Evaluating Surface Casing Depths of Oil & Gas Operations in an Effort to Protect Local Groundwater: A GIS Enabled Process

by

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This thesis and the many hours of hard work it represents is dedicated to my son, Sloan R. Nienkamp-Glasscock. Your unconditional love and smile kept me motivated the many times I questioned myself.

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List of Abbreviations

API	American Petroleum Institute
ASR	Aquifer Storage and Recovery
DFC	Desired Future Condition
EBK	Empirical Bayesian Kriging
EPA	Environmental Protection Agency
FBSL	Feet Below Sea Level
GAM	Groundwater Availability Model
GAU	Groundwater Advisory Unit
GCD	Groundwater Conservation District
GIS	Geographic Information System
GMA	Groundwater Management Area
GPS	Global Positioning System
LPI	Local Polynomial Interpolation
RRC	Railroad Commission of Texas
SAWS	San Antonio Water Systems
SP	Spontaneous Potential
SSTVD	Subsea Total Vertical Depth
TCEQ	Texas Commission on Environmental Quality
TDS	Total Dissolved Solids
TWDB	Texas Water Development Board

Abstract

As groundwater is a vital resource, it is important that oil and gas operations do not jeopardize water quality. Many consumers, including farmers and municipalities, rely year after year on the freshwater provided by aquifers. Along South Texas, oil and gas companies are targeting the Eagle Ford formation containing hydrocarbons. In this same region, the Carrizo-Wilcox aquifer must be drilled through to reach the Eagle Ford below. To protect the above aquifer, cemented surface casing is used to seal the Carrizo-Wilcox from contaminants within the well borehole. This study incorporated Geographic Information Systems (GIS) to evaluate surface casing depths of oil and gas wells, to verify if they are deep enough to adequately protect the aquifer. To understand the geologic structure occurring in this region, aquifer depths obtained from well logs were used to interpolate the base of the Carrizo Sands. After comparing three interpolation methods, the Empirical Bayesian Kriging (EBK) interpolator, using the *Exponential Detrended* semivariogram, was selected to create a predicted surface and a standard error map. Surface casing depths of Eagle Ford wells were mapped and queried to determine if they are deeper or shallower than the predicted surface representing the aquifer. Over half of the wells within the study area had surface casing shallower than the aquifer. However, most of those fell within areas where groundwater was brackish. Results from this study should motivate regulatory agencies in tightening up policies and guidelines pertaining to oil and gas operations affecting aquifers within the State of Texas. In addition, methodologies conducted during the study provide a viable means to improve the current process of determining surface casing depths.

Chapter 1

Groundwater describes water that fills the fractures and pores between rocks and soil below the earth's surface. Groundwater is a vital, natural commodity which should be monitored and protected. Because many consumers rely on groundwater to provide fresh water, it is important that great care is taken to protect this valuable resource. Many state and federal agencies are responsible for and involved with the various aquifer systems across the nation, including Texas. However, in Texas, only one regulatory agency, the Railroad Commission of Texas (RRC), has jurisdiction when it comes to oil and gas operations affecting groundwater. This thesis evaluates the protection of groundwater in an active oil and gas producing area, by investigating surface casing depths regulated by the RRC.

1.1 Motivation

As of 2009, the Eagle Ford Shale Play in South Texas became an active area for oil and gas production. Figure 1 shows this region where Eagle Ford wells are being drilled. This is also the area of focus for this study. Oil and gas companies are drilling through the Carrizo-Wilcox aquifer to extract petroleum from the Eagle Ford formation below. Surface casing, composed of steel and cement, is used to line the borehole which seals the local aquifer from any contaminants.

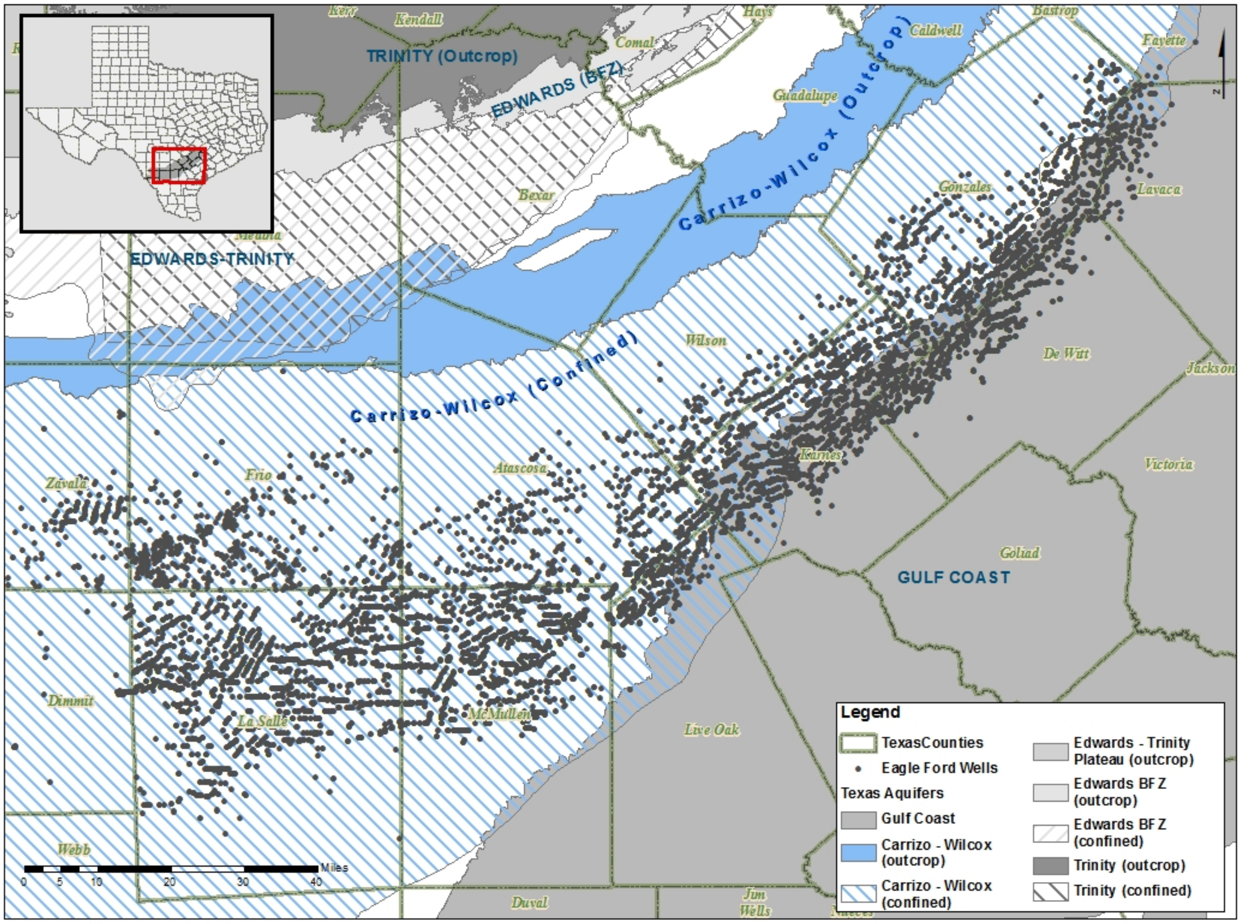


Figure 1 Eagleford Wells along South Texas.

In Texas, before an oil or gas well can be drilled, a Groundwater Protection Determination letter must be received from the Railroad Commission of Texas (RRC). This letter states the depth to which the cemented surface casing must reach. If this surface casing is not set deep enough, the base of the aquifer is not fully penetrated, and therefore may be susceptible to contamination. Currently there is no evidence that the RRC is conducting any actual subsurface mapping of the Carrizo-Wilcox.

The primary objective of this study is to demonstrate an applicable method for mapping a subsurface geologic formation in an effort to identify appropriate surface casing depth recommendations. Information from well logs are used to create a continuous surface representing a geologic horizon, in this case, the base of an aquifer. After this geologic representation has been created, surface casing depths of already-drilled, Eagle Ford oil and gas wells can then be compared to the aquifer depth. Thus, the two key goals of this study are:

1) Determine an appropriate interpolation method, available in ArcGIS, for mapping subsurface geology.
2) Determine if surface casings of drilled wells adequately protect the local aquifer, as defined by the interpolated surface.

The research described in this document found that over half of Eagle Ford wells within the study area do not have surface casings to the base of the Carrizo-Wilcox aquifer. As a result of these findings, this study provides a method of improving the current process of determining the required surface casing depth by using Geographic Information Systems (GIS) and enhanced subsurface maps.

1.2 Thesis Organization

The remainder of this thesis is structured into five additional chapters. Chapter Two provides contextual information regarding groundwater regulation in Texas and the Carrizo-Wilcox aquifer. Chapter Two also explains oil and gas operations and how groundwater is vulnerable to these operations. Chapter Three outlines a procedure for creating a continuous representation of a subsurface geologic formation. Chapter Four describes the methodology conducted during this thesis. Chapter Five summarizes the outcomes produced and Chapter Six offers concluding comments and recommendations.

Chapter 2 Groundwater Regulation, Aquifers, and Oil and Gas Operations in Texas

Before introducing geologic mapping, it is important to examine some background information concerning groundwater, and oil and gas activity in Texas. This chapter provides: (1) a framework of Texas groundwater and the regulatory agencies involved; (2) context on the Carrizo-Wilcox aquifer and groundwater quality; and (3) information regarding oil and gas operations, especially surface casing.

2.1 Groundwater Regulation in Texas

Sixty percent of water used within the state of Texas is supplied by groundwater (Texas Water Development Board 2015). Over eight billion gallons a day of groundwater is pumped from aquifers throughout the state (National Groundwater Association 2010). Because of the heavy use of groundwater for human consumption and activity, this vital resource requires protection.

In Texas, groundwater is owned by landowners and is, therefore, considered private property. However, groundwater is managed and regulated through various state organizations. The Texas Commission on Environmental Quality (TCEQ) is responsible for protecting water quality while the Texas Water Development Board (TWDB) is responsible for managing and financing adequate water supplies. The TCEQ is the primary environmental organization for the State of Texas. The organization has more jurisdiction with water quality and quantity than any other state agency (Sansom 2008). The TCEQ's roles and responsibilities are directed by federal laws and Environmental Protection Agency (EPA) rules. The Texas governor appoints three commissioners who are accountable for the overall direction of the agency.

The TWDB is composed of board members also appointed by the governor. Using predictive groundwater availability modeling, the TWDB's chief responsibility is to establish and publish a state-wide water plan every five years (Sansom 2008). This groundwater availability model (GAM) predicts future groundwater trends including water levels and recharge, plus the characterization of geology and aquifer properties for all aquifers within the state. Initially, the TWDB was developed to offer low-interest loans for water improvement projects. Since then, the board has taken on additional responsibilities including facilitating water rights transfers between sellers and buyers, and managing the Water Trust. Water can be donated, leased or purchased for environmental purposes, through the Water Trust.

In 1949, groundwater conservation districts (GCD) were generated as political boundaries to manage groundwater at the local level (George, Mace and Petrossian 2011). Today, there are 100 GCDs that are responsible for managing water well spacing and production, the permitting of new water wells, and major alterations of existing water wells (Texas Water Development Board n.d., Porter 2014). When evaluating permits, it is the GCD's responsibility to ensure that the water is dedicated to beneficial use, and does not exceed amounts that would adversely affect groundwater resources. In addition, GCDs work closely with the TWDB by submitting local GAMs, every five years, for approval (Texas Water Development Board, n.d.).

Groundwater conservation districts cover approximately 66% of the state, with the remaining areas not being protected by a groundwater conservation district (George, Mace and Petrossian 2011). Areas not protected by a GCD have no regulation and therefore have no limits on water pumping. This study overlies five groundwater conservations districts. Of note there is one small area in the southeast portion of Gonzales County not within a GCD. The top of Figure

2 displays the groundwater conservation districts in relation to the study area. The study area boundary is displayed here for reference and is discussed in further detail in Chapter Four.

Groundwater management areas (GMA) were established in 2005 as a means for regional planning of groundwater (Porter 2014). These GMAs are displayed on the bottom of Figure 2. While the GCD boundaries closely follow many of the county borders, GMA boundaries align better with aquifer borders and therefore cover much larger areas. Groundwater management areas are responsible for conserving, preserving, protecting, recharging, and preventing waste of groundwater resources (Texas Water Development Board 2015). Also, GMAs regulate any subsidence caused by the pumping of groundwater. Another important role of the GMAs is to create long-term goals which support the desired future conditions (DFC) of the aquifer they are responsible for. DFCs are defined as "the desired, quantified condition of groundwater resources (such as water levels, spring flows, or volumes) within a management area at one or more specified future times as defined by participating groundwater conservation districts within a groundwater management area as part of the joint planning process" (Texas Water Development Board 2015). For a DFC to pass, it must receive a two-thirds majority vote of all GCDs within the GMA, and will assist in guiding those included GCD's policies. DFCs are submitted every five years, but may be modified at any time (Porter 2014). There are three groundwater management areas within this study area.

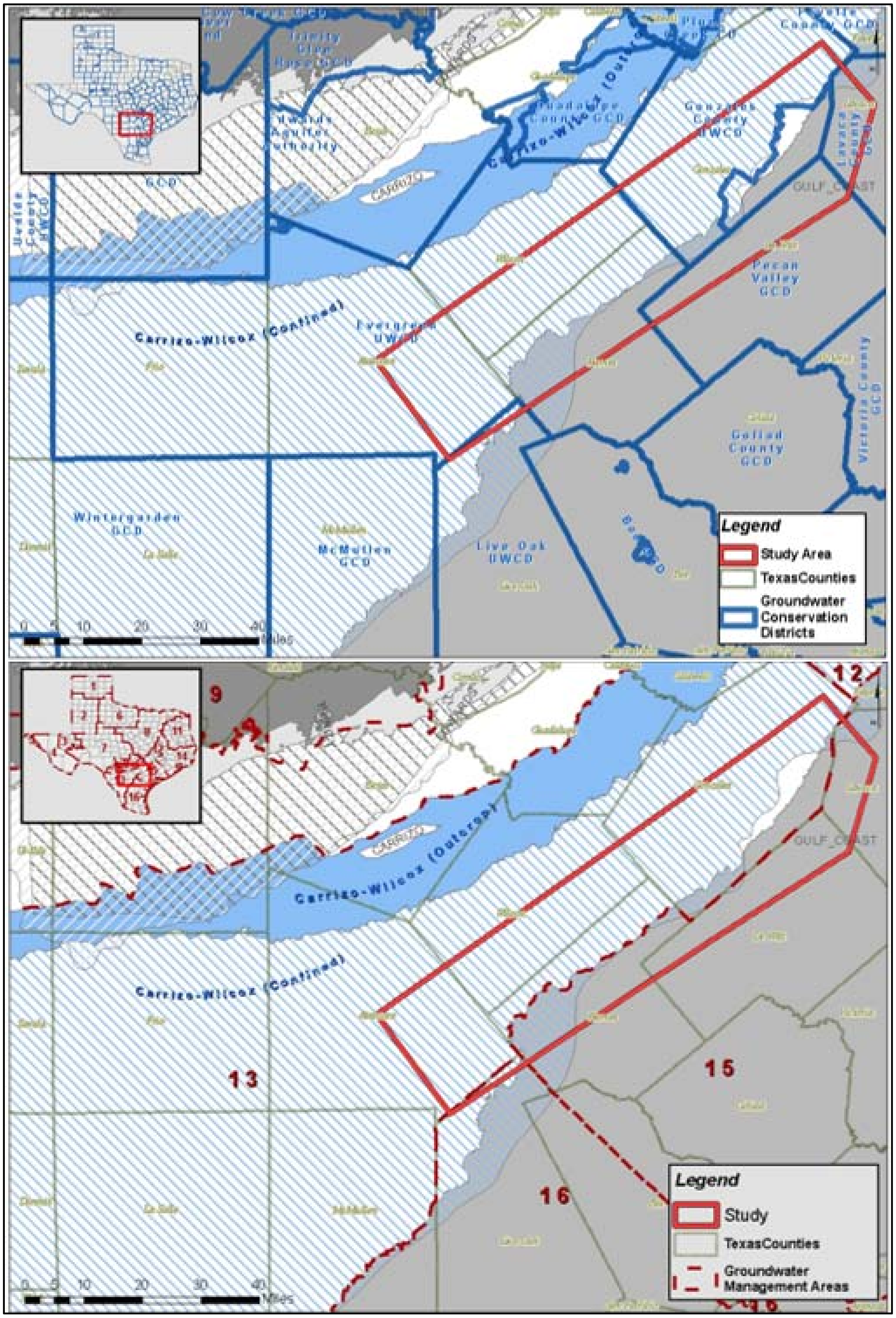


Figure 2 Groundwater Conservation Districts (top) & Groundwater Management Areas (bottom).

What is interesting is that these state and federal agencies have no authority over groundwater when it comes to oil and gas operations. This role belongs to the Railroad Commission of Texas, which in 1919 was granted jurisdiction over oil and gas operations for the State of Texas (Railroad Commission of Texas 2015). Table 1 summarizes the responsibilities of the various agencies involved with Texas groundwater. Further detail regarding the Texas Railroad Commission is addressed later in the chapter.

Table 1 Regulatory agencies involved with Texas groundwater.

Organization	**Acronym**	**Area**	**Responsibilities**
Texas Commission on Environmental Quality	TCEQ	Statewide	Responsible for protecting water quality.
Texas Water Development Board	TWDB	Statewide	Manages & finances adequate water supplies for the state. 5-year statewide water plan.
Groundwater Conservation Districts	GCD	Local	Local management of groundwater levels. Water wells permits & regulation.
Groundwater Management Areas	GMA	Regional	Regional groundwater planning. Creates desired future conditions
Groundwater Advisory Unit (Railroad Commission of Texas)	GAU (RRC)	Statewide	Regulates oil and gas operations, including those involved with groundwater.

2.2 Carrizo-Wilcox Aquifer

The Carrizo-Wilcox Aquifer is one of nine major aquifers in Texas, and spans from the Louisiana border to the Mexico border (Figure 3). The aquifer runs parallel to the Gulf of Mexico, covering 66 counties in Texas. The Carrizo-Wilcox reaches up to 3,000 feet thick in some areas, with freshwater thickness averaging 670 feet (George, Mace and Petrossian 2011).

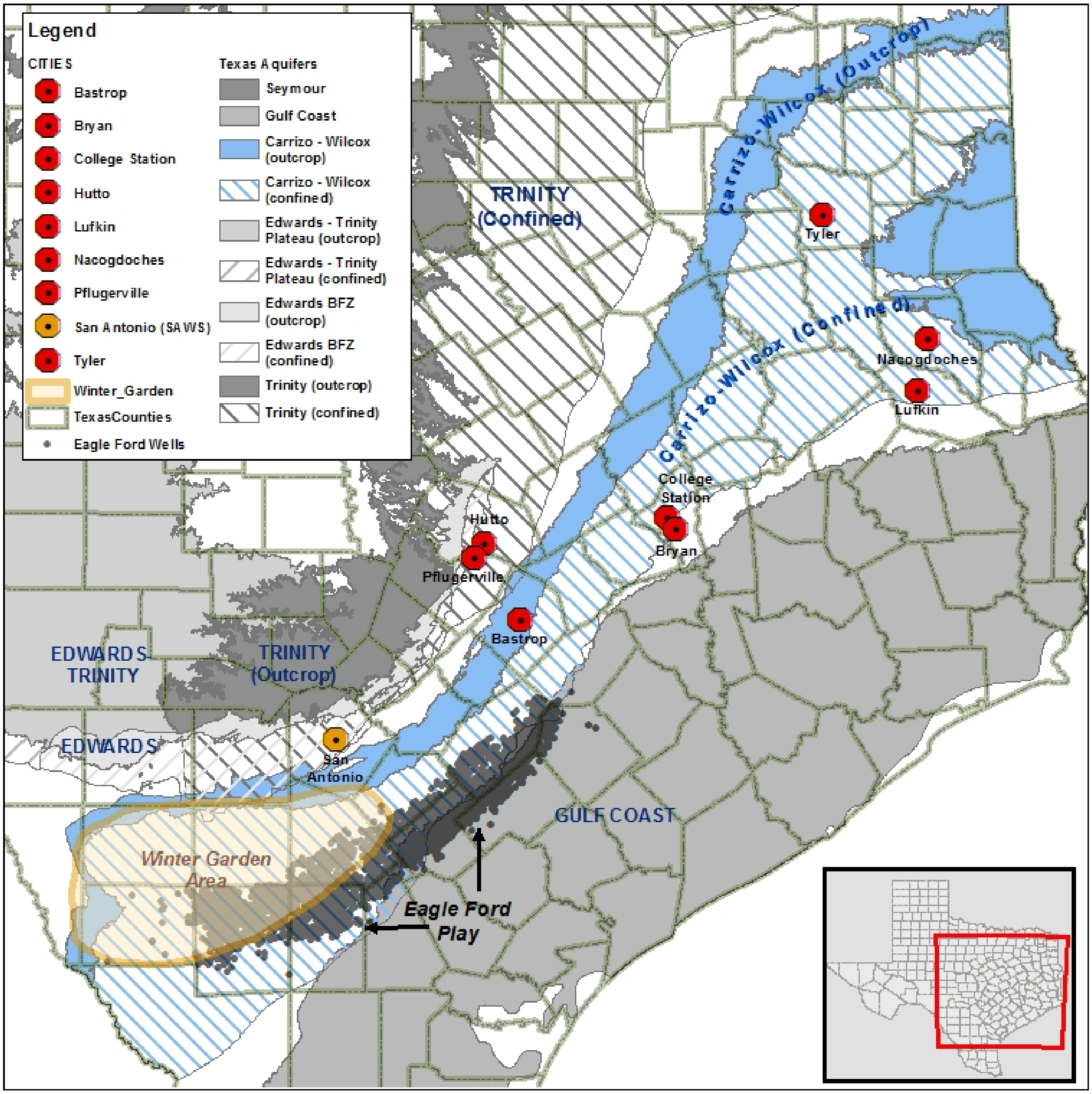


Figure 3 Distribution of Carrizo-Wilcox aquifer across Texas.

The aquifer is mostly composed of sand, interbedded with gravel, slit, clay and lignite. The Carrizo-Wilcox consists of two hydrologically connected aquifers composed of the Carrizo Sand, located at the base of the Claiborne group, overlying the Wilcox group (Huang, et al. 2012). Figure 4 shows the stratigraphic order of the formations within the study area.

