FILLING IN THE GAPS:

3D MAPPING ARIZONA’S BASIN AND RANGE AQUIFER IN THE PRESCOTT ACTIVE MANAGEMENT AREA

by

Amanda Cuesta

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To my mom and friends- thank you for all your support.

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List of Abbreviations

3D	Three dimensions or three-dimensional
ADWR	Arizona Department of Water Resources
AMA	Active Management Area
ANFIS	Adaptive Neuro-fuzzy Inference System
AZGS	Arizona Geological Survey
DEM	Digital elevation model
EBK	Empirical Bayesian Kriging
EBK3D	Empirical Bayesian Kriging 3D
GMA	Groundwater Management Act
GWSI	Groundwater Site Inventory (Database)
IDW	Inverse Distance Weighting
INA	Irrigation Non-expansion Area
LAU	Lower Alluvial Unit
MAU	Middle Alluvial Unit
NAD27	North American Datum 1927
NAD83	North American Datum 1983
NAVD88	North American Vertical Datum 1988
TIN	Triangulated Irregular Network
UAU	Upper Alluvial Unit
USGS	United States Geological Survey

Abstract

Despite Arizona relying on Arizona groundwater to meet a significant portion of its water needs, the locations of Arizona's groundwater aquifers are not fully mapped, and methods to interpolate the locations of aquifers from test boreholes remain inaccurate. In response, this study implements a workflow leveraging three-dimensional (3D) interpolation to fill in that knowledge gap within a study site: the Prescott Active Management Area surrounding Prescott, Arizona. Using borehole log data and digital elevation models, the 3D extent of permeable layers are mapped, serving as proxies for aquifers and aquitards, respectively. This project makes use of Empirical Bayesian Kriging 3D (EBK3D) to interpolate permeability data in three dimensions. When tested on four random boreholes, this model correctly predicted an aquifer 80% of the time in comparison to 42% using traditional 2D interpolation. The model's improved accuracy provides an approach to improve drillers', policymakers', and scientists' understanding of the hydrologic activity in the area. Such an improvement may lead to better-informed storage models, changes in water management, and greater cost efficiency when drilling new wells.

Chapter 1 Introduction

Arizona is a rapidly growing desert state. This means increased demands on our total water supply, even though the state is in an ongoing drought. In order to meet these growing needs, Arizona heavily relies on groundwater. It is little wonder, then, that groundwater is thoroughly monitored within the state. In fact, in 1980, the Arizona Department of Water Resources (ADWR) designated five areas as needing extra legislation and monitoring efforts. These areas, known as active management areas (AMAs), have depth-to-water measurements taken more often than other parts of the state and are subject to stricter regulations.

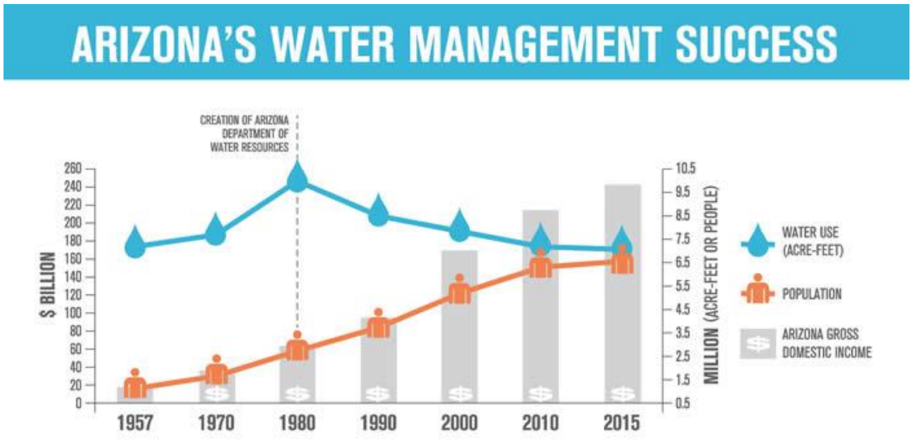
Despite the extra attention given to these areas, knowledge of the aquifers that supply their water is somewhat lacking. The United States Geological Survey (USGS) released a water atlas in 1995, summarizing the aquifers that can be found throughout the United States (Robson and Banta 1995a; Robson and Banta 1995b). Arizona was shown to have two principal aquifers, the Basin and Range aquifer and the Colorado Plateau aquifer. These maps are useful for showing where the groundwater is in planar space, but what about its vertical extent? Current data tend to cover specific study areas if it is in 3D. Still, most data regarding aquifer locations are either in 2D in the form of cross sections or simply left as tabular descriptive data.

This study aims to fill in both the knowledge and model gaps by using interpolation to create a 3D model of the Basin and Range aquifer. The present study only focuses on the Prescott AMA, but it will likely be extended to the other AMAs in the future. As lithologic data can be assumed to be stable, barring significant tectonic activity, all available borehole data is eligible for inclusion, regardless of observation date.

1.1. Managing Arizona’s Water

As discussed previously, Arizona is a desert state that relies on groundwater to meet a large portion of its water needs. To combat the overuse that was occurring throughout the state, Arizona legislation adopted strict codes for managing the state’s water resources with special emphasis placed on preserving its groundwater. This effort was brought to the forefront of public awareness when the state government signed the Groundwater Management Act (GMA) into effect in 1980 (Jacobs and Holway 2004; ADWR n.d.b)

The GMA accomplished several critical goals, the effects of which are still affecting daily life in Arizona. First, it established the Arizona Department of Water Resources, the agency responsible for monitoring and preserving the state’s water. Second, it outlined a plan to allocate groundwater so that safe yield, or net-zero aquifer withdrawal, may in time be achieved. The act also involved securing funding for the Central Arizona Project, a canal that carries water from the Colorado River for use in Maricopa, Pima, and Pinal counties to decrease their reliance on groundwater. Finally, it established four active management areas and two Irrigation Non-expansion Areas (INAs). A fifth AMA was later distinguished from a portion of the Tucson AMA and a third INA were established in 1982. These areas are subject to tighter regulations than the rest of the state, each with a specific goal. For the Phoenix, Tucson, and Prescott AMAs, this goal is reducing groundwater withdrawal to the safe yield amount. The Santa Cruz AMA’s goal is to maintain safe yield to prevent water table drawdown and protect riparian habitats. Pinal AMA’s goal is to safely continue agriculture without jeopardizing future water supplies (ADWR 2010a; ADWR 2010b; ADWR n.d.c; Jacobs and Holway 2004). The effectiveness of the GMA is illustrated in Figure 1.



