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Horizontal wells are the most commonly drilled wells in the Wattenberg Field, located in Weld County, Colorado. Petroleum engineers have become interested in determining how many horizontal wells can economically be drilled per section in this vertically, well-developed field. Using the Colorado Oil and Gas Conservation Commission's spacing unit regulations as a guide, a GIS workflow was developed to create the deliverables required for further analysis. Spacing units were created by applying a buffer to horizontal well surveys, and using this buffer to select intersecting quarter-quarter sections. The selected quarter-quarter sections were simplified using the dissolve tool and then spatially joined to producing wells. The resulting tabular data is exported, edited, and formatted for delivery to engineers for subsequent analysis.

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Abstract

Horizontal wells are the most commonly drilled wells in the Wattenberg Field, located in Weld County, Colorado. Petroleum engineers have become interested in determining how many horizontal wells can economically be drilled per section in this vertically, well-developed field. Using the Colorado Oil and Gas Conservation Commission's spacing unit regulations as a guide, a GIS workflow was developed to create the deliverables required for further analysis. Spacing units were created by applying a buffer to horizontal well surveys, and using this buffer to select intersecting quarter-quarter sections. The selected quarter-quarter sections were simplified using the dissolve tool and then spatially joined to producing wells. The resulting tabular data is exported, edited, and formatted for delivery to engineers for subsequent analysis.

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Tables and Figures

List of Abbreviations

API- American Petroleum Institute

BH - Bottom Hole

COGCC- Colorado Oil and Gas Conservation Commission

DJ- Denver-Julesburg

GIS- Geographic Information System

GWA- Greater Wattenberg Area

Loc- Location

Surf- Surface

TD- Total Depth

Introduction

Noble Energy, Incorporated (Noble) is a leading independent energy company engaged in worldwide oil and gas exploration and production. The Company has domestic, onshore, core operations in the Denver-Julesburg (DJ) basin, the Marcellus Shale, as well as in the deepwater Gulf of Mexico areas in the United States (Noble Energy Inc. 2013, 1). This project focuses on the Greater Wattenberg Area, a subset of the Wattenberg Field, in the DJ Basin, in Northern Colorado.

The state of Colorado, like the United States of America, has a rich history of oil and gas exploration and production. The state was home to the second domestic discovery of oil in 1861 (Randall 2009, 1). The Wattenberg Field is one of the largest fields in the United States and the most active drilling area in Colorado. It was discovered in 1970 (Sonnenberg 2006, 5), and currently holds over twenty thousand wells (Colorado Public Radio 2012). In 2009, the Energy Information Administration ranked Wattenberg as the tenth largest gas, and the thirteenth largest oil field in the United States (2004, 1). Considering the technologic and regulatory advances in the last four years, this statistic is surely dated.

Despite the stereotype, oil and gas development is approached with anything but a "wild west" mentality. In the industry's infancy wells were drilled haphazardly, nearly on top of each other, in an attempt to follow an

underground "river of oil." Fortunately, modern science has brought new understanding to the industry, along with comprehensive rules and regulations. Protecting precious, non-renewable, petroleum resources, the people who extract them, and the general public are now an essential part of the oil and gas industry and its regulatory counterparts.

Spacing units are one of the significant regulations governing the drilling and production of oil and gas. They are defined by Schlumberger as an area allotted to a well by regulations, or field rules, issued by a governmental authority having jurisdiction for the drilling and production of a well (2013). Spacing units are designed to prevent the drilling of unnecessary wells, avoid the waste of hydrocarbon resources, and to protect the interests of all invested parties (Montana Code 2011). Nearly every state with drilling activity has some form of well spacing regulation. The state of Colorado is no exception. In the state the regulatory body with jurisdiction over oil and gas wells is the Colorado Oil and Gas Conservation Commission (COGCC). The commission's Rule 318A spells out the spacing unit requirements for the Greater Wattenberg Area (GWA) and will serve as a guide for this analysis.

Background

API Numbers

To best understand the methodology laid out in later sections, it is important to have a basic understanding of a few standard industry terms and practices. Hundreds of thousands, if not millions, of wells have been drilled

in the United States. Each well is identified by a unique, permanent, numeric identifier, called an American Petroleum Institute (API) number (American Petroleum Institute 1979, 1). Today's standard API numbers are 14 digits in length and are broken into five portions as follows:

05-123-12345-01-02

The first two digits on an API number designate the State in which a well is drilled; the "05" above denotes a well drilled in Colorado. The next three digit number refers to the county in which the well was drilled; this code, as a general rule, matches the Federal Information Processing Standard, or FIPS code. In this example "123" indicates the well was drilled in Weld County. The five digit portion of an API number is the "Unique Well Code," these numbers are assigned by the regulatory body, usually consecutively. The final two sets of two digit numbers designate a well's side track and recompletion statuses respectively. A sidetrack occurs when a secondary wellbore is drilled away from the original. Sidetracks are drilled for a variety of reasons including testing new formations, avoiding unstable geology, or due to other drilling related issues. Each sidetrack is sequentially numbered. A recompletion is essentially a repair performed to a wellbore, restoring a well's productivity. Many vertical wells in the GWA have been recompleted three or more times, creating three or more API numbers. When no sidetracks or recompletions have been performed, these numbers are zeros.

Drilling Techniques

Today there are three methods to drilling an oil or gas well. Vertical drilling is as old as the oil and gas industry itself. This method entails placing a well directly above a target and drilling straight down to tap into oil or gas reserves. The second method is directional drilling. This method entails the intentional deviation of a wellbore from its naturally occurring path by exploiting various drilling parameters such as weight on bit or rotary speed (Schlumberger 2013). Utilizing this drilling technique, oil or gas reserves can be tapped with strategically placed wells. The final drilling technique, and focus of this project, is horizontal drilling, which is an extension of directional drilling. Horizontal wells begin drilling like any other vertical well until they drill down to the designated "kick-out" point. This point is the measured depth where the bit begins to deviate from vertical, pushing out until reaching a ninety degree angle. At this point the well is drilled horizontally until reaching its total depth (TD).

Directional Surveys

In the state of Colorado every horizontal or directional well drilled is required to have a directional survey performed and submitted to the COGCC. Directional surveys are attained by feeding a tool into a wellbore to measure its depth, inclination from vertical, and azimuth (or compass heading). These measurements are then used to delineate a wells' three dimensional path within the earth on a two dimensional map. These surveys play an important

role in shaping a well's spacing unit. Where a well has been drilled within a section determines which quarter-quarter sections make up its spacing unit.