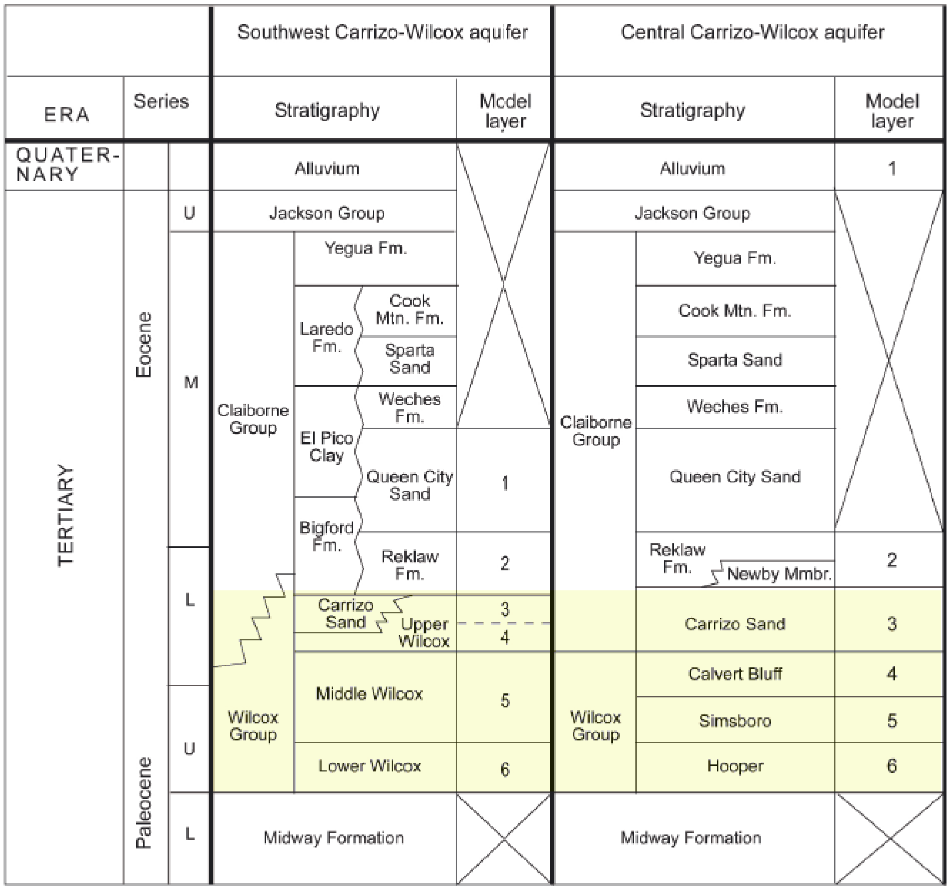


Figure 4 Geologic stratigraphy of the study area. Modified from Dutton, et al 2003.

The Carrizo-Wilcox supplies water for multiple uses across Texas, including irrigation, municipal water supply, manufacturing, steam power and watering livestock. In 2013, almost 415,000 acre-feet of water was pumped from the Carrizo-Wilcox, with irrigation and municipal water supplies using 89% of the groundwater (Figure 5) (Texas Water Development Board 2013). The Winter Garden area – a farming region - of the Carrizo-Wilcox aquifer occupies Zavala, Frio, Atascosa, Wilson and Dimmit counties (Figure 3) (Boghici 2009). With respect to irrigation pumpage, this farming area uses 35% of extracted Carrizo-Wilcox groundwater. The primary municipalities that depend on the fresh water from this aquifer include Bryan-College Station, Lufkin-Nacogdoches, Bastrop, Tyler, Pflugerville, and Hutto, while San Antonio is relying on the Carrizo-Wilcox for untraditional water supply, and is further explained in section 2.2.2 (Figure 3).

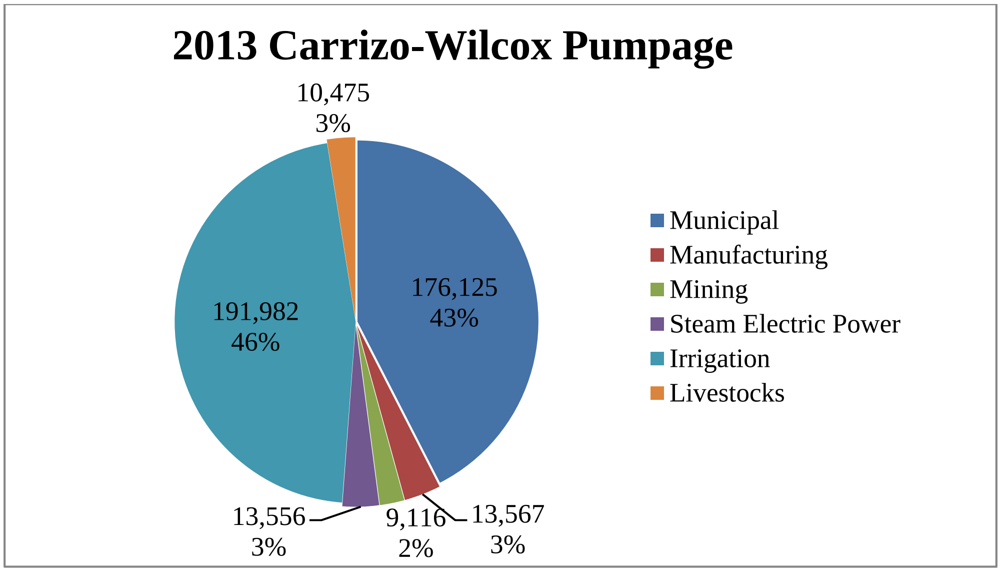


Figure 5 Groundwater pumpage estimates for 2013, in acre-feet. *Source*: Texas Water Development Board.

2.2.1. Water Quality of the Carrizo-Wilcox Aquifer

Total dissolved solids (TDS) describe the amount of mineral content within groundwater (George, Mace and Petrossian 2011). TDS is measured as milligrams per liter (mg/L) of water, and if values are too high, the water could be undrinkable, unsuitable for irrigation or watering livestock, or even toxic. According to the Texas Water Development Board (2011), groundwater TDS values of less than 1,000 mg/L are considered fresh, and therefore suitable for human consumption. Groundwater with these low TDS values typically lie near the surface, in the outcrop region of the Carrizo-Wilcox Aquifer. This is because the aquifer recharges here from surface runoff. As the formation dips downward toward the Gulf Coast, water collects minerals and sodium from the rock composition, and groundwater quality degrades. Groundwater with TDS values up to 1500 mg/L could be used to irrigate crops, and lie in the subsurface region.

Groundwater with TDS values of 3,000 mg/L or less, located further down-dip, could be used to water livestock.

2.2.2. San Antonio Water System Activity

The San Antonio Water System (SAWS) provides water to the City of San Antonio, and much of Bexar County. Although the Edwards Aquifer provides SAWS with nearly all of their water, SAWS is turning to alternatives as a way to diversify their water supply. These alternatives rely on the Carrizo-Wilcox aquifer to provide support. In 2002, SAWS began constructing an Aquifer Storage and Recovery (ASR) facility, completing Phase I in 2004 (Crow 2012). Because the Edwards aquifer is a karst formation, the aquifer fills and drains rather quickly compared to a sand aquifer. Therefore when the Edwards aquifer is sufficiently full and consumption is low, water is pumped out of the Edwards and injected into the Carrizo-Wilcox ASR for storage. During times of drought and higher consumption, there is additional water in the ASR available to the community.

Another means of diversifying SAWS's water supply is through the construction of their desalination plant. This plant will pump brackish water from the Wilcox portion of the Carrizo-Wilcox aquifer and utilize reverse osmosis treatment to remove the dissolved solids, making the water drinkable (San Antonio Water System 2015). Phase I is expected to complete in 2016, providing twelve million gallons of freshwater per day. This project indicates the necessity of water in the region and that brackish water should also be protected from contaminants. These developments demonstrate alternate ways to utilize this plentiful aquifer other than traditional pumping of fresh groundwater.

2.3 Oil and Gas Operations in Texas

Texas is known for its leading role in oil production within the United States. The Eagle Ford shale play has become the most recent "boom" in Texas, providing more than one million barrels of oil equivalent per day (boe/d) (Eagle Ford Shale 2015). In addition to oil and gas, the Eagle Ford has provided jobs, money and growth to the region. While it is important to continue facilitating this increased economic development, it is also important to insure that the environment (including groundwater) sees no negative impact.

2.3.1. Baseline Water Sampling

It would be ideal to have water sampling conducted in the region prior to oil and gas operations to determine the baseline water quality. Although most states do not require this, it has been recommended by the American Petroleum Institute (Holloway and Rudd 2013). Groundwater could then be sampled during drilling and fracking operations, and even long after a well is completed, to ascertain if local groundwater quality has deteriorated. There are some historical records of water wells in the region. However, a systematic method of water sampling was not conducted prior to oil and gas operations.

2.3.2. Well Casing

When drilling oil and gas wells, shallow aquifers are penetrated to reach a formation below filled with hydrocarbons. Therefore, the first step of drilling an oil or gas well is to set the surface casing. Surface casing is intended to run from the top of the borehole to below the base of the aquifer (Figure 6). Surface casing consists of a steel, hollow pipe set in cement between it and the borehole wall (Holloway and Rudd 2013). The initial cementation of the casing is critical as it seals the annular space before further operations occur. This hydraulic barrier isolates fresh groundwater from the inside of the well. If the surface casing is not deep enough or is not properly installed, contaminant leakage into the groundwater could occur.

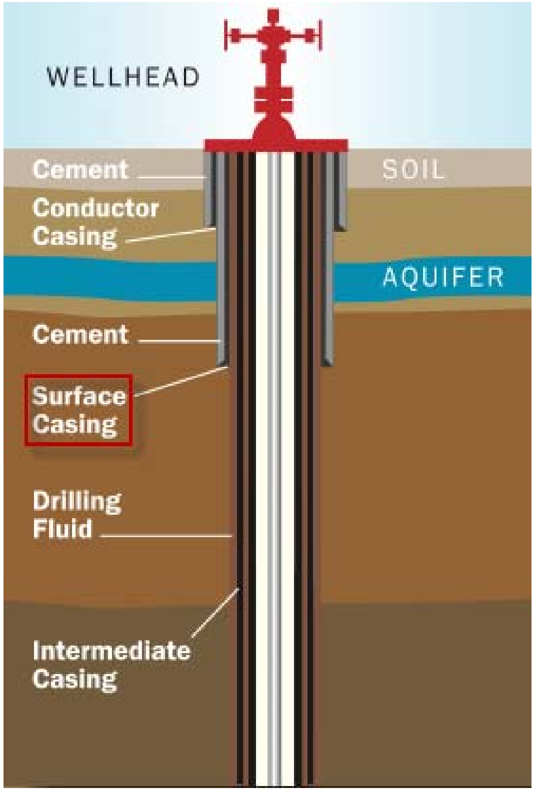


Figure 6 Example of surface casing. *Source:* (Bonanza Creek 2015).

2.3.3. Railroad Commission of Texas Regulation

The Railroad Commission of Texas (RRC) is responsible for regulating oil and gas operations for the state of Texas, including water quality aspects related to those operations. The Groundwater Advisory Unit (GAU) is a division of the Texas RRC which provides guidance on issues such as saltwater disposal wells, and groundwater contamination and protection, including casing depths (Gearhart 2014).

Prior to January 2014, the Texas Administrative Code Rule 3.13, which addresses well casing, cementing, drilling, well control and completions, had not been revised since 2003 (Gronewold 2014). Rules from the new revision increase regulation guidelines which protect groundwater as well as safety procedures. Rule 3.13 outlines several requirements for surface casing. For example, surface casing must be at least one and one-half inches less than the wellbore diameter and must be pressure tested (Texas Administrative Code 2014).

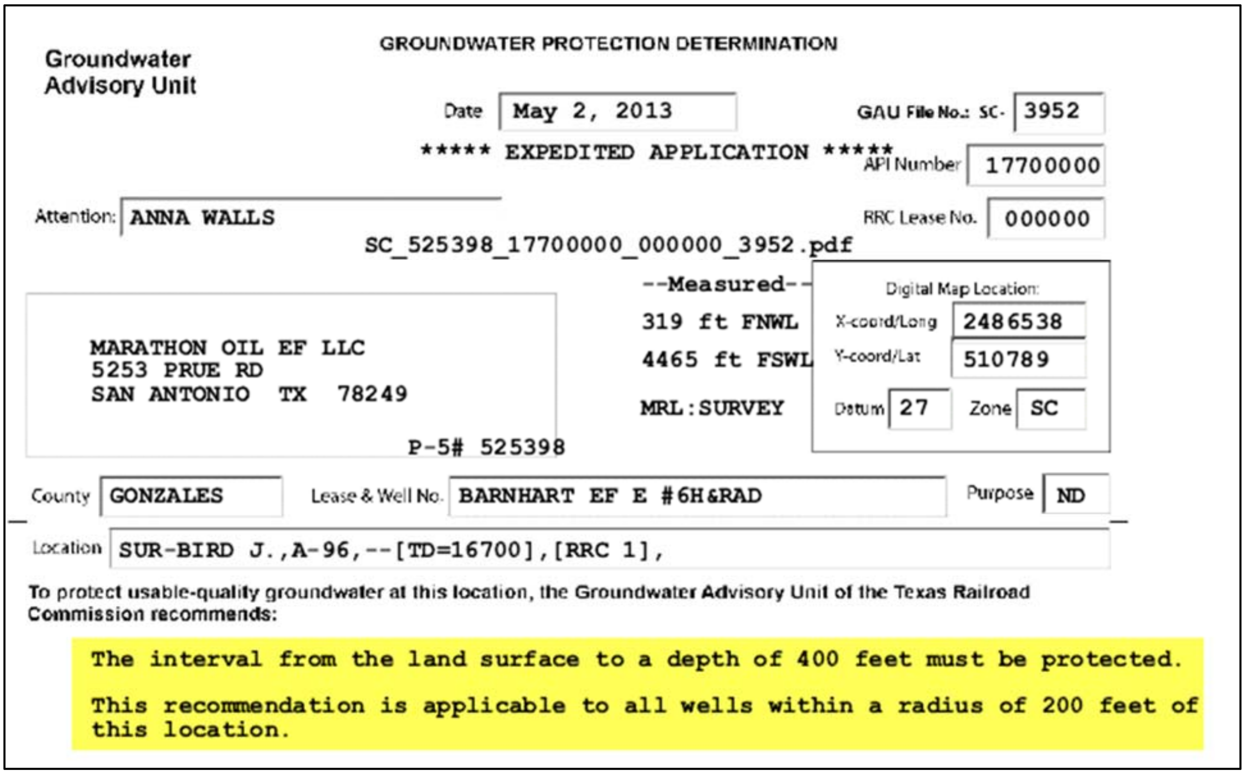
After the upper portion of the borehole is drilled, the steel casing is set with cement down past the *protection depth*. According to Part 1, Chapter 3, Rule 3.13 of the Texas Administrative Code, the Texas RRC defines the protection depth as,

> Depth to which usable-quality water must be protected, as determined by the Groundwater Advisory Unit of the Oil and Gas Division, which may include zones that contain brackish or saltwater if such zones are correlative and/or hydrologically connected to zones that contain usable-quality water. (Texas Administrative Code 2014).

The difficulty with this definition is the word "usable" because it is a not a quantitative unit of measure. Therefore, there are some instances where groundwater with TDS values of up to 7,000 mg/L are protected with surface casing, and other instances where groundwater with less than 3,000 mg/L are not. In addition, being hydrologically connected could mean anything between two impermeable formations, or aquitards.

To find this usable depth, operators are referred to the "Surface Casing Estimator" website hosted by the Bureau of Economic Geology and located at http://coastal.beg.utexas.edu/surfacecasing/. This site displays a map with satellite imagery and several oil and gas wells. Here, the operator can view casing information and well logs, if available, of nearby, pre-existing wells. The results of the well logs identify various formation characteristics such as lithology and fluid content. This will assist in finding an estimated depth for surface casing. Although this method is functional, it is certainly not ideal because the aquifer base nor salinity information is not shown. Additionally, the site provides a limited number of wells, where the closest well to the area of interest may be several miles away. A map displaying Carrizo-Wilcox depth would be a more informative approach to this part of the process.

After estimating a depth by using a nearby well, the operator must then submit a Groundwater Protection Determination Request form (GW-1) to the groundwater advisory unit (GAU). After review, the GAU will issue a surface casing letter which outlines where fresh and usable water is located (Figure 7).



Groundwater Advisory Unit

GROUNDWATER PROTECTION DETERMINATION

Date: May 2, 2013

GAU File No.: SC- 3952

***** EXPEDITED APPLICATION *****

API Number: 17700000

Attention: ANNA WALLS

RRC Lease No.: 000000

SC_525398_17700000_000000_3952.pdf

MARATHON OIL EF LLC
5253 PRUE RD
SAN ANTONIO TX 78249

P-5# 525398

--Measured--
319 ft FNWL
4465 ft FSWL
MRL:SURVEY

Digital Map Location:
X-coord/Long: 2486538
Y-coord/Lat: 510789
Datum: 27 Zone: SC

County: GONZALES

Lease & Well No.: BARNHART EF E #6H&RAD

Purpose: ND

Location: SUR-BIRD J.,A-96,--[TD=16700],[RRC 1],

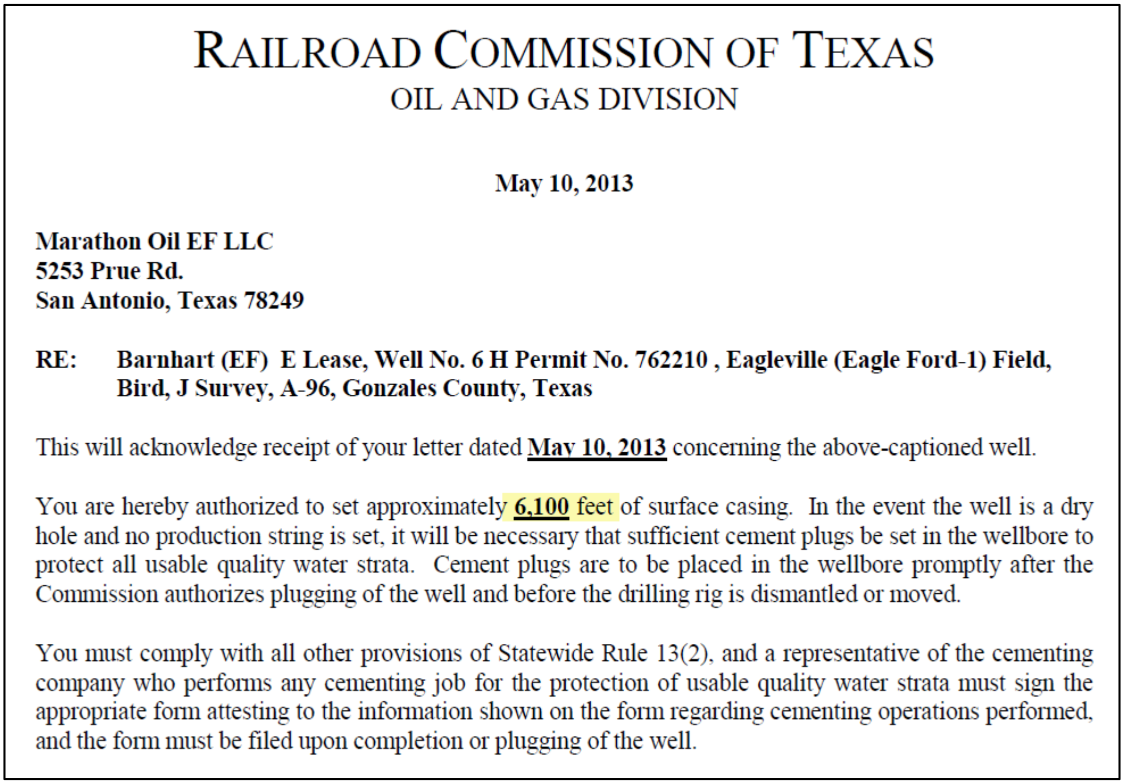
To protect usable-quality groundwater at this location, the Groundwater Advisory Unit of the Texas Railroad Commission recommends:

The interval from the land surface to a depth of 400 feet must be protected.

This recommendation is applicable to all wells within a radius of 200 feet of this location.

Figure 7 Sample of surface casing letter from the groundwater advisory unit.

Once an operator receives this letter, this is the depth they are to protect with surface casing. No shallower, and no deeper. If an operator feels that the casing depth should be deeper because they have better information, they are instructed to submit an exception request to the GAU, and present this evidence (Gearhart, Email message to Railroad Commission of Texas 2015). After further review, the GAU will then issue a new letter (Figure 8) and use the newly gathered information for future Groundwater Protection Determination letters, according to Gearhart (2015).



RAILROAD COMMISSION OF TEXAS
OIL AND GAS DIVISION

May 10, 2013

Marathon Oil EF LLC
5253 Prue Rd.
San Antonio, Texas 78249

RE: Barnhart (EF) E Lease, Well No. 6 H Permit No. 762210 , Eagleville (Eagle Ford-1) Field, Bird, J Survey, A-96, Gonzales County, Texas

This will acknowledge receipt of your letter dated **May 10, 2013** concerning the above-captioned well.

You are hereby authorized to set approximately **6,100** feet of surface casing. In the event the well is a dry hole and no production string is set, it will be necessary that sufficient cement plugs be set in the wellbore to protect all usable quality water strata. Cement plugs are to be placed in the wellbore promptly after the Commission authorizes plugging of the well and before the drilling rig is dismantled or moved.

You must comply with all other provisions of Statewide Rule 13(2), and a representative of the cementing company who performs any cementing job for the protection of usable quality water strata must sign the appropriate form attesting to the information shown on the form regarding cementing operations performed, and the form must be filed upon completion or plugging of the well.

Figure 8 New surface casing letter after an exception was filed.

The drawback to this process is that some less-responsible operators might see this as a nuisance, costing too much time. The operator might set the casing depth to that which was recommended by the RRC, whether it protects the aquifer or not.

It is important to understand the framework of oil and gas operations, and groundwater protection and regulation. Having described this in Chapter Two, the next chapter introduces subsurface geologic mapping and the use of Geographic Information Systems (GIS) in that context.

Chapter 3 Geologic Mapping Practices

Mapping geologic subsurface structures and features is not entirely easy because it cannot be directly observed. Therefore, locations where the formation (or aquifer) has been identified are used to interpolate a predicted surface where direct observations cannot be made. This chapter highlights how well logs are used as observation points, summarizes traditional geologic mapping techniques, and explains interpolation methods for subsurface mapping available in GIS.