SOURCE: ADWR, 2016

Figure 1: This diagram illustrates the impact of the GMA and concurrent creation of the Arizona Department of Water Resources. Note that after ADWR is established, total water use continuously decreases.

1.2. Motivation

Every year, the state of Arizona relies on groundwater to meet the demands of its growing population, accounting for 43% of the state's total water supply from 2001 to 2005 (ADWR 2010b). Since the inception of the Arizona Department of Water Resources (ADWR), the population has grown from about 3 million people to 7 million. This averages to a 3% growth in population per year (ADWR 2010b). Surprisingly, this growth is not translating to increasing use of the state's groundwater supply. In fact, recent reports indicate that the state is using the least groundwater it has since the 1950s. This is due to strict regulations and shifting dependence to other sources, such as the Colorado River (ADWR n.d.). Even though these statistics are promising, Arizona must carefully track how much groundwater is being used, who is using it, and where it is being drawn from.

In an effort to better track and regulate groundwater use, the Arizona Department of Water Resources has designated five "active management areas" since its inception. These are areas where groundwater withdrawal most severely exceeds its safe yield, or the amount of groundwater that can be considered renewable. The active management areas, where 82% of the population lives and where most withdrawal occurs, are targeted for additional regulatory measures. These include, but are not limited to, restricting the amount of groundwater that can be withdrawn legally, preventing the expansion of irrigated areas, and strict permitting requirements for new withdrawals (ADWR 2016).

All of these regulations serve one primary purpose— to protect Arizona's aquifers. One of Arizona's two primary aquifers, the Basin and Range aquifer underlies approximately 200,000 square miles of land, extending through seven states (Robson and Banta 1995a). Of particular interest to this study is the stretch underneath southern Arizona that lies under all five active management areas. As mentioned previously, these are the areas with the greatest overuse of groundwater. For them to all be withdrawing from the same aquifer makes it critical that scientists understand where exactly the aquifer is in three dimensions. This allows accurate volume calculations and, by extension, more accurate monitoring of aquifer conditions. Additionally, the Basin and Range aquifer was chosen for representation over the Colorado Plateau aquifer because the water-bearing units can generally be identified with more confidence and the geologic structures within the basins, where the aquifer is located, are relatively straightforward (Robson and Banta 1995 a; Robson and Banta 1995b).

Modeling the entire Basin and Range aquifer is outside the scope of this project. Instead, it is modeled within a single AMA with the intention to expand its coverage in the future. The study is conducted within AMA boundaries in order to inform both scientists and decision makers of subsurface details within the state's most hydrologically delicate areas. The AMAs are population hot spots, the focus of most groundwater scientists' models, and the areas that see the most groundwater-related issues.

Of the five AMAs, Prescott is the focus of this study. The primary reason for this decision is that it has the highest density of wells covering its entire area, as shown in Figure 2. More wells in an area equate to more borehole data to inform the model and, by extension, a more accurate model. The Prescott AMA's areal extent is reasonable to complete in the timeframe of this study but large enough to hold significance. Finally, and perhaps most importantly, such a model does not exist yet for the area. All the information on the aquifer is currently stored as descriptions, tables, or cross sections (Anderson, Freethey, and Tucci 1992; Gootee, et al. 2017). The move to 3D representation is long overdue.

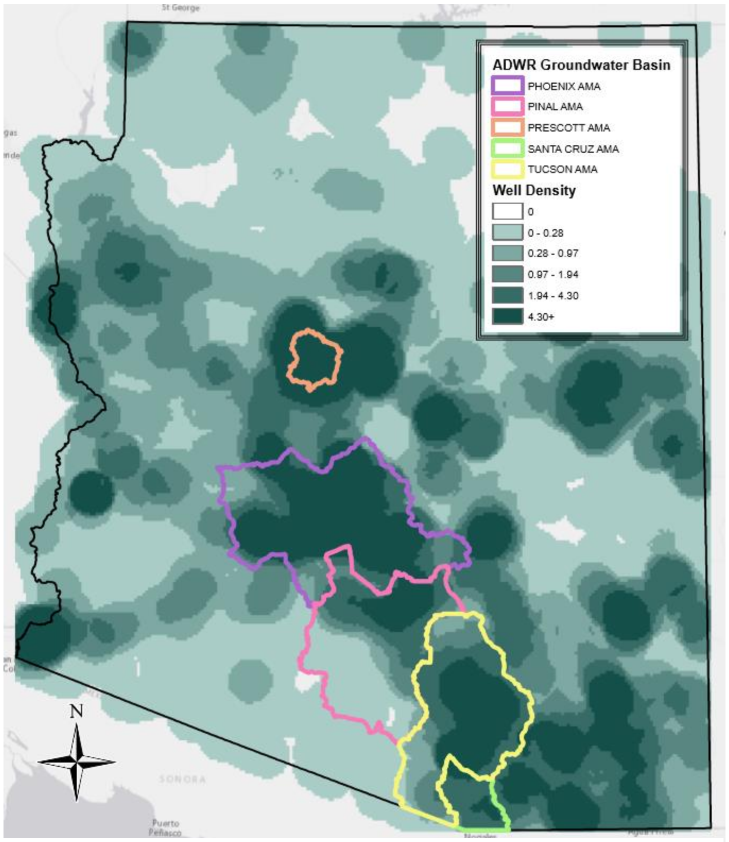


Figure 2: A density map of well locations overlain by outlines of the AMAs with the Prescott AMA in orange. Darker greens indicate greater well density.

This model benefits several groups. The Field Services Section at ADWR has expressed interest in such a model to help better explain what their field measurements represent. They hope to be able to input well construction data and see how the well relates to permeable layers. For example, is it screened within multiple distinct layers, creating a composite water level? Or does the water level represent a single hydrologic unit?

Policymakers can use the data collected by the Field Services section in combination with information about the area's permeability to decide whether to implement new use restrictions or where to focus recharge efforts. Groundwater modelers have also expressed interest for the sake of better informing their models.

The groups that will most benefit from this model, though, are well owners and drillers. It can help them make more informed decisions regarding where to place a new well and how deep to drill it in order to successfully and sustainably withdraw water. It will also help avoid wasting time and resources associated with drilling beyond a water-bearing unit and having to backfill the hole or drilling a completely dry well.