Project Area

The GWA is defined by the COGCC as the area between Townships 2 South to 7 North, and Ranges 61 West to 69 West, 6th Principle Meridian. Figure one shows a map of the GWA area and the oil and gas wells drilled in the area.
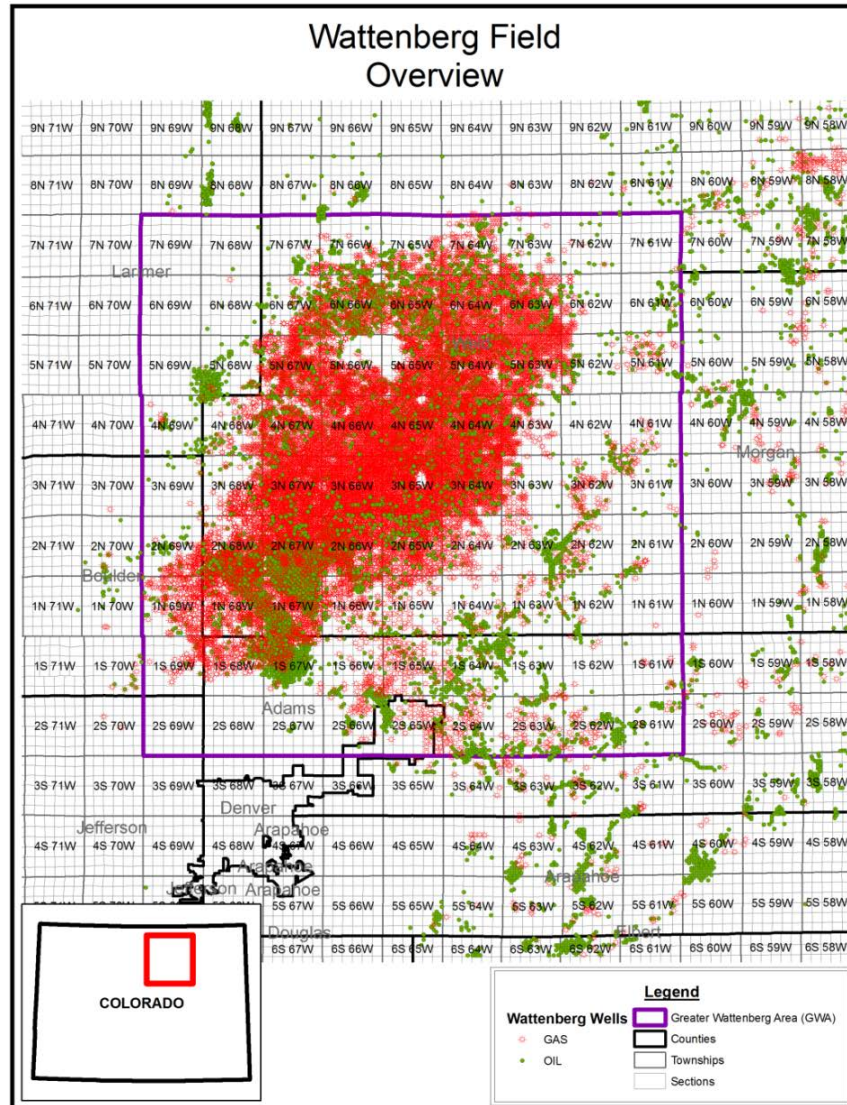
Intent

Due to the GWA's long and dynamic history, many of the current active, or
producing, well bores are vertical or directional in nature. With the advent
and increasing popularity of horizontal drilling Noble and other companies
are faced with a number of important decisions. First, are vertical wells
draining reservoir rocks adequately? Would horizontal wells be more

effective? Are they economically feasible? How many horizontal wells can be drilled per section in a historically, vertically drilled field?

Narayan Choudhary, an engineer with Noble was tasked with answering these questions. His approach hinged on determining the number of vertical, directional, and when applicable horizontal wells, are producing within a horizontal spacing unit. In order to accomplish this, spacing units need to be created for each horizontally drilled well in the GWA. Then the producing wells need to be tied to the spacing units.

Unfortunately, the standard, geologic, GIS program used at Noble, IHS' Petra, is not capable of efficiently performing the required analytical steps. This software is focused on wellbores, and therefore views the world vertically. To enter anything into the database, the data must be tied to a specific location in a wellbore. In other words, instead of an X/Y location, Petra only requires a Z, or depth value. That's not to say Petra doesn't require an X/Y location, it relies on the well location for that information. Another complication to using Petra is its inability to perform the basic geoprocessing tools available in ArcGIS software. Utilizing ArcGIS and the geoprocessing tools, a finished Microsoft Excel workbook can be produced in a relatively short amount of time. Narayan can then use this data, to acquire production values and perform the required, engineering analysis.

Literature Review

Spacing Units

Aside from regulations and law reviews, there is very little written about spacing units; a regulation, governing the drilling and production of oil and gas. Previously defined as an area allotted to a well by regulations, or field rules, issued by a governmental authority having jurisdiction for the drilling and production of a well; spacing units prevent the drilling of unnecessary wells, avoid wasting hydrocarbons, and protect invested parties (Montana Code 2011). Mineral owners, an invested party, have "correlative rights," or the right to develop their minerals (Hoffman 2011, 38). These rights cannot infringe upon other nearby mineral owners. There are many scenarios in which an infringement can occur. A trespass transpires when a well is drilled too near a lease line and drains resources from the neighboring lease (Hoffman 2011, 38). In the state of Colorado, wells are to be drilled no less than six hundred feet from any lease line to prevent trespass (COGCC 2013, 32). However, each mineral owner can "capture" oil and/or gas under their property before it flows off of their property and onto the next.

Another infringement occurs when wells are drilled too closely together. This improper spacing results in a drop in reservoir pressure and compromises production (Haines 2006, 95). In this case, spacing units protect the reservoir's ability to produce, as well as protecting the mineral owner's rights to exploit "their" hydrocarbons.

GIS in Oil & Gas Production

Given the nature of the data, geographic information systems have been used in the conventional oil and gas industry for some time. The ability to spatially view tabular well data is vital to the industry. To achieve this, a number of industry specific GIS are available including Petra, Geographix, Petrel, etc.; each with the ability to accept for import and create for export ESRI shapefiles. "With recent advances in the software, broadening its capabilities, making it easier to use, and an increased awareness, the number of ArcGIS users has grown dramatically (Petroleum GIS Perspectives 2009/2010, 6). From mapping and analysis to data management ArcGIS is gaining ground in the oil and gas industry.

One example of GIS being used in the industry is the merger of Statoil and Hydro Oil and Gas. In October of 2007 the Norwegian Statoil Energy Company merged with Norsk Hydro's Oil and Gas Division, creating StatoilHydro. The newly created, company utilized GIS in nearly all phases of its business including business development, exploration, field development, production, and downstream retail (Petroleum GIS Perspectives 2009/2010, 6). At Statoil, and every oil and gas company, GIS is integrated into every division dealing with spatial data. For example, facilities development, utilizes spatial data for installation and operational support, while pipeline installation and inspection, marine surveillance, and environmental studies also make use of GIS.

Moreover, in 2003, after obtaining a grant from the United States Department of Energy (DOE), the Alaska Department of Administration, and the Alaska Oil and Gas Conservation Commission (AOGCC) collaborated to create a comprehensive, GIS based website for Alaska's oil and gas data. Three goals were identified for the project; first, publish geo-technical information, automation of reviews of exploration and development projects, and third, create a shared GIS to be used among state agencies (Fed. Energy Tech. Center 2003, 3), along with oil and gas industry professionals and the general public. GIS was utilized in accomplishing all three goals. The first goal, publishing geo-technical information, used GIS to quality control the non-confidential directional surveys (well sticks) as well as for the delineation of oil producing basins agencies (Fed. Energy Tech. Center 2003, 3). The second goal was accomplished in conjunction with the third. As the shared, multi-agency, GIS took shape, functionality permitting applicants to locate project boundaries via either a map interface or a text description was included, agencies (Fed. Energy Tech. Center 2003, 8). This functionality aided in the fulfillment of automation in respect to reviews of exploration and development projects.

Finally, completion of the third goal created an enterprise level GIS populated by state agencies, and utilized by those agencies, industry professionals, and the general public agencies (Fed. Energy Tech. Center 2003, 9). The completed webmap can be found at:

http://dog.dnr.alaska.gov/PublicGIS/. This webmap is a remarkable example of a fully integrated web map; it brings together data from multiple agencies and creates valuable product.

GIS for Data Integration

Merriam-Webster's defines integration as forming, coordinating, or blending into a functioning or unified whole (2012). GIS data integration is one of the most important topics in the whole field of GIS (Flowerdew 1991, 375). As it continues to become a core component of the enterprise landscape, the need to integrate GIS with other traditional enterprise applications is becoming more apparent. Generally speaking, GIS integration involves meshing spatial or attribute data into a homogeneous dataset, (Scheepmaker 2007, 7). The third phase of the AOGCC project exemplifies a well-executed data integration outcome.

In an attempt to simplify the process of geothermal exploration in Iran, a team of scientists built a series of GIS models to integrate exploration, environmental, and well data (Noorollahi 2008, 108). The first model was built to integrate exploration data. This dataset included volcanic rocks, faults and fractures, acidic hydrothermal alteration zones, hot springs, and low electrical resistivity. Using a Boolean model, each layer was weighted, combined, and/or merged; resulting in a "Most favorable area for geothermal resource exploration" raster layer (Noorollahi 2008, 119). The same Boolean model was used to create an "Environmental Suitability" layer

from the environmental layers: topology, surface drainage, residential area, land use, and vegetation cover and density (Noorollahi 2008, 124-125). Finally, the two created layers were combined into a "Site Suitability Index" map, identifying high priority areas for exploratory drilling (Noorollahi 2008, 130).