3.1 Interpreting Well Logs

Often geophysical tools are sent down the borehole of a well to record geophysical properties of the subsurface (Evenick 2008). Sometimes, these tools are sent downhole after a well has been drilled, and other times these tools are on the same assembly as the drill bit and records data while drilling. The results of these recordings are called well logs and are typically provided on paper, as well as in digital files. By recording geophysical and physical properties, well logs provide insight on subsurface geologic formations and conditions.

The first page of a log contains general information such as well name and number, API (American Petroleum Institute) number, well operator, logging company, and elevation. This first page is called the well header. The following pages, or body, contain the recorded data separated into tracks, or columns. Three primary logs, which are implemented most often, include gamma ray logs, resistivity logs and spontaneous potential (SP) logs. However, there are numerous other types of logs available which provide further detail of geophysical properties.

Gamma ray logs record the radioactivity produced naturally by a formation (Evenick 2008). These logs are useful in identifying clays and shales because these materials emit high gamma ray values (Camp and Outlaw Jr 1993). Additionally, gamma ray logs are valuable because they are fairly inexpensive, simple to interpret and provide great vertical resolution, allowing for easy stratigraphic correlations. Resistivity logs record the resistance of electrical flow through a formation. Resistivity logs aid in identifying fluid type and formation porosity. Like resistivity logs, SP logs are also electrical logs, but record the electrical current caused by the mixing of two fluids with contrasting salinities. Drilling mud will typically have different salinity than the formation fluids producing certain measurements (Hyne 2001). SP logs are also useful in identifying formation permeability (Evenick 2008). However, SP logs do not offer great vertical resolution, and can therefore lose detailed information on formations which are very thin. Figure 9 demonstrates a simplified example of these three logs curves.

When identifying fresh water bearing formations such as aquifers, the log should reflect low gamma ray values, high resistivity values and high SP values. However, as an aquifer becomes more brackish, resistivity and SP will decrease.

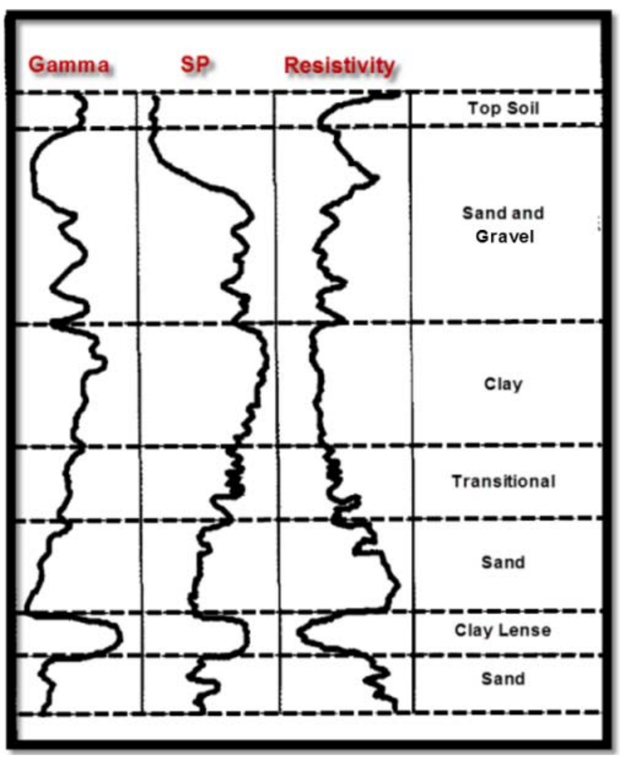


Figure 9: Sample well log. Modified from Camp and Outlaw 1993.

To effectively map the subsurface, it is important to logically pick horizontal changes in formations, or horizons. This is not easy as there are many variables that contribute to the output of a well log, and therefore require the technical experience of a geologist.

Well logs provide the “observed” information needed to begin correlating and interpreting a regional formation. Correlating well logs describes finding matching patterns between multiple wells. Recognizing these matching patterns is important in finding these same formation boundaries, or picks, across an area of interest. Accurate well correlations are necessary to map subsurface structures.

3.2 Structure Maps

By correlating well logs from multiple wells, the structure of a formation can be interpreted and ultimately mapped. When mapping the subsurface, geologists are interested in understanding geologic structure and stratigraphy. Often areas are complicated where the structure can be folded or faulted (Tearpock and Bischke 2002). These complications can make mapping difficult and require a good understanding of basic geologic principles. Geologists create many different types of maps in an effort to understand what is occurring deep in the earth, including structure maps, thickness maps, fault maps, facies maps, hydrologic maps and cross sections.

The most common map generated is one that represents a stratigraphic horizon of interest and is called a structure map. Structure maps represent the depth of a formation, including its structural features, and are created from correlated well log picks (Evenick 2008). If all of the overburden were removed, a subsurface elevation map, or topographic map, representing a single horizon would be left. Structure maps, or depth maps, can be represented by either contour lines, or a continuous surface, or both. Whichever method is selected to represent the horizon of interest, the outcome should still be reviewed with geologic intuition to be sure that it makes sense within the region.

Traditionally, depth maps are created by hand by generating contour lines that connect points of equal depth (Evenick 2008). Because there are many rules applied to contouring that must be followed to create mechanically correct maps, this process requires technical knowledge of an experienced geologist (Tearpock and Bischke 2002). However, the advancement of computer technology and mapping software applications have made this process simpler and automated. In addition to contour maps, software applications can use interpolation methods to create a continuous surface that represents a geologic horizon.

Interpolation describes a technique where measured values at known locations are used to predict values at locations where measurements have not been directly observed. For subsurface features, this creates a digital model of a continuous surface representing a phenomenon such as the base of an aquifer.

3.3 Interpolation Techniques in GIS

Well logs provide the control points needed to interpret a viable structure map of the subsurface. Geographic Information Systems (GIS) use these control points to interpolate or predict values between them. In GIS, the result is usually a raster dataset.

There are two categories of interpolation methods: (1) deterministic; and (2) geostatistical (Esri 2015). Deterministic interpolators use predefined, smoothing, mathematical functions of distance from known points to assign values to a predicted location. Deterministic interpolators have the option of considering all of the points in the dataset globally, or only considering points in smaller areas, locally (Esri 2015). Deterministic interpolation methods tried during this thesis include Spline and Kernel.

Geostatistical interpolators not only use the values of surrounding locations directly, but also the statistical spatial relationship between the values at those locations. Geostatistical interpolators have the added benefit of providing a measure of uncertainty of the predicted values. Empirical Bayesian Kriging is a geostatistical interpolation method tested during this thesis.

Utilizing the most appropriate interpolation method for creating a raster depth surface is a key aspect of this project. Often, in the field of geology, the traditional minimum curvature technique is applied when interpolating a geologic surface (Zoraster 2003). In ArcGIS, the spline interpolation tool is representative of this function.

3.3.1. Spline Interpolation

The Spline interpolation method creates a smooth, gently varying, predicted surface by using a minimum curvature mathematical function (Esri 2015). The interpolator passes exactly through all control points, meaning that at the location of a control point, the observed value will be the same as the predicted value. There are two Spline types available with the ArcGIS tool: (1) regularized; and (2) tension. The regularized option creates a smoother output and allows values to extend beyond the data range of the control points. The tension option creates a slightly more uneven surface by constraining the predicted values to the data range of the control points. One advantage of the Spline interpolator is that it has the option to honor barriers, such as faults. However, this project did not require this as the Carrizo-Wilcox fractures are minimal within the study area, providing slight displacement of rock, and no influence on the movement of fluid (Phillips 2015). The biggest disadvantage of the Spline interpolation method is the lack of any uncertainty measurements associated with the predicted surface.

3.3.2. Kernel Interpolation

The Kernel interpolation method utilizes a *moving window* method to predict values at locations where values are unknown. This local interpolator is similar to the Local Polynomial Interpolation (LPI) method, but varies by estimating regression coefficients which reduces model instability (Esri 2015). By altering the ridge parameter, bias in the model can be increased to allow for a more stable model. Because bias is added to the model, the ridge parameter should be kept as small as possible. As there are six Kernel functions available in ArcGIS, cross-validation and validation diagnostics can help determine which Kernel function is most appropriate for the sample dataset. The Kernel interpolator in ArcGIS has the ability to honor barriers, to a certain extent. Values can still be interpolated around barriers if the shortest distance between points still fall within the searching neighborhood specifications.

Unlike the Spline method, the Kernel method is an inexact interpolator, meaning that the predicted surface does not have to pass through the values of the control points. This feature is acceptable within this study because of the type of phenomena being modeled. This study is focused on modeling subsurface geology- the base of the Carrizo-Wilcox aquifer. When geologic formations are transitioning from one to another, in most cases, there is no hard, defining line between them. There will be a transition zone where one ends and another begins. Therefore, some flexibility is acceptable.

3.3.3. Empirical Bayesian Kriging

Kriging is a geostatistical form of interpolation that uses statistics to model spatial autocorrelation between observed values (Esri 2015). By using statistics, there is probability associated with the predicted values. Therefore, uncertainty can be quantified by the standard errors produced (Krivoruchko 2012). Kriging is considered a robust interpolator because there is less prediction uncertainty and error is minimized. Kriging quantifies the spatial dependence within the data by using semivariogram and covariance functions. A semivariogram is calculated by comparing the values at each pair of points, and dividing the squared difference of values in half. Each halved, squared difference is plotted against the distance in points. Once the values for every pair are plotted, a best-fit model is estimated, and predictions are made using generalized linear regression techniques (Esri 2015). Within ArcGIS, there are several different kriging methods available and many parameters which can be tweaked to find the best model. This requires considerable interaction from the user. Because there can be uncertainty within a semivariogram model, prediction standard errors are sometimes underestimated.

Empirical Bayesian Kriging (EBK) is one form of Kriging offered within Geostatistical Analyst of ArcGIS, which automates many of the difficult parameters by using simulated models of subset data (Esri 2015). The EBK method creates several semivariograms within these subset neighborhoods (defaulted to 100 points). To accomplish this, a semivariogram is first estimated using a subset of values, new values are estimated at the input locations based off of the original semivariogram. Next a new semivariogram is created from the new estimated values. The original semivariogram is used to repeat the process several times creating many semivariograms. By averaging these semivariograms, a suitable model is determined without reliance on the user making arbitrary parameter choices.

Figure 10 shows an example of the many simulated semivariograms plotted together, using project data of wells with the base of the aquifer interpreted from well logs. Here, the average value is represented by the solid red line (Esri 2015). Quantile lines represent the 25th and 75th percentiles and are symbolized by dashed red lines.

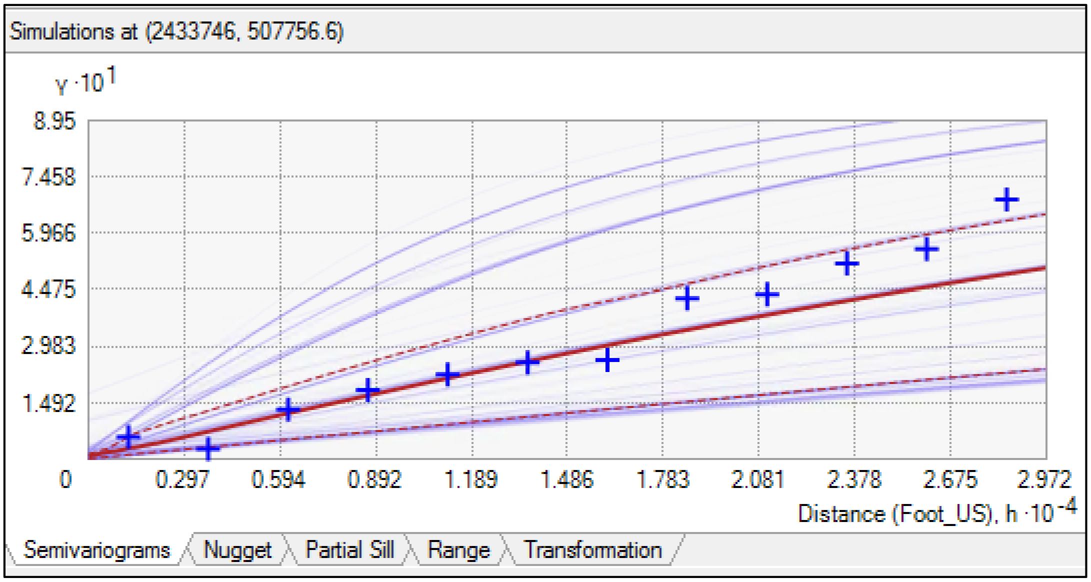


Figure 10 Simulated Semivariograms created from project data.

Because the regional geology within the study area has a physical trend, where the formations dip downward to the Southeast, utilizing an EBK model which detrends the data will provide a surface with less error. When a dataset is nonstationary, meaning that average values vary over space, EBK offers the ability of removing this large scale variation, by applying a first-order trend removal (Krivoruchko 2011, Esri 2015). EBK provides several kriging models which apply transformations to the simple kriging model, three of which will remove data trends. Using validation and cross-validation diagnostics help determine the best model.

The EBK interpolation method does not have means of employing barriers, such as faults. Therefore, when interpolating a geologic formation with faults, this would not be an ideal interpolator. However, in this study, as stated above, faults are not significant. Additionally, like the Kernel method, the EBK method does not pass exactly through the measured values of the control points, which is acceptable within this study.

3.3.4. Error

Error is described as the difference between an observed value and a predicted value. Both Kernel and Empirical Bayesian Kriging (EBK) interpolation methods provide predicted error statistics to aid in selecting a suitable interpolation method. Validation and cross-validation techniques are used to generate error values and asses the quality of the model (Esri 2015). The validation process removes a sample of input data points and utilizes the remaining input data points to create predictions at the omitted point locations. Cross-validation removes one point at a time and uses the remaining dataset to predict a value at the omitted point. Predicted values are compared with the control point values to determine the amount of error in the prediction.

One way ArcGIS illustrates the errors produced during the interpolation is by using scatterplots. Here the predicted value is plotted against the measured value. Another way ArcGIS presents this data is by providing statistics of the prediction errors. The best model will have a standardized root-mean-squared prediction error near one and a standardized mean prediction error near zero (Esri 2015). In addition to the statistical output, the Kernel and EBK interpolators also provide standard error maps. These maps show the margin of error from the actual value with a 95% confidence (Krivoruchko 2011). In other words, by adding and subtracting the error values from the predicated value, there is a 95% chance that the actual value falls within this range. These error statistics and error maps provide great insight as to how well the selected model performs.

Table 2 compares the interpolation methods investigated during this project and the available functionality they offer.

Table 2 Comparison of Interpolation Method Functionality.

Functionality	**Spline**	**Kernel**	**EBK**
Exact interpolator	Yes ✓	No	No
Honors barriers	Yes ✓	Yes ✓	No
Provides standard error map	No	Yes ✓	Yes ✓
Model spatial autocorrelation	No	No	Yes ✓
Ability to detrend data	No	No	Yes ✓

This study uses ArcGIS and the interpolation methods available within it. The Spline interpolation method was selected to evaluate because it is a traditional algorithm used by geologists. The Kernel and empirical Bayesian Kriging interpolators were chosen to examine because they provide quantitative error analysis. Chapter Four provides detail of the methodologies conducted within the project to create an interpolated surface, and compare surface casing depths to that surface.

Chapter 4 Data and Methods

To determine if the surface casings of oil and gas wells drilled into the Eagle Ford shale are set deep enough to adequately protect the shallower Carrizo-Wilcox aquifer, geologic and associated data were manipulated within a Geographic Information System (GIS). GIS is the ideal toolset for analyzing and managing spatial information in a project such as this. The following sections first delineate a study area boundary to conduct analysis within. Next, an explanation of the data needed is provided. The methods discussed in Chapter Three are then conducted within GIS to complete this analysis. In addition, evaluating the data in a 3D environment brings a true sense of where features lie in relation to each other, spatially.

4.1 Study Area Boundary

To define the working area of this project, a boundary was created to limit the investigation spatially. The recently discovered Eagle Ford Shale region was selected because this play is still very active, with 88 rigs operating in December 2015 (Alford 2015). Because of this, applicable mapping techniques are needed to provide a good basis for determining surface casing depths. However, the study area does not cover the entire Eagle Ford drilling region, and a boundary was created to encompass wells where picks of the Carrizo-Wilcox aquifer has been completed. Therefore, the study area boundary covers almost half of the Eagle Ford region. The method demonstrated in this study can easily be extended to cover the entire Eagle Ford area. Figure 11 displays the study area of this project in relation to the Eagle Ford drilling region. The red stars represent wells in which the Carrizo sand base has been picked from well logs. These points were used to create an interpolated surface. The grey dots represent all Eagle Ford wells drilled along South Texas, as of September 2015.

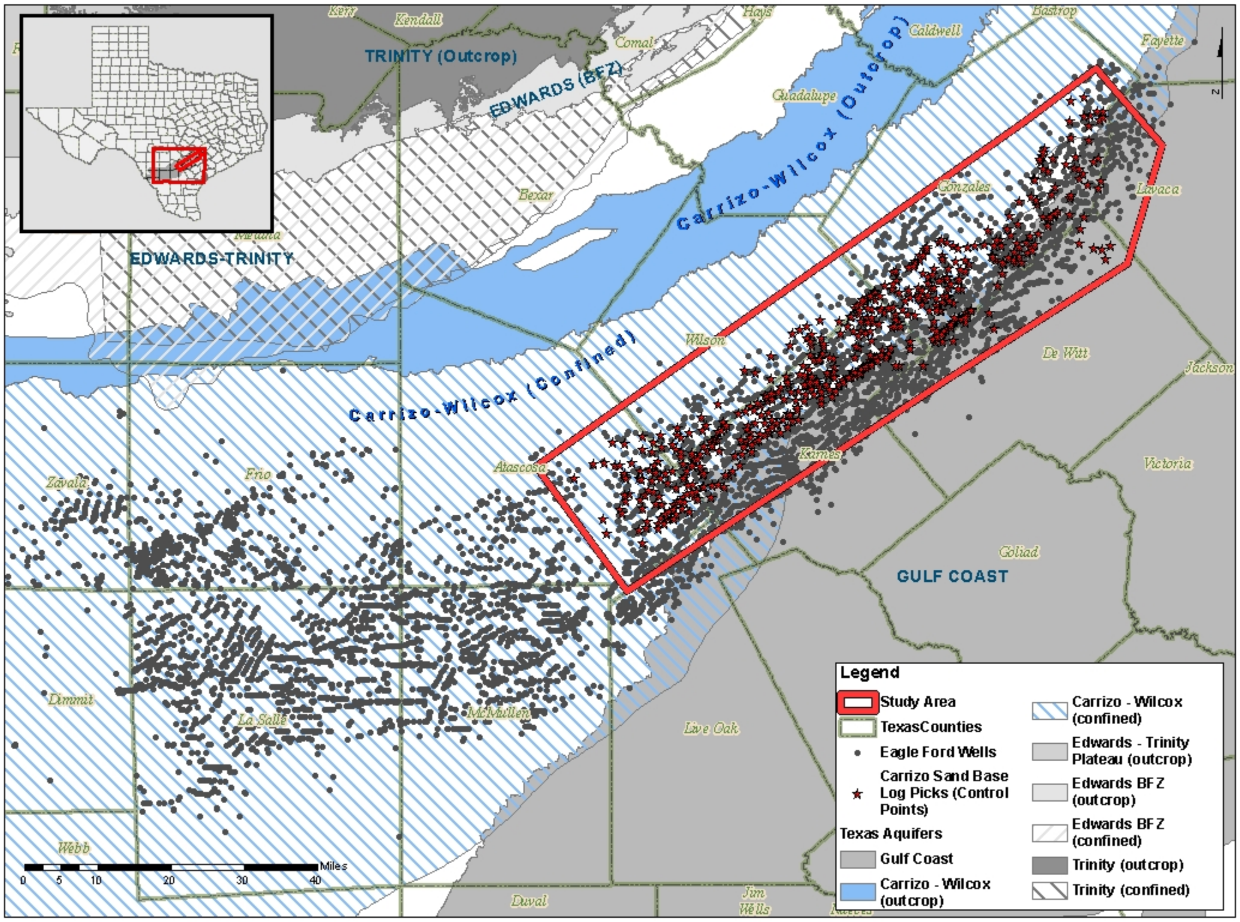


Figure 11 Eagle Ford drilling region in South Texas with study area boundary.

4.2 Data Acquisition and Manipulation

To pursue this project, three primary datasets were needed: (1) well locations of all oil and gas wells within the study region; (2) purchased well logs of older oil and gas wells; and (3) surface casing depths of recently drilled Eagle Ford wells. These were all obtained from various data management companies involved in the oil and gas industry which market such datasets for a fee. Also, salinity lines provide guides as to where water quality is freshest, and where it deteriorates.

4.2.1. Well Locations

All facts pertaining to the drilling and completion of oil or gas wells in the State of Texas are recorded with the Railroad Commission of Texas (RRC). The RRC makes much of this data available for free through their website on a well by well basis through a query interface. However, it can be tedious querying the data and then combining data from multiple queries. For a fee, companies such as IHS Energy (IHS) and P2 Energy Solutions (P2) offer well attributes such as coordinates, well name, drilling details, completion information, etc. in various formats such as access databases, excel spreadsheets, .csv files for download, or also live direct connections. These datasets are continually updated, with some attributes updating daily and others weekly.

X,Y locations of both IHS Energy (IHS) and P2 Energy Solutions (P2), were evaluated. IHS offers information focused on the drilling and completing of an oil or gas well. Well locations and various identification data were downloaded through IHS's data portal, as an Excel spreadsheet. P2 Energy Solutions provides well locations, in addition to other types of spatial data, such as abstract lines (original Texas survey lines), ownership lines, lease polygons, etc. P2 provides their data within a file geodatabase, and it was also downloaded for this project through a data portal. Both sources include pertinent well header information, including well name, operator, and most importantly, the US Well Number. This US Well Number, previously called API number, is the unique well identifier (UWI) of a well, and is provided by the Railroad Commission of Texas.

Preliminary comparisons of well locations provided by the two data sources confirmed that many well locations, especially those drilled in the 1980s or later, were spatially coincident. This is likely due to modern surveying technology. However, several older well locations varied up to eight miles between the two sources. A sample of locations with great variances were further investigated by reviewing the header of the well logs. In the well log header, these older wells identified spatial locations by using metes and bounds. This is a classic surveying method which uses a known landmark as a point of beginning and then calls distance and directions from there. ArcMap was used to measure these distances. Well locations from P2 aligned better with the metes and bounds recorded on the well log headers. As a result, this dataset was selected to be used during analysis throughout the remainder of the study.

Figure 12 shows the spatial distribution of oil and gas wells provided by P2. Attributes used in the table consist of well name and number, operator, X, Y, and US Well Number, which will later be used for joining to other tables.

