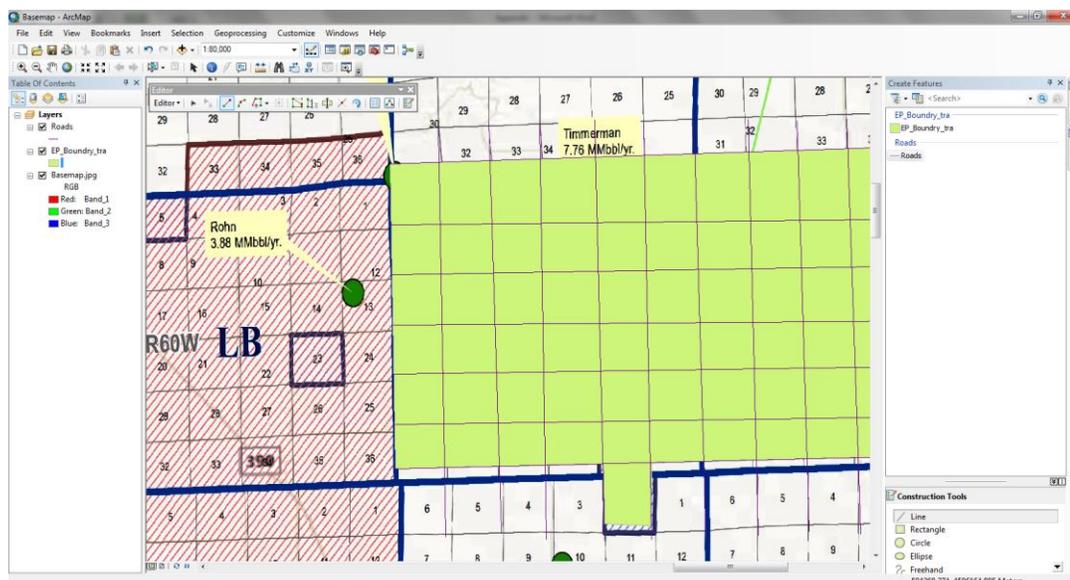


Figure 32. Screenshot showing the roads shapefile drawn on top of the boundary shapefile with create features window pinned to the right side

18. Now observe the development plan patterns and create boundaries for each development plan areas according to the table, which shows which sections are going to be developed together. This will help in creating the well points accurately bound within the areas of developments. In the area under consideration here, the areas hatched in blue color lie under the development plan 11 and the boundaries drawn for that look as shown in figure 32. Do this for all the development plans and have the boundaries ready before you move on to the next step.

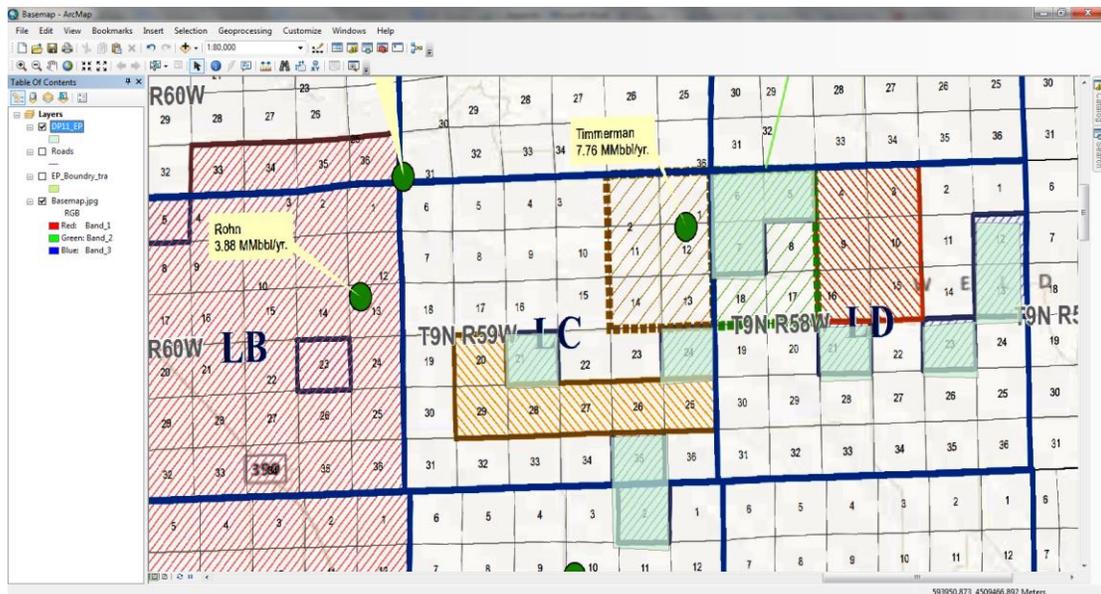


Figure 33. Screenshot showing drawn boundaries of development plan 11 using editor toolbar

19. Now the map is ready for plotting the well locations. For plotting the well locations the Create Random Points tool is used. This tool is located in the Data Management Tools under the Feature Class system toolbox in the Arc Toolbox.

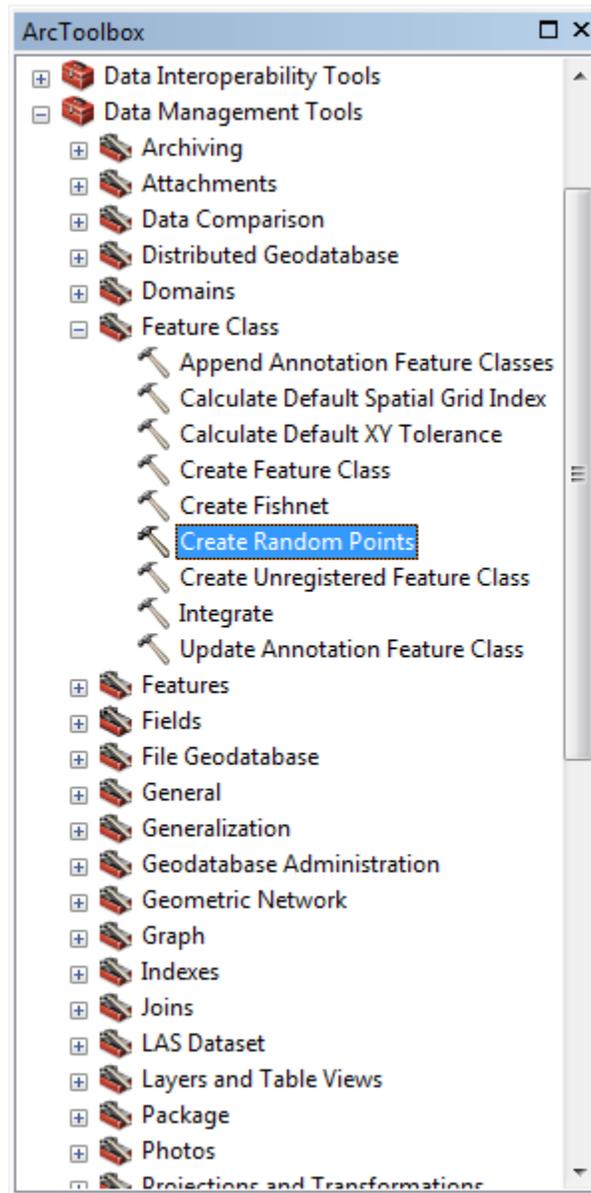


Figure 34. Screenshot showing the location of Create Random Points toolbox in the Arc Toolbox

20. Once you open the Create Random Points tool specify the output location of the output feature class and name it in the respective fields as shown in figure 34. Specify the area in which the points representing the wells will be plotted in the Constraining Feature Class field, which in this case will be the shapefile created for development plan 11 as shown in the figure. The Number of Points field is a bit tricky. One has to input the number of points to be plotted in each closed boundary present under the particular shapefile if there are multiple boundaries staggered all over the area; like in the present case there are six closed polygons present under the development plan 11 shapefile as shown in figure 32. Suppose if there are 12 wells to be drilled under that development plan in the particular quarter, one has to enter number 2 in the Number of Points field so that 12 points will be plotted in the six closed polygon boundaries, two points in each. In the Minimum Allowed Distance field, I have used 100 feet as the minimum distance between the points considering my field experience.

