University of Nevada, Reno

Developing a three-dimensional hydrogeologic framework in northern Ghana, West Africa

A thesis submitted in partial fulfillment
of the requirements for the degree of Master of Science in
Hydrogeology

By

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Abstract

Groundwater development has increased in northern Ghana due to increasing population, accelerating socio-economic development, and unreliable/poor quality surface water sources. Drilling successful boreholes, however, has been difficult due to complex geology in the basin and limited data on aquifer characteristics. A modified approach to constructing a three-dimensional hydrogeologic framework of the basin is implemented using 900 boreholes from World Vision International's Ghana Integrated Water, Sanitation, and Hygiene Project, located in northern Ghana. The study's approach consists of: collecting borehole drilling logs; data QAQC; data standardization and normalization; analysis for trends and correlations; and creation of cross sections and an interpolated map of the regional hydrogeology. This study serves as the basis for a better understanding of the regional hydrogeology and a start for a future regional groundwater/surface water flow model.

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1.0 Introduction

This study focuses on characterizing hydrogeological features in the northern Voltaian Basin in Ghana, West Africa, for purposes of groundwater development. Demand for groundwater in northern Ghana is intensifying because of factors including rapidly increasing population, accelerating socio-economic development, and unreliable/poor quality surface water sources. Developing groundwater, however, is not straightforward in northern Ghana; complicated geological features cause difficulties for drilling successful boreholes. Few aquifer characteristics are available and those given are poorly described. In order to improve drilling success rates and sustainably manage groundwater development, a better understanding of the regional hydrogeology is needed. In this context, sustainable refers to maintaining groundwater water availability as groundwater extraction rates increase with continued development (Alley et al., 1999; Lutz et al., 2007). Approximately 900 borehole logs from World Vision International's (WVI) Ghana Integrated Water, Sanitation, and Hygiene (GI-WASH) Project, located in Savelugu, northern Ghana, were electronically captured. The purpose of this study is to evaluate a borehole management and mapping program, compare hydrogeological units with final yield values for mapping of favorable drilling locations, to create a sub-surface map of the hydrogeology to assist in targeting future drilling locations, and to provide the foundation for more robust studies. The study was carried out by conducting a rigorous analysis of these logs with respect to geology, lithology, and pumping tests for development of a regional hydrogeologic framework.

Starting in the 1970s, the government of Ghana commissioned a formal policy that communities with fewer than 500 inhabitants be equipped with hand dug wells, and communities with up to 2,000 inhabitants be supplied with boreholes fitted with hand pumps (Dapaah-Siakwan and Gyau-Boakye, 2000). In 2000, Ghana's population was estimated at 18.9 million and has been increasing at a rate of 2.5% per year (Lutz et al., 2007). Based on this rate of increase it is estimated that the 2013 population is approximately 26 million. The northern portion of Ghana is comprised of the Northern, Upper East, and Upper West Regions (Akudago et al., 2009); this project mainly focuses on the Northern Region. The population in the Northern Region makes up approximately 20% of the total population (Lutz et al., 2007; Obuoble and Berry, 2012), or 5.2 million based on the 2013 population estimate. Sixty eight percent of the total population is living in rural communities, which are defined as less than 5,000 inhabitants (Dapaah-Siakwan and Gyau-Boakye, 2000). Rural communities describe most of the Northern Region (Dapaah-Siakwan and Gyau-Boakye, 2000). In 1998 approximately 52% of the rural population in Ghana depended on boreholes fitted with hand pumps or open wells (Lutz et al., 2007).

Rural, subsistence family farms describe much of the setting of northern Ghana. Approximately 70% of the population relies on agriculture for subsistence farming, which is their primary source of income (Akudago et al., 2009). Across West Africa, food security, droughts, and famine are persistent problems. Groundwater is not only important as a source of potable water, but can also improve the socio-economic status of a community. In sub-Saharan Africa, poverty rose from 42% in 1981 to 47% in 2001, and was mainly attributed to issues in food security. In comparable developing countries in Asia poverty levels decreased due to the development of groundwater for irrigation purposes, which increased food security (Akudago et al., 2009).

Traditionally, surface water has been a primary water source, but it is no longer viable due to changes in rainfall patterns, long drought periods, water-borne pathogens, and pollution (Lutz et al., 2007; Akudago et al., 2009), leading to groundwater development as a cost effective means for supplying rural communities with potable water (Anku et al., 2008). Groundwater in Ghana generally has good chemical and microbial quality as compared to surface water, which makes it the preferred choice for safe drinking water (Obuobie and Barry, 2010).

In northern Ghana, boreholes are drilled into weathered and fractured zones of the Voltaian Sedimentary Basin, which is part of the basement complex (Acheampong and Hess, 2000). Boreholes average 48 m in depth (Akudago et al., 2009). The GI-WASH project strives for a minimum yield of 19 m^3 day^{-1} (13 L min^{-1}) from one borehole to be considered a "successful" well that ensures adequate water supply to a population size of approximately 400 people (Samuel Edusei, personal communication, 2013). Access to at least 50 L of water per person per day is required to ensure water needed for drinking, sanitation services, bathing and food preparation (Gleick, 1998). In 1997 approximately 50% of the populations in sub-Saharan Africa obtained water from wells and springs in the basement geological formations (Akiwumi, 1997). Many agencies have contributed to drilling boreholes as a source of potable water for the rural communities over the past fifteen years. Population increase and socio-economic development has remained constant with groundwater development resulting in the percent without access to potable water to remain constant.

Demand for groundwater in the rural communities, and a 55% success rate of boreholes drilled by GI-WASH that meet the minimum yield requirement of 19 m^3 day^{-1} (13 L min^{-1} [Sander et al., 1996]) emphasizes the need to obtain more information on the region's hydrogeology to increase drilling success rates and support water needs for this rapidly growing and developing population. Data on aquifer characteristics are limited and poorly characterize the geologically complicated Voltaian Basin. In order to achieve sustainable groundwater use, a better understanding of the hydrogeology must be developed. As a step towards this, over 900 borehole drilling logs from GI-WASH in the northern Voltaian Basin were scanned and electronically captured. These borehole records were used to analyze the lithology in an attempt to correlate aquifer and well characteristics with lithological features. A three-dimensional (3D) map and two-dimensional (2D) cross sections of the basin were constructed to gain a better understanding of the hydrogeology, and serve as a framework for a future groundwater/surface water flow model.

2.0 Literature Review

The literature reviewed is a broad spectrum approach on any available information on groundwater and associated development in Ghana. The goal of this review was to obtain knowledge on the type of information available and how it could be useful for designing the scope of this project. The below summaries will overview aquifer characteristics, and the geologic and lithological framework of the area.

2.1 Study Area Geography

Ghana is located in sub-Saharan West Africa between latitude 4^{o} 44'N and 11^{o} 15'N and longitude 1^{o} 12'E and 3^{o} 15' W (Figure 1). The total land area is approximately 239,460 km^2 (Obuoble and Berry, 2012). The northern portion of the country is comprised of the Northern, Upper East, and Upper West Regions (Figure 2 [Akudago et al., 2009]). These areas make up approximately 40% of the total land area in the country (Lutz et al., 2007; Obuoble and Berry, 2012). Surface water features are shown in Figure 3.