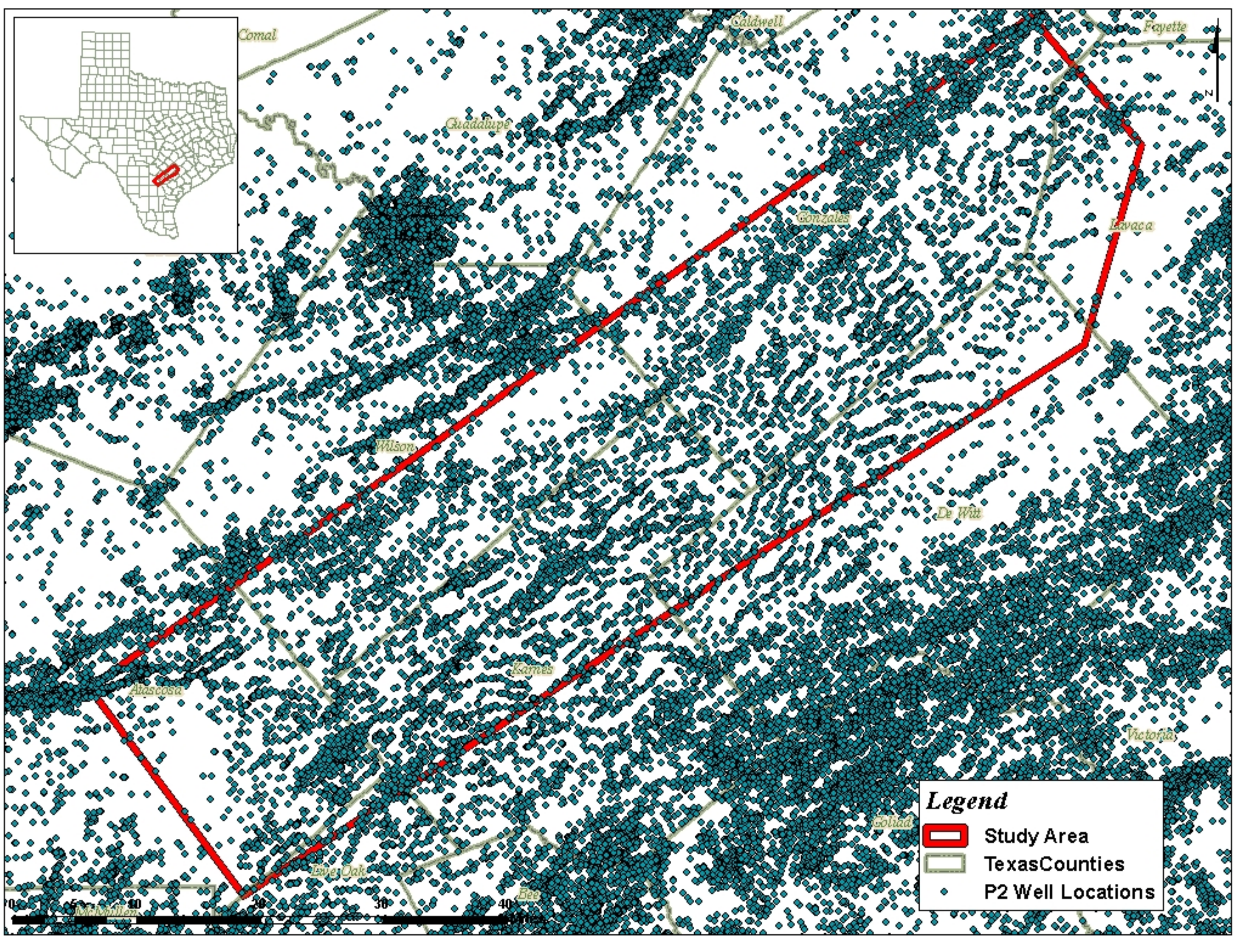


Figure 12 Distribution of well locations from P2 Energy Solutions.

4.2.2. Well Logs

Geophysical tools are sent downhole in a well to gather borehole data in the form of well logs. Well logs offer various information about rock characteristics, such as lithology and fluid content. By identifying the depth at which sandstone composition occurs, the base of the Carrizo sand can be determined from these logs. Logs used within this study were purchased from a petroleum data management company, TGS, and are stored in a geological software application called Petra.

Selecting formation depths, or “picks”, from a well log is an interpretive process, requiring direct analysis by a geologist or petraphysicist. Figure 13 exhibits a screen capture of Petra’s cross-section module displaying several logs with correlated depth picks of different sections of the Carrizo-Wilcox group.

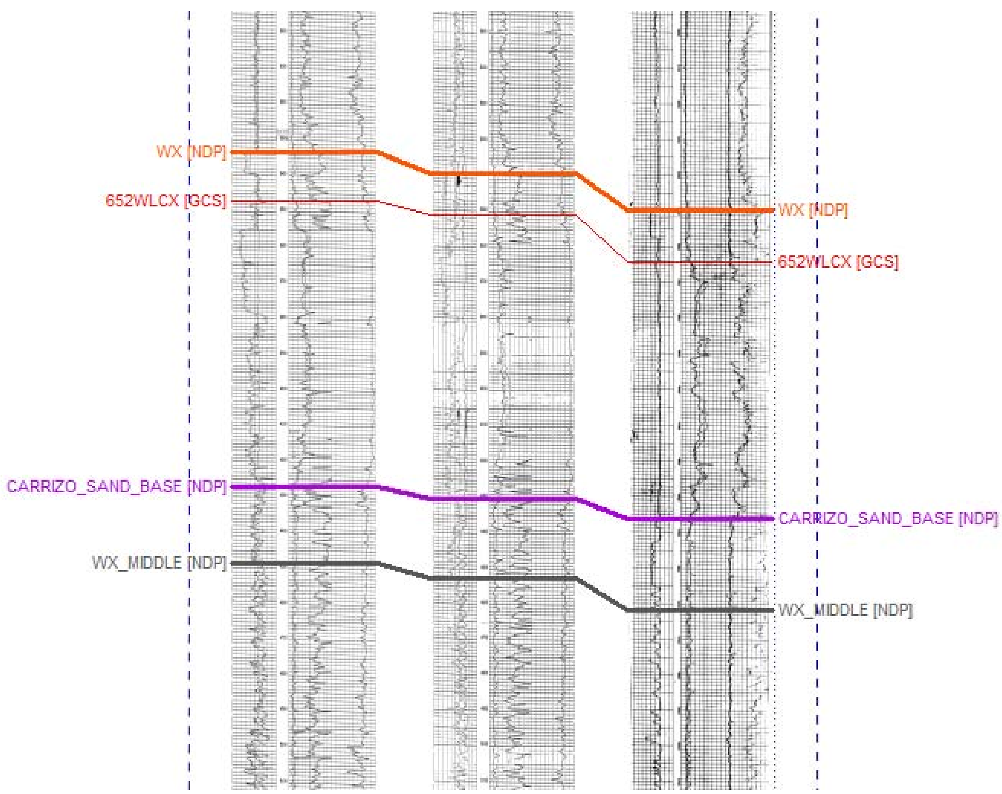


Figure 13 Screen capture of Petra's cross section module displaying vertical correlated well logs with depth being in feet.

Within the study area, there are over 5,000 oil and gas wells with either raster or digital logs. Raster logs are scanned-in paper logs, like those shown in Figure 13, and digital logs are provided in a columnar digital file such as a .txt or .csv. However, not all of these wells are logged through the entire Carrizo-Wilcox, and many of the older raster logs are of poor or inadequate quality. As a result, a total of 520 wells were selected that have the base of the Carrizo sands identified on their logs.

These well logs are stored and interpreted within the cross-section module of Petra, a geological software application. When a geologist identifies a horizon of interest, they create a new pick entry and this data is stored within the Petra software. These depth picks are recorded in feet below sea level (FBSL), also known as subsea total vertical depth (SSTVD). In Petra, these depth picks were queried to create a subset of wells with Carrizo sands base picks. To create a dataset that ArcMap can read, the depths and identifying well information, such as US Well Number and well name, were exported as an ASCII file and imported into Excel. In Excel, the column headers were cleaned up to remove unsupported characters such as spaces, dashes, etc. After preparing the Excel spreadsheet, it was joined to the well locations in ArcMap, only keeping matching records. This means that well locations that do not have an aquifer depth picked from a log were dropped from the layer. The joined dataset was then exported into its own feature class to use as the control points for the interpolation process. Figure 14 shows the 520 selected wells with Carrizo sand depth picks, symbolized by depth.

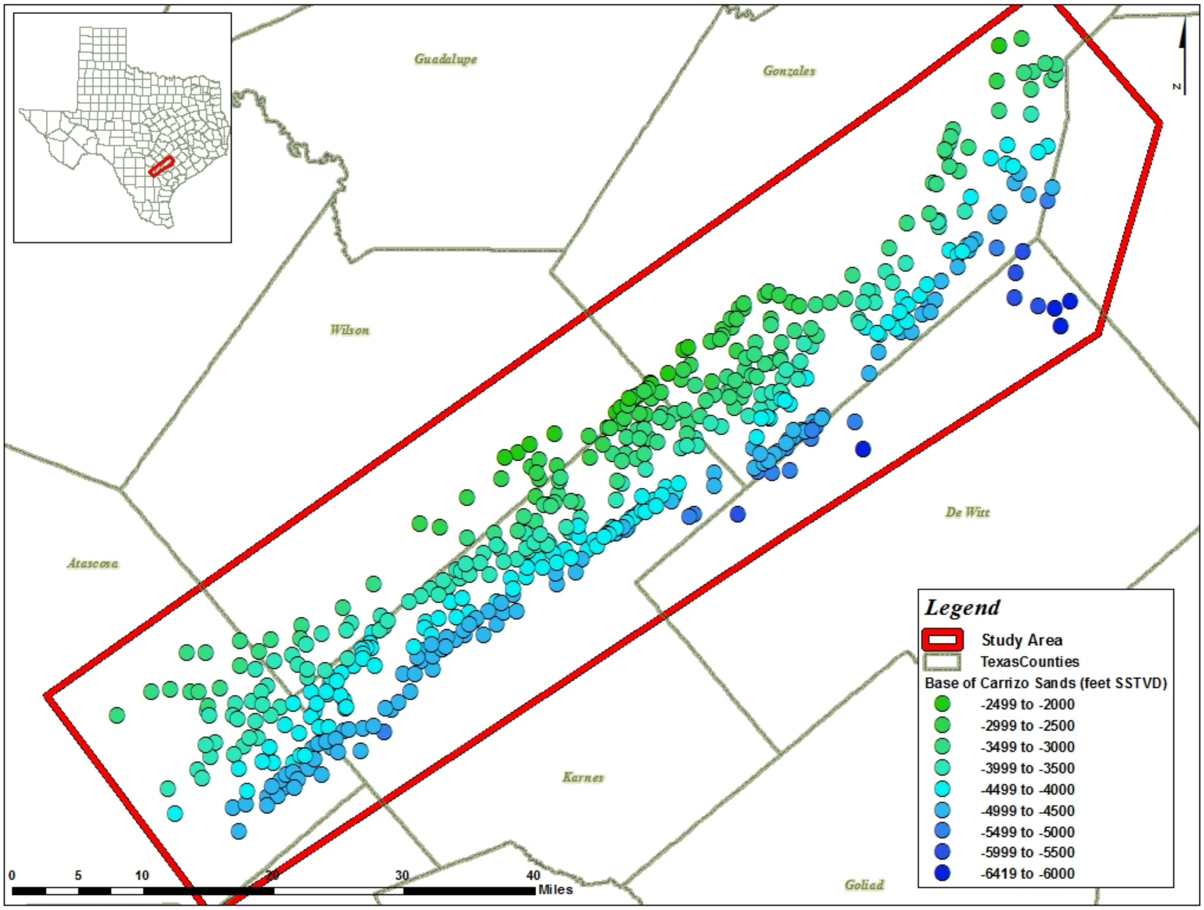


Figure 14 Carrizo Base Depth Picks from Well Logs in feet.

4.2.3. Surface Casing Depths

Although it was not used for the well locations, the IHS database provides detailed information pertaining to the drilling and completion process of oil and gas wells. Therefore, it was used to acquire surface casing depths, recorded with the Railroad Commission. This data, as well as additional attributes, including well name and number, US well number, operator and ground elevation were downloaded from the IHS internet data portal in Excel format. Ground elevation is obtained using Global Positioning System (GPS) equipment, and was useful in converting the casing depths from measured depth values into subsea values.

Because there are many older wells within the study area which were drilled into other formations, this study is only focused on evaluating the surface casing depths of oil and gas wells producing from the Eagle Ford formation. The Eagle Ford lies below the Carrizo-Wilcox aquifer, meaning that the aquifer must be penetrated. Also, this shale play is a fairly recent discovery, with wells drilled since 2009. This formation was selected to keep the dataset current. Because of this, regulatory agencies should already have processes in place to accurately identify aquifer depths and therefore it is assumed would recommend casing depths accordingly. Although there are many other older non-Eagle Ford wells within the region, they were filtered out of the dataset in Excel.

The standard size of surface casing in this region is 9.625 inches. Therefore, the wider conductor casing and the narrower intermediate and production casings, were also filtered out of the dataset. The “base depth” field gives the depth of the surface casing in measured depth. This is a positive number, but measures how many feet the casing is from ground elevation. Because the base depth value is not in subsea format, it needed to be converted. A simple formula which subtracts the ground elevation from the base depth and then multiplied by -1 was applied within Excel. Therefore, when displaying data in a 3D environment, a digital elevation model was not needed to acquire base heights and extrusion values, as these were already within the table.

This spreadsheet is also joined to the well locations in ArcMap, only keeping the records that match. All other wells were excluded from the study. The joined dataset was then exported into its own feature class. The final attributes in the feature class include US Well Number, well name and number, operator, spud date, producing formation, ground elevation, casing diameter, base depth and casing depth SSTVD. Table 3 displays the attribute data associated with a portion of the Eagle Ford wells within the study area.

Table 3 Attribute data for Eagle Ford wells.

FID	API/ US Well #	OPERATOR	WELL_NAME	WELL_NUM	SPUD_DATE	GR_ELEV	Diameter	ProdForm	BaseDepth	CasingDepth (SSTVD)
0	42177336130000	EOG RESOURCES INCORPORATED	KERNER CARSON UNIT	17H	6/10/2015	298	9.625	EAGLEVILL	2520	-2222
1	42123340760000	BURLINGTON RESOURCES O&G C	KRAUSE UNIT A	9	5/20/2015	320	9.625	EAGLEVILL	3824	-3504
2	42123337340000	BURLINGTON RESOURCES O&G C	MUELLER A UNIT A	2	2/18/2015	408.6	9.625	EAGLEVILL	3766	-3357
3	42255343190000	1776 ENERGY OPERATORS LLC	DRAGON	1H	2/9/2015	408	9.625	EAGLEVILL	4600	-4192
4	42255316720000	PLAINS EXPLORATION & PRODU	KOWALIK UNIT	2H	6/12/2010	298.9	9.625	EAGLEVILL	4300	-4001
5	42123333160000	BURLINGTON RESOURCES O&G C	KLEIN G UNIT C	2	5/31/2014	522	9.625	EAGLEVILL	3739	-3217
6	42123329860000	DEVON ENERGY PRODUCTION C	FISHER C	4H	4/21/2013	254	9.625	EAGLEVILL	9872	-9618
7	42177333370000	MARATHON OIL EF LLC	BARNHART (EF) K	8H	8/1/2014	221	9.625	EAGLEVILL	4430	-4209
8	42177335430000	EOG RESOURCES INCORPORATED	SPRADLIN UNIT	3H	4/14/2015	321	9.625	EAGLEVILL	4239	-3918
9	42123335910000	BURLINGTON RESOURCES O&G C	RUCKMAN RANCH UNIT	24	11/28/2014	411	9.625	EAGLEVILL	3482	-3071
10	42177335040000	MARATHON OIL EF LLC	BARNHART (EF)	501H	1/3/2015	273	9.625	EAGLEVILL	4470	-4197
11	42177336140000	EOG RESOURCES INCORPORATED	KERNER CARSON UNIT	18H	5/30/2015	297	9.625	EAGLEVILL	2501	-2204
12	42255342240000	EOG RESOURCES INCORPORATED	SIMMONS UNIT	2H	2/2/2015	410	9.625	EAGLEVILL	4618	-4208
13	42493327720000	MATADOR PRODUCTION COMPA	LYSSY A	1H	3/3/2014	320	9.625	EAGLEVILL	4509	-4189
14	42493327820000	EOG RESOURCES INCORPORATED	JOECKEL UNIT	1H	5/20/2014	336	9.625	EAGLEVILL	4470	-4134
15	42177335060000	MARATHON OIL EF LLC	BARNHART (EF)	502H	1/25/2015	252	9.625	EAGLEVILL	4410	-4158
16	42123337070000	BURLINGTON RESOURCES O&G C	KRAUSE UNIT A	3	3/30/2015	320	9.625	EAGLEVILL	4300	-3980
17	42123337090000	BURLINGTON RESOURCES O&G C	KRAUSE UNIT A	5	3/23/2015	319	9.625	EAGLEVILL	3939	-3620
18	42255340160000	EOG RESOURCES INCORPORATED	ALTON UNIT	12H	3/11/2015	382	9.625	EAGLEVILL	2700	-2318
19	42177335350000	EOG RESOURCES INCORPORATED	BARRE UNIT	21H	3/11/2015	295	9.625	EAGLEVILL	2510	-2215
20	42123339770000	BHP BILLITON PETROLEUM(TXLA	CLARK A	5H	3/9/2015	344	9.625	EAGLEVILL	3159	-2815

Figure 15 shows the distribution of Eagle Ford wells throughout the study area, symbolized by surface casing depth.

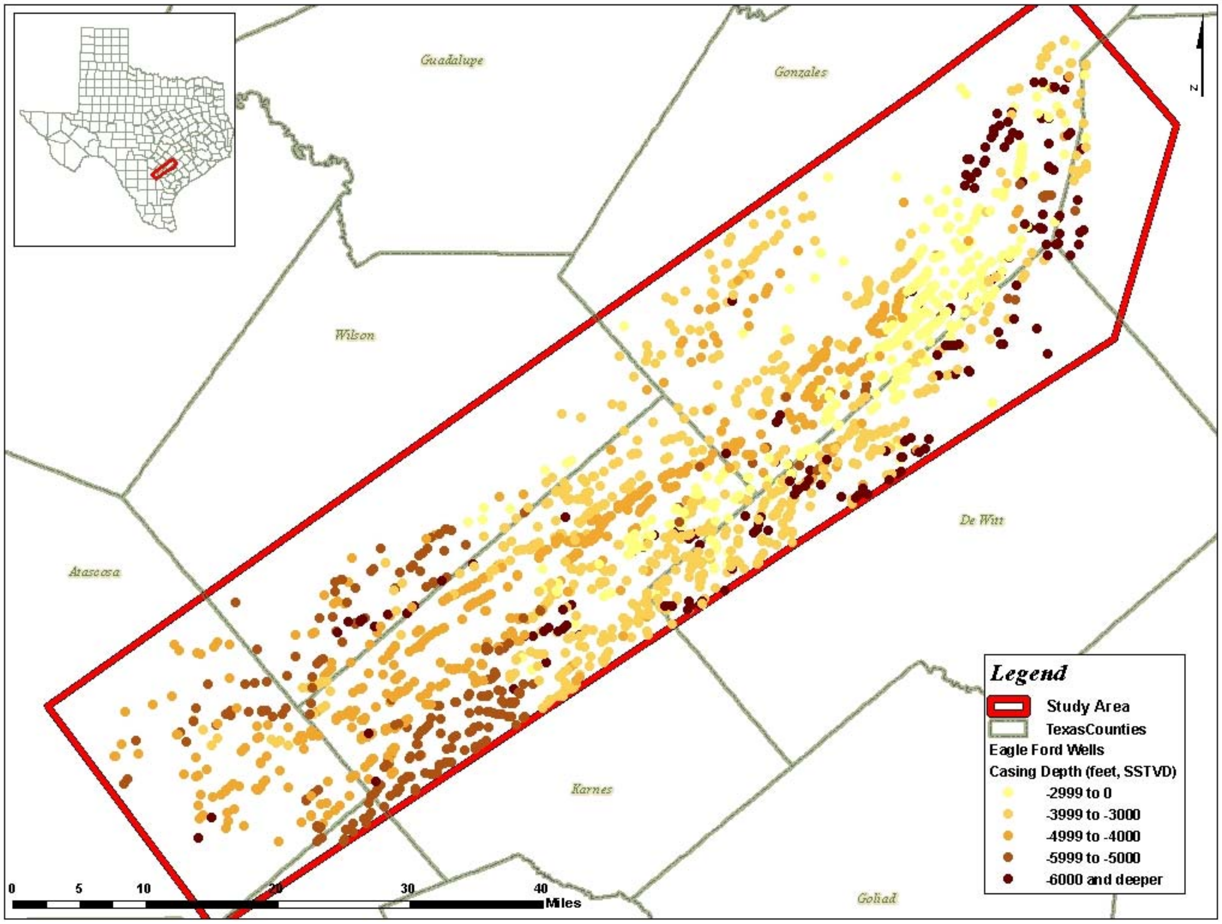


Figure 15 Depth of surface casing of Eagle Ford wells within study area.

4.2.4. Salinity Determination Lines

To understand where water within the Carrizo-Wilcox is freshest and where it becomes more brackish, identifying these areas spatially, is helpful. A map produced by the U.S. Army Corp of Engineers (USACE) in 1976, delineates the boundaries between water with less than 1000 mg/L of total dissolved solids (TDS), and water with more than 3,000 mg/L of TDS (Figure 16) (Klemt, et al. 1976). Although the Carrizo-Wilcox is considered a slow moving aquifer, it is likely that these areas have migrated since 1976. However, more current data was not found, and it still provides a general reference of salinity. This map was scanned into a .tif image. The image was georeferenced in ArcMap, and the lines digitized into a shape file. Although these lines are approximate, they provide a good idea of where groundwater salinity varies.