The planning department of Langley Township, British Columbia is another instance of successful data integration. The department successfully integrated their aerial imagery, with parcel and land management data into a web mapping tool. Using the web-mapping tool, property data located in a Land Management System was charted on top of existing aerial imagery. This successful integration leveraged each applications' "touch points" to integrate the existing web-mapping tool with the Land Management System (Scheepmaker 2007, 28). By utilizing an existing application, not only was the desired level of integration achieved, but end user training was minimized.

Design and Implementation

Data and Sources

The data used for this analysis was collected from a variety of public sources. Table one details each data layer and its source.

Table #1, Layers & Sources

Entity	Feature	Source
State Boundaries	Polygon	US Census http://www.census.gov/
County Lines	Polygon	US Census http://www.census.gov/
Townships	Polygon	Geocommunicator http://www.geocommunicator.gov/
Sections	Polygon	Geocommunicator http://www.geocommunicator.gov/
Quarter Sections	Polygon	Geocommunicator http://www.geocommunicator.gov/
Wells- Bottom Hole Locations	Point	COGCC http://cogcc.state.co.us/
Wells- Surface Locations	Point	COGCC http://cogcc.state.co.us/
Well Deviations (Well Sticks)	Line	COGCC http://cogcc.state.co.us/

Despite the original source, each shapefile listed in table one was downloaded with the same Datum and Projection information. Shapefiles obtained were unprojected, however they were all assigned the North American Datum of 1983. Before being integrated into the Spacing Unit geodatabase, each layer was projected to the Universal Transverse Mercator, North American Datum 1983, Zone 13 North projection in United States feet. This projection was chosen to match that of other GIS systems used within Noble. It is very likely that the created shapefiles will be imported into Petra or other GIS systems.

The well location and directional survey layers are updated by the COGCC daily. The Shapefiles used for analysis were accessed on the 3rd of April

2013. If further analysis is desired, reacquiring these shapefiles is

recommended.

Data Dictionary

Table two demonstrates the structure of the GWA Spacing Unit geodatabase.

GWA Spacing Unit Geodatabase		
Culture Feature Dataset		
Feature Class	**Type**	**Source**
CO_Counties	Polygon	BLM Geocommunicator
CO_State	Polygon	BLM Geocommunicator
GWA_QtrQtr_Sections	Polygon	BLM Geocommunicator
GWA_Sections	Polygon	BLM Geocommunicator
GWA_Townships	Polygon	BLM Geocommunicator
WBU_GWA_Boundary	Polygon	Created From GWA_Townships
SpacingUnits Feature Dataset		
Feature Class	**Type**	**Source**
GWA_SpacingUnit_Report	Point	Created from GWA_SpacingUnits_QC & GWA_Prod_Wells_BH
GWA_SpacingUnits	Polygon	Created from GWA_WB_Buff & GWA_QtrQtr_Sections
GWA_SpacingUnits_Dissolve	Polygon	Created from GWA_SpacingUnits
GWA_SpacingUnits_QC	Polygon	Created from GWA_SpacingUnits_Dissolve
WellData Feature Dataset		
Feature Class	**Type**	**Source**
GWA_BH_Loc	Point	Clipped from COGCC Well Bottom Hole Locations
GWA_DirSurvey	Line	Clipped from COGCC Well Deviations
GWA_Horiz_BH_Loc	Point	From GWA_BH_Loc
GWA_Horiz_WellBores	Line	From GWA_DirSurvey
GWA_Prod_Wells_BH	Point	From GWA_BH_Loc & GWA_Surf_Loc
GWA_Surf_Loc	Point	Clipped from COGCC Well Surface Locations
GWA_WB_Buff	Polygon	Created by Buffering GWA_Horiz_WellBores

Methodology

Data Management

The Colorado State boundary ("CO_State") and Colorado counties ("CO_Counties") were imported into the "Culture" feature dataset of the file geodatabase as is. However, other datasets downloaded from the COGCC and the BLM Geocommunicator websites are extremely large. Because most of this data is outside the scope of this project, the remaining shapefiles were scaled back to focus on data found in the immediate vicinity of the GWA. A secondary effect of the extent reduction will be improved software performance, and a reduction in size of the geodatabase.

Townships, sections, and quarter-quarter sections one township outside of the GWA (within 8N-70W and 3S-60W) were imported into the geodatabase. The overrun allows for any horizontal wells just inside the perimeter of the GWA to be included in analysis. These layers are named, "GWA_Townships," "GWA_Sections," and "GWA_QtrQtr_Sections" in the "Culture" feature dataset of the file geodatabase. A Greater Wattenberg Area square feature class was also created. This layer was vital for the initial data management tasks. A square stretching from township 7N-61W to 2S-69W, this feature class was incorporated into the "Culture" feature dataset of the file geodatabase as "WBU_GWA_Boundary." The following flowchart, figure two, depicts the workflow involved in creating the feature classes in the Culture Feature Dataset.
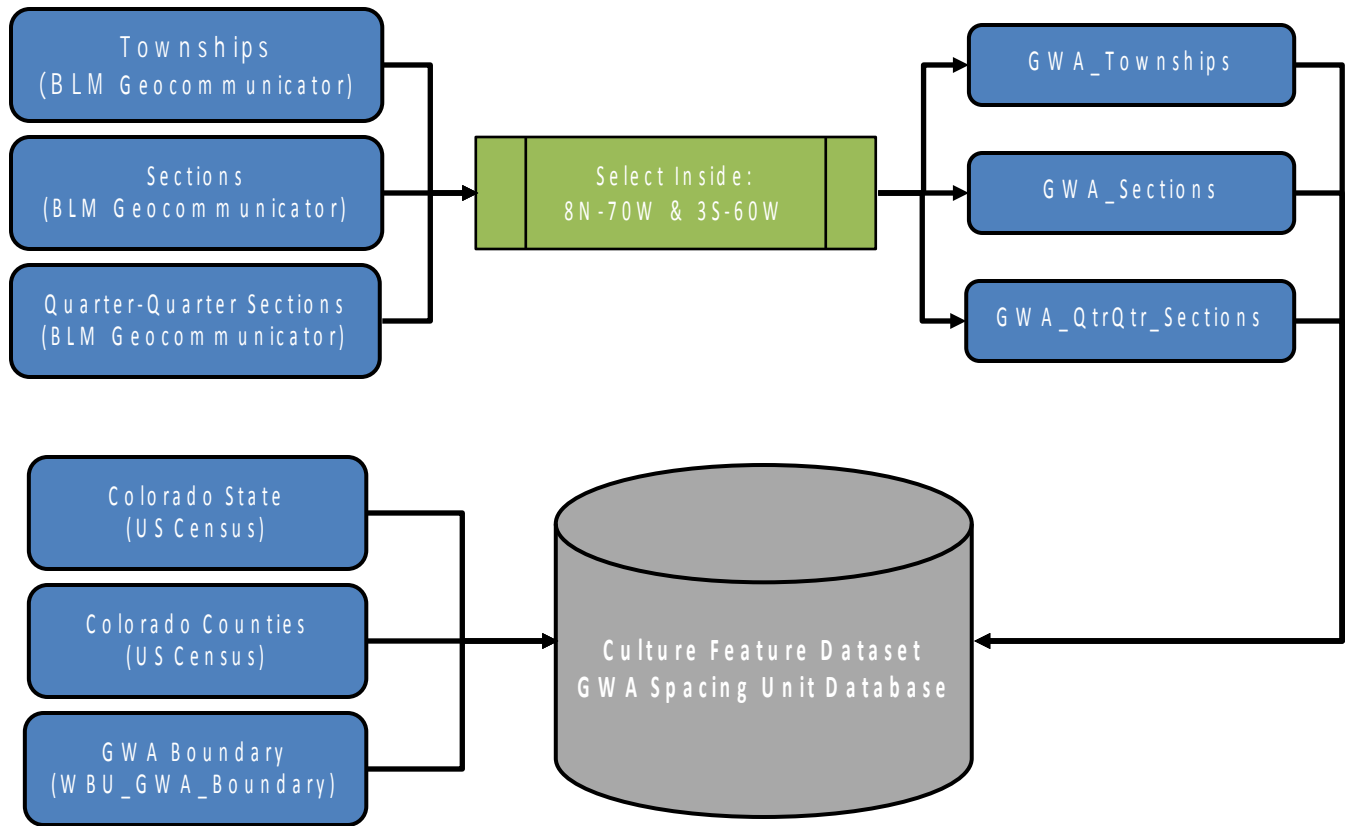
Figure #2, Culture Feature Dataset