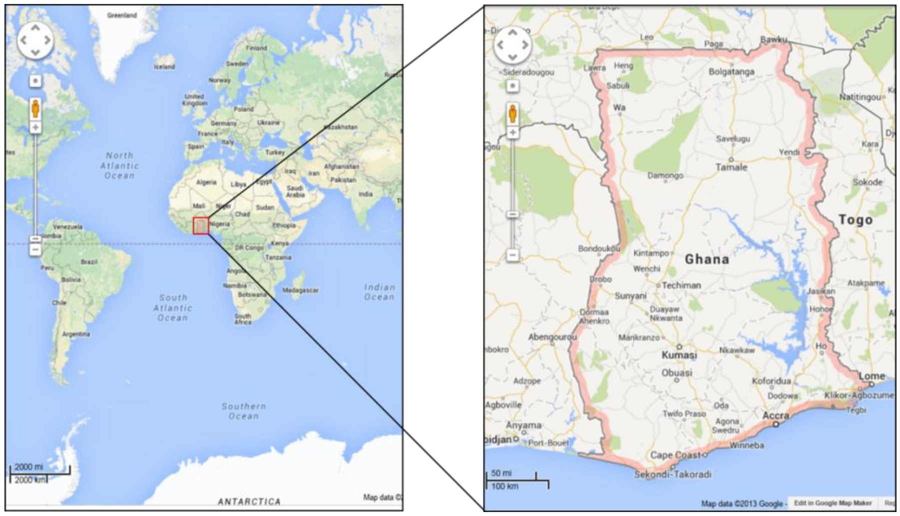

Figure 1. Left: world map locating Ghana's location on the African continent.
Right: inset of Ghana the country (Google Images, 2013).

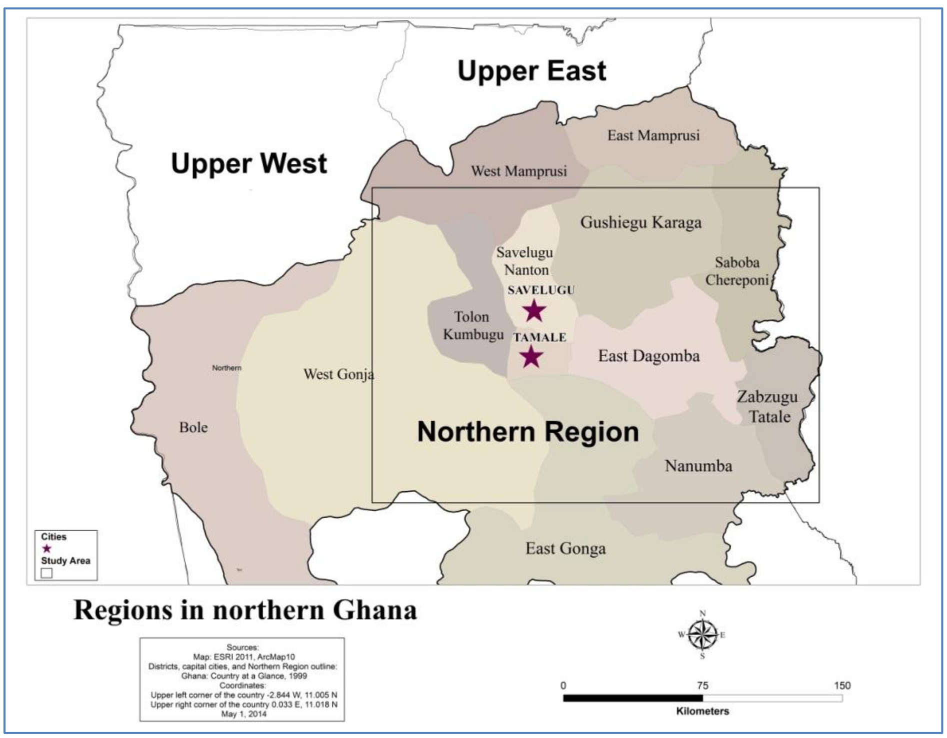

Figure 2. Northern Ghana's three regions: Northern, Upper East, and Upper West. The Study area is outlined on the map in the Northern Region. Tamale is the capital city in the Northern Region. Savelugu is the city where World Vision's northern office is headquartered. The districts in the Northern Region are displayed in different colors and labeled with the district name (Created in ESRI 2011, ArcMap 10; shapefile from Ghana: Country at a glance, 1999).

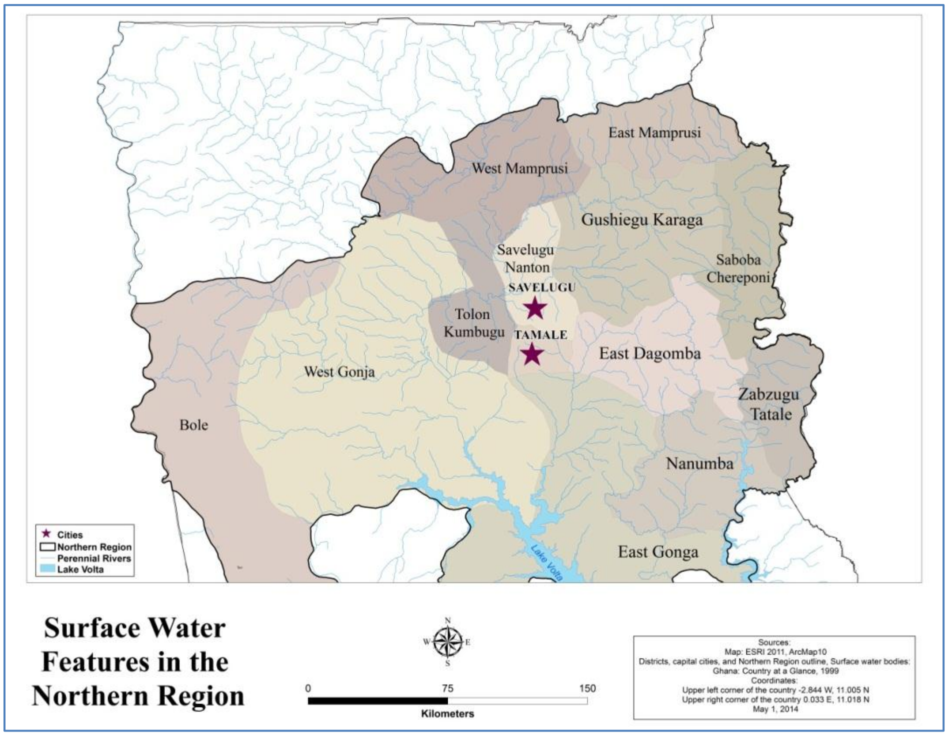

Figure 3. Perennial rivers and Lake Volta, surface water sources, in the Northern Region. Tamale is the capital city in the Northern Region. Savelugu is the city where World Vision's northern office is headquartered. The districts in the Northern Region are displayed in different colors and labeled with the district name (Created in ESRI 2011, ArcMap 10; shapefile and surface water locations from Ghana: Country at a glance, 1999).

2.2 Climate

Climate in the northern portion of the country is within the tropical continental or savannah zone, which experiences a single rainfall season and a long drought period (Lutz et al., 2007). Rains begin in May, peak between July and August, and taper off by October. From November to May the Northern Region experiences dry, drought-like conditions. The estimated annual mean precipitation ranges from 900 to 1,140 mm (Figure 4 [Lutz, et al., 2007]). In the Savelugu-Nanton District, which is the headquarters for GI-WASH in the Northern Region, annual rainfall ranges between 1,005 and 1,150 mm with a relative humidity value of 65 to 85% in the rainy season, and 20% in the dry season (Tay, 2012). This single rainfall season governs the Northern Region's economic stability, since employment in the area is dominated by rain fed agriculture. Annual temperatures average 30 ^{o}C, but range between 18 ^{o}C during the rainy season and 42 ^{o}C during the dry season (Anku et al., 2008). Evapotranspiration rates depend on season, location, and local vegetation and may range between 650 and 1,300 mm year^{-1} (Lutz et al., 2007), with an approximate average of 890 mm year^{-1} within the Voltaian Basin (Akudago et al., 2009).