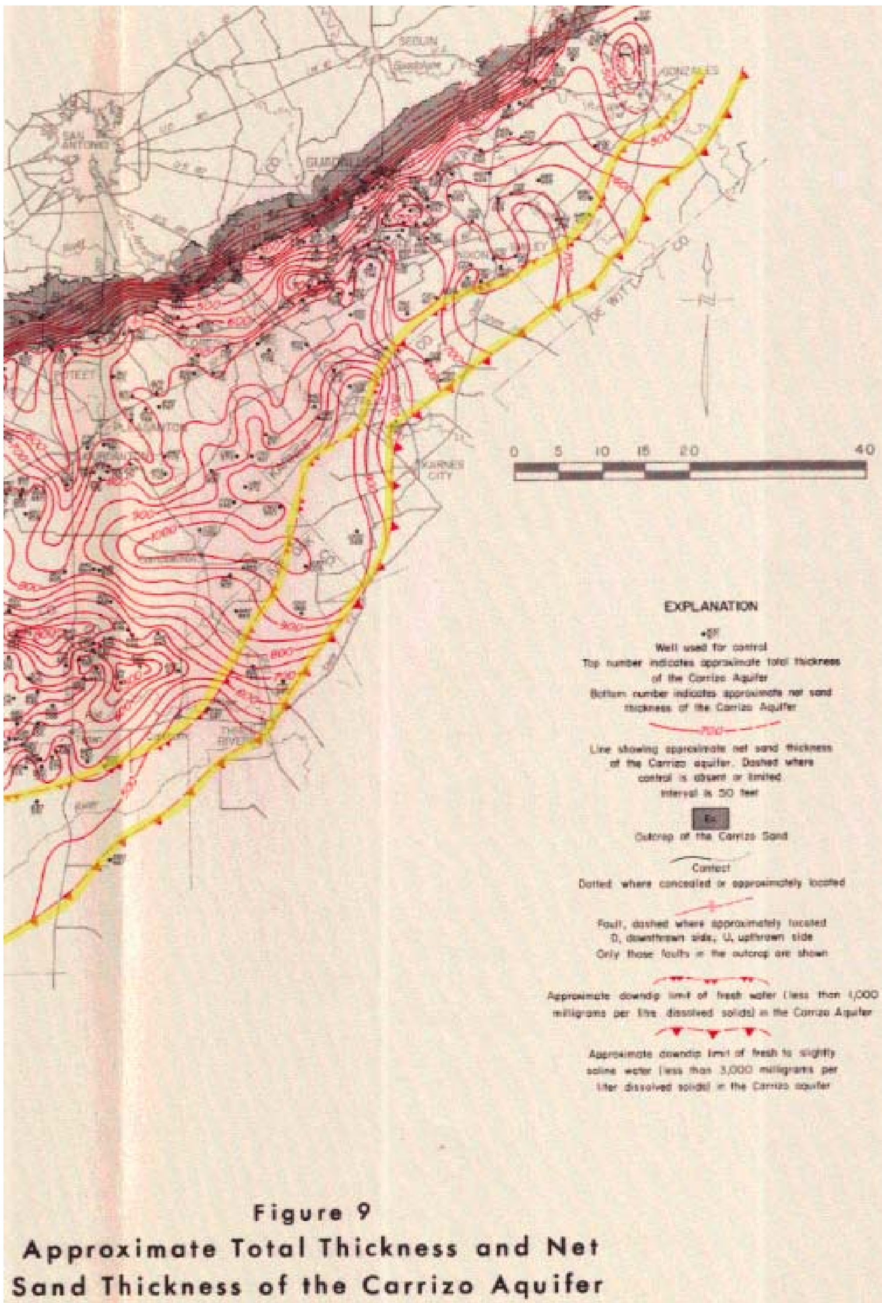


Figure 16 Carrizo-Wilcox thickness map modified from the Army Corps of Engineers, with salinity lines highlighted in yellow. *Source*: Klemt et al. 1976.

4.3 Methodology

The two primary datasets needed to conduct this study, (1) wells with Carrizo-Wilcox aquifer depths, picked from logs, and (2) Eagle Ford wells with recorded surface casing depths, provide the basis for further analysis. This section shows the results of evaluated interpolation methods, and reveals how surface casing depths of Eagle Ford wells compare to the aquifer digital representation.

4.3.1. Interpolating a Surface

To recognize the geologic structure of the Carrizo-Wilcox, the next step was to create a continuous surface representing the base of the aquifer within the study area. Three interpolation methods were considered and evaluated to determine the most suitable digital representation.

4.3.1.1. Spline

The *Spline* technique is a deterministic method and creates a smooth minimum curvature output. If geostatistical tools are not available, this is generally considered to be an ideal interpolation method for mapping subsurface geology as it has been traditionally used in the field of earth modeling and geophysics. This exact interpolator method precisely honors the measured values at the control points and has the option to honor barriers such as faults. Figure 17 shows the results of the Spline interpolation method. When compared to other interpolators, it is apparent that the Spline method does not handle the known northwest to southeast trend of the formation as well. Also, because the map passes through all the measured control points, the boundaries of the data ranges undulate.

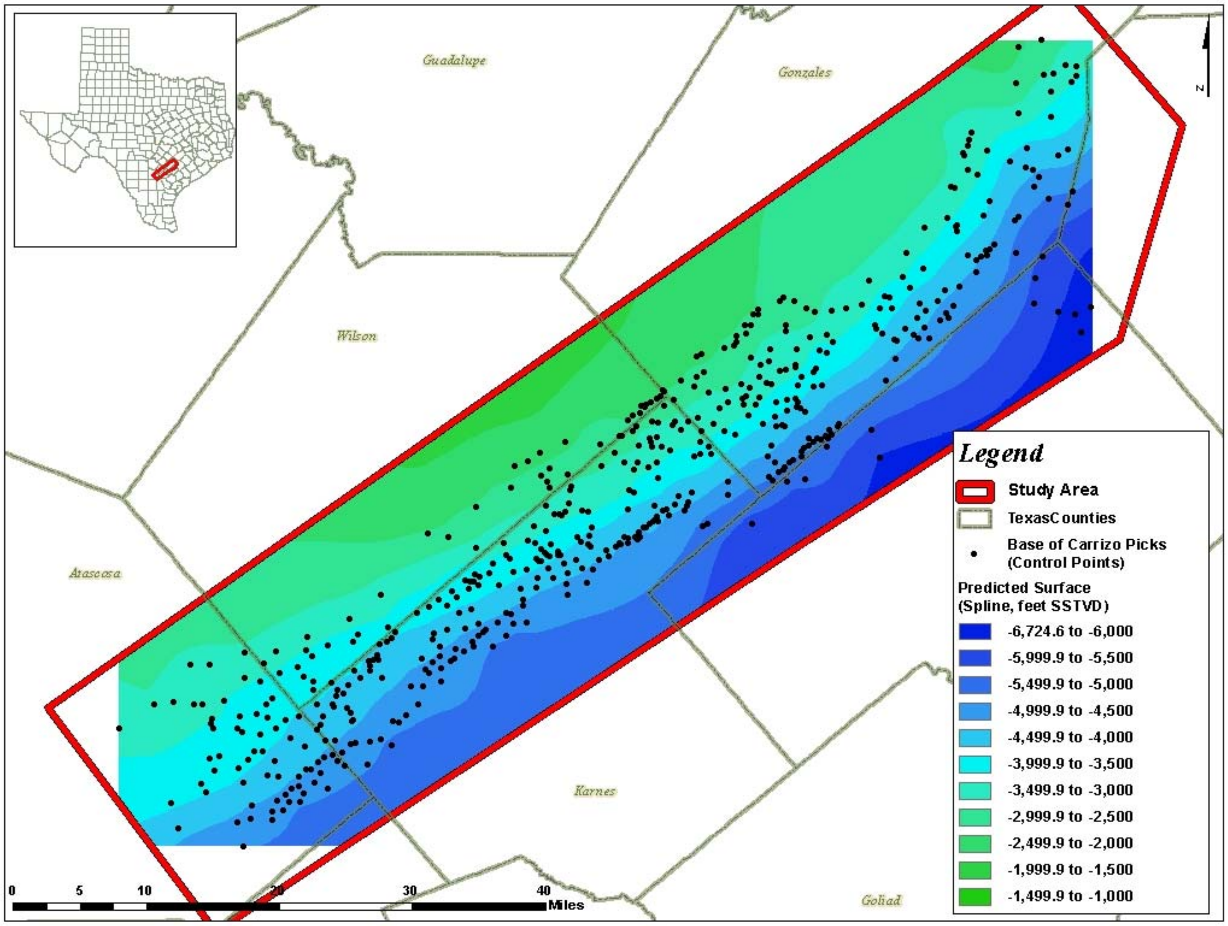


Figure 17 Predicted Base of Carrizo-Wilcox Aquifer using Spline Interpolation Technique.

4.3.1.2. Kernel

Unlike the commonly used spline method, the Kernel and Kriging interpolation methods provide quantitative assessments of their predictions, as well as standard error maps. They are inexact interpolators, meaning that the resulting surface is not required to precisely pass through all the measured values at the control points. This is acceptable in this study because there is not a hard, defined boundary, or depth, between geologic transitions. This section discusses the Kernel interpolation and the next section focuses on the Kriging method used.

Although considered a deterministic interpolator, the Kernel interpolation method is provided with Geostatistical Analyst in ArcGIS. This interpolator was evaluated and the different Kernel functions were compared. The *Constant* function provided a prediction surface with the best root-mean-square standard error of all Kernel functions tested. Figure 18 shows a map of the results of the Kernel interpolation method. Near the control points, this output appears to follow the geological trend of dipping downward to the southeast. However, further away from the control points, the interpolator does not predict as well. In many areas, it does not predict all the way out to the study area boundary.

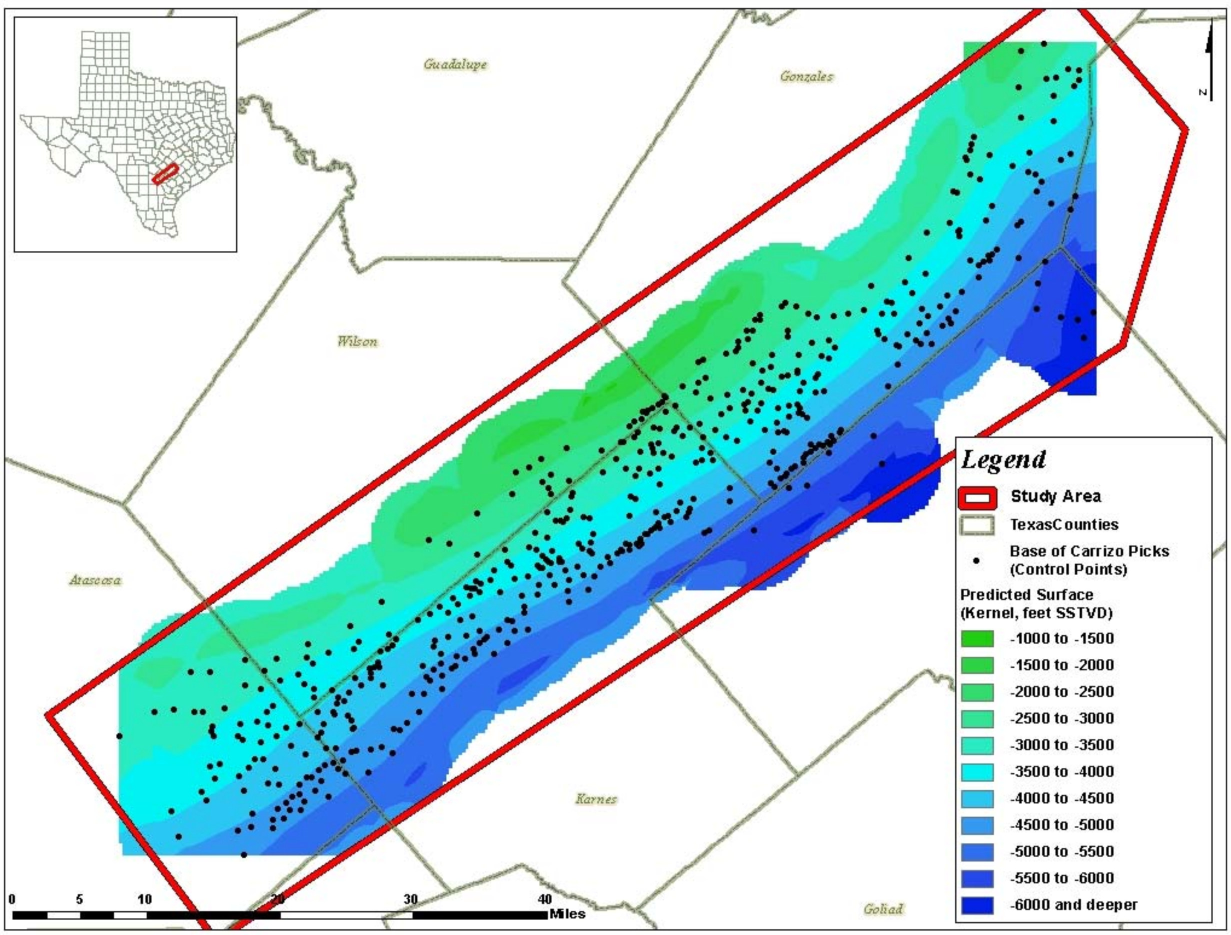


Figure 18 Predicted Base of Carrizo-Wilcox Aquifer using Kernel Interpolation Technique with the Constant Function.

Because it is provided with Geostatistical Analyst in ArcGIS, the Kernel interpolation method does create a standard error map. Figure 19 shows the standard error map produced from the constant function Kernel interpolation method, and shows how quickly error increases as you move away from the control points. Error here is displayed in feet, the same unit of measure as the predicted values. It is important to take note of the scales in the error maps, as they are symbolized differently by geometric interval. These default symbology classes were kept to show the full range of standard error values on each map.

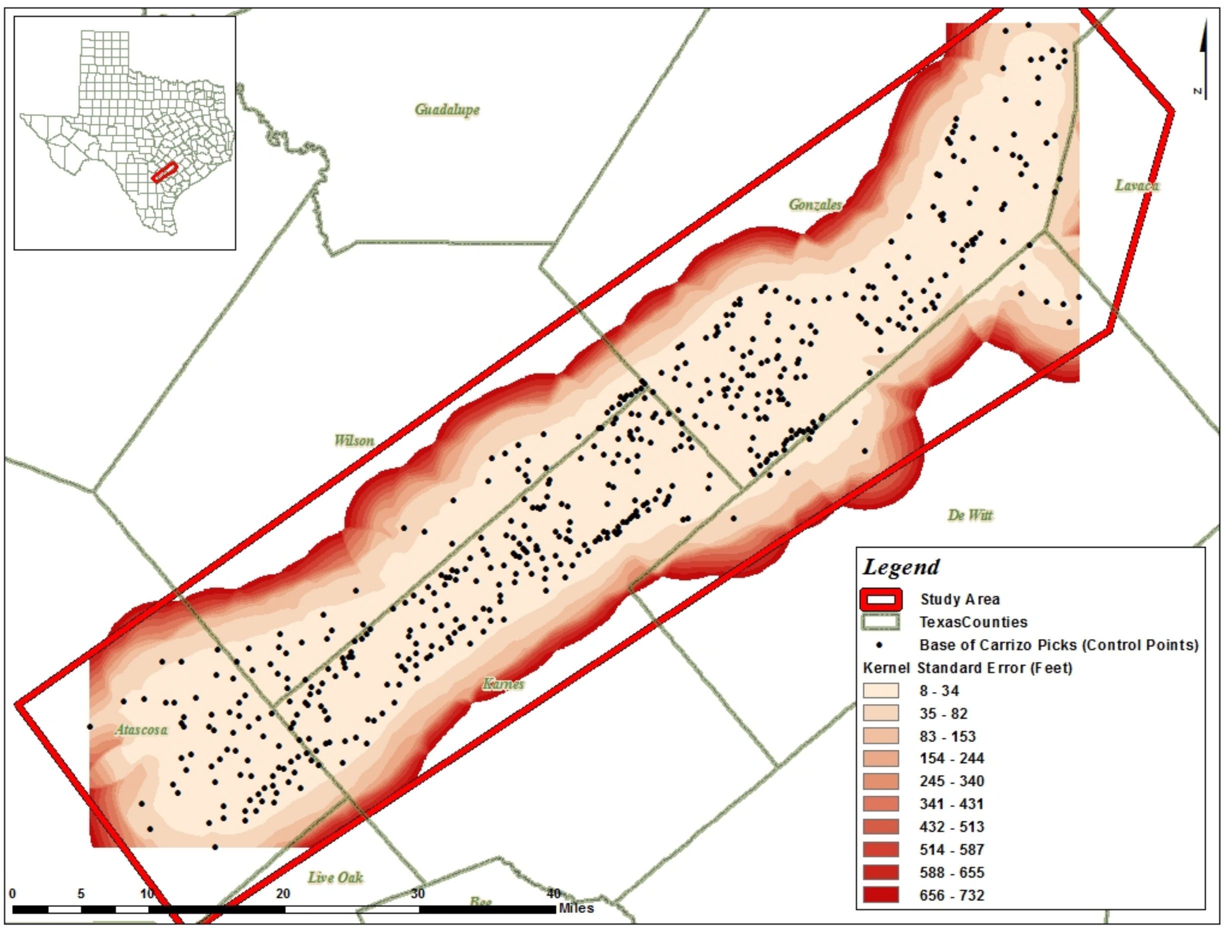


Figure 19 Predicted Standard Error Map produced with Kernel Interpolation.

4.3.1.3. Empirical Bayesian Kriging

Empirical Bayesian Kriging (EBK) is a geostatistical interpolator and offers the robust functionality of kriging, while automating many of the parameter choices required to create optimal results. One great advantage of the technique, particularly in this study area, is the ability to detrend the data. Because the geologic trend in the region is for the formations to dip downward toward the southeast, this option is very powerful. EBK offers the ability to account for this trend and still provide good quantitative error results. Many semivariogram models of the EBK method were compared. The *Exponential Detrended* model worked best with this dataset, with the root-mean-square standard error closest to one, at 0.9958. Figure 20 shows the results of the exponential detrended EBK interpolation method. The first thing to note is how well the interpolator appears to predict past the control points due the detrended model. Recall that the Kernel interpolator did not predict out to the edges of the study area boundary. In addition, by applying a detrending function and not strictly honoring the control points, the resulting map shows smoother boundaries of ranges than the map generated by the Spline interpolation method.

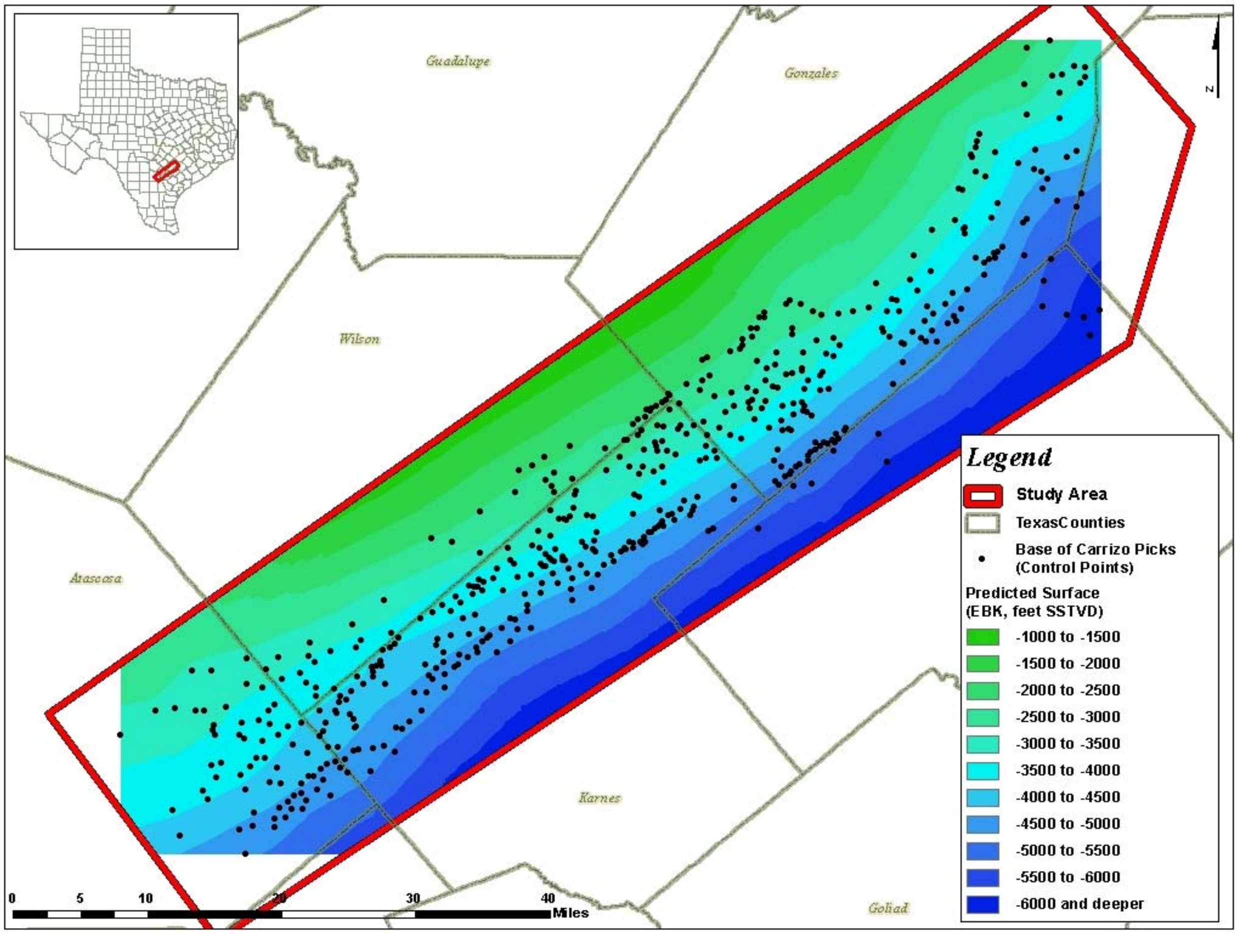


Figure 20 Predicted Base of Carrizo-Wilcox Aquifer using Empirical Bayesian Interpolation Technique with the Exponential Detrended Semivariogram.

The error map generated by the EBK interpolation method shows a smaller range in error than the Kernel interpolator. The error produced by the EBK method has a minimum value of 8 feet and a maximum value of 450 feet. The error produced by the Kernel interpolator has a minimum value of 8 feet and a maximum value of 732 feet.