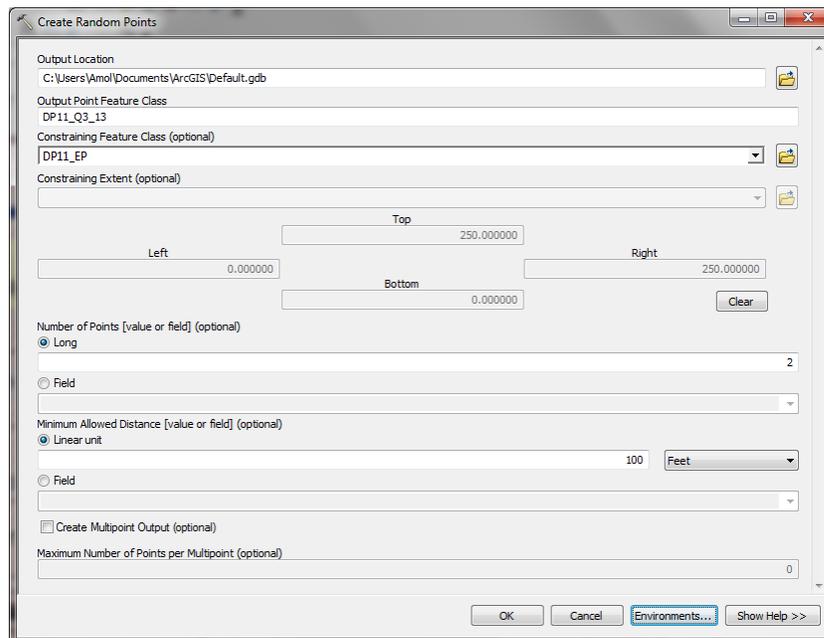


Figure 35. Screenshot showing the details of the Create Random Points tool

21. Now click on the Environments button present at the bottom right of the Create Random Points tool window. Under the environment settings open the Output Coordinates tab and specify the Output Coordinate System as Same as the layer of the development plan shapefile, which in this case will be the development plan 11 boundary as shown in figure 35. This will help maintain the homogeneity of the coordinate systems throughout the analysis. Also under the Processing Extent tab specify the extent as development plan boundary shapefile. This just reduces the computer's efforts to find the Constraining Feature Class mentioned in the main tool window throughout the extent of the map and makes the overall process faster. Once this is done click on OK button at the bottom right of the Environment Settings window and again click on OK button of the main tool window. This will run the tool and create the points.

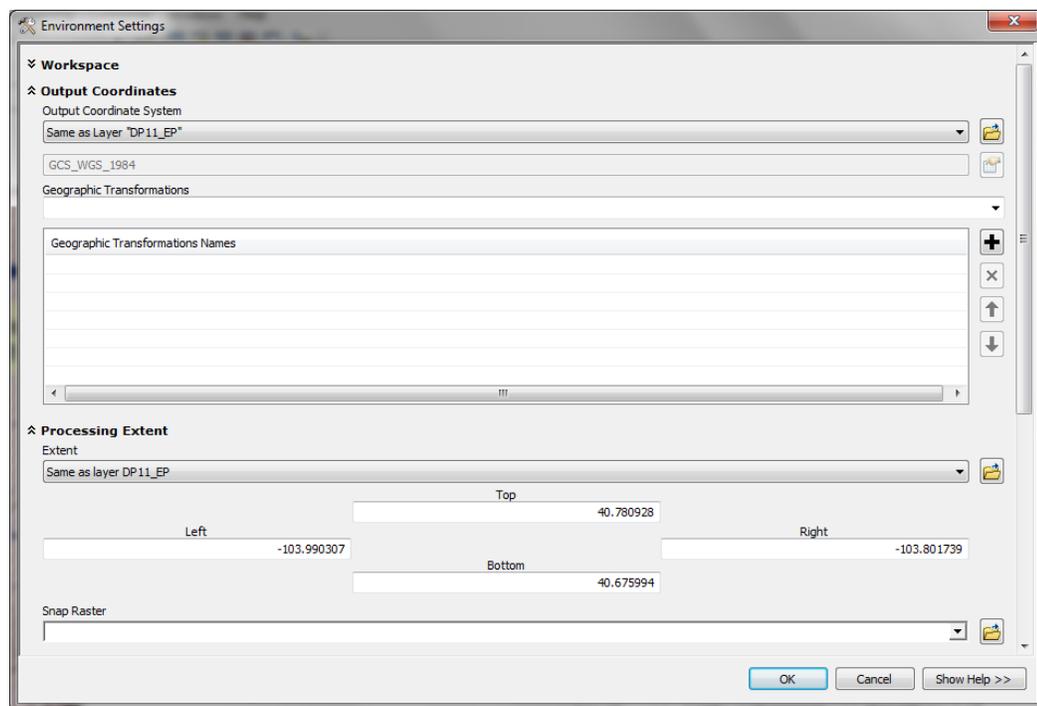


Figure 36. Screenshot showing the Environment Settings of the Create Random Points tool

22. After the tool is run the created points will appear on the map as shown in figure 36.

Sometimes the number of points created might a bit different than what you intended to create. It all depends on the conditions provided while running the tool.

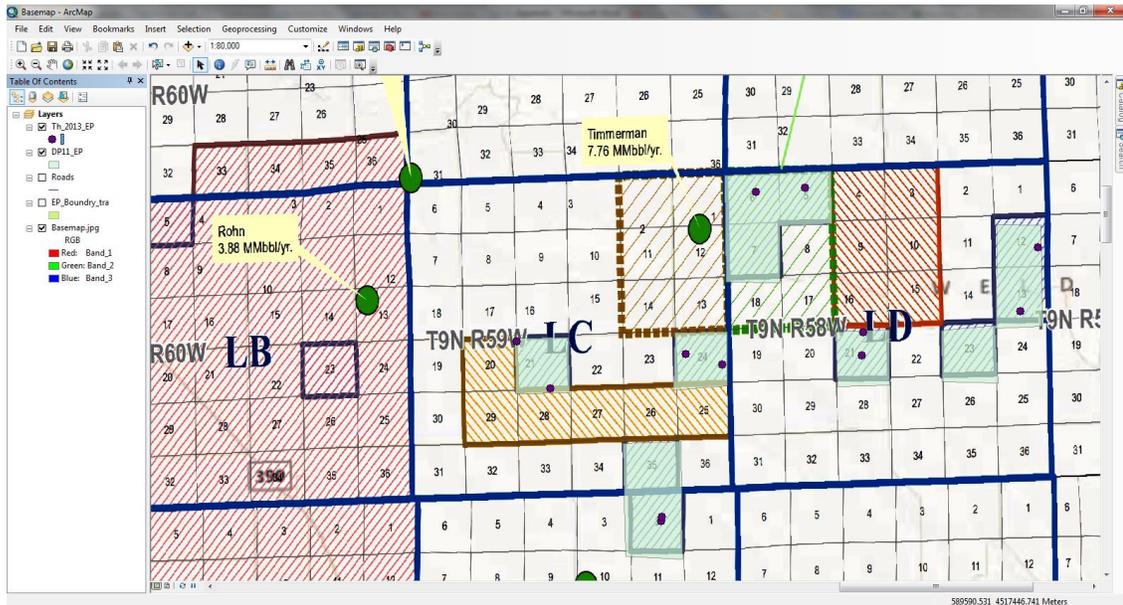


Figure 37. Screenshot showing the points created after the Create Random Points tool

23. Open the Attribute Table of the wells shapefile by right clicking on it and then clicking on Attribute table. Now click on the Table Options button and select add field as shown in the figure.