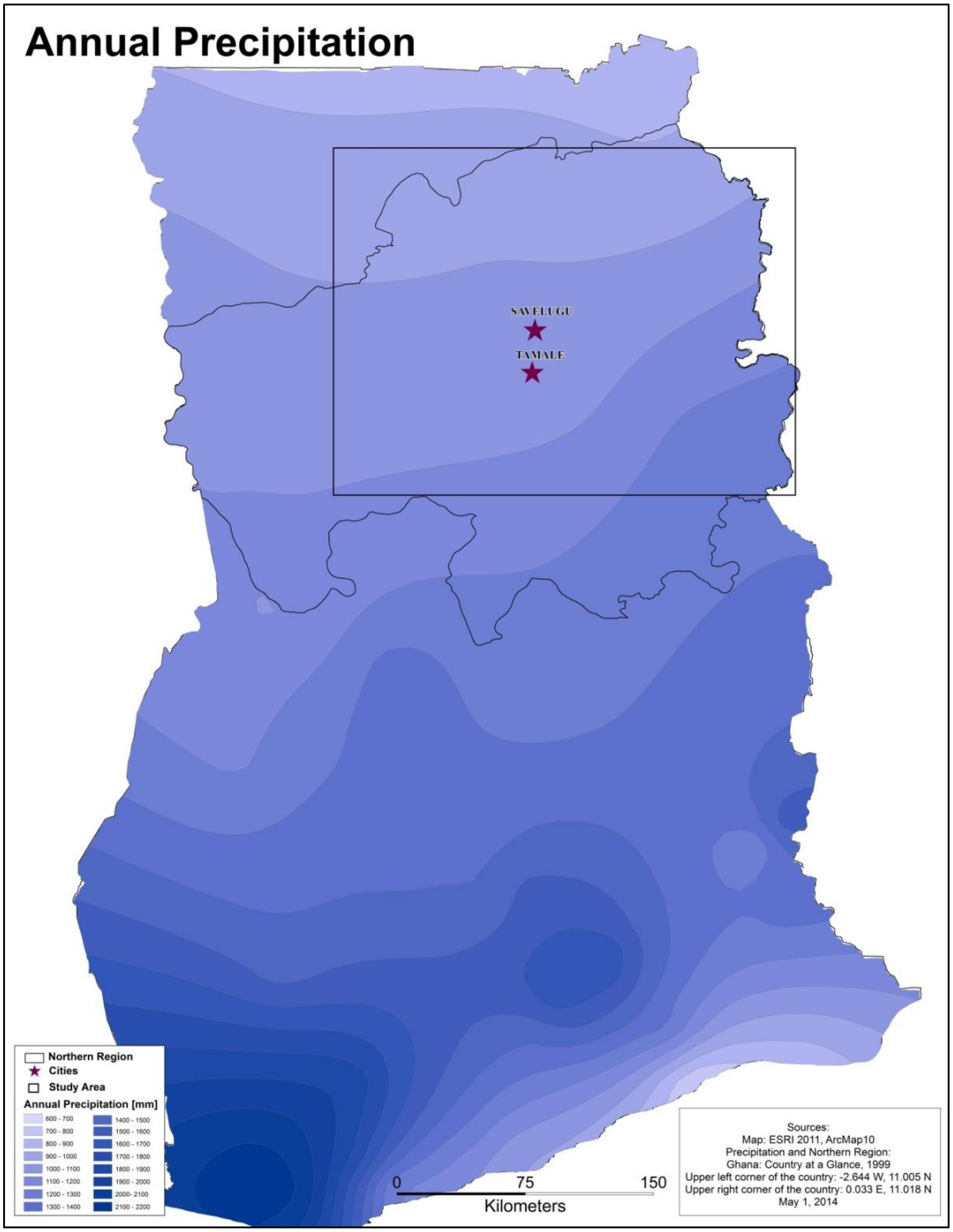

Figure 4. Annual rainfall distribution throughout Ghana. Measurements range from 600 to 700 mm (lightest blue color) to 2100 to 2200 mm (darkest blue[Created in ESRI 2011, ArcMap 10; shapefile and precipitation data from Ghana: Country at a glance, 1999]).

Rainfall reduction and rainfall pattern changes have been observed in forested and savannah zones throughout West Africa since the 1970s (Lutz et al., 2007). In approximately a 50 year time period between 1945 and 1993, the mean annual temperature in northern Ghana has risen by nearly 1 ^{o}C which also increases evaporation rates. These measurements were taken at the synoptic station in Tamale, the largest city in the Northern Region (Lutz et al., 2007).

2.3 Geology

The Voltaian (Paleozoic) Sedimentary Basin (Basin) underlies approximately 45% (approximately 100,000 km^2) of the country (Dapaah-Siakwan and Gyau-Boakye, 2000) and is approximately 3,000 to 4,000 m thick (Akudago et al., 2009). The Basin consists of sandstone, shale, mudstone, sandy and pebbly beds, siltstone, and arkose (Dapaah-Siakwan and Gyau-Boakye, 2000; Lutz et al., 2007), and is subdivided into three classifications based on lithology and field relationships. The three classifications are characterized as the Upper Voltaian, Middle Voltaian, and Lower Voltaian (Dapaah-Siakwan and Gyau-Boakye, 2000). This study will mainly focus on the Middle Voltaian unit which is comprised of Obosum and Oti beds made up of shale, sandstone, mudstone, limestone, and conglomerate from the crystalline basement rocks (Figure 5 [Yidana et al., 2011]).

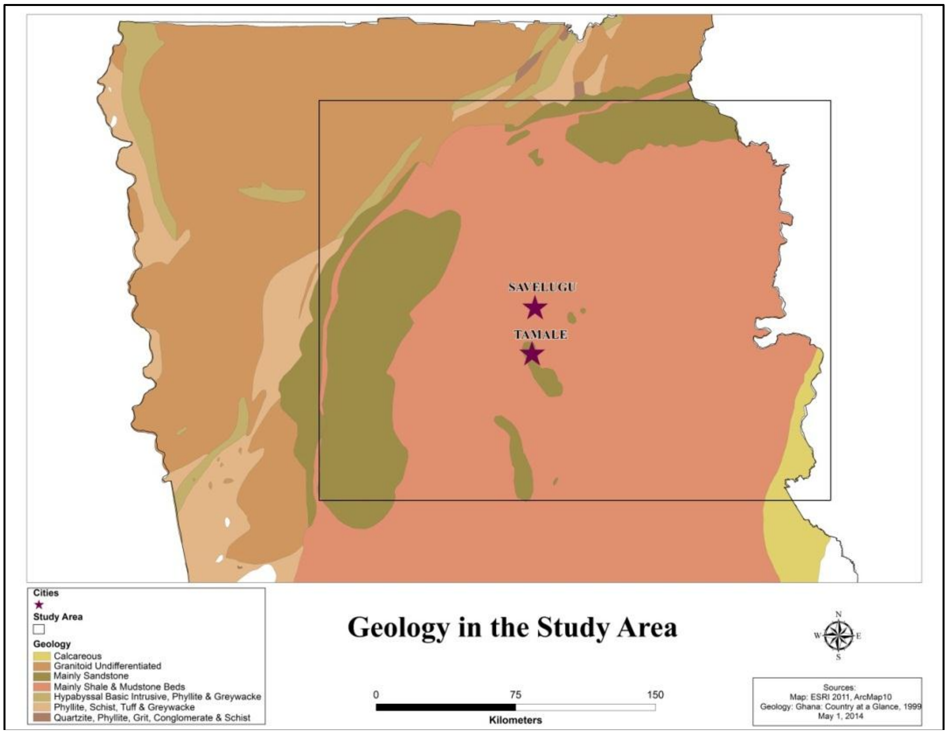

Figure 5. Geologic map of the Northern Region in Ghana. A box is drawn around the study area (Created in ESRI 2011, ArcMap 10; shapefile of geology from Ghana: Country at a glance, 1999).