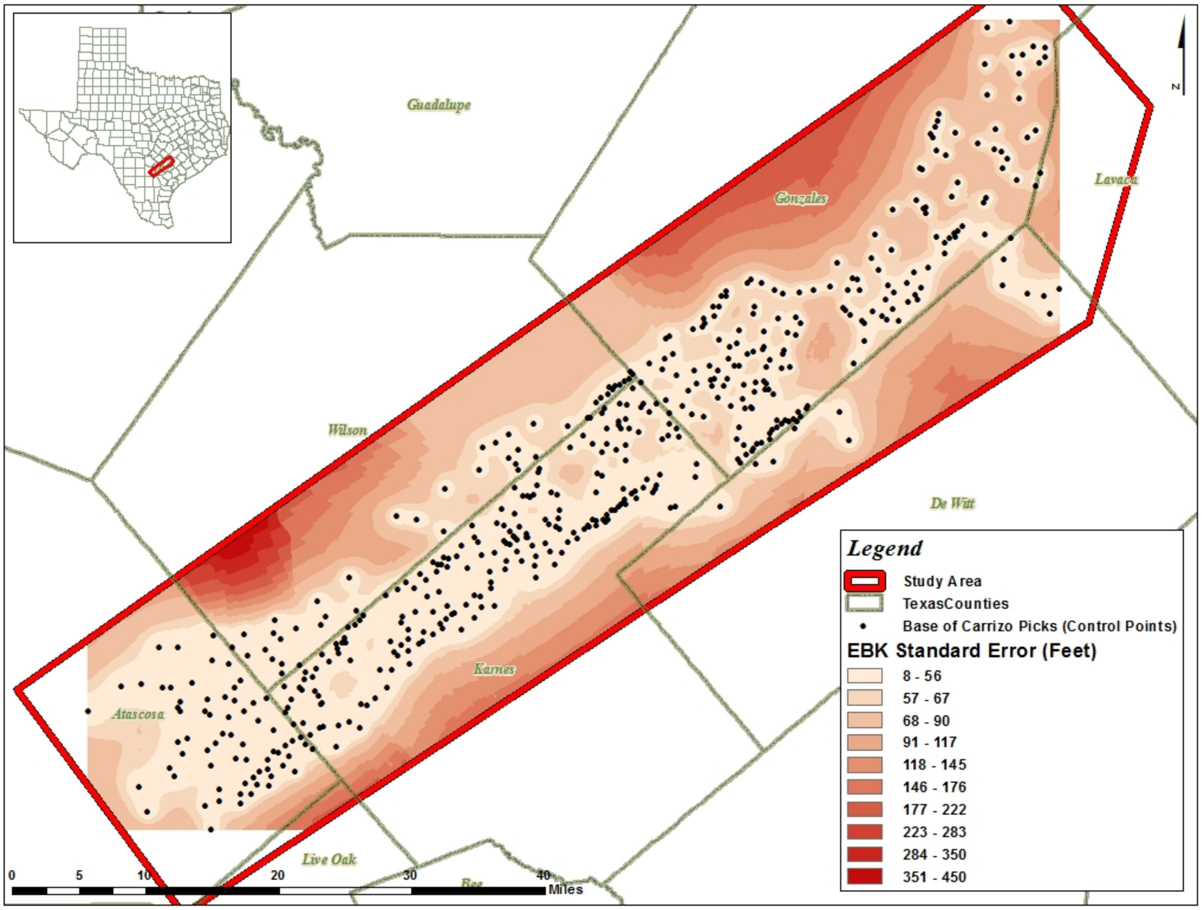


Figure 21 Predicted Standard Error Map produced with Empirical Bayesian Kriging Interpolation.

Table 4 displays a comparison of the error diagnostics generated using the Kernel and EBK interpolators. Because the Empirical Bayesian Kriging interpolation method provided better error diagnostics, the resulting predicted surface was selected for further analysis.

Table 4 Diagnostic Comparrison between Kernerl and EBK interpolation methods.

Error Diagnostics	Kernel	EBK	Objective
Root-mean-square standardized prediction error	1.0148	0.9958	Closest to 1
Mean Standardized	-0.1410	-0.0143	Closest to 0
Root-mean-square prediction error	66.512	54.144	Lowest value
Average Standard Error	65.006	53.259	Closest to RMS prediction error

Figure 22 provides a side-by-side comparison of the evaluated interpolated surfaces with their standard error maps. All prediction maps are symbolized with the same ranges as they were in previous figures. Both EBK and Kernel standard error maps have had their symbolized ranges adjusted to match each other. This provides a better sense of the true difference in error. The Kernel error map looks similar to the previous figure (Figure 19). However, in the EBK standard error map, looks different than previously (Figure 21). The dark red areas no longer appear because with the new symbology those darker colors now fall in the 500 to 800 foot range.

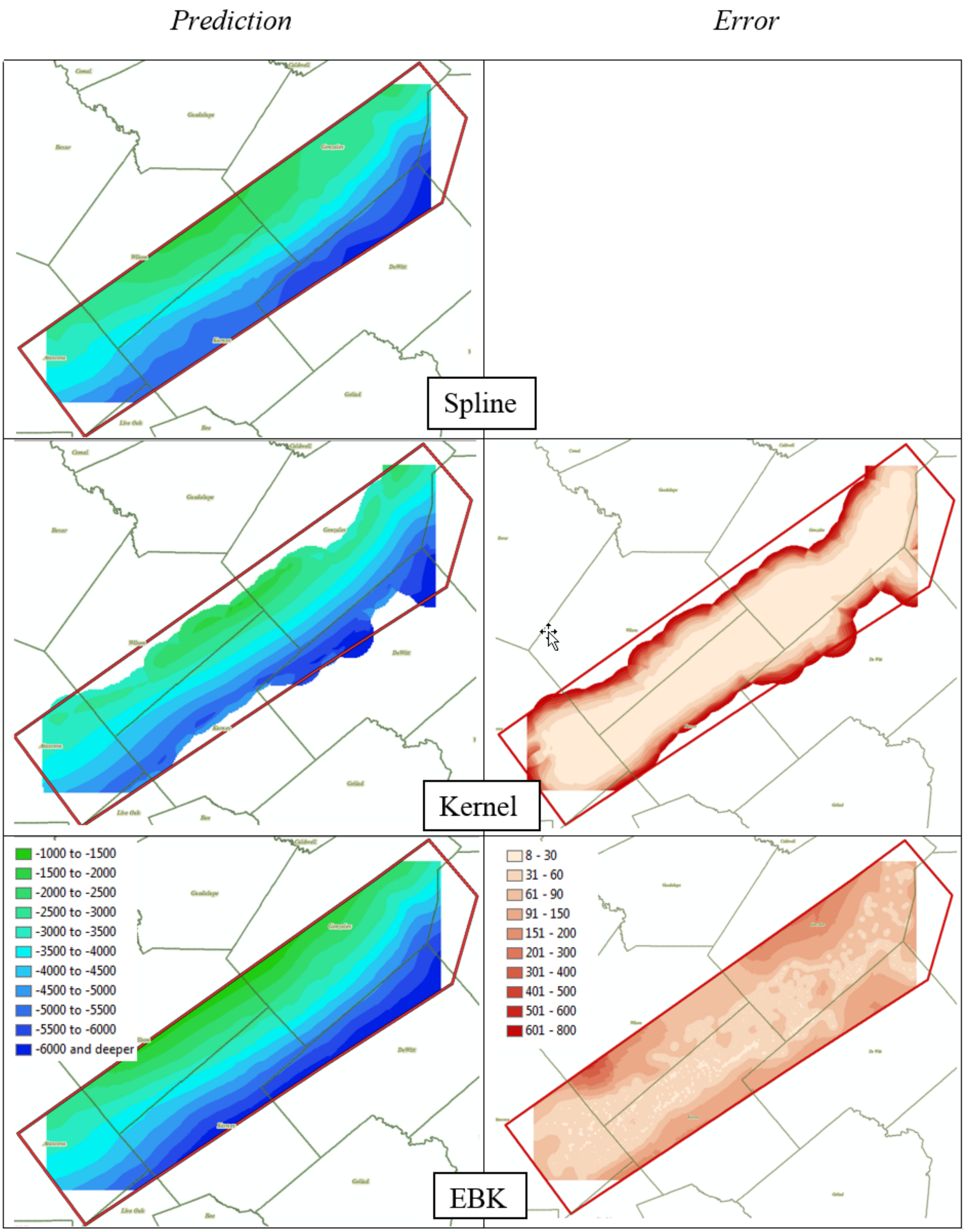


Figure 22 Side-by-side comparison of evaluated interpolated predictive depth surfaces (feet) and their accompanying standard error map (feet).

Overall, the surfaces produced by the three interpolators were very similar. Because the Empirical Bayesian Kriging method has the best root-mean-square standard error, predicts well past the control points and models the southeast downward dip of the regional geology the best, it was selected to be used for continued analysis.

4.3.2. Depth Comparison

After selecting a final interpolated surface, the next step was to compare the depths of the surface casings against the predicted depths from the predicted aquifer. To accomplish this, the *GA to Points* tool was used to extract predicted and error values from the digital surfaces to each point, in this case the Eagle Ford wells. It was then simple to determine which wells do not fully protect the aquifer by subtracting the surface casing depth from the predicted value of the aquifer base. Any results that are a negative value do not penetrate the base of the aquifer. Figure 23 shows which wells penetrate the predicted surface (white) and which wells do not (black). Also shown are the lines representing the boundaries of water quality zones obtained from the Army Corps of Engineers. These lines separate the freshwater area to the northwest at 1,000 mg/L or less of total dissolved solids (TDS), and the brackish area at 1,000 – 3,000 mg/L of TDs. This is important when determining if “usable” water is protected and is investigated further in the next chapter.

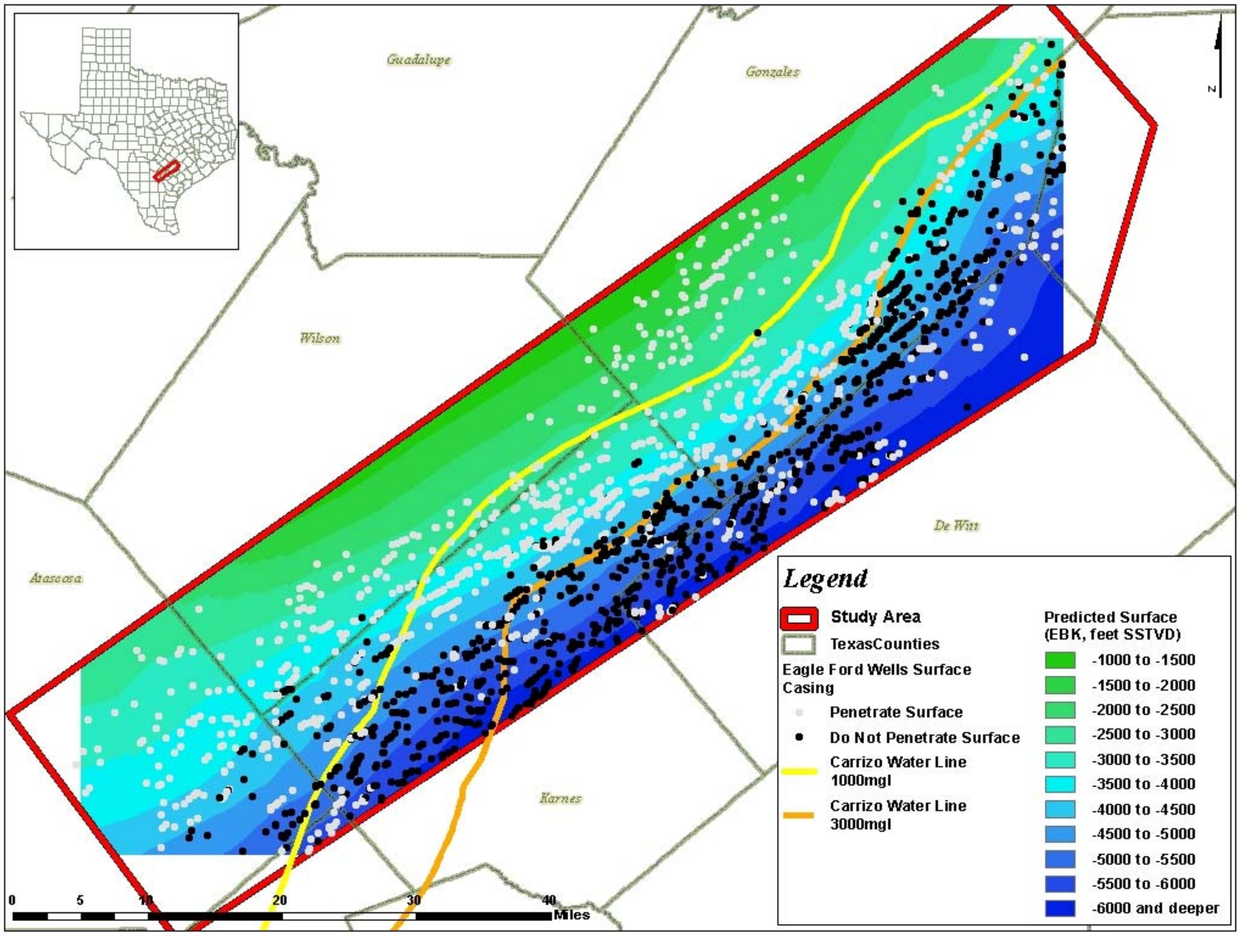


Figure 23 Predicted base of aquifer surface showing wells with surface casing that penetrate the surface (white) and well with surface casing that do not (black).

Additional fields were calculated to help understand error. Each point record in the table contains the predicted value and standard error value. By adding and subtracting the standard error values from the predicted values, this creates a range of bounding minimum and maximum values in which the actual value falls within with 95% confidence.

4.3.3. 3D Representation

ArcScene provides a 3D environment to view datasets containing elevation information. By viewing in 3D, a user can get a true sense of where subsurface features lie in relation to each other. The interpolated surface representing the Carrizo-Wilcox aquifer is an elevation surface where the units are in sub-sea total vertical depth (SSTVD). Therefore, it was easily brought into an ArcScene project. The point feature class representing Eagle Ford wells contain ground elevations and surface casing depths. Before this layer can be displayed properly in ArcScene, the *Feature to 3D by Attribute* tool was used to assign the ground elevation field as Z values of the layer. After this was completed, the point layer was displayed correctly in vertical space. To create a vertical line representing the depth of the surface casing, the point layer was extruded to the SSTVD depth. Another copy of the Eagle Ford well layer was added to the ArcScene project. This time the points were extruded to a common value of -15,000. This layer was displayed in a different color and represents the remaining vertical portion of the well.

The same Eagle Ford well layer was added a third time. On this layer, the base height was set to the Minimum field, which represents the shallower margin of error of the predicted surface. This layer was extruded to the Maximum field, which represents the deeper margin of error. By doing this, the layer was symbolized to create an error halo above and below the predicted surface. Figure 24 is a capture of the ArcScene project containing these symbolized layers. Here, one can quickly see if a well's surface casing is shy of penetrating, and thus protecting, the aquifer, and by how much.

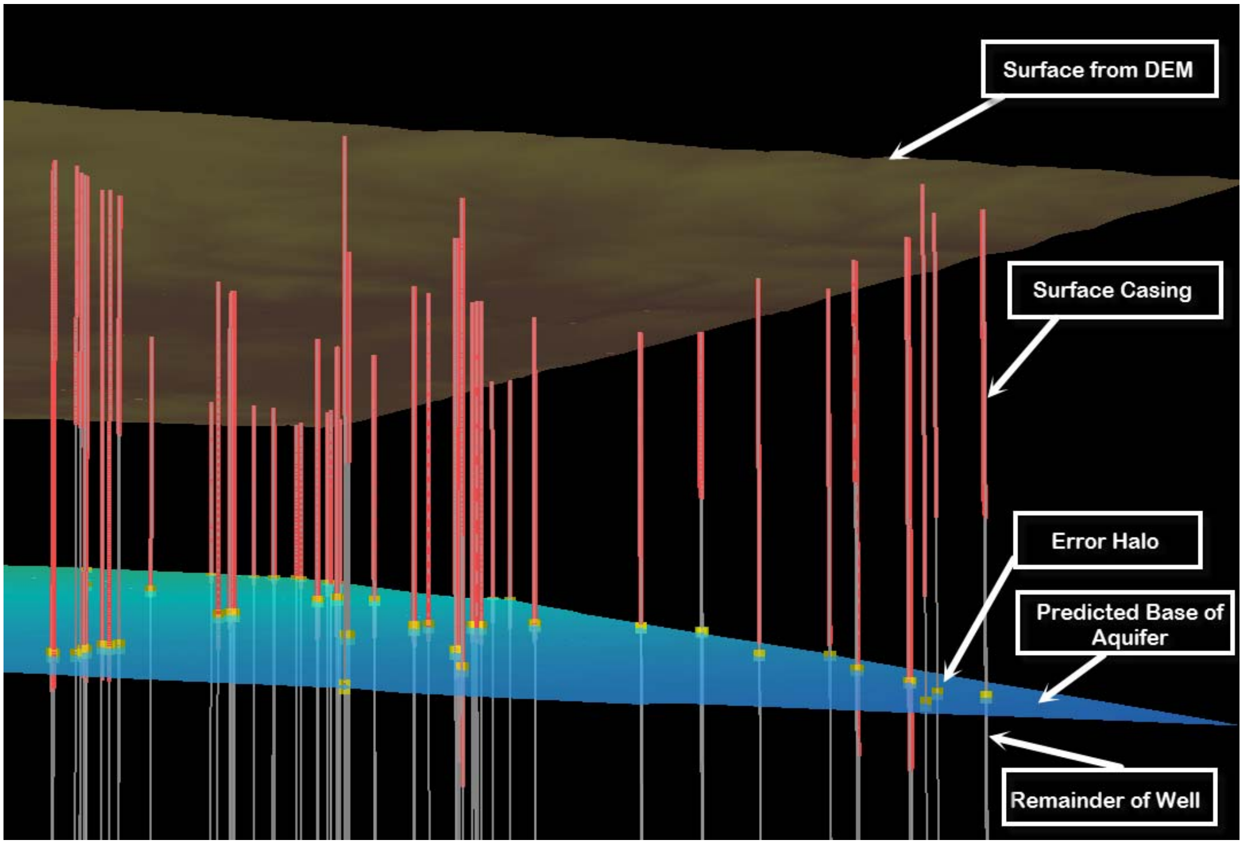


Figure 24 Screen capture of 3D environment displaying a predicted surface, representing the base of the aquifer (blue), standard error halos (yellow) and surface casings (red).

Chapter Five provides quantitative analysis of the results produced while conducting the methodologies outlined in Chapter Four.

Chapter 5 Results

As mentioned previously, two goals of this project were: (1) to find an appropriate interpolation method to create a digital model of the base of Carrizo-Wilcox aquifer; and (2) to determine if regional oil and gas wells penetrate this surface. Chapter Five summarizes the results found by the methods defined in Chapter Four.

5.1 Is the Carrizo-Wilcox Aquifer Protected?

After analysis, it was determined that the groundwater within the Carrizo-Wilcox is not completely protected from oil and gas operations. Of the Eagle Ford wells drilled within the study area, 56.5% do not have surface casings that penetrate the surface representing the base of the aquifer. Figure 25 shows the overall percentages of aquifer protection.

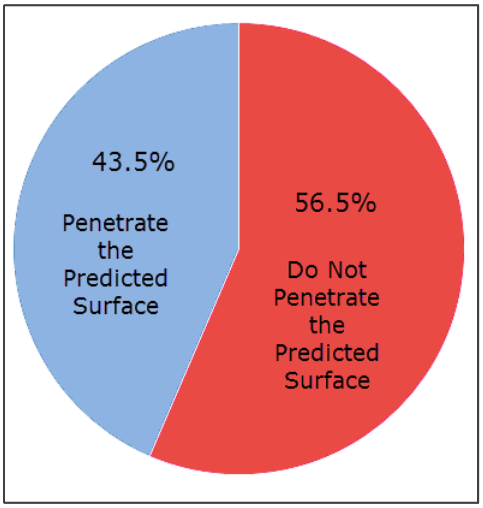


Figure 25 Pecentages of wells with surface casing that penetrate the predicted surface representing the aquifer base.

Figure 26 is reproduced from the previous chapter for ease of analysis here, and provides a spatial representation of Eagle Fords wells within the study area. Wells in white have surface casings that are deeper than the predicted aquifer, and would therefore protect it. Wells in black have surface casings shallower than the predicted aquifer and therefore leave it susceptible to contamination.

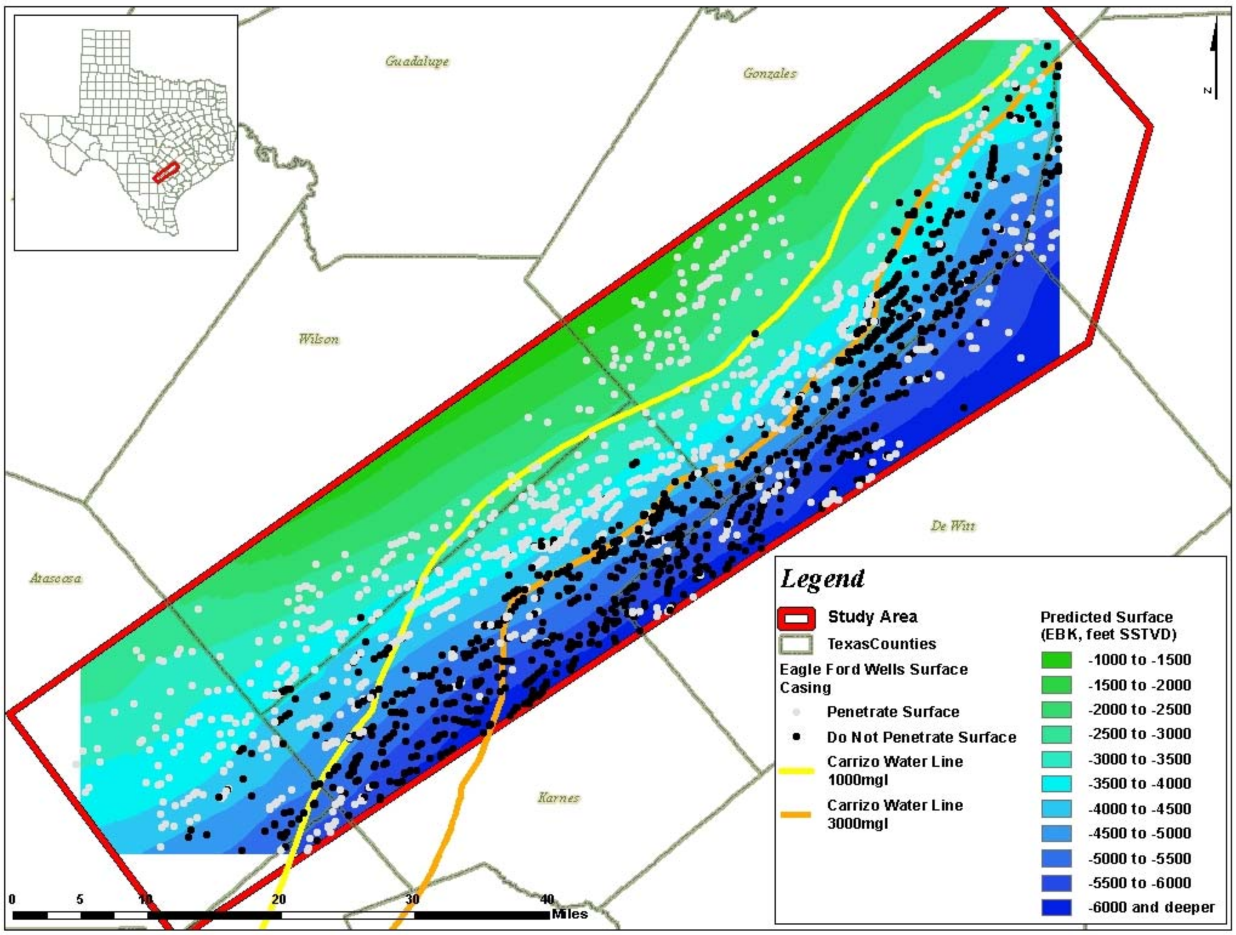


Figure 26 (Reproduced Figure 23) Predicted base of aquifer surface showing wells with surface casing that penetrate the surface (white) and well with surface casing that do not (black).