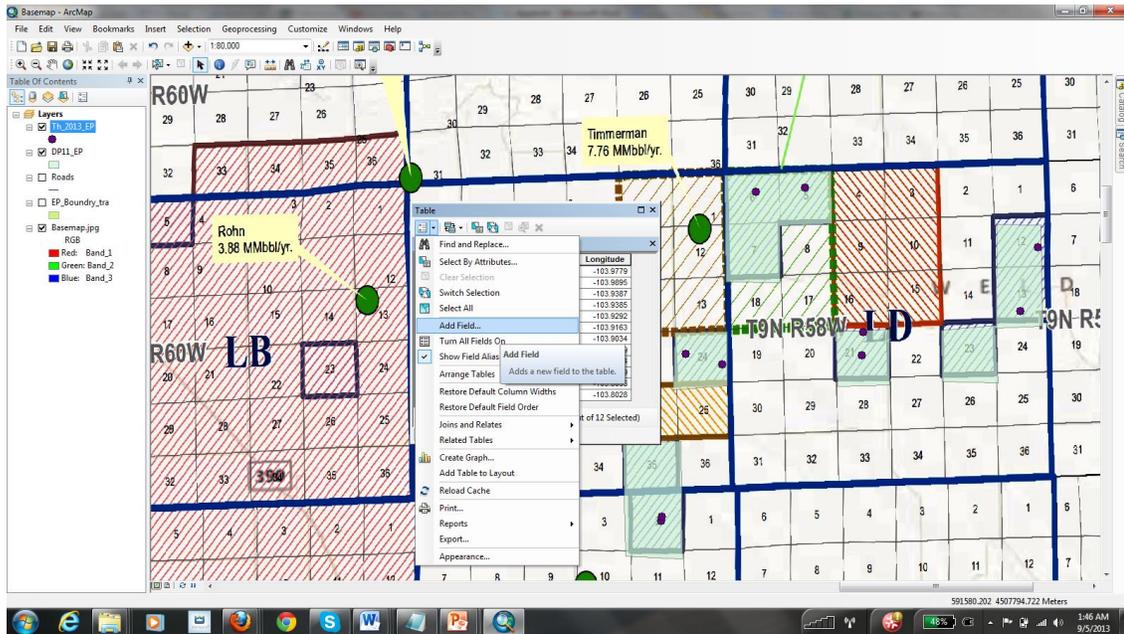


Figure 38. Screenshot showing the Add Field option in the Table Options of the Attribute Table of the wells shapefile

24. Here we need to add four fields to the Attribute Table for the Water Prediction to work. In the Add Field window you have to enter the name of the field and type of it. Following are the fields and the type of each of them. Write the names of the fields as described in the table. Otherwise the prediction tool will not work.

Field	Type
Latitude	Float
Longitude	Float
DRILL_DATE	String
Days	Integer
WaterProdu	Double
WaterCuml	Double

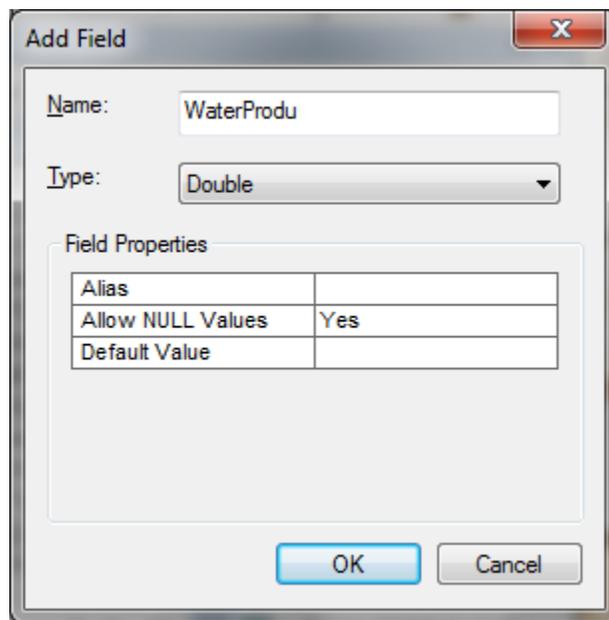


Figure 39. Screenshot showing the contents of the Add Field window

25. Now pull out the Editor Toolbar as described in step 9. Then click on the Editor Button on the toolbar and then click on start editing. Now enter the drilling date for each well point in the Attribute Table under the DRILL_DATE attribute. IF the dates

are available, you can enter those. At the time of analysis the dates weren't available, so the wells were evenly distributed over the period of a certain development plan.

26. Now is the time to bring in the prediction tool to do the further analysis. Click on the Customize menu in the menu bar and then click on Add-In Manager.

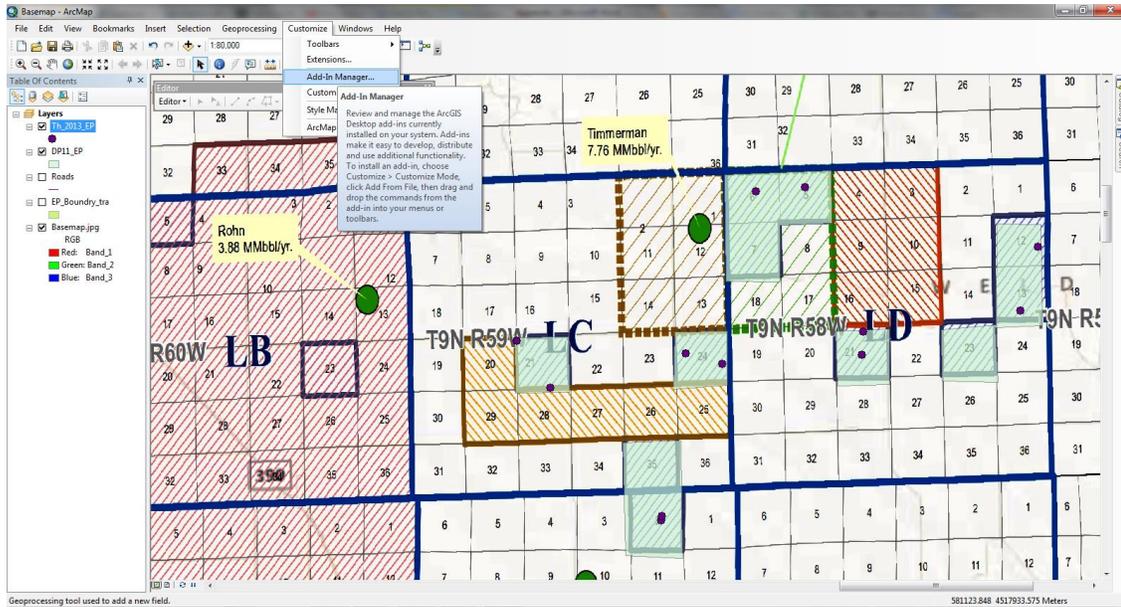


Figure 40. Screenshot showing the location of Add-In Manager in the menu bar

27. Now launch on the Customize dialogue by clicking on the options tab in the Add-In Manager and then click on the Customize button on the bottom right corner.

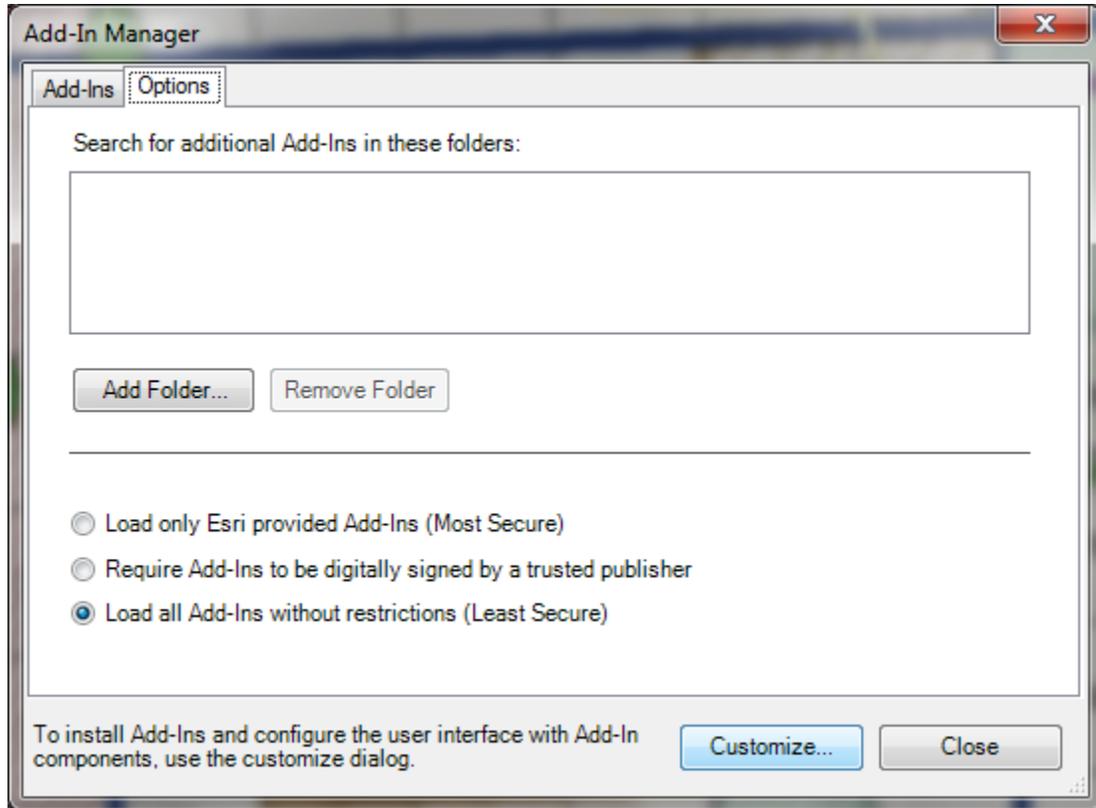


Figure 41. Screenshot showing the Add-In Manager window

28. In the Customize window click on the Commands tab and then click on the Add From File button present in the bottom and browse to the location of the Add-In file and then click on the file and click on the Open button. The tool will then appear in the Commands window as shown in the Figure 41. Now drag the tool from the Commands window to the area beneath the Menu bar. The tool will appear as a button in the area beneath the Menu bar as shown in Figure 42.