Given the above information, a 3D model of Arizona's aquifers could benefit nearly everyone in the state either directly or indirectly. The remainder of this manuscript follows the process of creating the model, beginning with related works followed by the methodology to be used in creating the model. It concludes with a presentation of the results and a discussion of the findings.

Chapter 2 Related Works

This chapter presents a review of the literature related to creating this 3D model of the Basin and Range Aquifer. The review begins with an overview of hydrogeology within Arizona, including characteristics of major aquifers. That is followed by a discussion of the value of 3D modeling in the spatial sciences. The chapter concludes with a look at what has been done in the past regarding aquifer modeling with a focus on the methods used.

2.1. Arizona Hydrogeology

With Arizona's groundwater being so strictly regulated, it is valuable to understand the conditions under which these aquifers formed and how to identify them in drill logs. The majority of this information is provided by the United States and Arizona Geological Surveys (USGS and AZGS, respectively).

In 1995, the USGS released a Groundwater Atlas of the United States. This document, which provides identifying and contextual information for all major aquifers in the United States, identifies two main aquifers within Arizona. These are the Colorado Plateau aquifer in the northeast and Basin and Range aquifer in the south and west (Miller 2000). Both of these primary aquifers are comprised of multiple sub-aquifers and are often referred to as plurals (i.e., Basin and Range aquifer*s*).

The Colorado Plateau aquifer consists of four sub-aquifers: Coconino-De Chelly, Dakota-Glen Canyon, Mesaverde, and Uinta-Animas. The hydrogeologic layers in this aquifer are mostly consolidated sedimentary rocks, including sandstone, conglomerates, and shales. Limestone, coal, and gypsum are also fairly common layers. The relationships between these layers has been described as "complicated" (Robson and Banta 1995b). As Robson and Banta

(1995b) indicate, the layers' properties are so inconsistent that individual layers have been shown to be aquifers in one area while acting as aquitards, or flow-inhibiting layers, in another. The large number of hydrogeologic units and their inconsistencies create too much uncertainty for inclusion in this project. Instead, the Basin and Range aquifer is the focus.

The Basin and Range aquifer, the extent of which is shown in Figure 3, is much more straight-forward, hydrogeologically speaking. Depending on the classification scheme used, there are only two to four hydrogeologic units (Gootee et al. 2017). The discrepancy regarding the number of hydrogeologic units stems from differing opinions on whether to designate certain sections as a new unit or the continuation of a series of deposits. These units are, for the most part, consistent throughout the aquifer's extent. The tectonic disturbances that created the aquifer's namesake basins and ranges occurred prior to the deposition of the alluvial units. That is to say that there were no major deformations in the area after deposition of the aquifer units began (Anderson, Freethey, and Tucci 1992; Robson and Banta 1995a).

Figure 3: The extent of the Basin and Range Aquifer. The aquifer is highlighted in yellow. Modified from Robson, S G, and E R Banta 1995.

Using Gootee et al.'s classification scheme, which is also the one used by ADWR, there are three hydrogeologic units: the upper, middle, and lower alluvial units. Anderson, Freethey, and Tucci (1992) group Gootee's upper and middle alluvial units into a single unit, but their lower units are in agreement. The shallow upper alluvial unit (UAU) is characterized by fine sediment with coarser deposits near mountains. The middle alluvial unit (MAU) is well-cemented conglomerates and mudstones. Sand and siltstone grading into mudstone are characteristic of the lower alluvial unit (LAU). Evaporite deposits are also common in this unit near basin centers.

2.2. The value of 3D modeling

Three-dimensional modeling is utilized in a wide variety of disciplines, both those that are commonly associated with the spatial sciences such as geology and those that are not, like surgery. This wide range of uses speaks to the value of 3D modeling. With 3D modeling being used in such a wide variety of disciplines, it is important to examine what exactly makes it more beneficial than other forms of data storage and manipulation.

The primary advantage of 3D modeling is that it allows the data to be explored as it would be in person. We experience the world in three dimensions, so it is more intuitive to have information displayed in three dimensions than in two dimensions. Such a display makes it easier for experts to spot errors and anomalies than it would be when looking at 2D displays or tabular data (Akpan and Shanker 2017). It also makes conveying information to non-experts easier because it is an intuitive format that accurately conveys the world as it is experienced.

A meta-analysis by Apkan and Shanker (2017) found that most researchers from a variety of fields conclude that displaying information in three dimensions is "more potent and leads to better analysis". Aldiss et al. (2012) reached a similar conclusion, citing 3D models' ability to incorporate geologic features exactly as observed, by extension allowing them to understand structures in a way that they were unable to using other methods of examining their data. An analysis by Brzobohata et al. (2012) found that 3D modeling had fewer errors when compared to traditional methods used in bone reconstructions. Though that study is concerned with medical modeling instead of geographic modeling, it would not be a stretch to assume that the same would be true in a geographic context.

Finally, 3D models allow phenomena to be visualized that cannot be readily observed in person. Whether it be because the object of observation is under hundreds of feet of rocks, such as an aquifer, or the object is too delicate to be handled, such as in medical observations (Brzobohata et al. 2012) and archaeology (D'Amelio, Maggio, and Villa 2015), 3D modeling gives form to the otherwise unseeable.

2.3. Modeling aquifers in 3D

There have been numerous studies completed modeling groundwater aquifers in three dimensions. Each study uses a somewhat unique approach, but most share some broad similarities. The current study drew on the similarities to create a basic plan of action. The differences between studies were carefully considered while deciding the specific methods to be used, such as software and interpolation method. In making these decisions, methods that exactly honor the data were preferred, as were methods that could accomodate data with spatial trends.

The first major similarity between all reviewed studies is the inclusion of borehole lithologic logs. Most of this data comes from drilling water wells, but some researchers have also used oil exploration boreholes and wells (Gootee, et al. 2017; Jerbi, et al. 2018; Neinkamp 2016; Nury, et al. 2010). Additional data that has been used less consistently includes digital elevation models (DEMs), cross sections, water levels for unconfined aquifers, as well as seismic and resistivity data.

The process of generating 3D aquifer data is generally agreed upon between the studies mentioned previously. The first, and most tedious, step is gathering borehole information and interpreting the logs. Drillers often use inconsistent wording on their logs, creating the need for human interpretation before correlation is possible. Once the logs are reinterpreted, the bounding surface between units can be plotted and interpolated in 3D.