It is interesting to see the overall spatial distribution of aquifer protection. As the formation dips downward to the Southeast, the amount of total dissolved solids (TDS) in the water increases, causing the water within the aquifer to become more brackish. The lines in yellow provide a rough boundary where TDS values become higher than 1,000 mg/L, and higher than 3,000 mg/L. For the most part the aquifer is protected where water is freshest at 1,000 mg/L or less. However, where water has between 1,000 mg/L and 3,000 mg/L, the Southwest region has many wells whose surface casings do not penetrate the aquifer. Where water is the most brackish at 3,000 mg/L TDS or more, there are very few wells that actually penetrate the base of the Carrizo sands. Figure 27 shows the percentages of wells within the study area which penetrate the base of the aquifer, grouped by TDS.

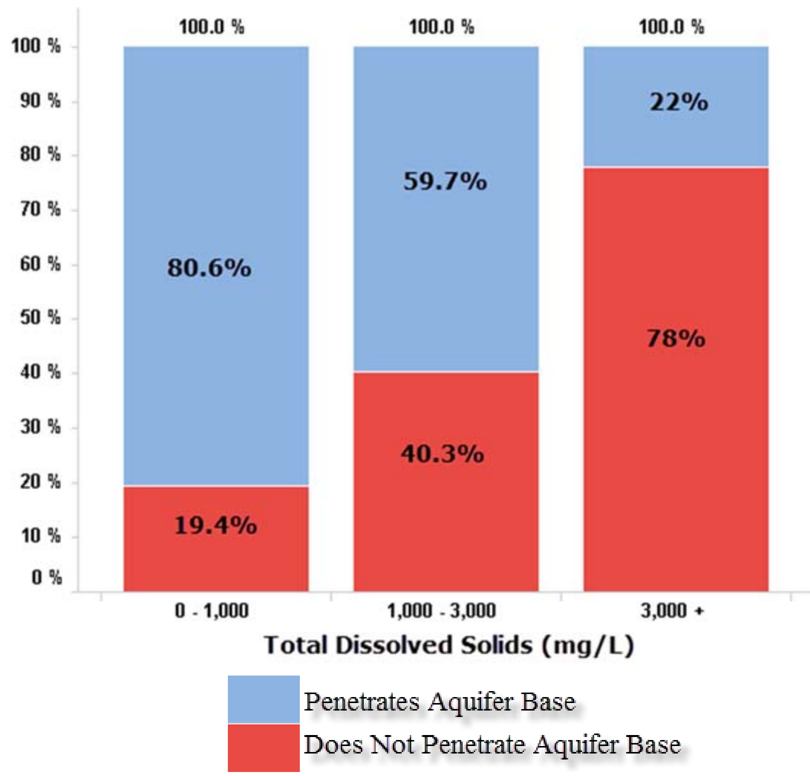


Figure 27 Percentages of Eagle Ford Wells whose surface casings penetrate the aquifer by TDS.

Where water is freshest at 1,000 mg/L or less, and used for human consumption, 80.6% of Eagle Ford wells within the study area had surface casings which penetrated the Carrizo-Wilcox aquifer. However, this percentage decreases immensely to 22% where groundwater within the aquifer is brackish to saline at 3,000 mg/L or more.

5.2 Error

There is added value in obtaining the standard error values from the interpolators that provide them. This offers a quantitative assessment of how close the predicted values are to the actual values. In this study the Empirical Bayesian Kriging (EBK) was selected to create a surface representing the base of the aquifer. In addition to predicted values, this interpolator also provides standard error values. The standard error values can be used to calculate a range by adding and subtracting the standard error from the predicted value. The actual value is likely to fall into this range with 95% confidence. Figure 28 exhibits the EBK surface of standard error values along with the distribution of Eagle Ford wells. Areas near the control points, or well logs with depth picks, have less error than areas far from the control points. The areas with dark blue circles are where the original control points lie. One item to point out is that nearly all standard error falls within the range of 200 feet or less.

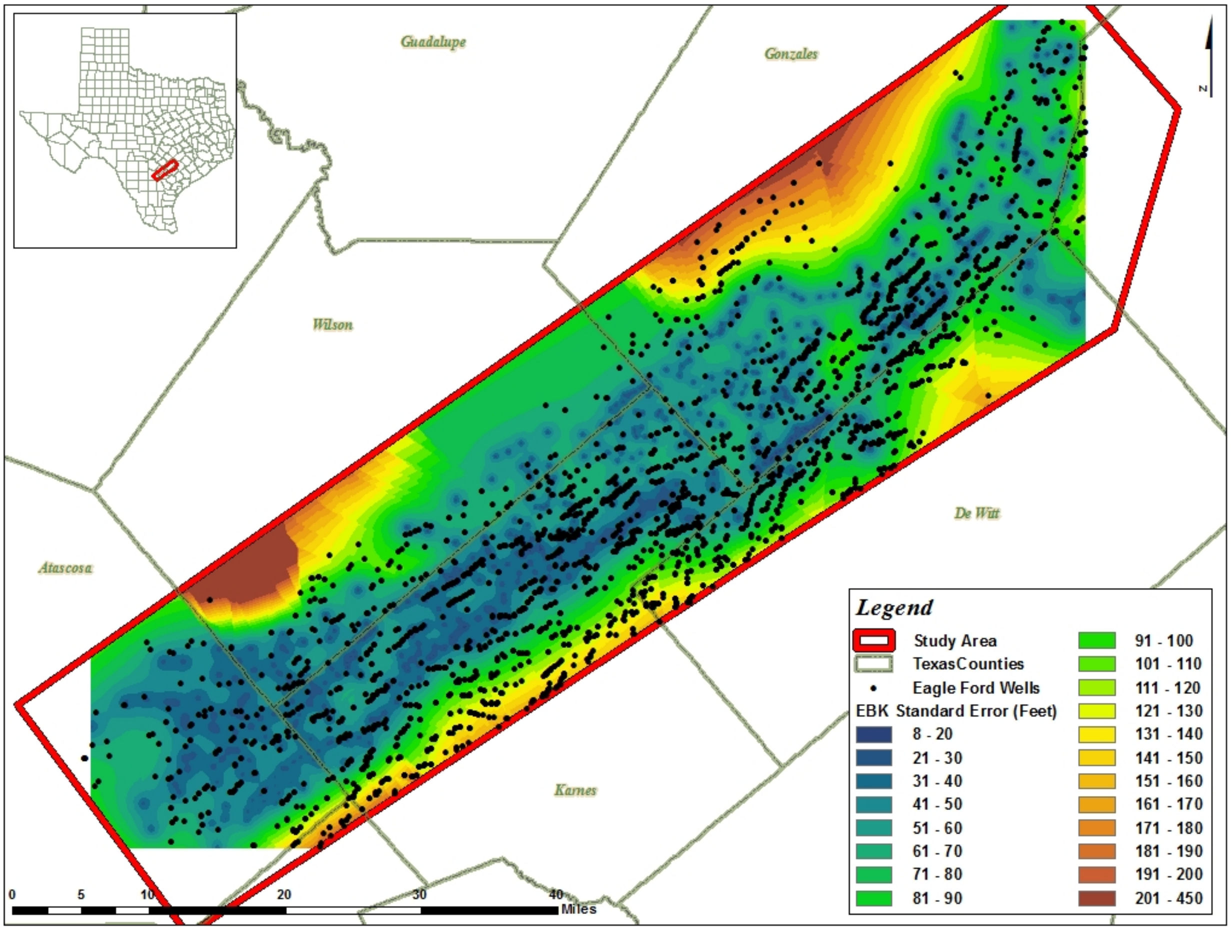


Figure 28 Standard Error Surface: Actual value falls within the range of the predicted value, plus or minus the standard error with 95% confidence.

By using the GA Layer to Points tool in ArcGIS, the standard error values from the error surface is extracted to the Eagle Ford well points. The bar chart below (Figure 29) represents the number of wells within each error range. This bar chart uses the same ranges as the previous map. Most of the error values fall within 30 to 60 feet, with over 900 wells in the study area falling in these categories. Again, nearly all error values are 200 feet or less. If surface casing continues to 200 feet deeper than the predicted value, that should be sufficient to protect the aquifer.

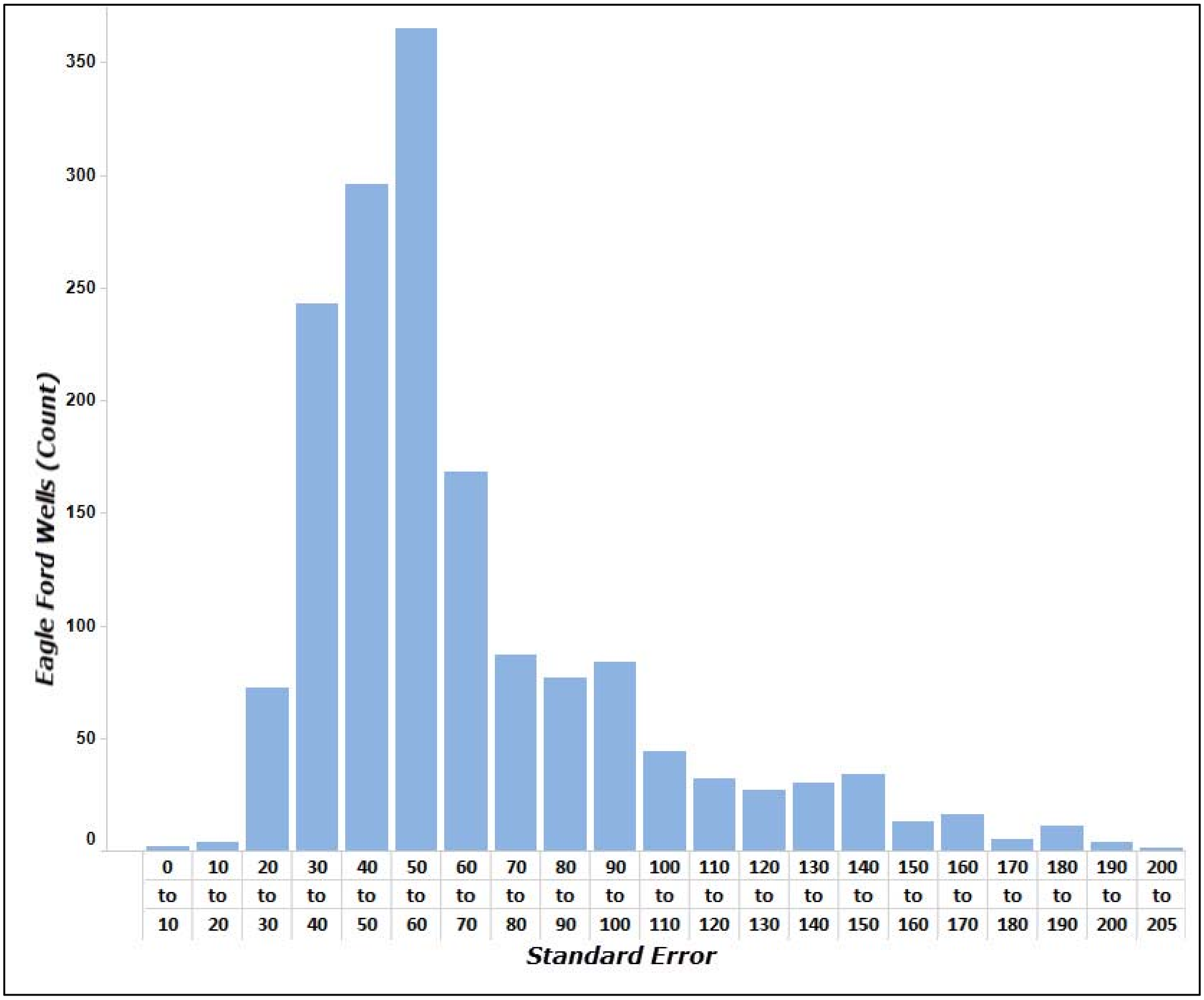


Figure 29 Histogram of Standard Error Values for the EBK surface.

By adding and subtracting the standard error from the predicted value, a range can be created in which there is 95% confidence that the actual value will fall. Using the minimum error value and the maximum error value, these ranges are shown as error halos within the 3D environment (Figure 30).

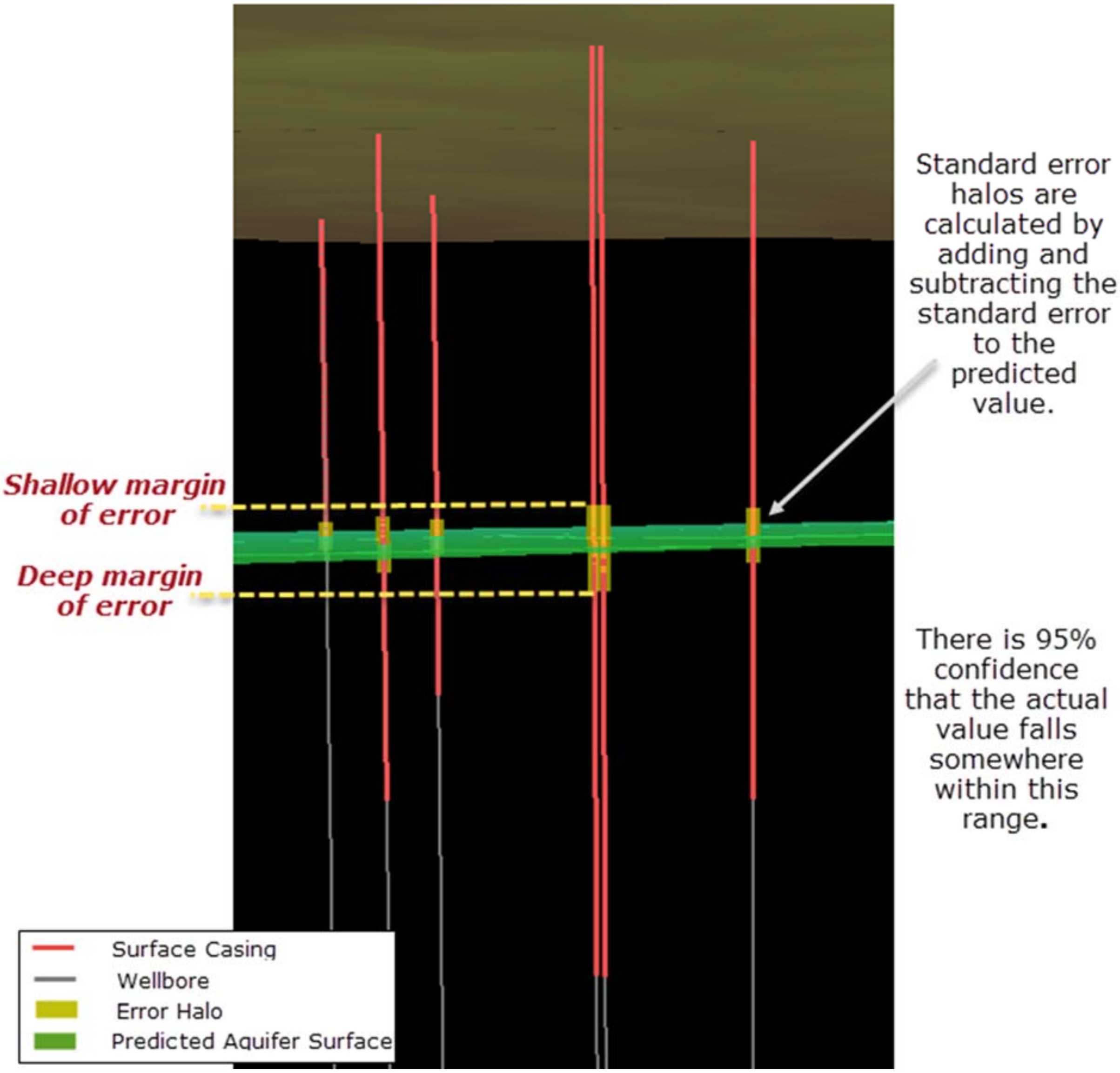


Figure 30 Close-up of surface casings, the predicted aquifer surface, and the margin of error.

By including the margin of error, this somewhat alters the final percentages of how many Eagle Ford wells with surface casings penetrate the base of the aquifer. If we use the shallowest error value to represent the predicted surface, the number of Eagle Ford wells in the study area with surface casings going below that increases 1.5%, from 43.5% to 45%. This is still not half of the wells within the study area. By using the deepest error value, the number of wells which have surface casing deeper than the base of the aquifer decreases 2%, from 43.5% to 41.5%.

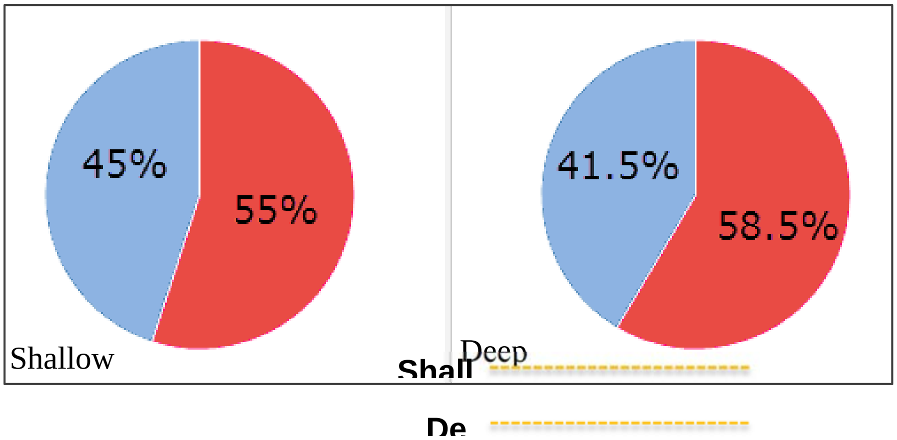


Figure 31 Percentage of wells for which the surface casings penetrate the shallower error value (left), and deeper error value (right). Blue represents surface casings that protects the aquifer and red represents surface casings that do not.

5.3 Aquifer protection over time

To identify any temporal patterns, Eagle Ford wells were grouped by the year they were drilled, to see if surface casing depths have improved or declined over the years. Figure 32 shows a bar chart of the percentage of wells within the study area which have surface casings that penetrate the aquifer, by year. This chart demonstrates that there has not been a steady trend throughout the years. Surface casings which penetrate the aquifer generally improved through 2013. After 2013, the number of wells protecting the aquifer decreased until the time of this study. This outcome was somewhat surprising as it was believed that maps and regulations would improve over the years, committing operators to set deeper surface casings. However, these results show otherwise. Figure 33 shows the spatial distribution of Eagle Ford wells symbolized by spud year, or year that the well was drilled. It is evident that there is no clear spatial trend of when wells were drilled.

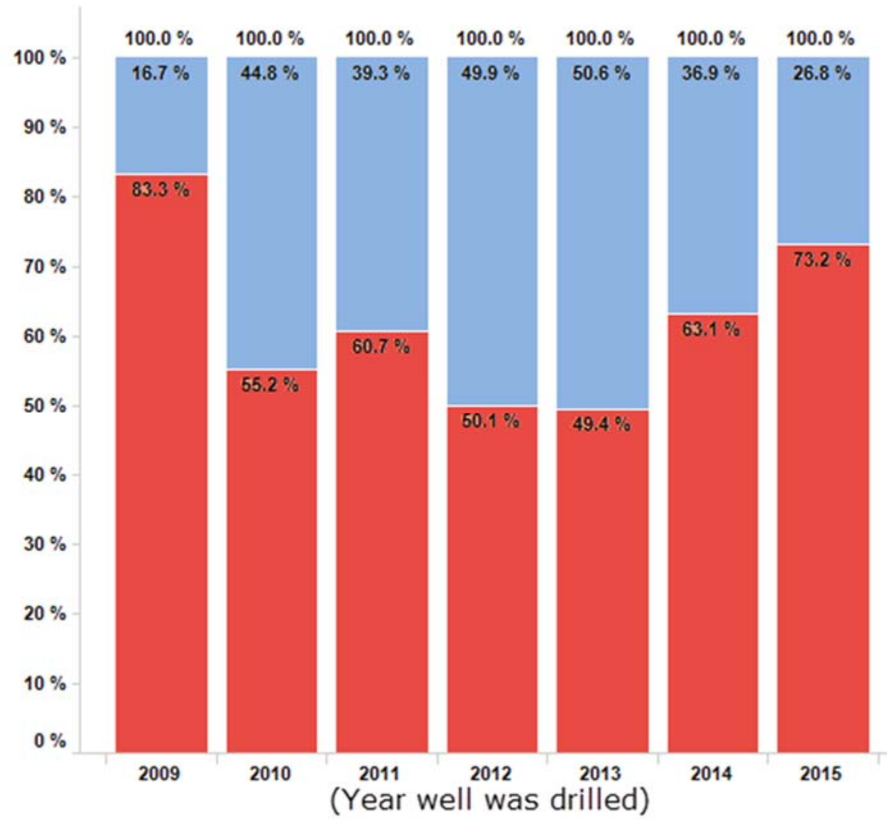


Figure 32 Percentage of wells whose surface casings penetrate the predicted aquifer surface, by year. Blue represents surface casings that protect the aquifer and red represents surface casings that do not.