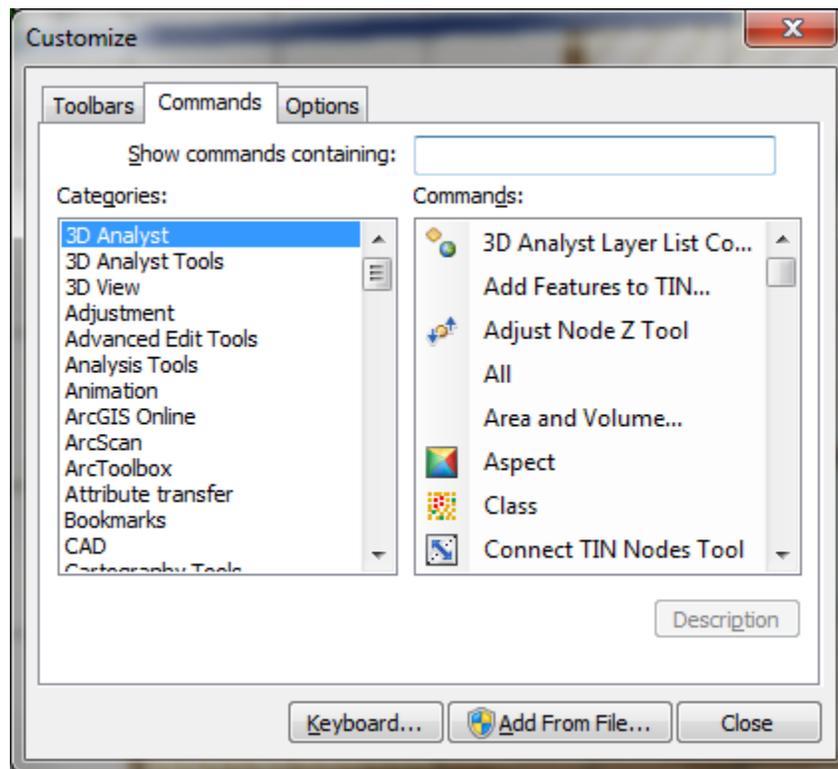


Figure A.25. Screenshot showing the Customize dialogue box

29. Once the tool is added to the window double click on the button and a GUI will pop up on the left hand side of the window which will consist of calendar as shown in the Figure 42. Also the shapefile has to be renamed as “All_WR_HZ_wells.” This has to be done because the tool can’t read any file with a name other than this name. Now select a date in the calendar which will be the ending date of the particular quarter of the year in consideration. This date is the date for the end of the analysis. The tool will use this date as the ending date for the analysis and will calculate the water volumes using the drill dates entered.

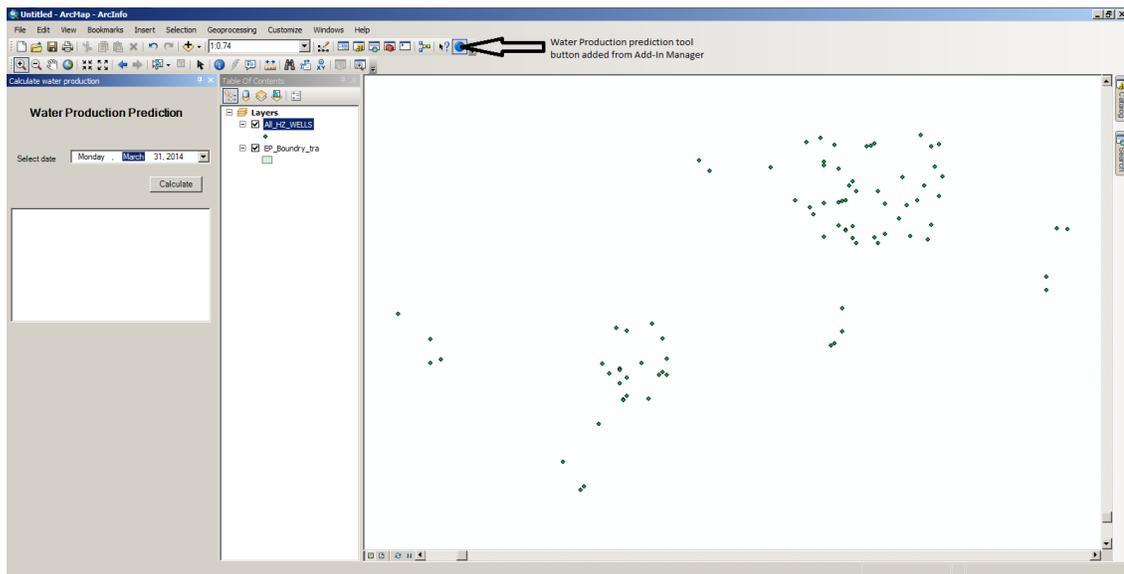


Figure 42. Screenshot showing the GUI of the water prediction tool

30. Now the shapefile is ready for the spatial analysis. We will need to create different rasters (Refer to 5th point in 4.3). The Feature to Raster tool is located in the Arc Toolbox under the Conversion Tools in the To Raster tab.

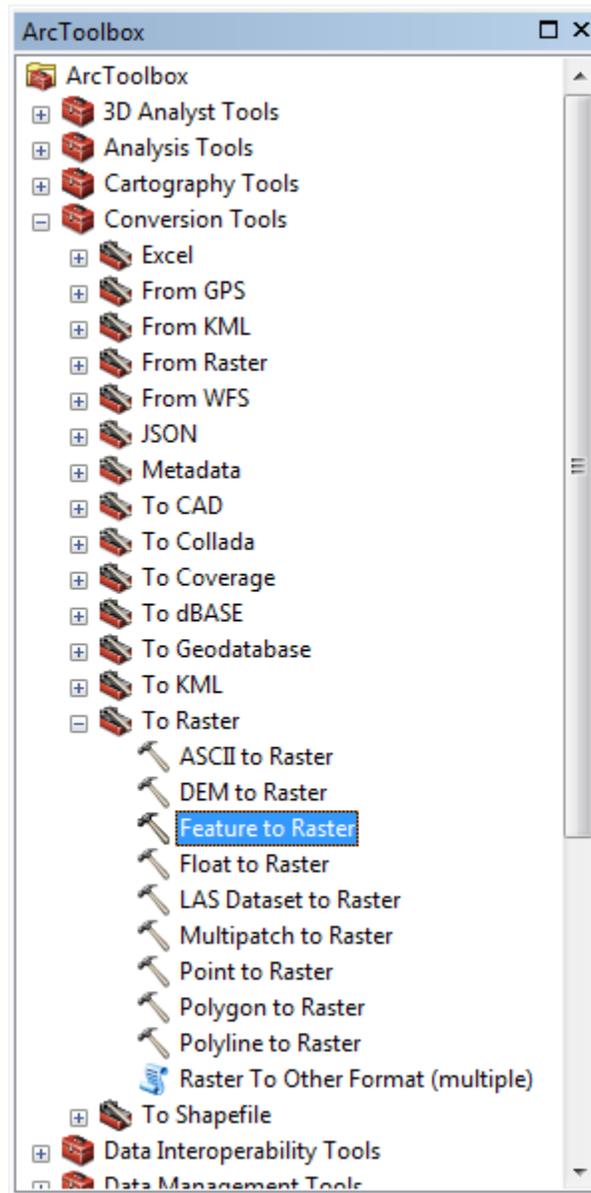


Figure 43. Screenshot showing the location of the Feature to Raster tool in the Arc Toolbox

31. Once you double click on the tool, the tool window will open up. Now select the wells shapefile from the drop down menu of the Input Features. Now select the field based on which the raster is to be created which will be the “WaterProdu” field for the current analysis. Now define the output directory of the output raster along with the name of it in the Output Raster section and define the cell size as 1000. This cell size works better and gives results with the intended visual differences in the output raster. This cell size was chosen after a number of iterations. Use the same Environment Settings as to the Output Coordinate System and Processing Extent as described in Step 20. In addition to that under the Environment Settings, in the Raster Analysis tab, again specify the Cell Size 1000 just to maintain the integrity of the cell size throughout the analysis the same. Also use the mask as the boundary shapefile created before which will avoid the unnecessary processing of the raster outside of the specified boundary saving the time of the analysis.