2.4 Hydrogeology

Primary porosity in the Voltaian Basin is almost nonexistent due to high levels of consolidation and cementation, therefore, preferential groundwater flow paths are along the strike direction of fractures and in the weathered portion of the basin (Acheampong and Hess, 2000; Boadu et al., 2005; Lutz et al., 2007). Buckley (1996) and Bannerman (1990), reported in Sander et al. (1996), suggest sandstones and conglomerates are favored lithologies for groundwater development over siltstone, mudstone, and shale in the Voltaian Basin, but the presence of fractures is the dominant condition to obtain sufficient well yields. Because of these conditions, hydraulic properties show extreme variation over a short distance (Sander et al., 1996). For example, hydraulic conductivity has the potential to increase by several orders of magnitude over a few meters (Boadu et al., 2005), with typical values for fractured sandstone ranging between 0.01 and 3 m day^{-1} (Lutz et al., 2007).

According to a study by Obuobie et al. (2012), quantifying the amount of recharge to the aquifer is the first step for sustainable and efficient management of groundwater resources. Obuobie's study focused on the White Volta River Basin in the Upper East and Upper West portions of the country. A two to four month lag between the start of the rainy season and groundwater level increase was observed. In the Middle Voltaian Basin it is estimated that 2 to 4% of the annual rainfall recharges the regional aquifer, while 86% of the precipitation is lost to high levels of evapotranspiration, and 10% to runoff (Teeuw, 1995). Runoff is most likely stored in surface depressions until the water is infiltrated into the sub-surface or evaporated (Ward and Trimble, 2004).

Understanding the source and amount of recharge to groundwater is vital to ensuring long-term sustainability of groundwater development (Acheampong and Hess, 2000). Acheampong and Hess (2000) characterized recharge sources and age of groundwater in the shallow aquifer system of the southern Voltaian Sedimentary Basin using stable and radioactive isotopic analysis. A mean $\delta^{18}O$ value of -3.0‰ and a mean value of -14‰ for δD were reported for 44 groundwater samples from hand pump wells ranging between 20 and 60 m in depth. Most values plot close to and along the Global Meteoric Water Line (GMWL) which indicates that groundwater originated from local rainfall.

Recharge has been estimated in many studies for groundwater development throughout Ghana. Numerous efforts have attempted to characterize groundwater recharge in the Northern Region, with an average value of 1.26 x 10 m^3 $year^{-1}$ (Acheampong and Hess, 2000; Cobbing and Davies, 2004; Martin and van de Giesen, 2005; Lutz et al., 2007; Akudago et al. 2009). Obuobie et al. (2012) determined that annual recharge was 3.5 to 16.5% of the annual rainfall through the use of the Theissen Polygon and water table fluctuation methods. Teeuw (1995) reported recharge of 2 to 4% of annual rainfall in the central part of the Voltaian Basin. Quantitative analyses on recharge to the Voltaian system indicate total extraction from the system is less than 5% of the total recharge (Akudago et al., 2009). Akudago et al. (2009) report values for maximum groundwater storage and yield in northern Ghana of 6.44 x 10^9 m^3 $year^{-1}$ and 4.57 x 10^9 m^3 $year^{-1}$, respectively.

Transmissivity has been characterized throughout the entire Voltaian Basin. Lutz et al. (2007) report a value of 13 m^2 day^{-1} derived from aquifer pumping tests in the Nabogo Basin in the Northern Region, and Acheampong and Hess (2000) report 1 to 72 m^2 day^{-1} in the Southern Voltaian Basin. Transmissivity estimates from Kwei (1997), reported in Lutz et al. (2007), range from 1 to 30 m^2 day^{-1}.

2.5 Groundwater Exploration

Groundwater in the Voltaian system exists primarily in the fractured sandstone and is extracted through these fractures. Characterizing flow properties for these fractures is difficult and is usually done by drilling boreholes. A study conducted by Boadu et al.

(2005) looked at a geophysical approach to characterize flow properties of fractures using an inexpensive noninvasive technique known as the azimuthal resistivity method. This study was conducted in Nsawam, which is located within the southern Voltaian Basin, for the purpose of defining fluid flow for potential agricultural groundwater contaminant transport. This study concluded that the majority of fracture orientations were in the northwest-southeast direction. Quantitative measurements for fracture porosity, coefficient of anisotropy, mean resistivity, and specific surface area were obtained from this method and geological mapping of the area.

Sander et al. (1996) used remote sensing and geographic information systems (GIS) to locate preferential areas of groundwater. This study tests the hypothesis that groundwater in the Voltaian Basin is governed by fractures which can be identified as structural features in the bedrock. These structural features are discerned as lineaments on remotely sensed data. The remotely sensed imagery can also reveal anomalies in vegetation growth that may indicate areas of fractured rock or shallow groundwater. Results obtained from this study suggest drilling success rates decrease with distance traveled from the lineaments and fractured area can also be observed as exposed bedrock.

2.6 Boreholes

Boreholes experience variable yields within the Voltaian Basin, but typically a successful borehole is characterized by a minimum yield of 19 m^3 day^{-1} (13 L min^{-1} [Akudago et al., 2009; Samuel Edusei, personal communication, 2013]). Boreholes in the Voltaian Basin reach an average depth of 48 m, with little evidence of boreholes exceeding 90 m (Akudago et al., 2009). In the Middle Voltaian Basin, yields range from 9.8 to 216 m^3 day^{-1} (6.8 to 150 L min^{-1} [Dapaah-Siakwan and Gyau Boakye, 2000]).

Akudago et al. (2009) investigated reasons for an estimated 50% borehole drilling success rate and found 63% of successful boreholes with initial yields at the time of drilling were less than 28.8 m^3 day^{-1} (20 L min^{-1}) and drying up between one and four years after installation. Quantitative analyses on recharge and groundwater storage reported in the literature, suggest that the extraction rate from the basin is a small fraction of available groundwater, therefore drying boreholes are not a result of depleted groundwater. Possible reasons for drying boreholes are lowering of the groundwater table during the dry season, and poor borehole construction (Akudago et al., 2009).

3.0 Methods and Materials

The following sections will discuss the steps preformed throughout this project to achieve the desired objectives introduced in the introduction. Borehole drilling logs were collected and used to create a main database that consists of log locations, lithology descriptions, aquifer tests, and well construction. This data was evaluated for location accuracy before input into the borehole management package in RockWorks16 and 3D and 2D maps created.