After incorporating culture data into the geodatabase, attention turned to the sizeable task of manipulating well data into suitable formats. Well data acquired from the COGCC includes all oil and gas wells drilled in the state. Using the batch clip function, surface location, deviation surveys (well sticks), and two instances of bottom hole location were used as input data sets; the GWA square was the clip feature. The resulting shapefiles, "GWA_Surf_Loc," "GWA_Horiz_WellBores," "GWA_Prod_Wells_BH," and "GWA_Horiz_BH_Loc," respectively were imported into the "WellData" feature dataset of the file geodatabase.

These four feature classes included permitted wells. Because permitted wells are merely planned, both their surface and bottom hole locations may change or they may not be drilled at all for a variety of reasons. As such, these permitted locations were removed to ensure the integrity of the analysis. For the "GWA_Horiz_WellBores," "GWA_Prod_Wells_BH," and "GWA_Horiz_BH_Loc," the "BH_Status" attribute classified wells as either "active" or "planned;" the "planned" records were selected and deleted from the feature classes. The process for surface locations, ("GWA_Surf_Loc"), was slightly different as the classification system is not the same. Wells in this feature class were divided into thirteen different classifications. Wells classified as permits (XX), oil and gas wells converted to domestic water wells (DM), and abandoned locations (AL) in the "facility_s" attribute were removed.

The "GWA_Horiz_WellBores," and "GWA_Horiz_BH_Loc," feature classes contained data for both directionally and horizontally drilled wells. Because this project focuses on horizontal spacing units, the directional wells and well bores needed to be removed from their respective feature classes. Unfortunately, the "GWA_Horiz_WellBores," feature class did not contain an attribute to classify well bores as horizontal or directional. There is, however, a "deviation_" attribute in the "GWA_Horiz_BH_Loc," feature class. Fortunately, both layers have a ten digit API number attribute; "ET_ID" in the WellBore layer, and "API" in the BH_Loc layer. A one to one tabular join

was created using these two attributes. The "GWA_BH_Loc," feature class was identified as the join table, while "GWA_Horiz_WellBores," was utilized as the target table. After the join, wells classified as "directional" in the "deviation_" attribute of both "GWA_Horiz_WellBores," and "GWA_Horiz_BH_Loc," feature classes were selected and deleted. The join was removed. The next editing task performed on the two horizontal feature classes is to remove previous well bore entries. There were a number of wells that had been sidetracked at least once. When a well is sidetracked, the original well will not produce, and is therefore not needed for later analysis. The original well bores, and in a few instances, the first sidetracks were removed from the "GWA_Horiz_WellBores" feature class. The final horizontal well count for analysis is 455 wells.

The final well data management task is to create a bottom hole location layer for all wells producing in the Greater Wattenberg Area. This layer needs to include bottom hole locations for horizontal, directional, and vertical wells. The bottom hole location is used because that is where a vertical or directional well produces from. While horizontal wells produce differently, the bottom hole location of those wells is closer to the point of production than the surface location. The "GWA_Prod_Wells_BH" feature class was created in the geodatabase by clipping the COGCC's bottom hole location shapefile, and then removing the planned wells. As such, the "GWA_Prod_Wells_BH" feature class only includes directionally and

horizontally drilled wells. However, the majority of the wells in the GWA predate these drilling techniques. Vertical well locations will be added from the GWA_Surf_Loc file. The surface location is used for vertical wells, because for all intents and purposes, the surface and bottom hole locations are the same. A one to one tabular join needed to be created between "GWA_Prod_Wells_BH" and "GWA_Surf_Loc." Unfortunately, these two feature classes do not share a common attribute. "GWA_Prod_Wells_BH" had a ten digit API number in the "API" field while "GWA_Surf_Loc" had an eight digit API number in the "link_fld" field. In order to perform a tabular join a new field, called "link_fld" is added to the "GWA_Prod_Wells_BH" feature class. The field calculator was used to slice the existing, ten digit API number. Employing the python parser, the following script was used:

"!API![0:8]"

This script removed the last two numbers, in positions "9 and 10," from the existing "API" field; creating an 8 digit API number that will join with the "GWA_Surf_Loc" feature class.

The one to one tabular join was created "GWA_Prod_Wells_BH" feature class as the join table, while the "GWA_Surf_Loc," feature class was identified as the target table. Post join, those records with Null values in the added "GWA_Prod_Wells_BH" fields are assumed to be Vertical. To select the vertical wells, all records with non-null values in the

"GWA_Prod_Wells_BH.deviation_" field were selected. Then the selection was switched, and the newly selected "NULL" wells were copied and pasted into the "GWA_Prod_Wells_BH" feature class.

The tabular data in the "GWA_Prod_Wells_BH" was edited to reduce the number of data fields, as well as later confusion. First, the existing "facility_s" field; this field was null if the record refers to a directionally or horizontally drilled well. Therefore, the "NULL" values were assigned a "DD" code, for directionally drilled. Using the field calculator, "NULL" values in "API_Label," "Operator," and "Well_Name" were populated from "attribute_1," "attribute_2," and "attribute_3," respectively. After the data was pulled out of the later three fields, these non-normalized data fields were removed. Other fields deleted include: UTMX, UTMY, Link_fld1_Mdepth, tvd, Object_ID, KKey_API, and facility_t. Unfortunately, the newly combined API numbers did not have the same format. The bottom hole locations for directional wells do not contain the state code but contain the recompletion code; conversely the bottom hole locations for vertical wells include the state code but not the recompletion code. The directionally drilled wells were selected, and using the VBScript parser in the field calculator, the state code was added, employing the following script:

"05-" & [API_Label]

The recompletion code was removed by slicing the text string, using nearly the same method as was used to create the "link_fld" in the "GWA_Prod_Wells_BH" feature class. Once again, utilizing the python parser, the following script was used:

"!API![0:12]"

Figure three, portrays the workflow required for creating the feature classes in the Well Feature Dataset.

| Surface Locations (COGCC) |
| Bottom Locations (COGCC) |
| Bottom Locations (COGCC) |
| Deviation Surveys (COGCC) |