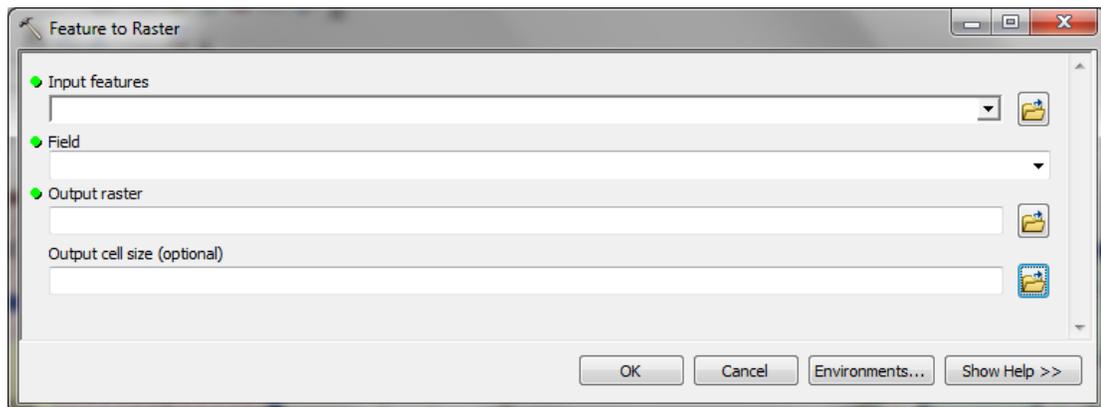


Figure 44. Screenshot showing the contents of the Feature to Raster tool window

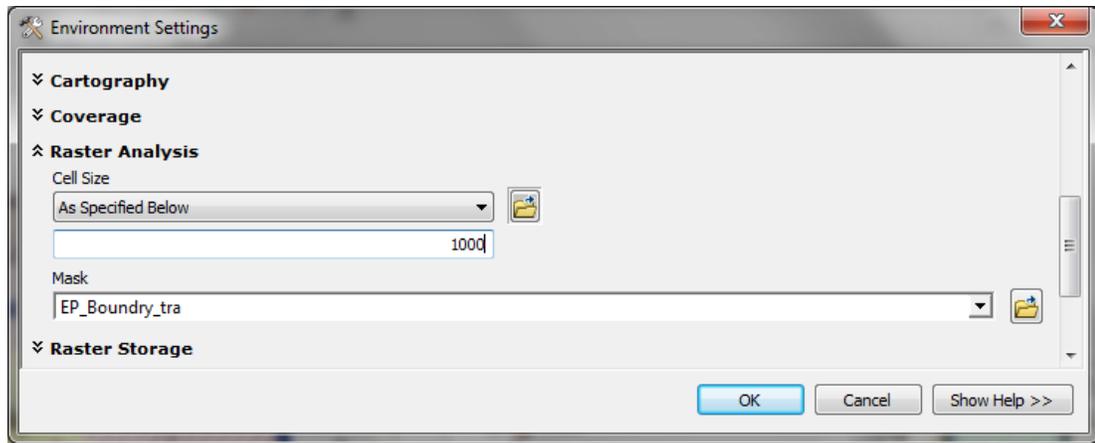


Figure 45. Screenshot showing the Raster Analysis tab in the Environment Settings of the Feature to Raster tool

32. We also need a raster based on the distances of the wells in current quarter and the distances from the roads. For that Near tool is used which located under the Analysis Tools in the Proximity tab.

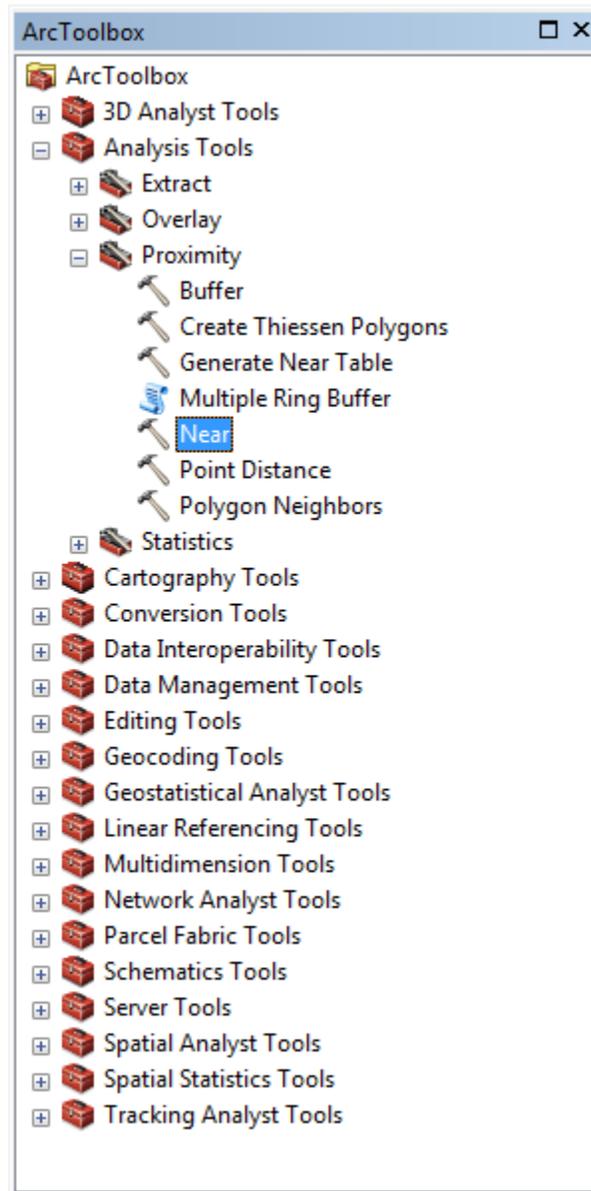


Figure 46. Screenshot showing the location of the Near Tool in Arc Toolbox

33. Once you double click on the tool the Near Tool dialogue box will open up. From the dropdown menu use the wells shapefile as the Input Features. Then use the roads shapefiles or the wells from previous quarter form the dropdown menu of the Near Features. Enter search radius as 5 miles as shown in Figure 47. Under the Environments Settings use the processing extent as the boundary shapefile as described in Step 20.

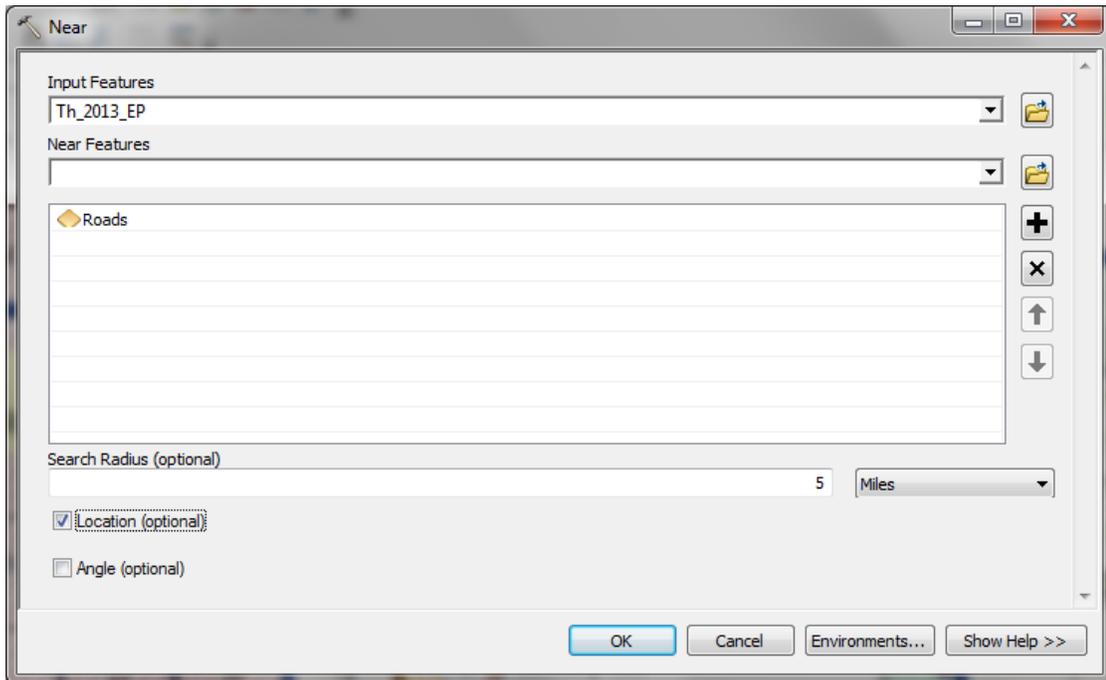


Figure 47. Screenshot showing the contents of the Near Tool window

34. After the tool is run it will add four more columns to the attribute table of the shapefile. Now use the Feature to Raster tool to obtain the raster based on the distances. Use the NEAR_DIST field for obtaining the raster. After one raster is created, you will have to run the tool again for the other near distance analysis. ArcMap doesn't save two different Near Tool analyses in the attribute table of the

shapefile and then again use the Feature to Raster tool to obtain the another raster.
Use the same Environment Settings as described in Step 30.