3.1 Data Collection

A total of 916 borehole drilling logs were collected from GI-WASH and captured electronically in Microsoft Excel. The Excel database was constructed based on methodology modified from Dumedahand and Schuurman (2008) and input parameters for the Borehole Manager RockWorks16 software. Attributes from the logs recorded included: location, coordinates, district/community name, and elevation; lithology at depth intervals in the borehole; stratigraphic intervals such as confining layers and aquifers; flow rate at intervals and final flow rate (yield); static and dynamic water levels; symbol of the well which was defined as either wet or dry; and well construction. The location information is the most important for import into RockWorks16, as the software cannot process well information without coordinates and elevation data.

3.2 Data QAQC

Data quality control on the borehole drilling logs was conducted based on coordinate and elevation information, as many borehole logs were incomplete with respect to coordinates and elevation and had to be manually entered with the use of Ghana Survey Topography maps and ESRI's ArcGIS. The ArcMap portion of ArcGIS was used to validate and, when necessary, make adjustments to coordinates for each well. The location of each well was converted to a shapefile and overlain on the district map of the country. Each borehole location was checked to make sure it resided in the correct district reported on the original log. Logs without coordinates or incorrect coordinates that could not be accurately adjusted were removed from the dataset.

Missing elevation information was also updated using ArcGIS. Digital Elevation Models (DEMs) were not used for this process since they are only available at 90 m resolution, which is too course for this study. Instead, boreholes were plotted over a Ghana Geological Survey elevation contour map of the country. Missing elevation data were read from the contour map. In cases where the borehole did not place on a contour line, the closest elevation reported was used. In areas where multiple known elevations were closest, an average was taken.

The final database includes 879 borehole logs which reflects those considered to have accurate coordinates and elevations. Assessing coordinate locations and elevation data was the only metric put into place to evaluate the quality of borehole logs before input into RockWorks16. Detailed information varied between logs, but due to the large study area it was decided that as many available logs as possible were used to create cross sections in RockWork16 to minimize the interpolation of the regional hydrogeologic framework.

3.3 Aquifer Characterization

Aquifer characteristics were calculated using 140 of the 879 logs. These 140 logs included borehole aquifer test data and static and pumping water levels, which are needed to calculate specific capacity and transmissivity. The aquifer tests were performed for two hours in most cases, but in others the pumping time recorded varied between one and six hours. In instances where no time duration between the static and pumping water level was recorded a time period of two hours was assumed, which is the standard protocol for the drilling crews (Samuel Edusei, personal communication, 2013).

Specific capacity is the yield of the well divided by the drawdown (Equation 1 [Fetter, 2001]). Equation 2 taken from Fetter (2001) was used to calculate transmissivity for a confined aquifer through iteration and the calculated values of specific capacity:

$$SC = \frac{Q}{(h0-h)} \qquad \text{Equation (1)}$$

$$T = \frac{Q}{(h0-h)}\frac{2.3}{4\pi}\log\frac{2.25Tt}{r^2\,S} \qquad \text{Equation (2)}$$

where: *SC* is specific capacity calculated in m^2 day^{-1}, *T* is the transmissivity calculated in m^2 day^{-1}, *Q* is the discharge in m^3 day^{-1}, *t* is time of 1 day, *r* is the radius of the pumping well which is 0.06 meters, h_0-h is the drawdown in m, and *S* is the storativity. A value of 0.001 was used for storativity as reported in Batu (1998) for confined aquifers.

The next step was to normalize the data reported in the drilling logs by standardizing the lithologic descriptions. Diverse expertise of the various drilling crews results in variability of the quality and the level of detail reported in the geologic units penetrated, and the possibility of several descriptions given for one sediment unit (Dumedahand and Schuurman, 2008). To standardize the descriptions and capture the main lithology attributes used in the logs, 11 categories were created using methodology modified from Dumedahand and Schuurman (2008) and Ross et al. (2003). Literature reviewed indicated that groundwater is most commonly found in fractures, therefore, lithology categories were focused around fracture characteristics as a dominant attribute.

The Middle Voltaian Basin mainly consists of sandstone, siltstone, mudstone, and shale, which are the main lithologies recorded on the logs. A few logs that included granite and associated minerals were lumped into a granite category. Typically an interval at the top of the borehole was recorded as top soil, which may consist of clay or laterite. Each lithology was classified into one of the following 11 categories shown in Table 1. Fracturing was described by moderately or highly fractured as reported in the logs. Slightly and no fractures were categorized as non-fractured. These standardized categories were used to compare lithology type to final yield values reported at completion of the borehole.

Table 1. Eleven dominant lithology types

1	Topsoil		
2	Sandstone	7	Fractured Sandstone
3	Mudstone	8	Fractured Mudstone
4	Siltstone	9	Fractured Siltstone
5	Shale	10	Fractured Shale
6	Granite	11	Fractured Granite

The dominant lithology represented at the aquifer interval was recorded for each log. The aquifer interval refers to the interval between the depth to water and the final depth of the borehole. Depth to water is recorded on each log during the borehole drilling process. In all cases where the borehole intersects water during the drilling process the yield is measured at depth intervals from the first depth to water recording to the end of the borehole. If the aquifer interval spanned over multiple lithology descriptions the most frequent lithologic unit, and most frequent degree of fracturing was determined as the dominant lithology. The dominant lithology for the aquifer interval was then used for comparisons with the final output yield for the purpose of assessing favorable lithologic units for drilling purposes.

3.5 Comparison Analyses

The goal of visually displaying yield and lithology is to assess lithological units best for developing groundwater. The following assumptions were made in comparing yield and lithology type for each borehole:

- Each well was constructed with the same well casing diameter.
- The method of measuring yield from the borehole was standardized for each well construction.

The aquifer interval length was used to normalize the yield for each well. Yield was divided by the aquifer interval length to obtain a yield value per meter of aquifer interval. Boxplots were constructed for each lithology category and normalized yield values. These graphs are used to visually compare lithology favorability for increased well yields (Appendix 8.1).

3.6 Cross Section Development

Rockworks16 was used to visualize the lithology across the study basin. Rockworks was chosen to develop cross sections that will represent the entire study. The software chosen to act as the borehole manager and develop regional sub-surface maps had to meet several requirements: user friendly interface; easy to import and export data, as well as update the database; capability to interact with ArcGIS and Google Earth; a detailed visual output for the 3D map and 2D cross sections; and has the ability to add additional information such as water quality data. RockWorks16 met all of these requirements. Several limitations, however, became apparent when interacting with this software and the study area's data. First is the limitation of scale. For this particular project the study area spans the majority of the Northern Region and maps 879 boreholes. When including borehole locations in the 3D map and 2D cross sections, wells appear to be on top of each other and are illegible. This issue may be eliminated by decreasing the size of the study area, but for the purpose of this project that was not an option. The next limitation is the interpolation method. Boreholes are clustered in certain areas and scattered in other areas throughout the domain space. In cases where boreholes are scattered, large amounts of interpolation in the sub-surface lithology occurs. It is also a limitation that the 2D cross sections are developed from the 3D interpolated map, instead of going through a separate interpolation process at the smaller cross section scale.