The program and method used to complete this interpolation seem to vary widely based on researcher preference and suitability for the study area. After thorough comparisons of methods, Neinkamp (2016) found that for study areas with trends in elevation, Empirical Bayesian Kriging (EBK) in ArcGIS is most suitable to use for interpolation. The Conde study (2014) found Inverse Distance Weighting to be acceptable, also in ArcGIS. Other researchers used more specialized software to complete the interpolation, such as Rockware (Jerbi, et al. 2018) or GOCAD (Nury et al. 2010). In my experience, most people that would use this model have ArcGIS available and are at least somewhat familiar with the program. Creating the model in ArcGIS ensures that interested parties will be able to view and manipulate the model. In contrast, a more specialized program may not allow the same due to proprietary file types. Because there is an elevation trend to the study area, EBK is the interpolation method used.

2.3.1. Interpolation methods

The remainder of this chapter examines interpolation methods used in similar studies. The largest portion discusses the various forms of kriging, followed by a discussion of other methods that have been used.

2.3.1.1. Kriging

Kriging is an exact interpolation method in which the data is honored as it was observed. This means that after interpolation, the output values at measured points match the input values at those points. It assumes that points near each other in space have values more similar to each other than to points that are farther away, a phenomenon known as spatial autocorrelation (Columbia University Mailman School of Public Health, n.d.). These two defining characteristics are ideal for this project as geologic data is always autocorrelated, and the data must be truthfully represented in the model for it to be an improvement over other representations.

In order to define the relationship between data points, kriging relies on semivariograms. Semivariograms are plots that display the distance between points on the x-axis and the squared difference of the points' values along the y-axis (Esri n.d). A model is then fit to this plot, similar to a line of best fit in regression analysis. The model is what allows predictions to be made in unmeasured locations since it is essentially an equation representing how the data changes between measured points.

There are several types of kriging methods available, each with unique benefits and assumptions. The two main categories are ordinary kriging, which assumes that the relationship between data points only depends on distance, and universal kriging, which assumes the direction of separation also matters (Dunlap and Spinozola 1984). A third, more recently developed type of kriging is Empirical Bayesian Kriging (EBK). This method can accommodate data for which a single model does not fit the entire study area. It automates the semivariogram modeling process by modeling subsets of the data and adjusting the model each time until the best fit for the full study area is achieved. EBK can also accommodate data that is not normally distributed, an advantage over most other kriging styles. Additionally, an estimate of errors may be created, which adds credibility to the interpolated surface (Esri n.d.).

2.3.1.2. Other methods

Though the various forms of kriging seem to be the preferred way to interpret hydrogeologic data, other methods are available. The most simplistic of these other methods is inverse distance weighting (IDW). Like kriging, IDW is an exact interpolation method. Rather than using semivariograms and models to determine the relationship between data points, IDW assumes a linear relationship based only on the distance between the points (Ohmer, et al. 2017). This method is less computationally demanding and requires fewer user-set parameters but is often less accurate than more sophisticated methods when dealing with geologic or hydrologic data.

A less commonly used interpolation method, specifically regarding hydrologic data, is adaptive neuro-fuzzy inference system (ANFIS). This method works on the assumption that there is not a clear or well-defined boundary to the data. ANFIS iteratively creates prediction rules for the fuzzy data and has been shown to generate outputs fairly similar to those from ordinary kriging. For a more detailed explanation, the reader is referred to Kurtulus et al. 2011. Though these other interpolation methods are useful, they are not the most appropriate for the data in this study due to trends in the data and its relatively well-defined boundaries.

Chapter 3 Data and Methods

This chapter outlines the project's design, as well as the data needed to complete the involved tasks.

3.1. Scope

This study covers the Prescott AMA with an approximately one square mile planar resolution model of the Basin and Range aquifer. Vertical data was aggregated into fifty-foot intervals during digitization prior to display and interpolation. These intervals were assigned one of three possible values: 100 if the interval is dominantly permeable, 0 if dominantly impermeable, or 50 if the log was not detailed enough to determine permeability. The data used to create the model and their related complications are discussed further in the next section.

3.2. Data

The primary data used to create this model was the well borehole logs that are completed by the drillers as wells are constructed. These contain lithologic information about the layers that are drilled through and are made publicly available as part of wells' registration documents through ADWR. All borehole data had to be joined to ADWR's Groundwater Site Inventory (GWSI) database, which contains GPS-verified location information for each well as well as all measured water levels. The GPS latitudes and longitudes are given in NAD27 degrees-minutes-seconds accurate to 0.5 seconds

Though every well has a borehole log and accurate location information, inconsistencies within the well borehole data complicated the interpolation stage of creating the model. A majority of wells only have driller logs instead of the more favorable geologist or lithologic logs.

Drillers do not have universal standards for descriptions or sampling intervals, and many do not have geologic training. Because there are no standard requirements, many logs do not contain sufficient information to discern hydrogeologic units and may not accurately reflect the permeability of an interval.

Even amongst the wells that do have adequate logs, the descriptions, and by extension coding, of units varies. Additionally, due to the drillers' lack of geologic training, there is no guarantee that the descriptions are accurate. For example, an interval may be described as "granite", implying no permeability, when in reality, it should have been described as "fractured granite," which is instead highly permeable. Errors such as these may obscure the true extent of permeable units, causing inaccurate representations and correlations. Unfortunately, there is little that can be done to correct these issues or verify the descriptions' accuracies, since many drillers discard the borehole materials after the log is complete. Logs that seem inconsistent with their surrounding area may be flagged as potentially erroneous but must still be included in the model. To selectively exclude these wells because they seem inconsistent would introduce bias in the model and would not be true to the data available.

Other data that is used to improve model accuracy include a digital elevation model (DEM) produced by and freely available through the USGS. The logs need to be plotted relative to the surface elevation at the wells' locations for proper correlation. The DEM, which has approximately 30-meter planar resolution and 3-meter vertical resolution, is used to define surface elevation. All data needs are summarized in Appendix A.

3.3 Design

3.3.1. Well selection

The first step in this process is deciding which wells to include in the model. There is no readily available database of well permeability status, and the time necessary to manually input that data for every single well in the study area would be far greater than that available for this study. For this reason, the wells are sampled from rather than including all available data.

To begin, the well logs must first be geocoded. Thanks to the GWSI database, this step was almost entirely automated. The database contains latitude and longitude coordinates for all wells that have been visited by ADWR field staff, as well as identifying information such as the wells registration identification numbers. Because registration documents, and by extension the borehole logs they contain, are stored by registration number, these files were easily joined to a shapefile of GWSI points to complete the geocoding. In this process, only matches were kept when joining the registration data so that only wells with completed logs were included. Finally, to speed processing time, the wells were clipped within a ten-mile buffer of the study area. The buffer helps minimize edge effects.