35. We also need to have two rasters based on the densities of the wells. One based on the density of the wells in current quarter and the one of the density of the wells in the next quarter. For that the Kernel Density Tool is used which is present in the Density tab of the Spatial Analyst Tools of the Arc Toolbox.

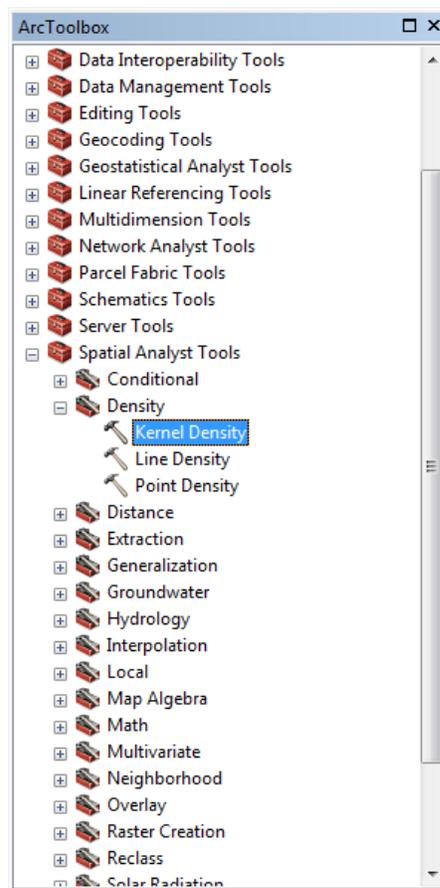


Figure 48. Screenshot showing the location of the Kernel Density Tool in the Arc Toolbox

36. Once you double click on the Kernel Density tool the tool window will appear as shown in Figure 49. Select the intended wells shapefile from the dropdown menu of the Input point or polyline features. Keep the population field as NONE. Then select the name of the output raster and its output directory. The rest of the things are as described in Step 30.

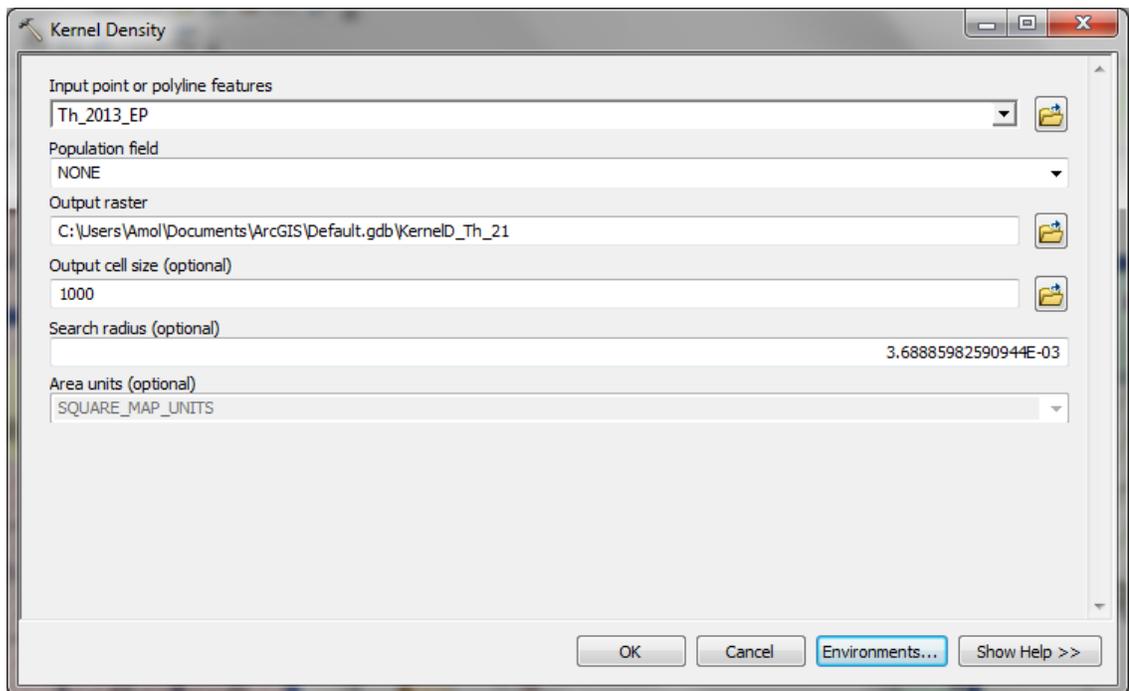


Figure 49. Screenshot showing the contents of the Kernel Density tool window

37. Once we have all these initial rasters ready now is the time for the fuzzy logic analysis. The Fuzzy Membership tool is present under the Overlay tab of the Spatial Analyst Tools in the Arc Toolbox.

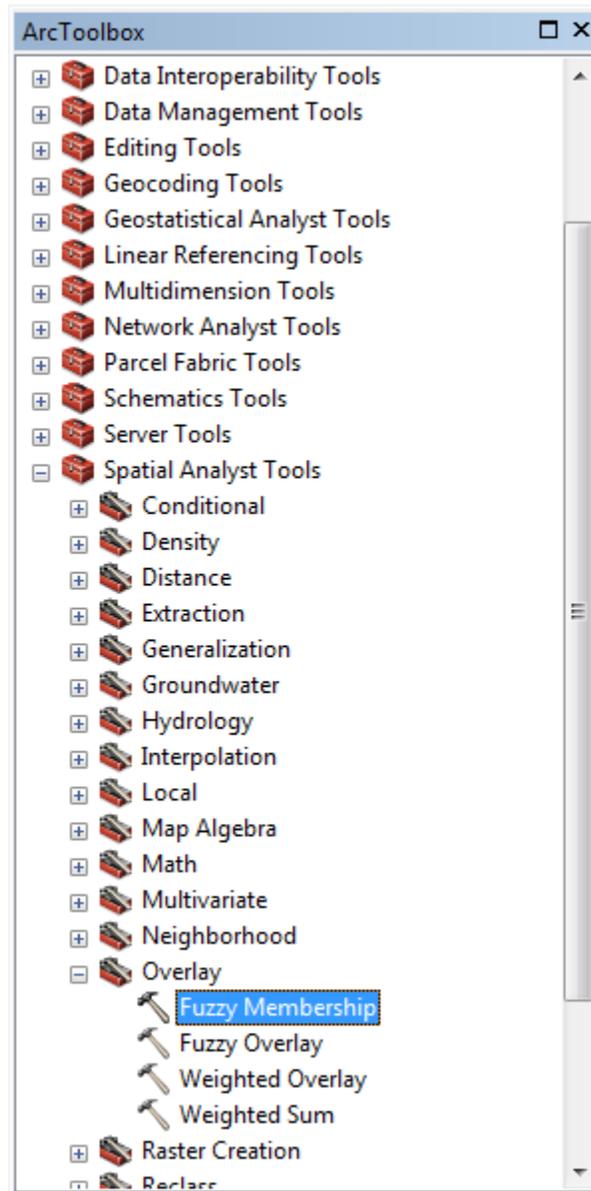


Figure 50. Screenshot showing the location of the Fuzzy Membership tool in Arc Toolbox

38. Once you double click on the tool the tool window opens up. Chose the input raster and then define the out raster name and the output directory. Then choose the Proper Membership type. Refer 5.5 for the proper membership for each raster. The Environment settings are same as described in Step 30.