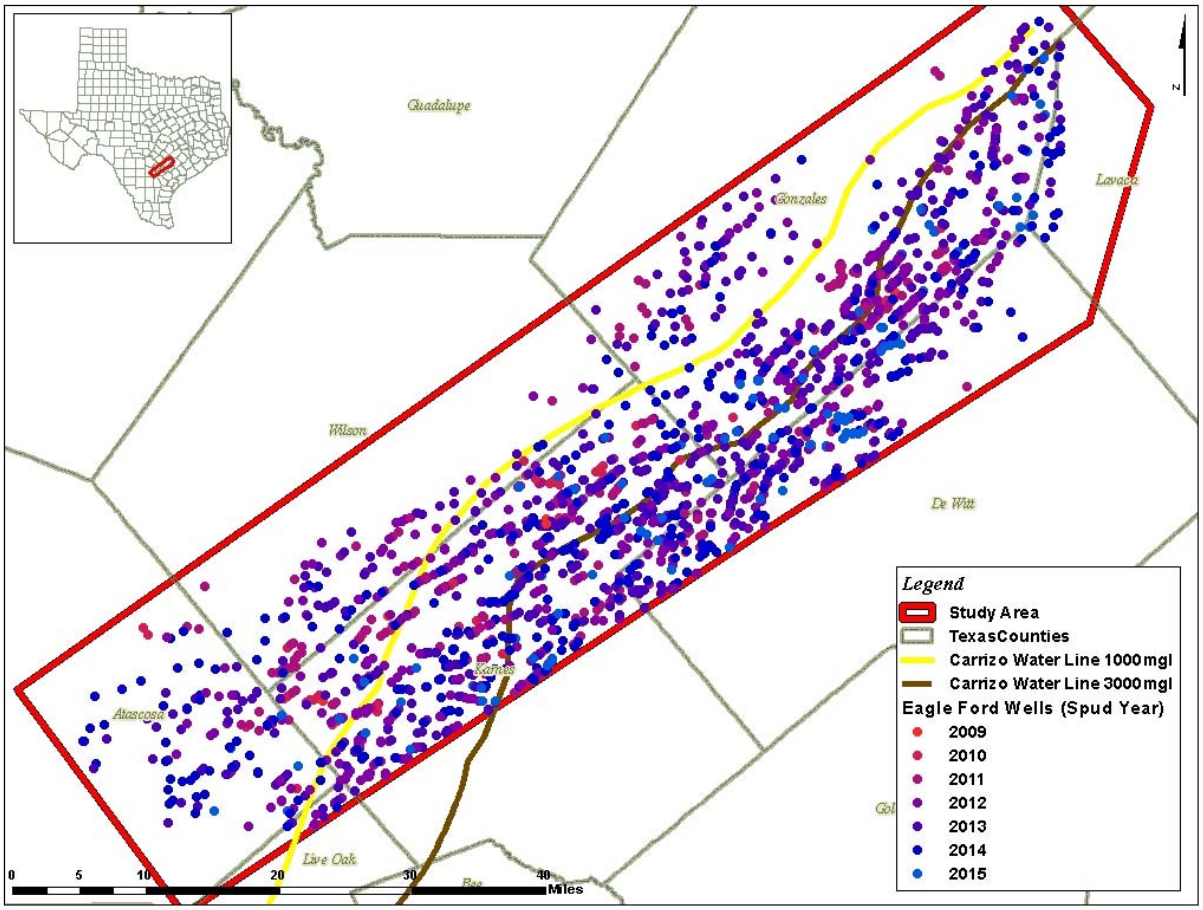


Figure 33 Eagle Ford Wells symbolized by year it was drilled.

5.4 Difference between depth of surface casing and predicted aquifer depth

It has been established that the Carrizo-Wilcox is not completely protected within the study area. The next question to address is "By how much?" Figure 34 displays a bar chart which reflects the difference between the surface casing depth and the predicted aquifer depth. One important item to point out is that most wells with surface casings that do not penetrate the base of the aquifer are short by over 2,000 feet. This leads one to conclude that when groundwater is considered "unusable" (and therefore protection is not needed), the casing is set well above the depth of the formation.

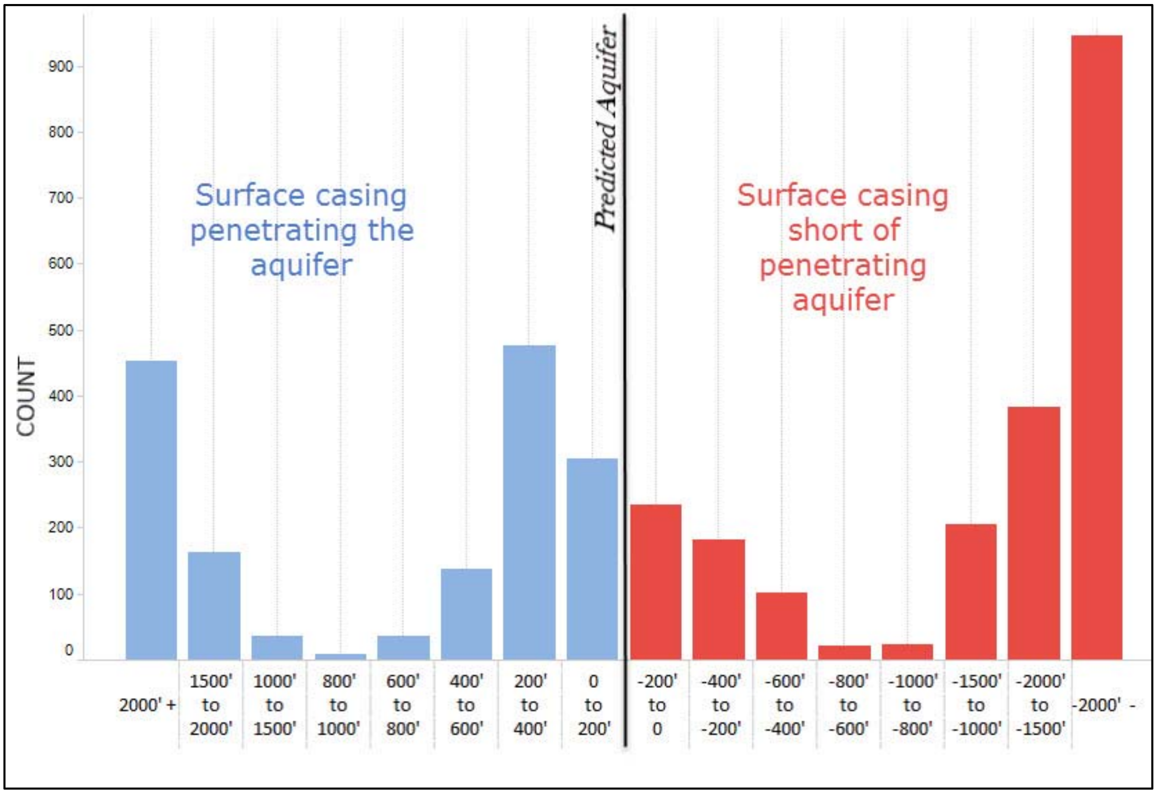


Figure 34 Difference between surface casing depth and predictd aquifer base depth.

The map below (Figure 35) displays the spatial distribution of the difference in surface casings across the region. The ranges used in the map are the same as the ranges in the previous bar chart. The surface casings of the wells in blue penetrate the base of the aquifer and wells in orange do not. As the colors become darker, the distance between the surface casing depth and the aquifer depth increases. The map clearly shows that when water is considered brackish to saline (or above 3,000 mg/L TDS), surface casing is set far above the base of the aquifer.

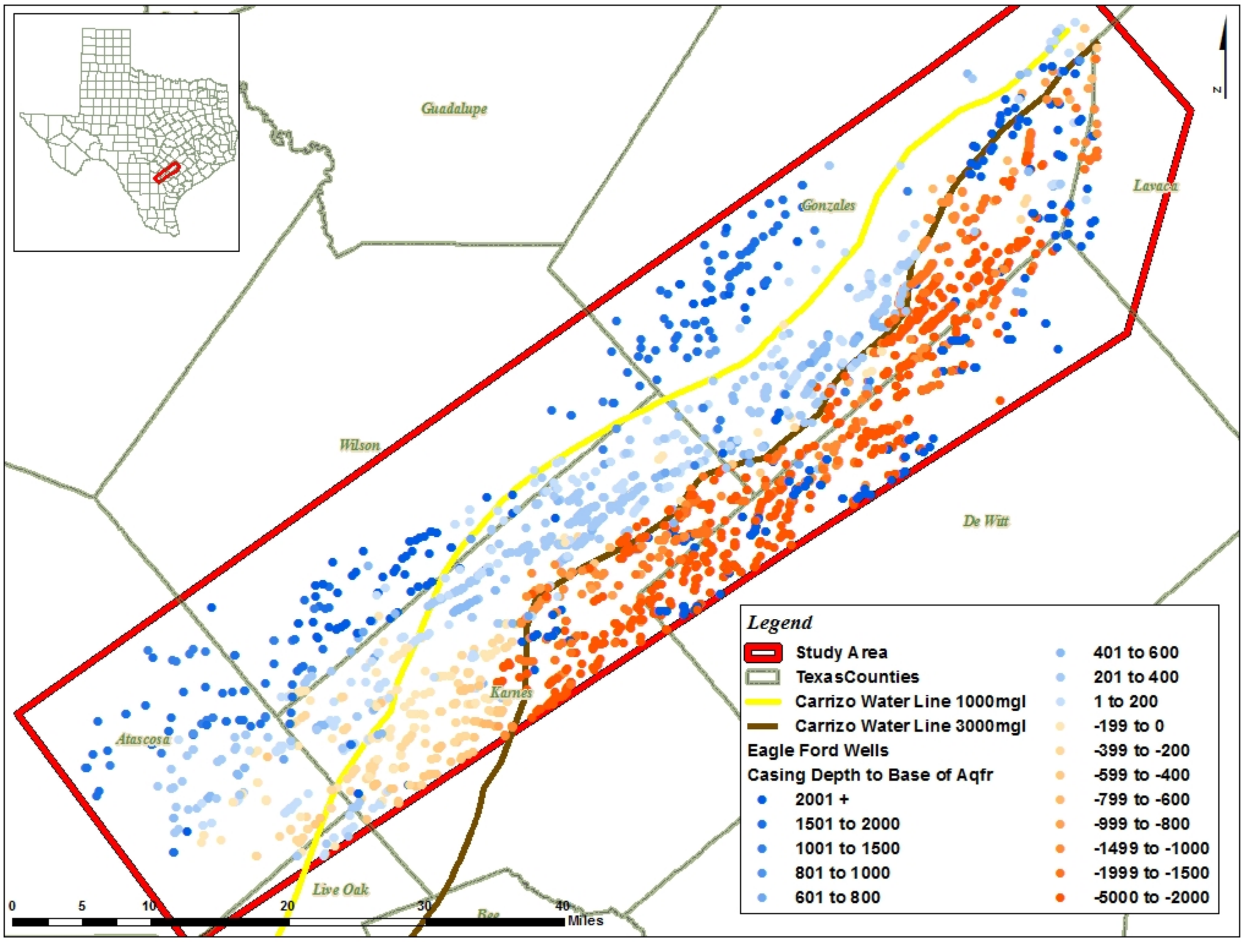


Figure 35 Difference between surface casing depth and base of aquifer in feet.

Chapter 6 Conclusions

Due to the Eagle Ford shale, South Texas has experienced a recent increase of drilling activity. Because the Carrizo-Wilcox lies above the Eagle Ford formation, it is being compromised every time the surface casing is not set below the base of the aquifer.

To understand the regional structure of the Carrizo-Wilcox, well logs were used to identify formation depth within a study area. Empirical Bayesian Kriging was selected as a suitable method to interpolate a continuous surface representing the base of the aquifer. The standard error values and accompanying map provide a quantitative assessment of how well the interpolator performs. These errors provide a range within which there is a 95% chance that the actual value falls.

Comparison of the surface casing depths of 3700 Eagle Ford wells against the predicted surface representing the base of the aquifer, produced unexpected results. Although it was expected that there would be some wells with surface casings which do not fully penetrate the base of the aquifer, it was surprising to discover that over half of Eagle Ford wells drilled within the study area fall into this category, even when considering the base depth at the shallowest value of the standard error range. These results provide justification for further extensive investigations.

In addition, the area examined during this study covers only a portion of the Eagle Ford drilling region. The same methods should be continued throughout the remainder of the region to determine if similar trends apply.

6.1 Limitations and Observations

This study was conducted on the premise that no previous groundwater contamination had occurred due to oil and gas activity. However, when considering the number of wells drilled in the region throughout the past, this seems improbable (refer to Chapter Four, Figure 12). It is likely that many older wells did not have standards regarding surface casings in place, as they are today. However, when dealing with old wells, especially prior to 1970, determining which wells penetrated the aquifer is a much more difficult task, as most drilling records are not complete. Often information such as wellbore depth and casing depths are not readily available, especially in a database form. Nonetheless, it would be worth conducting research and similar procedures on historic wells, if available.

As mentioned in Chapter Two, having groundwater quality sampled before oil and gas operations, would be an ideal situation. This would provide a baseline, and would better indicate if oil and gas operations were deteriorating groundwater quality. This could be accomplished during the exploration phase of a newly discovered, petroleum producing formation. Regulatory agencies could require operators to drill and sample a water well within a specified distance of newly drilled oil or gas well. After a number of wells were drilled, sampling at these locations could then be conducted on a regular basis by one of Texas's regulatory agencies.

6.2 Current and Future Work

As aquifers are an important topic, research is increasingly being conducted in an effort to model, map and protect this vital resource. The Texas Water Development Board recently announced a new project to be conducted by the Bureau of Economic Geology and INTERA, Inc. to map the fresh, brackish, and saline groundwater in the Carrizo-Wilcox (Texas Water Development Board 2015). The project is scheduled to be completed in 2017 and will contribute to the desired future condition of GMA 13. As lines delineating areas of salinity are investigated and perhaps modified since those created in 1976, it will be interesting to see how that could affect the results determined within this study.

Future work should also include modeling groundwater flow within the aquifer. Although the Carrizo-Wilcox groundwater moves slowly within the aquifer- it still moves. Increased pumping of fresh groundwater will affect this movement. Good groundwater flow modeling techniques could help determine if and by how much these regions are hydrologically connected. Even if protecting brackish water from oil and gas operations is not currently in the interest of the RRC because of usability, it should still be considered in case contamination could move through the aquifer to fresher "usable" areas.

One final thought regarding regulatory agencies involved with groundwater, is that they currently appear disconnected from each other. As new ideas and projects continue to develop and mature, communication amongst the agencies is vital for groundwater protection.

References

Alford, Elizabeth. 2015. *Eagle Ford Shale.* December 5. Accessed December 9, 2015. http://eaglefordshale.com/news/eagle-ford-rig-count-remains-steady-2/.

Boghici, Rudu. 2009. *Water Quality in the Carrizo-Wilcox Aquifer, 1990-2006.* Austin: Texas Water Development Board.

Bonanza Creek. 2015. *Technology & Innovation.* Accessed Nov 2015. http://www.bonanzacrk.com/about-bonanza/technology-innovation/.

Camp, C V, and J E Outlaw Jr. 1993. "Constructing Subsurface Profiles Using GIS." *Advances in Engineering Software* 18: 211-218.

Caumon, G, P Collon-Drouaillet, C Le Carlier de Veslud, S Viseur, and J Sausse. 2009. "Surface-Based 3D Modeling of Geological Structures." *International Association for Mathematical Geosciences* 41: 927-945.

Childs, Colin. 2004. "Interpolating Surfaces in ArcGIS Spatial Analyst." *ArcUser.*

Crow, Cassi L. 2012. "Water-Level Altitudes and Continuous and Discrete Groundwater Quality at and near an Aquifer Storage and Recovery Site, Bexar, Atascosa, and Wilson Counties, Texas, June 2004-September 2011."

Dutton, Allan R, Bob Harden, Jean-Philippe Nicot, and David O'Rourke. 2003. *Groundwater Availability Model for the Central Part of the Carrizo Wilcox Aquifer.* Technical Report, Austin: The University of Texas at Austin.

Eagle Ford Shale. 2015. *Eagle Ford Production.* October 27. http://eaglefordshale.com/eagle-ford-production/.

Esri. 2015. *An Overview of the Raster Interpolation Toolset.* October 23. http://desktop.arcgis.com/en/desktop/latest/tools/3d-analyst-toolbox/an-overview-of-the-interpolation-tools.htm.

—. 2015. *Deterministic Methods for Spatial Interpolation.* October 23. http://desktop.arcgis.com/en/desktop/latest/guide-books/extensions/geostatistical-analyst/deterministic-methods-for-spatial-interpolation.htm.

—. 2015. *How Kernel Interpolation with Barriers Works.* October 23. http://desktop.arcgis.com/en/desktop/latest/guide-books/extensions/geostatistical-analyst/how-kernel-interpolation-with-barriers-works.htm.

—. 2015. *How Spline Works.* October 25. http://desktop.arcgis.com/en/desktop/latest/tools/3d-analyst-toolbox/how-spline-works.htm.

—. 2015. "Performing Cross-Validation and Validation." *ArcGIS for Desktop.* October 26. http://desktop.arcgis.com/en/desktop/latest/guide-books/extensions/geostatistical-analyst/performing-cross-validation-and-validation.htm.

—. 2015. "Random Processes with Dependence." *ArcGIS for Desktop.* October 26. http://desktop.arcgis.com/en/desktop/latest/guide-books/extensions/geostatistical-analyst/random-processes-with-dependence.htm.

—. 2015. "Using Cross-Validation to Assess Parameter Values." *ArcGIS for Desktop.* October 26. http://desktop.arcgis.com/en/desktop/latest/guide-books/extensions/geostatistical-analyst/using-cross-validation-to-assess-parameter-values.htm.

—. 2015. *What are the Different Kriging Models.* October 23. http://desktop.arcgis.com/en/desktop/latest/guide-books/extensions/geostatistical-analyst/what-are-the-different-kriging-models-.htm.

—. 2015. *What is Empirical Bayesian Kriging.* October 24. http://desktop.arcgis.com/en/desktop/latest/guide-books/extensions/geostatistical-analyst/what-is-empirical-bayesian-kriging-.htm.

Esri: Help Files. n.d. "Introduction to Interpolation Methods."

—. n.d. "Surface Creation and Analysis."

Evenick, Ph.D., Jonathan C. 2008. *Introduction to Well Logs and Subsurface Maps.* Tulsa: Pennwell Corporation.

FracFocus. 2015. *Well Construction & Groundwater Protection.* Accessed June 15, 2015. http://fracfocus.org/hydraulic-fracturing-how-it-works/casing.

Gearhart, Norman. 2015. "Email message to Railroad Commission of Texas." July 24.

—. 2014. "Online Information and Completing Groundwater (GAU) Applications." *Railroad Commission of Texas.* Accessed June 28, 2015. www.rrc.state.tx.us/media/22886/9-gau-online-information-and-completing-applications-2014.pptx.

George, Peter G, Robert E Mace, and R Petrossian. 2011. *Aquifers of Texas.* Austin: Texas Water Development Board.

Gronewold, Nathanial. 2014. "Tighter Well-integrity Rules Take Effect in Texas." *The Texas Environmental News.* February 7. Accessed June 28, 2015. http://txenvironews.org/articles/fossil-fuels-governmentpolitics-waterriversgulf/tighter-well-integrity-rules-take-effect.

Holloway, Michael D, and Oliver Rudd. 2013. *Fracking: The Operations and Environmental Consequences of Hydraulic Fracturing.* Beverly: Scrivener Publishing.

Huang, Yun, Bridget R Scanlon, Nicot Jean-Phillipe, Robert C Reedy, Alan R Dutton, Van A Kelley, and Neil E Deeds. 2012. "Sources of Groundwater Pumpage in a Layered Aquifer System in the Upper Gulf Coastal Plain, USA." *Hydrogeology Journal* (20): 783-796.

Hyne, Ph.D., Norman J. 2001. *Nontechnical Guide to Petroleum Geology, Exploration, Drilling and Production.* Tulsa: PennWell Corporation.

Klemt, William B, Gail L Duffin, Glenward R Elder, and TWDB Geologists. 1976. *Ground-water Resources of the Carrizo Aquifer in the Winter Garden Area of Texas; Volume 1.* Report 210, Austin: Texas Water Development Board.

Krivoruchko, Konstantin. 2012. "Empirical Bayesian Kriging Implemented in ArcGIS Geostatistical Analyst." *ArcUser* 6-10.

—. 2011. *Spatial Statistical Data Analysis for GIS Users.* Redlands, CA: ESRI Press.

Lesikar, Bruce, Ronald Kaiser, and Valeen Silvy. 2002. *Questions About Groundwater Conservation Districts.* College Station: Texas A&M University.

National Groundwater Association. 2010. *National Groundwater Association.* October 18. http://www.ngwa.org/fundamentals/use/pages/groundwater-facts.aspx.

Phillips, Nestor. 2015. *Geologic Advisor* (October).

Porter, Charles R. 2014. *Sharing the Common Pool; Water Rights in the Everyday Lives of Texans.* College Station: Texas A&M University Press.

Railroad Commission of Texas. 2015. *Oil and Gas.* July 20. Accessed July 26, 2015. http://www.rrc.state.tx.us/about-us/history/informal-history-toc/oil-and-gas/.

San Antonio Water System. 2015. *Brackish Groundwater Desalination.* October 25. http://www.saws.org/your_water/waterresources/projects/desal.cfm.

Sansom, Andrew. 2008. *Water in Texas: An Introduction.* Austin: University of Texas Press.

Tearpock, Daniel J., and Richard E. Bischke. 2002. *Applied Subsurface Geological Mapping.* New Jersey: Prentice-Hall PTR.

Texas Administrative Code. 2014. "Part 1, Chapter 3, Rule 3.13, Casing, Cementing, Drilling, Well Control, and Completion Requirements." *Title 16: Economic Regulation.* January 1.

Texas Water Development Board. 2015. "Desired Future Conditions." *Texas Water Development Board.* October 26. http://www.twdb.texas.gov/groundwater/management_areas/DFC.asp.

—. 2015. *Groundwater.* November 9. https://www.twdb.texas.gov/groundwater/.

—. n.d. *Groundwater Conservation District (GCD) FAQs.* Accessed June 26, 2015. http://www.twdb.texas.gov/groundwater/faq/index.asp.

—. 2015. *Mapping fresh, brackish, and saline groundwater in the Carrizo-Wilcox, Queen City, and Sparta aquifers.* Accessed November 23, 2015. http://www.twdb.texas.gov/groundwater/models/research/czwx_qcsp_s_mapping/czwx_qcsp_s_mapping.asp.

Texas Water Development Board. 2013. "Water Survey Groundwater Pumpage Estimates." Data Table.

Zoraster, Steven. 2003. "A Surface Modeling Algorithm Designed for Speed and Ease of Use with All Petroleum Industry Data." *Computers & Geoscience* 1175-1182.