Once the data is reduced to only include the study area, the wells may be sampled. They were sampled to be approximately one mile apart by overlaying a one-mile fishnet grid on the study area and selecting the most central feature in each cell using the Central Feature tool. This method assures as even a distribution of data as possible. Due to artifacts from old data entry methods, some grid cells returned multiple central features with the same geographic coordinates. In this case, the first log of the group was selected for inclusion to prevent the introduction of biases.

3.3.2. Interpolation

Once the wells are selected for inclusion, they can be digitized. As mentioned in section 3.1, the fifty-foot intervals were assigned one of three values based on the dominant permeability status. Driller descriptions typically include a number of keywords that can be used to determine permeability, with the first material listed typically being the most dominant. To clarify, an interval listed as clay and sand would be determined to be mostly clay with some sand and thus designated impermeable. If the interval were instead described as sand and clay, it would be deemed permeable since sand is interpreted as the dominant material. A full list of keywords encountered while digitizing logs is included in Table 1, as well as whether they are permeable or not.

The spaces between well locations can then be interpolated. In this case, Empirical Bayesian Kriging (EBK) is used (Neinkamp 2016). The three-dimensional version of EBK, available through ArcGIS Pro, is used to avoid the time-consuming process of interpolating individual layers. Instead, the tool is run on all the data at once to produce a singular output. This output illustrates the predicted permeability throughout a series of stacked “sheets” that can be scrolled through to view different depths in the model.

There are six semivariogram models that can be used in the interpolation. In order to select the best fitting one, interpolation using each model was run on a subset of the data consisting of 151 data points. All parameters besides the semivariogram model were kept at their default values for this test. When all models were tested, the Whittle semivariogram model was found to produce the most realistic and true-to-data results. The cross-validation results were used to reach this decision, but it should be noted that this validation method is intended for continuous data. As such, the results should be viewed as a way of comparing outputs instead of a scientifically meaningful validation of the output itself. The results of the semivariogram comparison are included in Table 2.

Table 1: Material permeability. A table listing all keywords used to determine permeability. Drillers' logs contain these keywords in various combinations with many different descriptors to create unique logs for a well.

Permeable materials			
Sands	Conglomerate	Cinders	"Lost circulation"
Gravel	Breccia	Verde Formation	Coconino sandstone
"Fractured" anything	Malapai	Kaibab Limestone	Alluvium
Cavernous or honeycomb limestone	"Soft" anything	Toroweap formation	Redwall Limestone
Martin Formation	Tuff	Schnebly Hill Formation	Dolomite

Impermeable materials			
Clay	Limestone	Hickey Formation	Metamorphics
Silt	Volcanics or basalt	Supai Group	Shale
Bedrock	Caliche		

Table 2: Semivariogram model selection. Cross-validation results comparing the various available semivariogram models on a subset of the data.

Semivariogram model	Average CRPS	Inside 90%	Inside 95%	RMSE	RMSE Standardized	Average Standard Error
Goal:	Small as possible	= 90	= 95	Small as possible	= 1	Small as possible
Power	20.75	87.42	90.72	37.24	0.99	37.56
Linear	20.98	88.08	91.39	37.64	0.99	38.24
Thin plate spline	21.51	88.75	92.05	38.75	0.98	40.16
Exponential	20.72	88.74	90.07	37.4	1	37.52
Whittle	20.73	88.74	90.07	37.38	1	37.41
K-bessel	20.73	88.08	90.07	37.36	1.01	37.42

Once the semivariogram was selected, the interpolation could be run on the full dataset. It was run a total of five times, changing various parameters each time in order to get the most accurate results. Again, the output of cross-validation was used to compare the outputs but should not be considered a validation of the output. The parameter settings found to produce the most realistic results used the Whittle semivariogram, overlap factor of 3, 200 simulations, and first-order trend removal. Though it would be interesting to examine if other-order trend removals would be more appropriate for the data, the only options presented in this interpolation's parameters are first-order or no trend removal. Table 3 outlines the comparison of runs with custom parameters.

Table 3: Parameter comparison. A comparison of the cross-validation results on the full dataset using the Whittle semivariogram and various custom parameters.

	Average CRPS	Inside 90%	Inside 95%	RMSE	RMS Standardized	Average Standard Error	Notes
Goal:	Small as possible	= 90	= 95	Small as possible	= 1	Small as possible	
Default parameters	14.61	85.8	91.05	28.75	0.97	28.93	
Custom1	14.41	85.28	91.18	28.5	0.97	28.55	Overlap factor 3. 100 simulations.
Custom2	14.39	85.25	91.13	28.5	0.97	28.51	Overlap factor 3. 200 simulations.
Custom3	12	85	90.54	29.35	1.3	26.39	Overlap factor 3. 200 simulations. Empirical transformation.
Custom4	14.32	85.25	91.19	28.32	0.97	28.51	Overlap factor 3. 200 simulations. No transformation. First-order trend removal.

3.3.3. Analyses and demonstrations

Upon completion of model construction, the model must be checked for accuracy and validity. The model is manually cross-validated for an analysis of accuracy. To do this, a number of wells are examined that were not included in the model's creation. As with the interpolated wells, they are divided into 50-foot intervals that are deemed primarily permeable or not. Those same intervals are plotted in the model to determine predicted permeability. Matches between the model and log are counted as correct, mismatches are counted as errors. For the purposes of this study, a probability of 50% or higher is considered permeable, and thus a positive location of the aquifer, but future users may set the cut off to better suit their needs. For example, a driller may want to avoid drilling an area with under 70% certainty and so would only be concerned with locations above that threshold.

The final step in this process is to demonstrate ways in which the model can be used. After all, having this visualization is great, but it is ultimately unnecessary if it does not make answering questions easier than current data forms. To illustrate the improvement this model offers over traditional ways of working with the data, four wells throughout the study area were selected. These wells included information on where water was encountered during drilling or if the well was completely dry. Each 50-foot interval past the last water encounter is considered an error, since the driller is assumed to have expected water at the greater depths. Additionally, wells that were dry at the time of drilling are counted as incorrect at all intervals, as the driller expected to encounter water at some point in the well.

Chapter 4 Results

This chapter discusses the results of creating and validating the model. It also includes a measurement of accuracy for traditional methods for drilling decision-making.