A 3D map was generated from the lithology categories reported in the logs and interpolated across the domain space. The interpolation technique used in RockWorks16 is lithoblending, which extends the lithology out horizontally from the control point until it hits a voxel that has already been assigned a value (RockWorks16 Training Manual, 2013). Lithology interpolation throughout the whole domain space can only be achieved by implementing randomized blending and interpolating outliers in addition to lithoblending. Randomized blending maximizes the search radius around each borehole with depth. Interpolating outliers assigns all nodes a lithology value. If this setting is turned off, then a zero will be assigned to the nodes that lie beyond the interpolation cutoff distance (RockWorks16 Training Manual, 2013). Without these options turned on there are large holes in lithology throughout the domain area which makes 2D cross section profiles difficult to construct. The output dimensions of the interpolated solid model match those of the input boreholes, and a vertical exaggeration of 100 is applied to easily view the lithology model.

Cross sections are developed from the 3D map (Figure 1) across the entire domain space in the east-to-west direction and the north-to-south direction (Appendix 8.2.1 and 8.2.2). Smaller cross sections are created in areas where large clusters of dry or low yielding wells occur, and areas where high yielding wells occur (Appendix 8.2.3). ArcGIS was used to generate a map of all wet wells and their yield values and all dry wells (Figure 2).

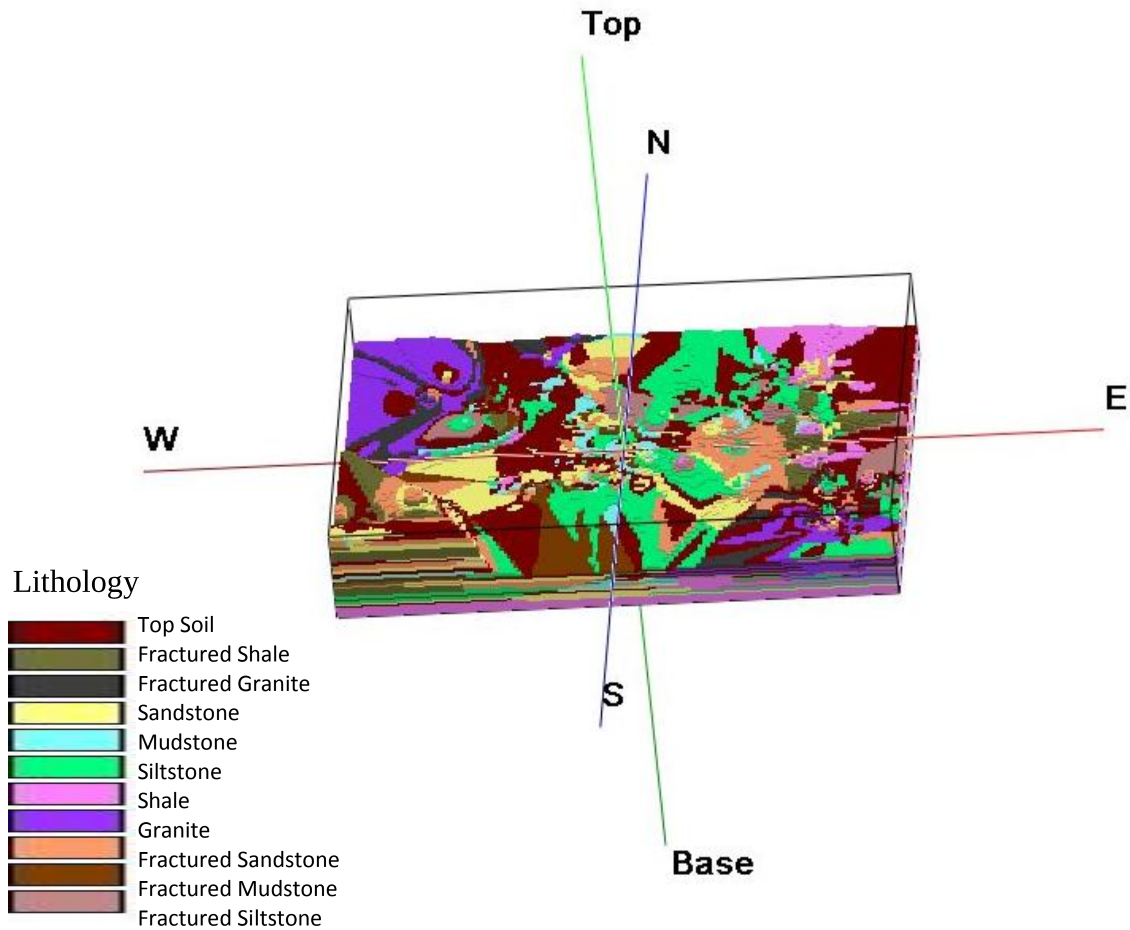

Figure 1. Three-dimensional solid model created from interpolation across the study basin from reported lithology types in each borehole. This model was created using 879 borehole drilling logs from the Northern Region in Ghana, which was the study area for this project. Coordinates UTM Zone 30: **Northwest corner**: easting 623112, northing 1136209 **Northeast corner**: easting 889132, northing 1169079 **Southeast corner**: easting 891794, northing 974177 **Southwest corner**: easting 622194, northing 973919 (RockWorks16, 2013).