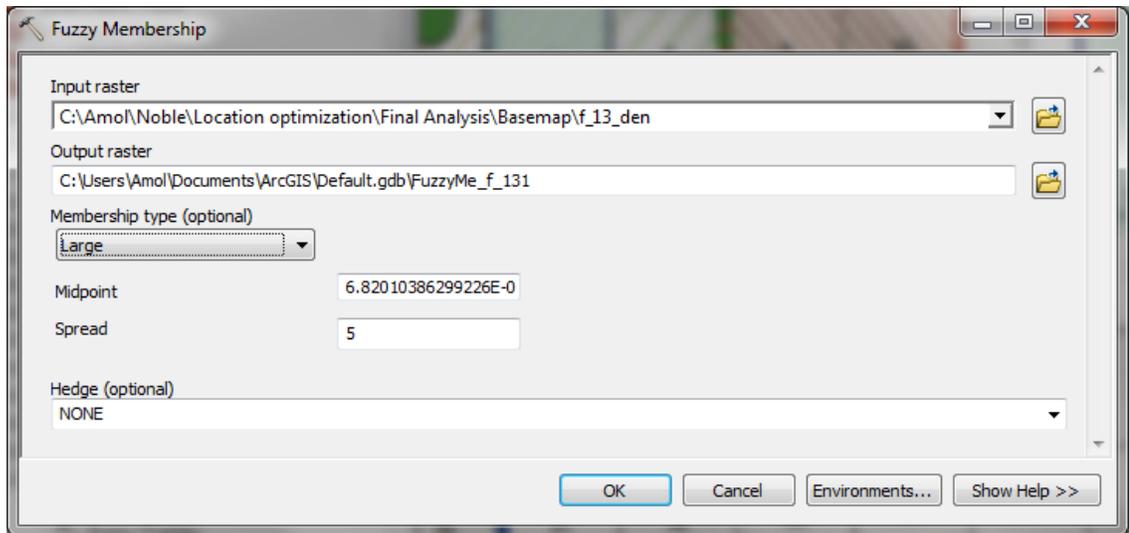


Figure 51. Screenshot showing the contents of the Fuzzy Membership tool window

39. Now to get all the values in the rasters in the form of integers, reclassify tool is used; which is present under the Reclass tab of the Spatial Analyst Tools in the Arc Toolbox.

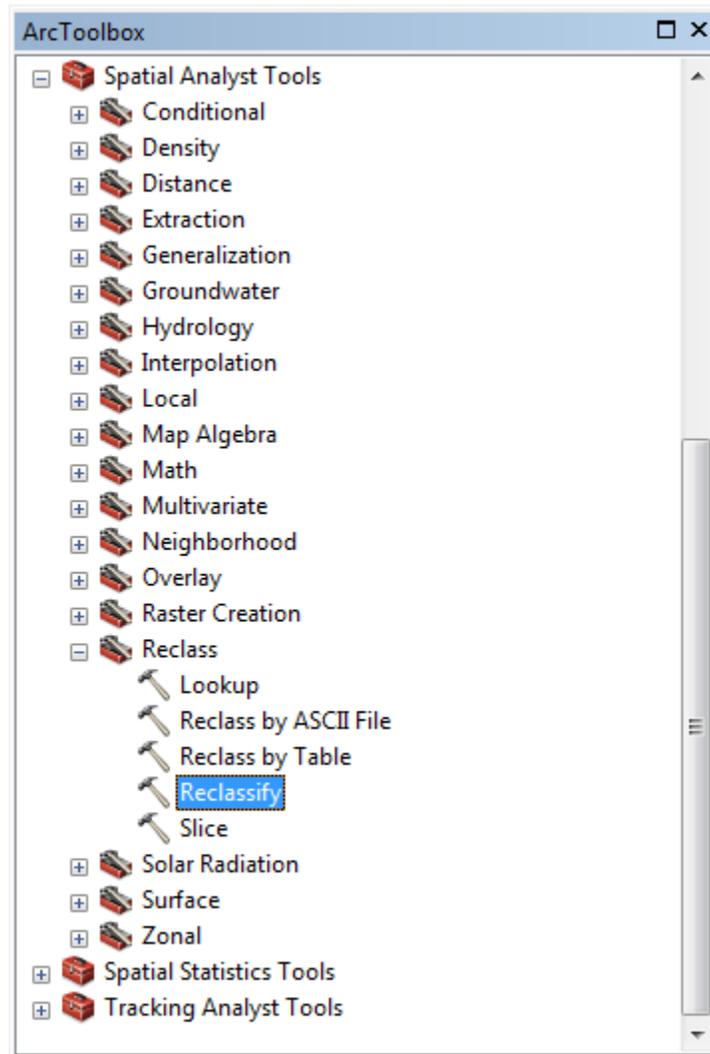


Figure 52. Screenshot showing the location of the Reclassify tool in the Arc Toolbox

40. After you open the window, chose the proper input fuzzified raster as Input Raster from the drop down menu. Chose the Reclass field as Value. For the reclassification pattern refer Table 4. Then define the output directory and the name of the output raster. Use the Environment Settings as described in Step 30.

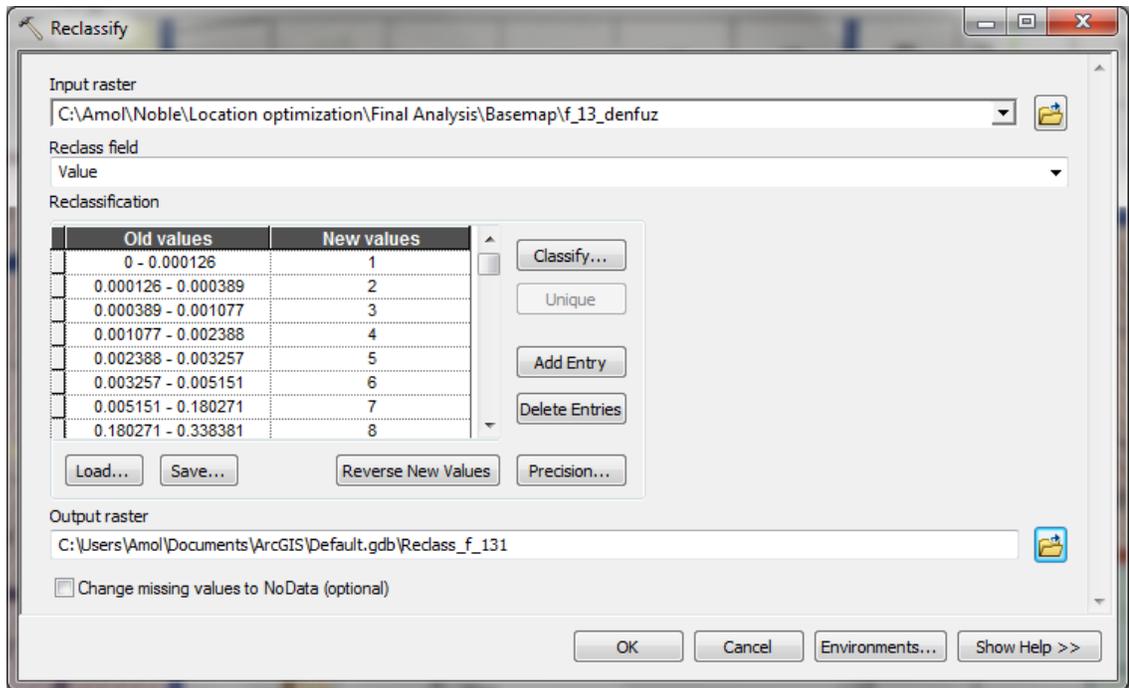


Figure 53. Screenshot showing the contents of the Reclassify Tool

41. Once all the rasters are reclassified it all comes to the final overlaying step. For this the Weighted Overlay tool is used. This tool is located the Overlay tab of the Spatial Analyst Tools tab in the Arc Toolbox.