Clip: GWA Boundary

GWA_Surf_Loc

GWA_Prod_Wells_BH

GWA_Horiz_BH_Loc

GWA_Horiz_WellBore

GWA_Prod_Wells_BH

Add: Vertical Surface Locations

GWA_Horiz_WellBore

GWA_Horiz_BH_Loc

Remove: Planned Locations

One-to-One Tabular Join to: GWA_Horiz_BH_Loc

Remove: Directional Wells

Remove: Locations, Domestic Wells, Abandoned Locations

Well Feature Dataset GWA Spacing Unit Database

GWA_Horiz_WellBore
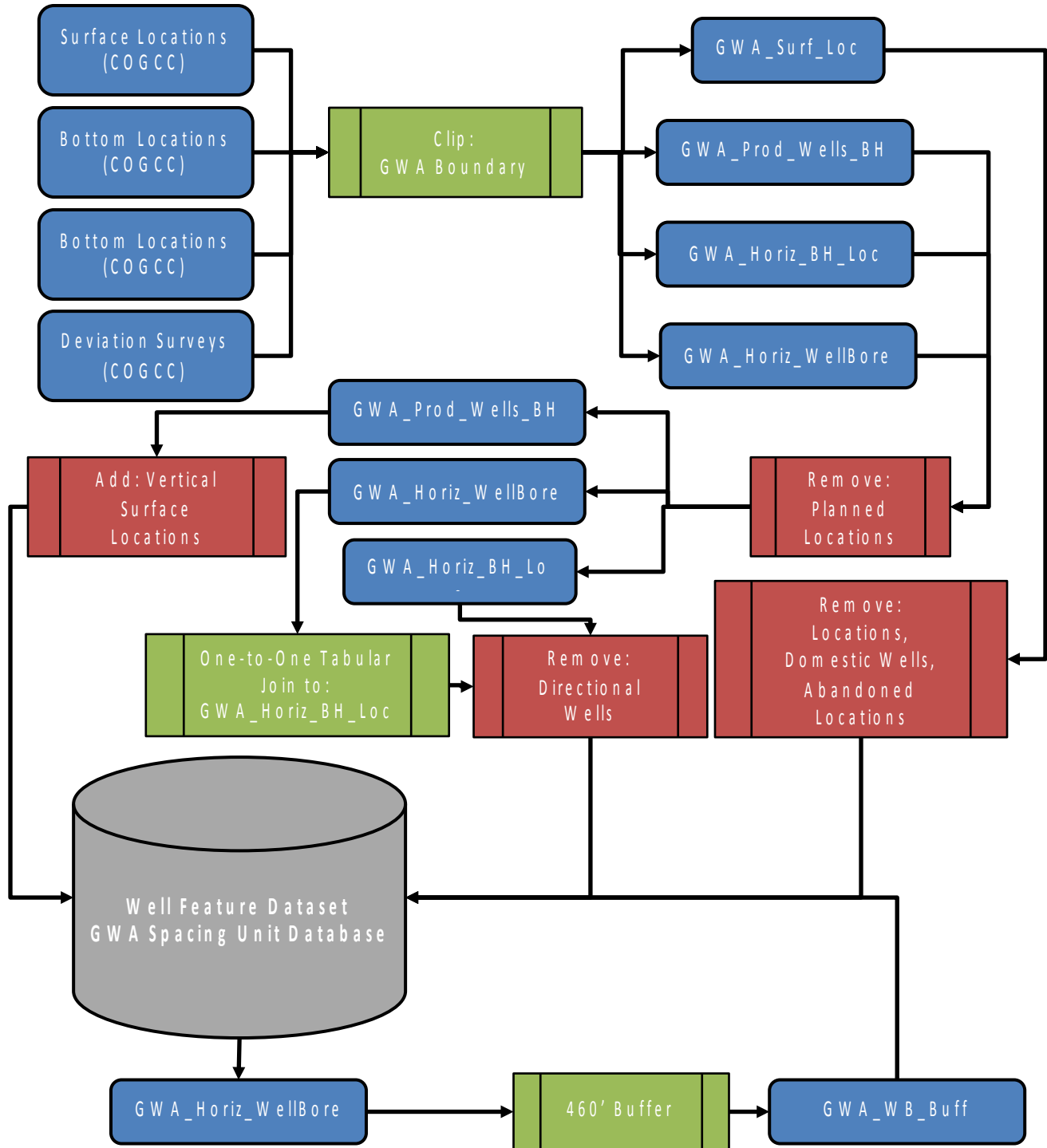
460' Buffer

GWA_WB_Buff

Figure #3, Well Feature Dataset

Building Spacing Units

The first step in creating spacing units for the horizontal wells in the GWA

was to apply a four hundred sixty foot buffer around each horizontal well

stick. The 460 foot width of the buffer is determined by the COGCC's rule 318A.a(4)C (COGCC 2013, 34).

> *"If a well is proposed to be located less than four hundred sixty (460) feet from the governmental quarter-quarter section boundary, a wellbore spacing unit ("wellbore spacing unit") for such well shall be comprised of the governmental quarter-quarter sections that are located less than four hundred sixty (460) feet from the wellbore regardless of section or quarter section lines."*

The buffer will be used not only to create the required spacing units, but also in the quality control process of verifying those spacing units. After creation, this buffer layer was added to the "WellData" feature dataset as "GWA_WB_Buff".

All quarter-quarter sections intersecting the "GWA_WB_Buff" layer were selected from the "GWA_QtrQtr shapefile. The resulting 2,468 quarter-quarter sections were exported out as a shapefile and not incorporated into the geodatabase, as this is a temporary file. This working, quarter-quarter shapefile was spatially joined, with a one to many relationship, to the "GWA_WB_Buff," layer and exported as "GWA_SpacingUnits" to the "SpacingUnit" feature dataset. The one-to-many relationship creates the required overlapping polygons required for spacing units. After which the temporary, working file was deleted.

The resulting "GWA_SpacingUnits" shapefile contains 4,263 individual polygons to create spacing units for 455 horizontal wells. The dissolve

function is used to aggregate multiple polygons with matching attributes into a single polygon. In this case, the "ET_ID" field, or API number, was used as the dissolve field. After aggregation, the resulting polygon count in the new "GWA_SU_Dissolve" feature class is 455. Figure four, below, demonstrates the amount of polygon overlap involved with spacing units in the GWA.
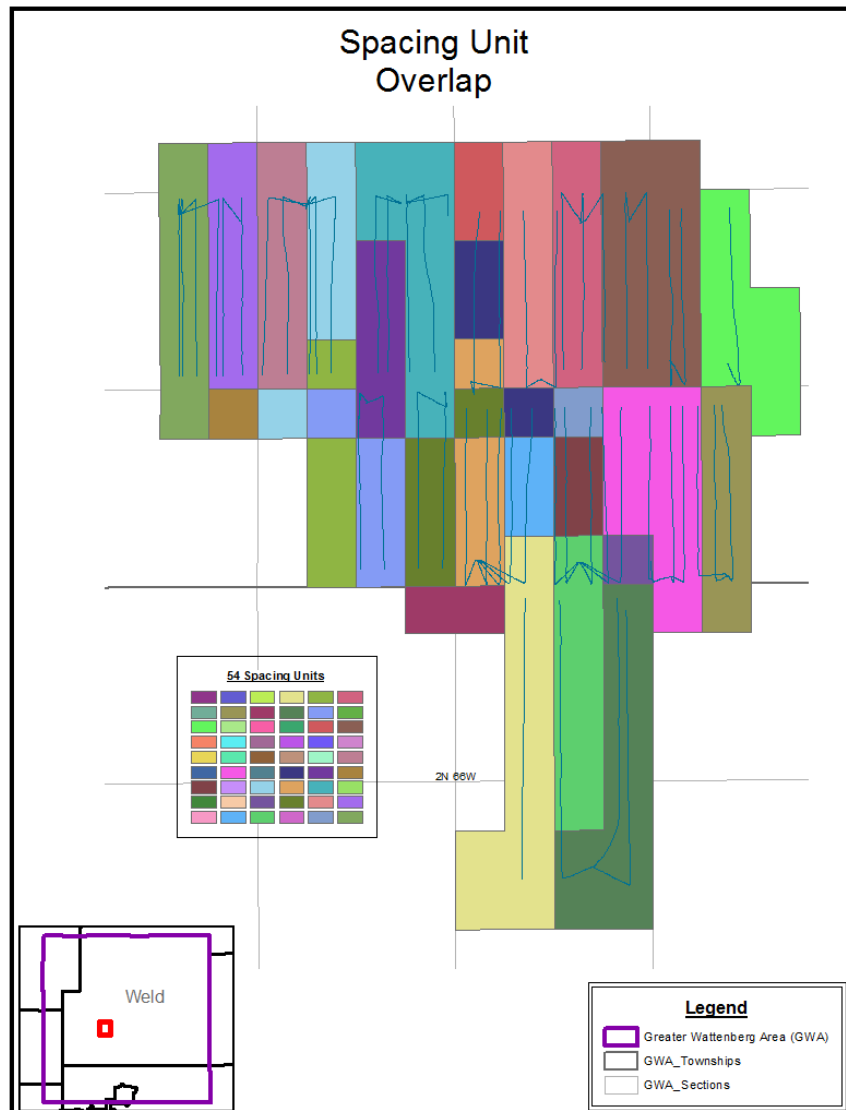
Figure #4, Spacing Unit Overlap

This figure shows approximately twelve sections in two townships. Within this small area, a total of fifty-four wells have been drilled. Determining whether this overlap is appropriate is the end goal of the engineer's analysis.