4.1. Model

Interpolating the well information yields a model consisting of layers illustrating permeability likelihood. Each layer represents one foot of depth. They can be scrolled through individually using the slider bar, or a range of values can be viewed at once by setting the top and bottom values on the slider bar.

In this model, darker blues represent greater certainty that the interval is permeable. By extension, these are also the intervals where the aquifer is most likely to be present. In Figures 4a through d below, only areas with 50 percent likelihood or greater are symbolized. The layers are shown in 500-foot aggregates in order to illustrate general trends with decreasing elevation, but any range of values can be represented.

At higher elevations, the aquifer is most likely to be in the southern portion of the study area. With increasing depth, the likelihood switches to be more probable in the northern portion of the study area.

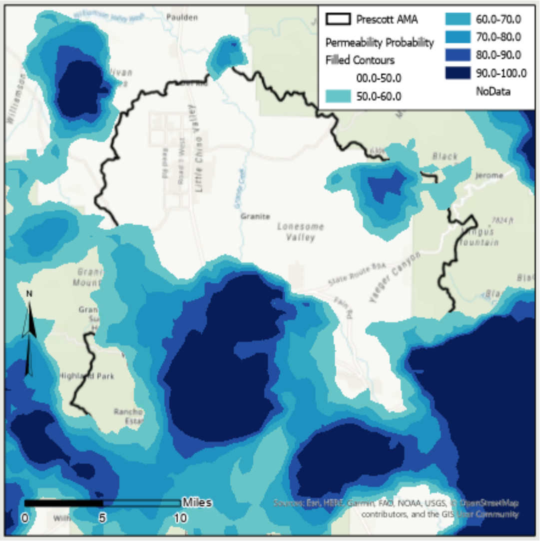
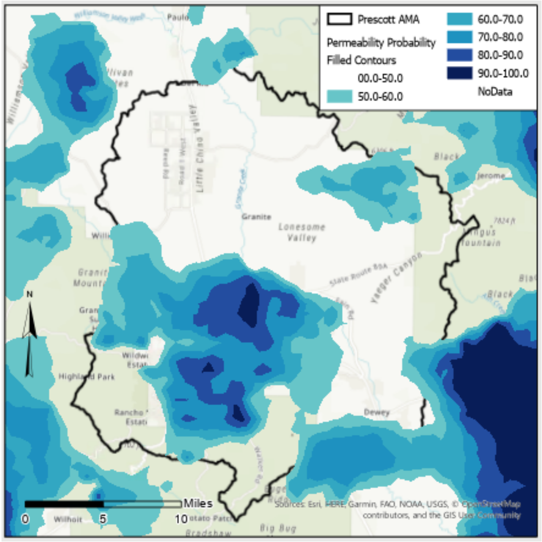
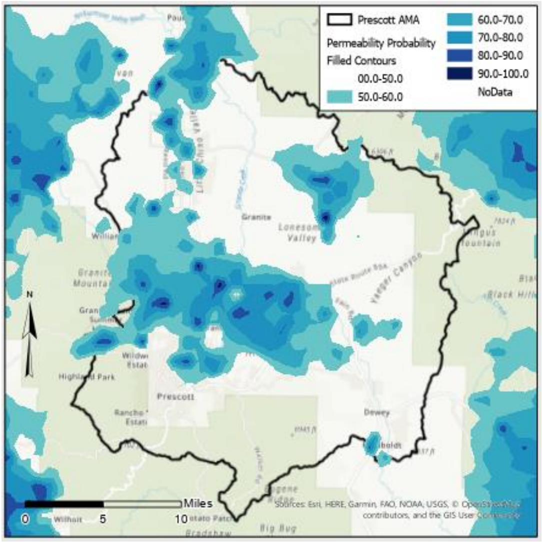


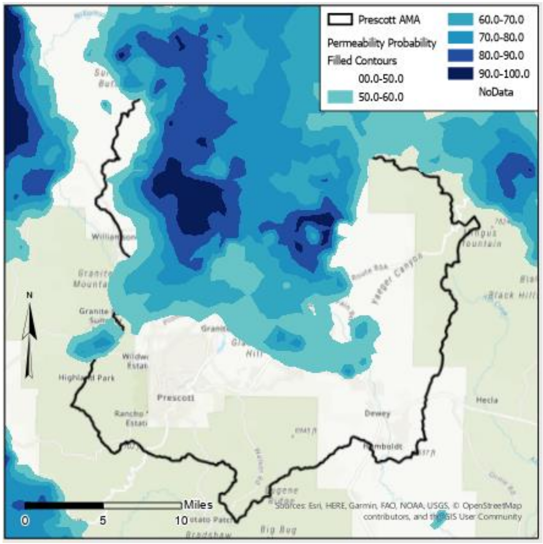
Figure 4a: 500-foot aggregate of the model. The interval shown is from the highest elevation, 2386 feet above datum, to 1886 feet.



4b: The next 500 feet in the model. Elevations represented are 1886 feet to 1386 feet.



4c: Elevations represented are 1386 feet to 886 feet.



4d: Elevations are 886 feet to 386 feet.

4.2. Validation

Validating the model yielded imperfect results. Four wells' drillers' logs were compared to the model output in order to determine whether the model accurately predicts permeability or not throughout the study area. These wells are shown in Figure 5. The four wells, randomly selected to represent their respective quadrants of the study area, consisted of a total of 35 intervals. Of those intervals, 14 did not have model-predicted permeability consistent with the permeability predicted based on the drillers' logs. This is a 60 percent accuracy.

The northeastern well, ID 203937, presented some issues during validation. Based on the driller's log, this well was drilled through different materials than its neighbors. Because of this, its permeability does not match its neighbors' and was predicted incorrectly for the majority of its intervals. Had this well not been included in the validation, the accuracy would have been 80 percent, or 20 of 25 intervals. Future work will have to examine if the model does a poor job representing that region of the study area or if that well happens to be a fluke. The results of validation for each interval are included in Appendix B.