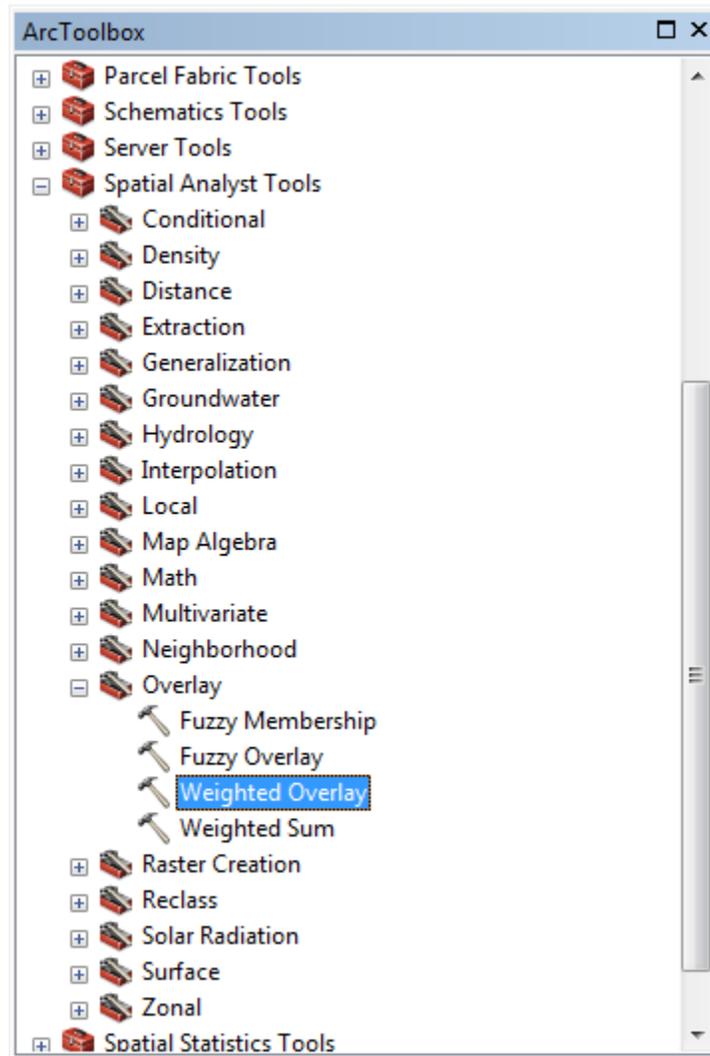


Figure 54. Screenshot showing the location of the Weighted Overlay tool in the Arc Toolbox

42. Once you open the tool, click on the Add raster now button as shown in the figure and add all the reclassified rasters required in the analysis. Then type in the %Influence for each raster such that the sum of all the influences is 100. Otherwise the tool will not work. Now define the output directory and the name of the output raster. The Environment Settings are same as described in Step 30.

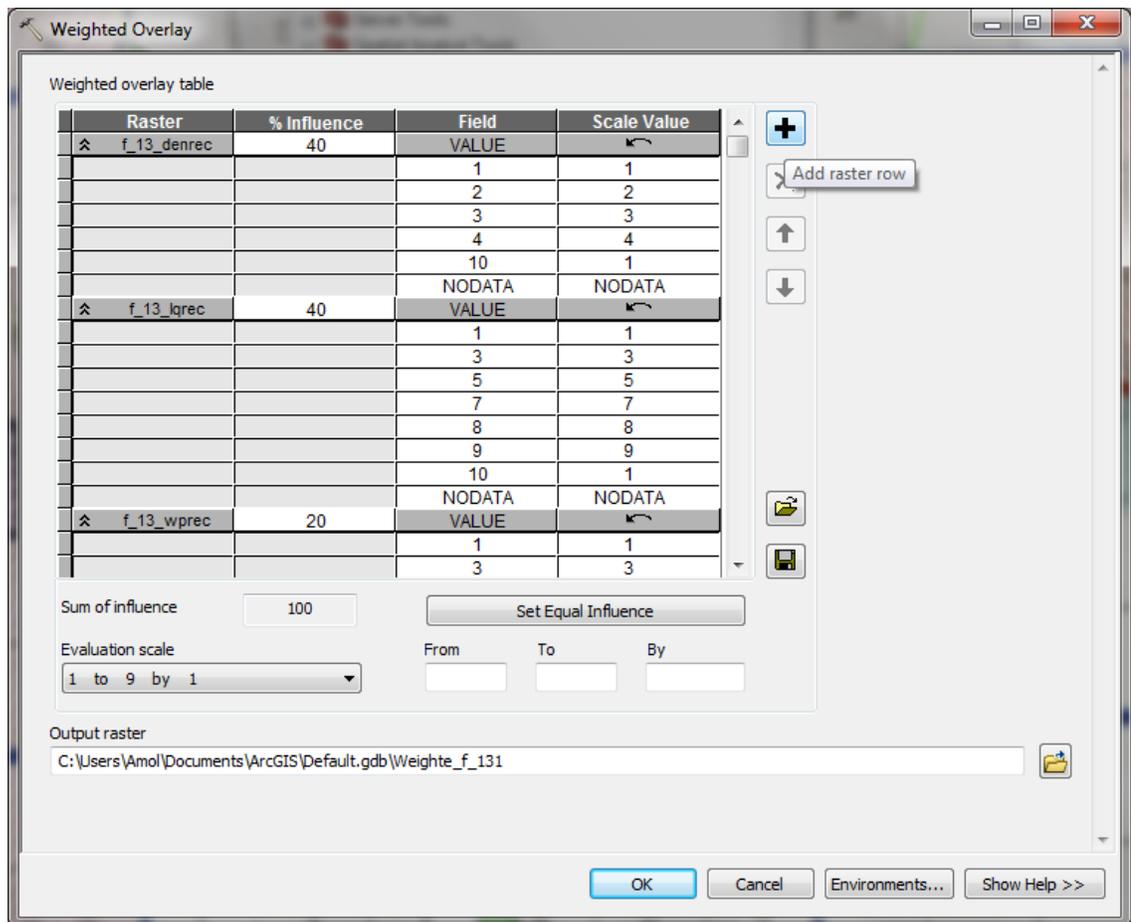


Figure 55. Screenshot showing the contents of the Weighted Overlay tool

A2. The Fuzzication Process.

Large: The Fuzzy Large transformation function is used when the larger input values are more likely to be a member of the set. The defined midpoint identifies the crossover point (assigned a membership of 0.5) with values greater than the midpoint having a higher possibility of being a member of the set and values below the midpoint having a decreasing membership. The spread parameter defines the shape and character of the transition zone.

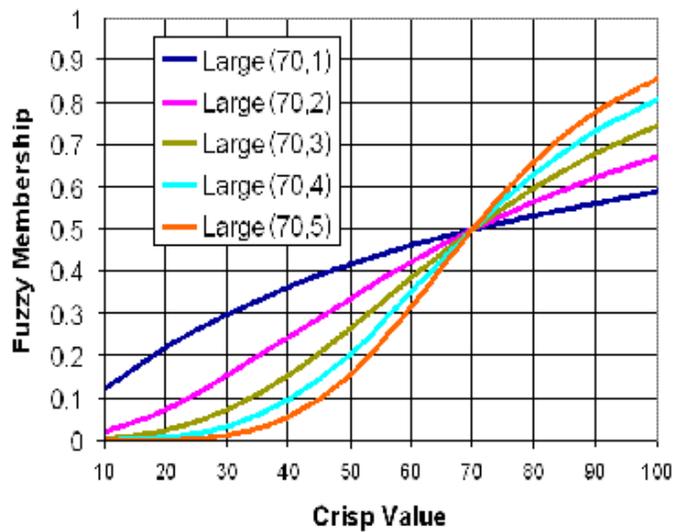


Figure 56. A graph of values in a large type of fuzzy membership showing the spread and the crossover point

Small: The Fuzzy Small transformation function is used when the smaller input values are more likely to be a member of the set. The defined midpoint identifies the crossover point (assigned a membership of 0.5) with values greater than the midpoint having a lower possibility of being a member of the set and values below the midpoint having a higher possibility of membership. The spread parameter defines the shape and character of the transition zone.

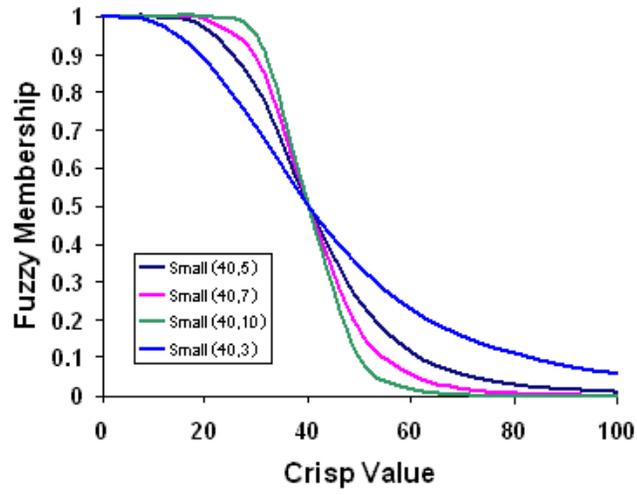


Figure 57. A graph of values in a small type of fuzzy membership showing the spread and the crossover point