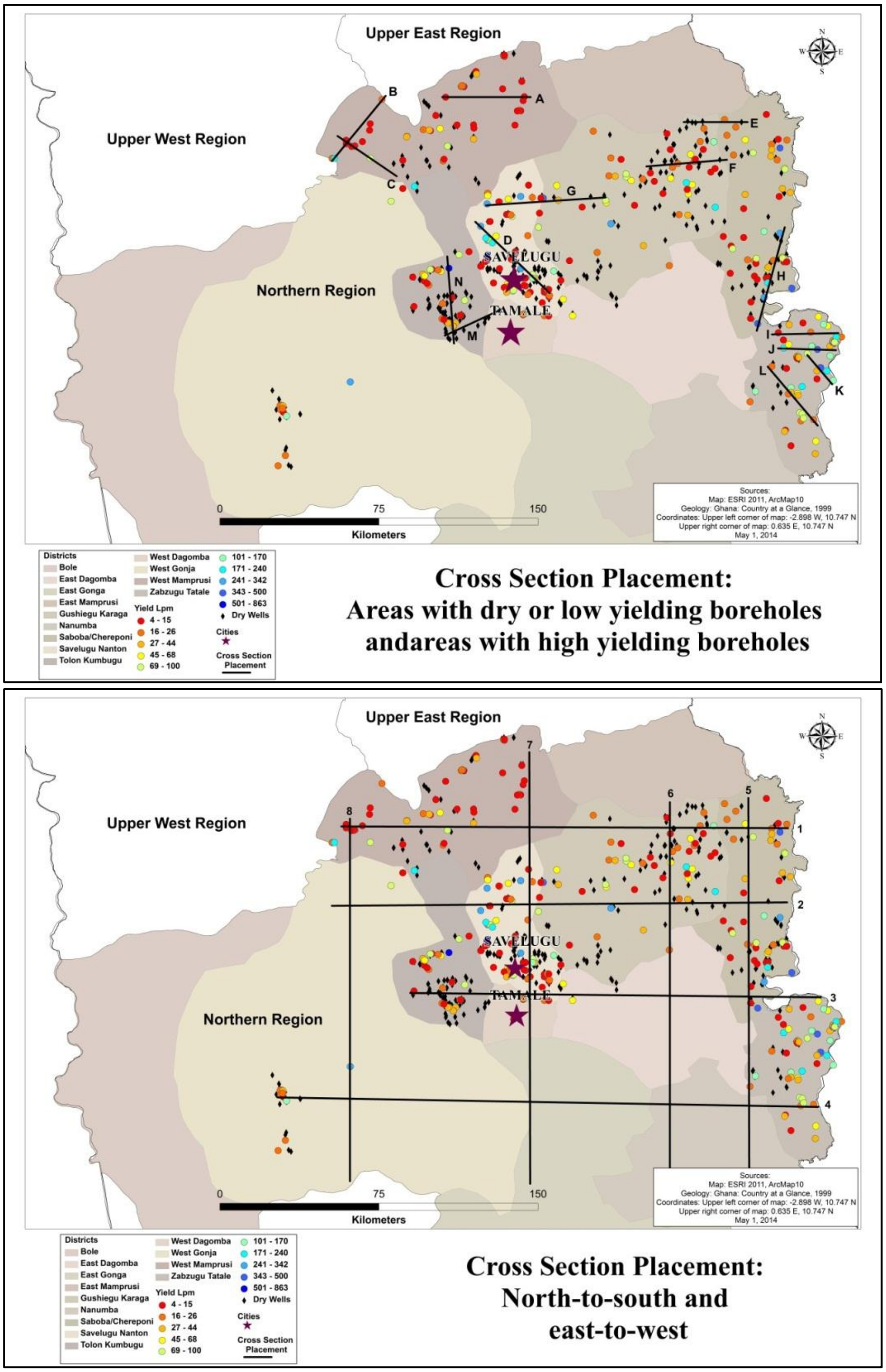

Figure 2. Top: cross section placement in areas of interest that display clusters of wet, dry, and high and low yielding wells. Bottom: cross section placement west-to-east and north-to-south to characterize the entire region (Created in ESRI 2011, ArcMap 10; shapefile of geology from Ghana: Country at a glance, 1999).

Two dimensional profiles of the water level were plotted on each area of interest cross section using the Water Level Table in RockWorks16. Visual connections can be made to which lithologies contain water. The interpolated aquifer model is constructed from interval depths recorded down the borehole that contain water. Limited spatial and temporal data necessitated the following assumptions for purposes of constructing these cross sections:

- The aquifer reported in the drilling logs is continuous and confined.
- Depth to water recorded during the drilling process was at the same time of year for each well to eliminate variation in water table levels from the wet and dry season.

This method of displaying the aquifer profile yields several limitations in the visual output and accuracy of aquifer locations. The depth to water is interpolated across the lithology profile and connected to the next depth to water profile on the closest well. In some cases, the aquifer appears to be above ground since the data set includes dry wells and the aquifer profile may be connecting to the next wet well. Additionally, the 2D lithology and aquifer profiles are made from a 3D map, so the swath from which the 2D profile is created may consist of data above or below the profile line giving the illusion that the aquifer profile is above ground.

4.0 Manuscript

Developing a three-dimensional framework of hydrogeology in Northern Ghana, West Africa

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Abstract

Groundwater development has increased in northern Ghana due to increasing population, accelerating socio-economic development, and unreliable/poor quality surface water sources. Drilling successful boreholes, however, has been difficult due to complex geology in the basin and limited data on aquifer characteristics. A modified approach to constructing a three-dimensional hydrogeologic framework of the basin is implemented using 900 boreholes from World Vision International's Ghana Integrated Water, Sanitation, and Hygiene Project, located in northern Ghana. The study's approach consists of: collecting borehole drilling logs; data QAQC; data standardization and normalization; analysis for trends and correlations; and creation of cross sections and an interpolated map of the regional hydrogeology. This study serves as the basis for a better understanding of the regional hydrogeology and a start for a future regional groundwater/surface water flow model.

Keywords: Northern Ghana, Hydrogeology, Groundwater, Hydrogeologic framework

Introduction

Demand for groundwater in northern Ghana is intensifying due to factors including rapidly increasing population, accelerating socio-economic development, and unreliable/poor quality surface water sources. Developing groundwater; however, is not straightforward; complicated geological features cause difficulties for drilling successful boreholes. Few aquifer characteristics are available, and those available are often poorly described. A better understanding of the regional hydrogeology is needed to develop successful boreholes while sustainably managing groundwater resources. In this context, sustainable management refers to maintaining groundwater availability as groundwater extraction rates increase with continued development (Alley et al., 1999; Lutz et al., 2007).

Starting in the 1970s the government of Ghana commissioned a formal policy that communities with fewer than 500 inhabitants be equipped with hand dug wells, and communities with up to 2,000 inhabitants be supplied with boreholes fitted with hand pumps (Dapaah-Siakwan and Gyau-Boakye, 2000). In 2000 Ghana’s population was estimated at 18.9 million and has been increasing at a rate of 2.5% per year (Lutz et al., 2007). Based on this rate of increase, it is estimated that the 2013 population is approximately 26 million. The population in the Northern Region, which is the focus of this paper, makes up approximately 20% of the total population (Lutz et al., 2007; Obuoble and Berry, 2012), or 5.2 million based on the 2013 population estimate. Sixty eight percent of the total population is living in rural communities, which are defined as less than 5,000 inhabitants (Dapaah-Siakwan and Gyau-Boakye, 2000). Rural communities define most of the Northern Region (Dapaah-Siakwan and Gyau-Boakye, 2000). In these rural areas, access to treated surface water is rare and unreliable (Lutz et al., 2007; Obuoble and Berry, 2012). Unreliable surface water sources are due to changes in rainfall patterns, long drought periods, water-borne pathogens, and pollution (Lutz et al., 2007; Akudago et al., 2009), leading to groundwater development as a cost effective means for supplying rural communities with potable water (Anku et al., 2008).

In 1998 approximately 52% of the rural population in Ghana depended on boreholes fitted with hand pumps or open wells (Lutz et al., 2007). Many agencies have contributed to drilling boreholes as a source of potable water for the rural communities over the past fifteen years. Population increase and socio-economic development has remained constant with groundwater development resulting in the percent without access to potable water to remain constant. Several studies have been conducted to quantify storage and recharge rates (Teeuw, 1995; Lutz et al., 2007; Akudago et al., 2009; Obuobie et al., 2012). Total groundwater extraction is estimated to be less than 5% of the total recharge rate to the basin (Akudago et al., 2009).

This study focuses on the Voltaian Sedimentary Basin (Basin) which characterizes the majority of the Northern Region. Boreholes are drilled into weathered and fractured zones of the Basin (Acheampong and Hess, 2000), averaging 48 m in depth and a minimum yield of 19 m^3 day^{-1} (13 L min^{-1}) from one borehole is required for a "successful" well (Akudago et al., 2009; Samuel Edusei, personal communication, 2013).

A minimum of 50 L of water per person per day is required to ensure adequate water needed for drinking, sanitation services, bathing, and food preparation (Gleick, 1998).

Over 900 borehole drilling logs from the northern Voltaian Basin were scanned and electronically captured from World Vision Internationl's (WVI) Ghana Integrated Water, Sanitation, and Hygiene (GI-WASH) Project based in Savelugu, Northern Region. These borehole records were used to analyze the lithology in the basin in attempt to correlate aquifer characteristics with lithological features. A three-dimensional (3D) map and two-dimensional (2D) cross sections of the basin were constructed to gain a better understanding of the hydrogeology, and serve as a framework for a future groundwater/ surface water flow model.