The newly created spacing units now require rigorous examination for quality control purposes. With so many wells being drilled in a section, it is imperative that each spacing unit is correct. The following figure five shows spacing unit creation guides for wells drilled with either north-south, east-west, or cater-corner orientations.

In addition to these spacing unit guidelines, there are a number of other rules that must be considered when building the spacing units. A few of the most common considerations have been included. First, exploratory wells, or "wildcats" can be listed as "confidential" for a period of six months. This period is intended to protect the operator from having to share information

with potential competitors (COGCC 2009, 1). One of the items considered confidential is a well's directional survey. When this information is missing, a simple line is drawn from the surface and bottom hole, leaving the actual well path, and potential spacing unit, up to the analyst to decipher. Figure six, shows an example of this situation, and the analyst's interpretation.
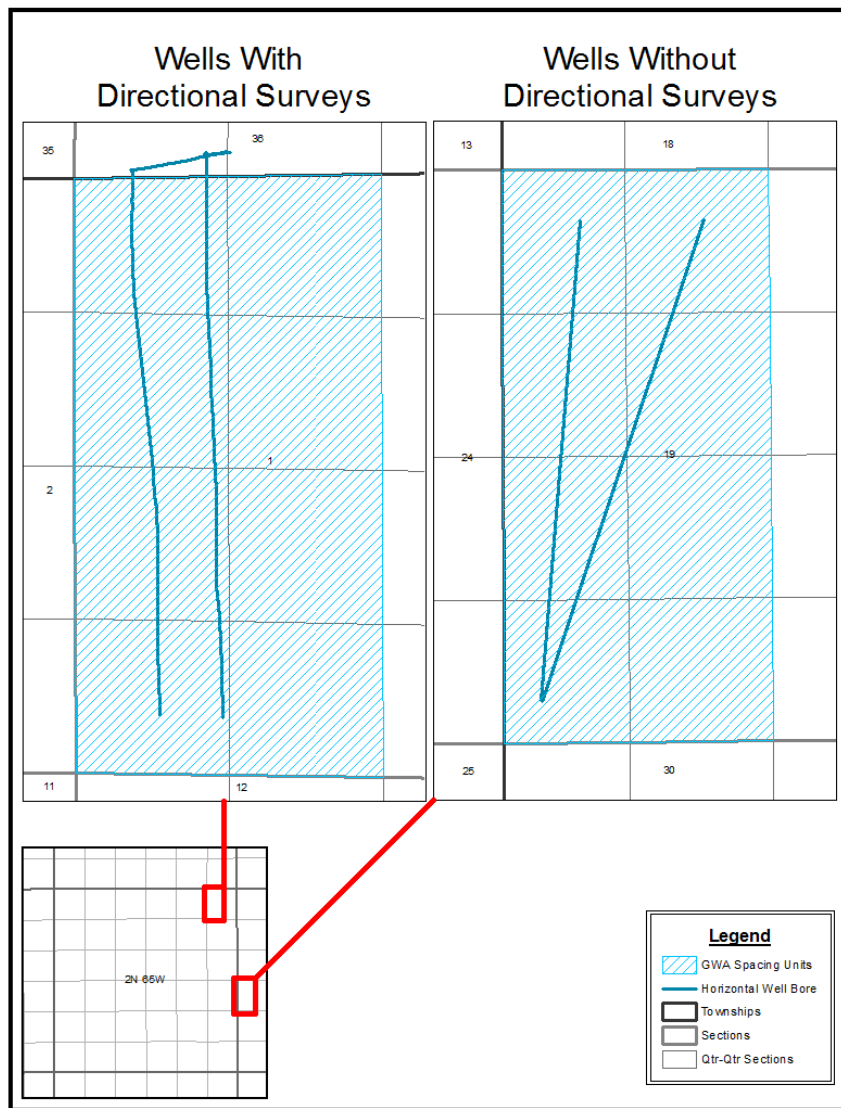
Figure #6, Wells without Directional Surveys

The wells without directional surveys, shown on the right, are most likely drilled in the same way as those shown to the left. Therefore a north-south spacing unit is applied, not a cater-corner type spacing unit.

Another common issue occurs in the buffering and quarter-quarter selection process. Buffers are applied around the entire well bore; however a well completion breaks up rocks perpendicular to the well bore. Any quarter-quarter sections selected just beyond the wellbore's TD are done so inaccurately. Furthermore, the entirety of a horizontal well bore, as shown on the map, is not completed. Essentially, the well bore shown is somewhat simplified in order to render it in two dimensional space. In cases where well bores "drill out" before going horizontal, the "drill out" portion is not completed, and therefore not included in the spacing unit. To correct these, and other issues every spacing unit is verified and edited by the analyst. As Spacing Unit shapes are verified, they are cut from the "GWA_SpacingUnits_Dissolve" feature class and pasted into the "GWA_SpacingUnits_QC" feature class. Figure seven, depicts the two most common spacing unit issues.
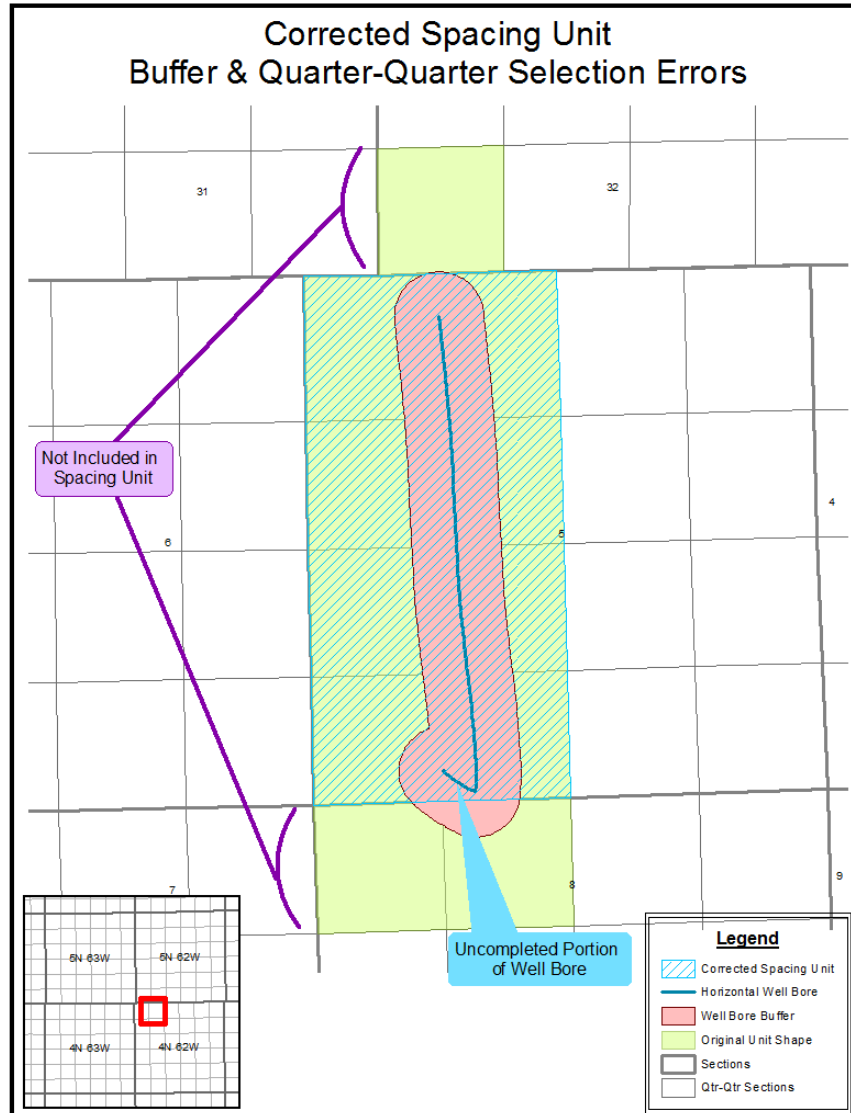
Figure #7, Buffering and Quarter-Quarter Selection Errors

In the process of performing the quality check of spacing units, a suspect

wellbore was identified in section one of township two north, sixty-six west.