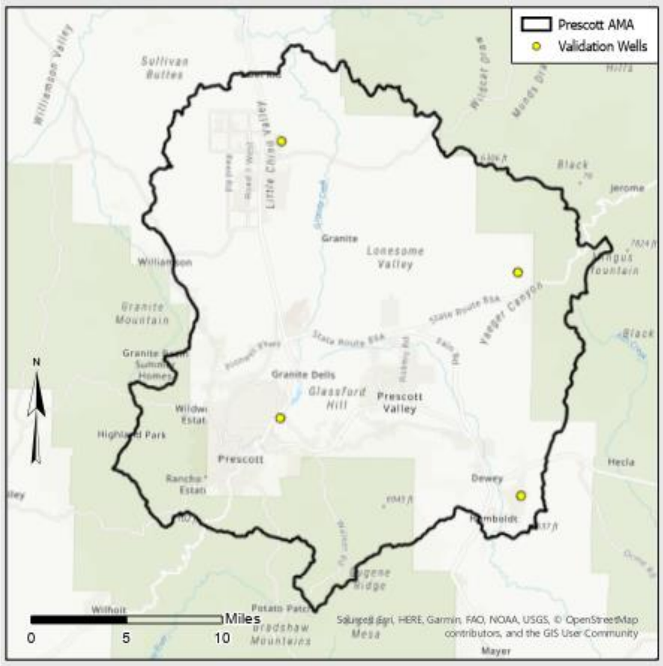


Figure 5: The four wells used to validate the model.

4.3. Accuracy without the model

To see if the interpolated model offered any improvement over the more traditional ways of deciding where and how to deep to drill, a comparable analysis of error was conducted on four similarly spaced wells. The locations of these wells are shown in Figure 6. These wells all had notes on their drillers' logs indicating the depth at which water was encountered or if the well was dry at the time of drilling. From these, the drillers' predictions of water location were noted as either correct or incorrect. If the well was dry, the full length was deemed incorrect since the driller assumed there would be water at some point in that drilling. Likewise, all depths drilled past the last water encountered were also considered incorrect. This is based on the assumption that the driller believed more water could be encountered by drilling deeper. Except in the case of dry wells, all intervals above the first water are designated "correct" because the driller would have assumed the need to drill deeper to reach water.

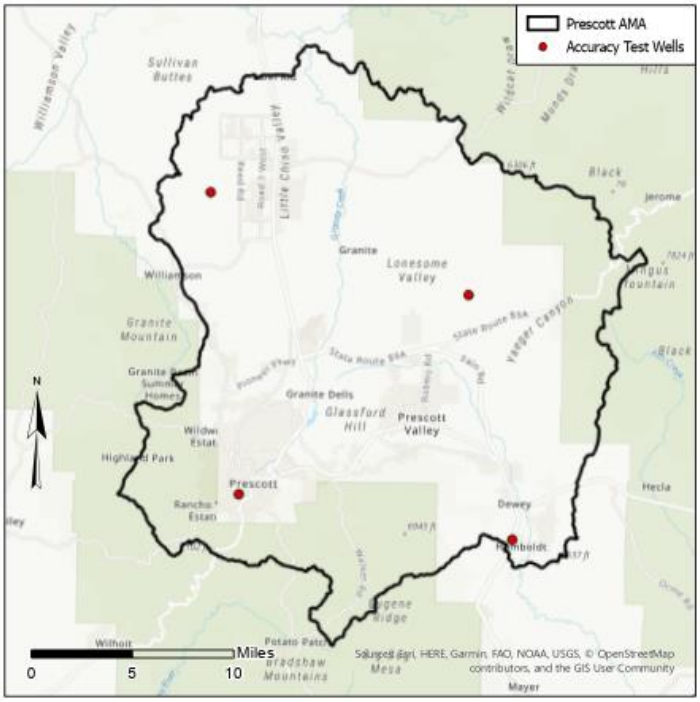


Figure 6: The location of wells used to examine standard drilling placement methods.

With these four wells, a total of 33 intervals were examined for accuracy. Of those intervals, 19 were incorrect. This equals an error of 57.6%, or a 42.4% accuracy. The results for each interval can be seen in Appendix C.

A nearly all of the incorrect intervals, specifically 17 of them, come from a single well that was dry at the time of drilling. This well, ID 229762, is the northeastern one of the group. An examination of this borehole log and its neighbors reveals a similar situation to the problematic model validation site. That is to say that this well is also through different material than its neighbors- the area changes rapidly between granite, basalt, ash, and other volcanic materials.

Chapter 5 Conclusions

This study created a 3D model of the aquifer located under Prescott, Arizona. Wells were selected to be approximately one mile apart and cover the full study area. Drillers' logs were examined in 50-foot intervals to determine permeability based on the materials drilled through. This information was then interpolated using Empirical Bayesian Kriging 3D in order to create prediction surfaces indicating how likely locations are to be permeable and thus act as an aquifer. Four wells were selected to evaluate accuracy for both the model and traditional methods of drilling.

Results indicate that the model is significantly more accurate than traditional methods, with the methods having 60 percent and 42.4 percent accuracies, respectively. Both assessments of accuracy include a single well with completely or nearly completely inaccurate predictions. In both instances, this well is the northeastern well of the group. This suggests that the geology of this region in the study area is more complicated than previously believed and is therefore difficult to predict aquifer locations from. The model performs poorly in such areas and should not be used in its current state to predict aquifer locations in areas that are not relatively homogenous. Still, when it comes to these two wells, the model performs better than traditional methods. The model predicted 1 of 10 intervals correctly, or 10 percent accuracy, whereas traditional methods predicted 0 of 17 correctly, 0 percent accuracy.

Though this model offers greater accuracy over standard decision-making methods for drilling, there is still plenty of room for improvement. As indicated by the low accuracy in heterogenous areas, the model cannot confidently be applied to areas with rapidly changing geology. Future iterations of this project could digitize the wells exactly as described in their logs instead of using 50-foot intervals. The output has one-foot vertical resolution anyway, and doing so would allow finer scale vertical changes to be captured and could potentially improve accuracy, especially in the northeastern region. Future versions may investigate other interpolation methods, as well. Though EBK was deemed most appropriate of the methods considered, the extent to which the user can control parameters in universal kriging could potentially increase the model's accuracy further. Whether another interpolation method is tested or not, it is critical that the current model be further validated using methods such as leave-one-out.

An additional use that I would like to illustrate in the future, which would be especially interesting to researchers, is incorporating and updating water levels yearly to track changes within the aquifer. Having these changes illustrated, rather than just listed in tables, could help researchers quickly spot areas with sharp declines in water levels and address the causes before it becomes a major water shortage. It could also help scientists notice when water levels are nearing the bottom of the permeable layer, indicating the end of the aquifer's utility. Adding this extra layer of information would also help improve the model. Water levels that are inconsistent with the model, such as being deeper than the permeable layer, would provoke deeper exploration of the area's geology and possibly revision of the model.