This well bore, a sidetrack, appears to be drilled with a different orientation

than the surrounding wells. The original well was added to the map to verify

the sidetrack's deviation survey. The original well bore appears to be drilling

a north-south trajectory, like the offset wells. Because wells are drilled to

leverage an area's geology, it is likely that the inconsistency is due to an inaccurate bottom hole location. While an erroneous directional survey could also be at fault, the straightness of the well bore line indicates no directional survey exists. Figure eight shows the suspect wellbore and the original well in addition to the offset wells.

In the interest of data integrity, these two wells were removed from the analysis, leaving a total of 453 total spacing units. The workflow for creating

the feature classes in the Spacing Unit Feature Dataset is presented in figure

nine below.

```
┌──────────────────────┐      ┌──────────────────────┐
│  Well Feature Dataset │─────▶│  GWA_Prod_Wells_BH    │──────────────────────────┐
│  GWA Spacing Unit     │      └──────────────────────┘                           │
│  Database             │      ┌──────────────────────┐   ┌──────────────────────┐│
└──────────────────────┘──────▶│  GWA_WB_Buff          │──▶│ Select by Locaton:   ││
                               └──────────────────────┘   │ Intersecting          ││
┌──────────────────────┐                                  │ GWA_QtrQtr_Sections   ││
│ Culture Feature Dataset│     ┌──────────────────────┐   └──────────────────────┘│
│ GWA Spacing Unit      │─────▶│  GWA_QtrQtr_Sections  │        │                  │
│ Database              │      └──────────────────────┘        ▼                  │
└──────────────────────┘                                  ┌──────────────────────┐│
                                                          │  Working QtrQtr.Shp   ││
┌──────────────┐  ┌──────────────────┐                    └──────────────────────┘│
│  Dissolve:   │◀─│  GWA_SpacingUnit │◀───┐                       │               │
│  ET_ID       │  └──────────────────┘    │               ┌──────────────────────┐│
└──────────────┘          │               └───────────────│ One-to-Many          ││
       │                  │                                │ Spatial Join to:      ││
       ▼                  │                                │ GWA_WB_Buff          ││
┌──────────────────────┐  │                                └──────────────────────┘│
│GWA_SpacingUnit_Dissolve│ │         ┌──────────────────────┐                       │
└──────────────────────┘  └────────▶│  SpacingUnit Feature  │                       │
       │                             │  Dataset              │  ┌────────────────────┐
       ▼                             │  GWA Spacing Unit     │◀─│GWA_SpacingUnit_Report│
┌──────────────────┐                 │  Database             │  └────────────────────┘
│  Quality Check   │                 └──────────────────────┘          ▲
└──────────────────┘                      ▲                   ┌──────────────────────┐
       │                                  │                   │ One-to-Many          │
       ▼                                  │                   │ Spatial Join to:      │
┌──────────────────────┐                  │                   │ GWA_WB_Buff          │◀──┘
│  GWA_SpacingUnit_QC  │──────────────────┘                   └──────────────────────┘
└──────────────────────┘
```
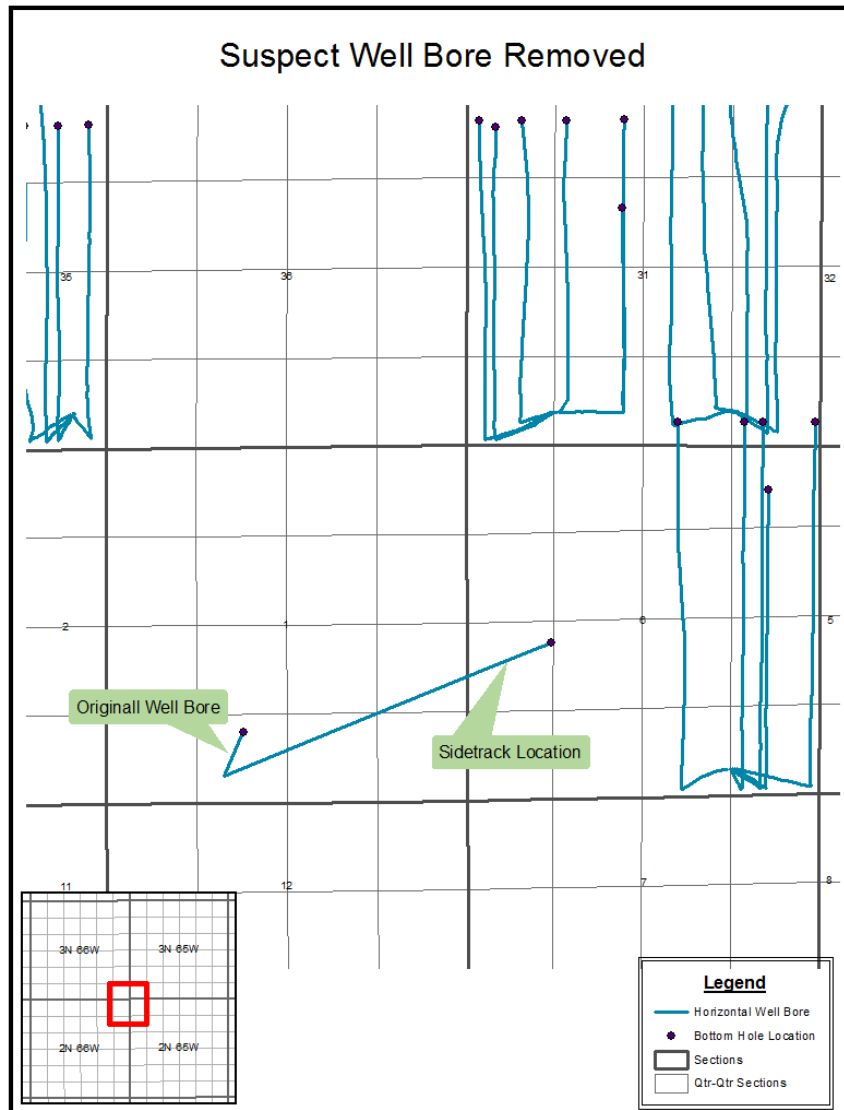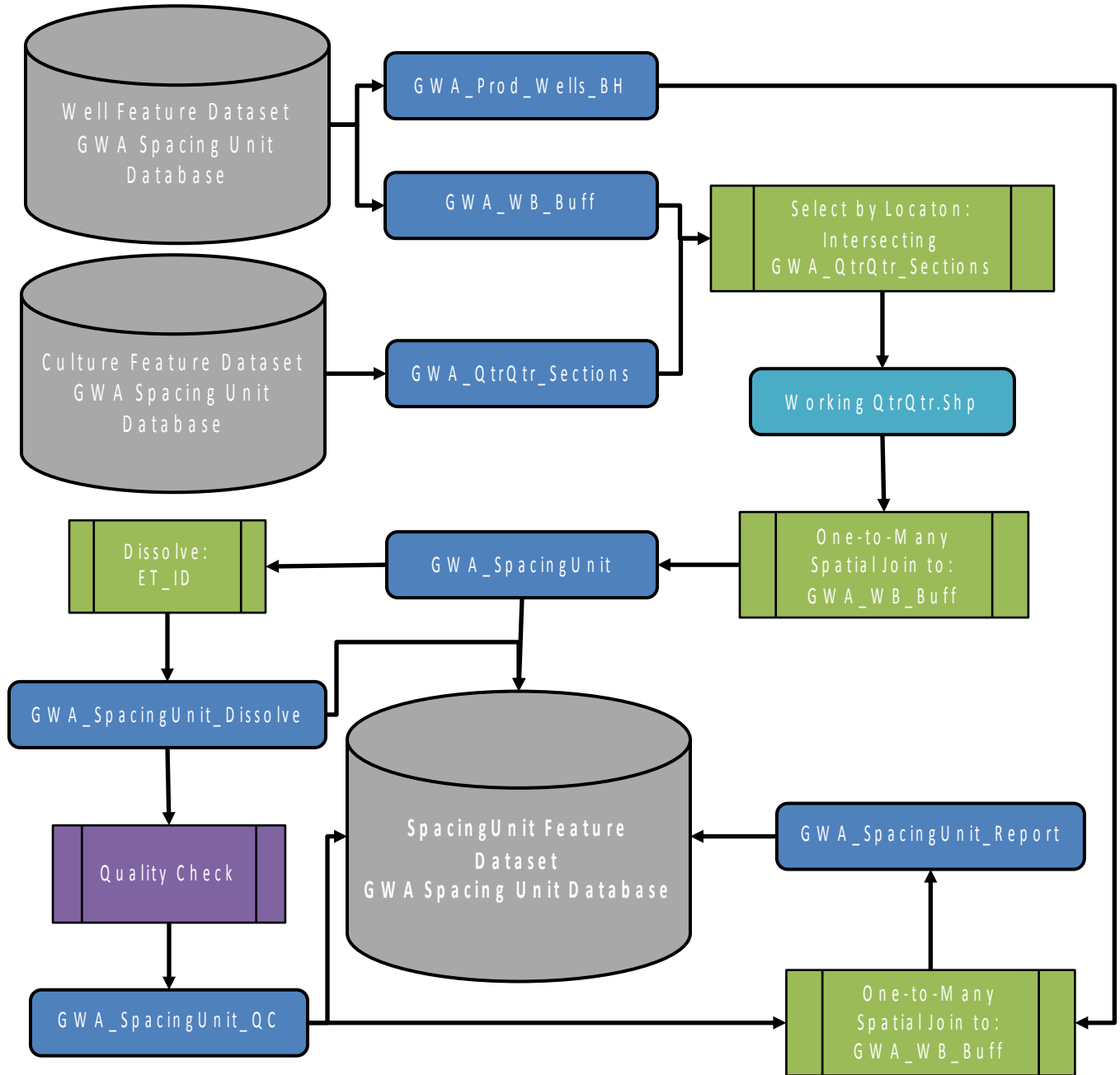
Figure #9, Spacing Unit Feature Dataset

Tying Spacing Units to Producing Wells

The final step in the ArcGIS workflow was to tie the producing wells to the

created spacing units. This task was accomplished by creating a one-to-

many spatial join. Because the producing well locations need to be preserved for future use, the "GWA_Prod_Wells_BH" was used as the target feature, "GWA_SpacingUnits_QC" was used as the join feature; and completely within was selected as the match option. The resulting feature class was saved in the "Well" feature dataset, as "GWA_SpacingUnit_Report." These steps are shown in the above, figure nine, workflow diagram.

Preparing the Table for delivery

The "GWA_SpacingUnit_Report" feature class includes a database table that needs to be exported and manipulated to be suitable for Narayan's use. After exporting the tabular data as a database file, it was resaved as an Excel workbook. All the columns, except ET_ID and API_Label were removed. For the analysis, these columns are meaningless to the engineer; deleted columns include: ObjectID, Join_Count, Operator, WellName, TARGET_FID, JOIN_FID, linkfld, facility_s, Lat_NAD83, LONG_NAD83. The remaining columns were renamed; "API" was changed to "Producing Well," and ET_ID was renamed "Spacing Unit."

The next data manipulation task was to correct the producing well records. In the original data table, API numbers in the "API" field contain dashes. Because these API numbers are used to acquire production data from a vendor, whose system doesn't recognize dashes, they were removed. Additionally, an "05-" is added to the API numbers in the "Spacing Unit" column for the benefit of the engineer.

After the identifying numbers were corrected, some basic tabular editing was performed. Because a well's own production will skew the analysis, its production record must be removed from its spacing unit record. Many spacing units do not contain any other producing wells, and are therefore removed from the workbook. The following table three shows a sample pulled from the Spacing Unit Report.

Table #3, Layers & Sources

Spacing Unit	Producing Wells
05-123-1512500	0512322285
05-123-1959700	0512334277
	0512334288
05-123-2270800	0512322706
	0512322681
	0512322680
	0512322709
	0512331647
	0512331666
05-123-2270900	0512322706
	0512322681
	0512322680
	0512322708
	0512331647
	0512331666

After tabular editing, there are a total of 395 spacing units containing producing wells. The resulting table was delivered to Narayan for his analysis.

Results

The workflow described herein was successful in creating accurate spacing units to assess the economic feasibility of drilling horizontal wells in the GWA. Utilizing ArcGIS, results were produced much sooner than if the analysis were done completely by hand or by using another software.

Discussion

By taking full advantage of software and employees' skills, a company is more nimble. In this case, by leveraging ArcGIS' geoprocessing tools; spacing units, producing wells, and a final report were produced quickly. The relatively short amount of time required to provide the final report allowed the engineering team ample time to assess the data. A well thought out assessment lead to a deliberate conclusion which reduces the risk of making a hasty decision.

By using ArcGIS, a large amount of the analyst's time is saved. ArcGIS has a number of built in functionalities that allow for a certain amount of automation in the process of building spacing units. Unfortunately, if spacing units were created in Petra, not only would each unit need to be drawn by hand, but the deliverable spreadsheet would have to be populated by hand as well. It is estimated that using ArcGIS cuts the amount of time to complete the project in half. This time savings equates to a sizeable, tangible benefit to the company, increased capital efficiency. Doing more with less frees up capital to spend on other projects or other needed staff. If

this workflow were applied to assets in other business units, the capital efficiency is sure to increase, perhaps exponentially.

Additionally, the successful completion of this analysis demonstrates the value of ArcGIS in the oil and gas workflow. While there are a number of petroleum specific software packages on the market, there isn't one that successfully combines surface mapping and analysis with subsurface mapping and analysis. Because shapefiles are a geospatial standard, data is easily transferred between software packages, allowing ArcGIS to fill this niche in the industry.

Areas for Further Research

This project leaves much opportunity for further research. Continuous monitoring is being considered for the GWA area. If it is decided that continuous monitoring is in fact necessary, it will be essential to automate as much of the data creation process as possible. Many, if not all, of the required steps, save the quality control checks, can be accomplished with a model. The creation of a model will save the analyst a great deal of time; producing results more quickly and accurately.

More potential for further research exists in reducing the need for quality control of spacing units. Results could be produced more quickly if this portion of the workflow could be abridged. Of course, this means creating more accurate spacing units on the first pass. A number of opportunities

exist to potentially accomplish this goal, including modifying the well deviation surveys, revising the buffering technique, or changing the quarter-quarter selection techniques.

The methodology described herein could easily be modified to apply to another field or play. Formation properties, such as porosity and permeability, vary between reservoir rocks. These inconsistencies influence spacing units across the country. In order to properly apply this methodology the buffering distance will require modification depending on the specific spacing unit regulations. Furthermore, this methodology could be applied to directionally or vertically drilled wells, so long as spacing regulations are honored.

Glossary of Terms

<u>Directional Survey</u> - Measurement of a wells' inclination (deviation from vertical) and azimuth (compass heading) of a well bore.

<u>Play</u> - An area in which hydrocarbon accumulations or prospects of a given type occur.

<u>Offset</u> - Existing wellbores close to a proposed, or drilling well, that provide information for planning purposes.

<u>Wildcat</u> - An exploratory well, a well drilled in a new area with few, or no, offsetting wells.

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