With the average well costing between 10 and 30 dollars per foot to drill (Merrill Drillng & Water Systems 2020), any misjudgment in placement or necessary depth can quickly become costly. In the case of the dry well discussed in the results chapter, the well was drilled to 808 feet- at an average cost of $20 per foot, that mistake cost over $16,000. Having a model such as the one created in this project could help prevent these dramatic losses that can be disastrous for the well-owner. One well driller based in Utah notes on their site that "in most cases, the depth required to produce an adequate yield from the groundwater supply cannot be determined before drilling begins" (Mike Zimmerman Well Service LLC 2015). Though few drillers are as open about the topic, this sentiment seems to be shared by most drillers. In a state like Arizona, where water is in short-supply and high-demand, this is not acceptable. The model developed for the present study represents a step towards a more systematic and scientific approach to well drilling— one that will result in higher confidence before drilling and less wasted resources for all involved parties.

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Appendix A Data

Dataset	Content	Format	Attributes	Quality	Source	Scale	Accuracy	Precision
Borehole logs	Scanned copies of the borehole logs. Not geocoded, joined to corresponding Groundwater Site Inventory (GWSI) point for location	PDF	Well Reg ID, Drill Code, USCS Code, Layer Top, Layer Bottom	Good. Format is inconvenient, but all wells have complete records that can be digitized.	Conde et al. 2014, De Donatis et al. 2005, Gootee et al. 2017, Neinkamp 2016, Nury et al. 2010	Statewide. Clip to study area.	Not ideal. Drillers are inconsistent with descriptions when completing logs	Not ideal. Drillers are inconsistent with observation intervals when completing logs
ADWR GWSI Database	All identifying information on field verified sites. Geocoded by NAD27 coordinates in degrees, minutes, and seconds	Oracle Database	Latitude, Longitude, Well Reg ID, Basin, Depth to Water	Good. All data is field verified and quality assured.	Conde et al. 2014, De Donatis et al. 2005, Gootee et al. 2017, Neinkamp 2016, Nury et al. 2010	Statewide. Clip to study area.	Location information to 0.5 seconds. Water level to 0.1 foot	High – strict standards and quality checks in place
DEM	1/3 arc-second resolution elevation data	Raster	Elevation	Good	Conde et al. 2014, De Donatis et al. 2005, Nury et al. 2010	Nationwide. Clip to study area.	Approx. 30 m horizontal, 3 m vertical	Med-high

Appendix B Model Validation Results

Registry ID	Cadastral	Interval Top	Interval Bottom	Top Elevation	Bottom Elevation	Permeability	Model Prediction
085371	B16002011ACD	0	50	1396	1346	N	N
085371	B16002011ACD	50	100	1346	1296	N	N
085371	B16002011ACD	100	150	1296	1246	N	N
085371	B16002011ACD	150	200	1246	1196	N	N
085371	B16002011ACD	200	250	1196	1146	N	N
085371	B16002011ACD	250	300	1146	1096	N	N
085371	B16002011ACD	300	350	1096	1046	Y	N
085371	B16002011ACD	350	400	1046	996	Y	Y
085708	B14002023DDC	0	50	1579	1529	Y	Y
085708	B14002023DDC	50	100	1529	1479	Y	Y
085708	B14002023DDC	100	150	1479	1429	Y	Y
085708	B14002023DDC	150	200	1429	1379	Y	Y
085708	B14002023DDC	200	250	1379	1329	Y	Y
085708	B14002023DDC	250	300	1329	1279	Y	Y
085708	B14002023DDC	300	350	1279	1229	N	Y
085708	B14002023DDC	350	400	1229	1179	Y	Y
085708	B14002023DDC	400	450	1179	1129	Y	Y
200015	A13001012DCB	0	50	1430	1380	Y	N
200015	A13001012DCB	50	100	1380	1330	N	N
200015	A13001012DCB	100	150	1330	1280	N	N
200015	A13001012DCB	150	200	1280	1230	N	N
200015	A13001012DCB	200	250	1230	1180	N	N
200015	A13001012DCB	250	300	1180	1130	N	N
200015	A13001012DCB	300	350	1130	1080	Y	N
200015	A13001012DCB	350	400	1080	1030	Y	N
203937	A15001013BBA	0	50	1686	1636	N	N
203937	A15001013BBA	50	100	1636	1586	Y	N
203937	A15001013BBA	100	150	1586	1536	Y	N
203937	A15001013BBA	150	200	1536	1486	Y	N
203937	A15001013BBA	200	250	1486	1436	Y	N
203937	A15001013BBA	250	300	1436	1386	Y	N
203937	A15001013BBA	300	350	1386	1336	Y	N
203937	A15001013BBA	350	400	1336	1286	Y	N
203937	A15001013BBA	400	450	1286	1236	Y	N
203937	A15001013BBA	450	500	1236	1186	Y	N

Appendix C Traditional Method Accuracy

Registry ID	Cadastral	Interval Top	Interval Bottom	Permeability	Assumption
221467	A13001015DBD	0	50	Y	C
221467	A13001015DBD	50	100	Y	C
900258	B16002019DBC	0	50	N	C
900258	B16002019DBC	50	100	N	C
900258	B16002019DBC	100	150	N	C
900258	B16002019DBC	150	200	N	C
900258	B16002019DBC	200	250	N	C
900258	B16002019DBC	250	300	Y	C
900258	B16002019DBC	300	350	Y	C
900258	B16002019DBC	350	400	Y	C
900258	B16002019DBC	400	450	Y	C
229762	A15001017CAB	0	50	N	I
229762	A15001017CAB	50	100	N	I
229762	A15001017CAB	100	150	N	I
229762	A15001017CAB	150	200	N	I
229762	A15001017CAB	200	250	N	I
229762	A15001017CAB	250	300	N	I
229762	A15001017CAB	300	350	N	I
229762	A15001017CAB	350	400	N	I
229762	A15001017CAB	400	450	N	I
229762	A15001017CAB	450	500	N	I
229762	A15001017CAB	500	550	N	I
229762	A15001017CAB	550	600	N	I
229762	A15001017CAB	600	650	N	I
229762	A15001017CAB	650	700	N	I
229762	A15001017CAB	700	750	N	I
229762	A15001017CAB	750	800	N	I
229762	A15001017CAB	800	850	N	I
581540	B13002004CBB	0	50	Y	C
581540	B13002004CBB	50	100	Y	C
581540	B13002004CBB	100	150	N	C
581540	B13002004CBB	150	200	N	I
581540	B13002004CBB	200	250	N	I