Study Area

Ghana is located in sub-Sahara West Africa between latitude 4^{o} 44'N and 11^{o} 15'N and longitude 1^{o} 12'E and 3^{o} 15' W (Figure 1). Total land area is approximately 239,460 km^2 (Obuoble and Berry, 2012). The country is divided into regions with the northern portion of the country broken up into the Northern, Upper East, and Upper West Regions (Akudago et al., 2009). These regions make up approximately 40% of the total land area in the country (Lutz et al., 2007; Obuoble and Berry, 2012). This study focused on the Northern Region (Figure 2).

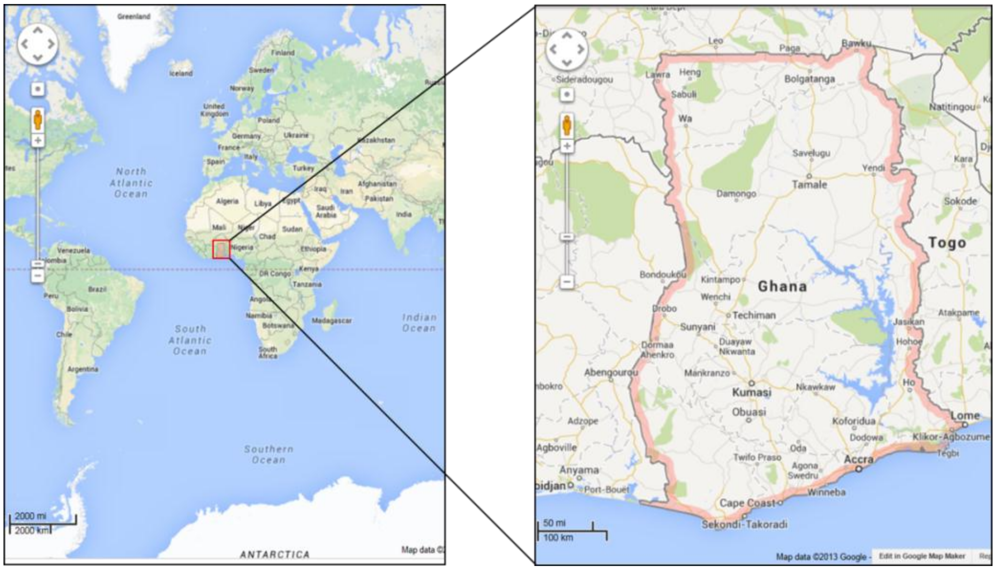


Figure 1. Left: world map locating Ghana's location on the African continent. Right: inset of Ghana the country (Google Images, 2013).

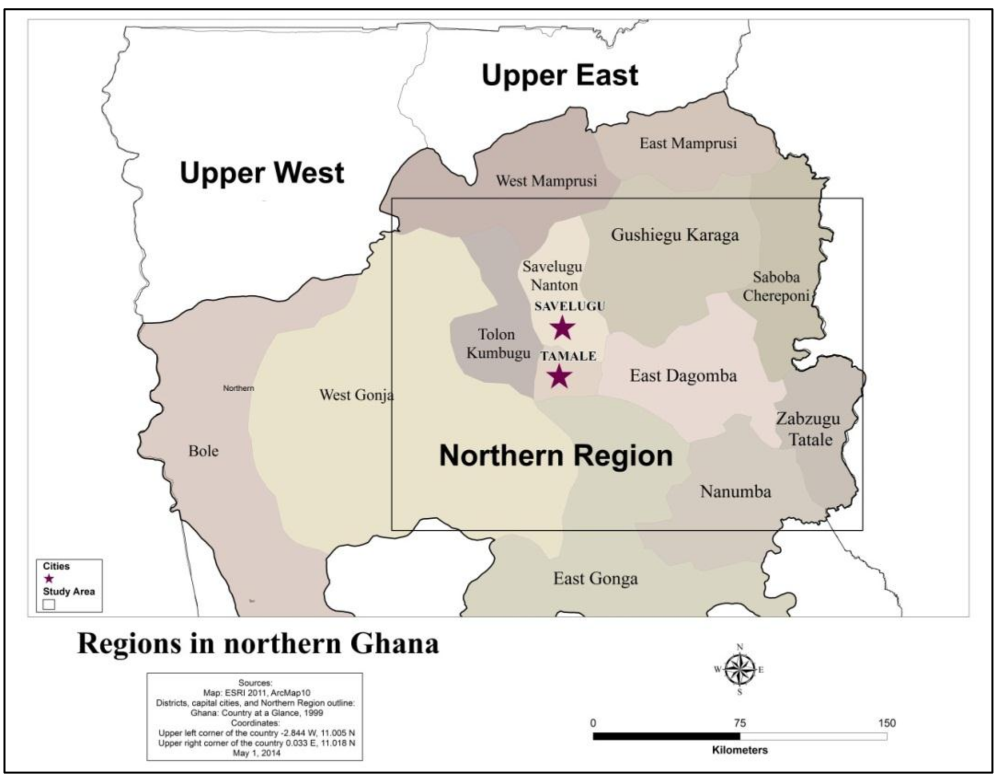


Figure 2. Northern Ghana's three major regions, Northern, Upper East, and Upper West (Created in ESRI 2011, ArcMap 10; shapefile from Ghana: Country at a glance, 1999).

Climate

The climate in the Northern Region is within the tropical continental or savannah zone and experiences a single rainfall season and a long drought period. Rains begin in May, peak between July and August, and taper off by October. From November to May the Northern Region experiences dry, drought-like conditions. The estimated annual mean precipitation ranges from 900 to 1,140 mm (Lutz, et al., 2007). In the Savelugu-Nanton District, the headquarters for GI-WASH in the Northern Region, annual rainfall ranges between 1,005 and 1,150 mm with a relative humidity value of 65 to 85% in the rainy season and 20% in the dry season (Tay, 212). Annual temperatures average 30 ^{o}C but range between 18 ^{o}C during the rainy season and 42 ^{o}C during the dry season (Anku et al., 2008). Evapotranspiration rates in northern Ghana depend on season, location, and local vegetation and may range between 650 to 1,300 mm year^{-1} (Lutz et al., 2007), averaging 890 mm year^{-1} within the Voltaian Basin (Akudago et al., 2009).

Rainfall reduction and rainfall pattern changes have been observed in forested and savannah zones throughout West Africa since the 1970s (Lutz et al., 2007). Over a 50 year time period between 1945 and 1993, the mean annual temperature in northern Ghana has risen by nearly 1 ^{o}C which also increases evaporation rates. These measurements were taken at the synoptic station in Tamale, the largest city in the Northern Region (Lutz et al., 2007).

Geology

The Voltaian (Paleozoic) Sedimentary Basin (Basin) underlies approximately 45% (approximately 100,000 km^2) of the country (Dapaah-Siakwan and Gyau-Boakye, 2000) and is approximately 3,000 to 4,000 m thick (Akudago et al., 2009). The Basin consists of sandstone, shale, mudstone, sandy and pebbly beds, siltstone, and arkose (Figure 3 [Lutz et al., 2007; Dapaah-Siakwan and Gyau-Boakye, 2000]), and is subdivided into three classifications based on lithology and field relationships. The three units are characterized as the Upper Voltaian, Middle Voltaian, and Lower Voltaian (Dapaah-Siakwan and Gyau-Boakye, 2000). This study will mainly focus on the Middle Voltaian unit which is comprised of Obosum and Oti beds made up of shale, sandstone, mudstone, limestone, and conglomerate from the crystalline basement rocks (Yidana et al., 2011).

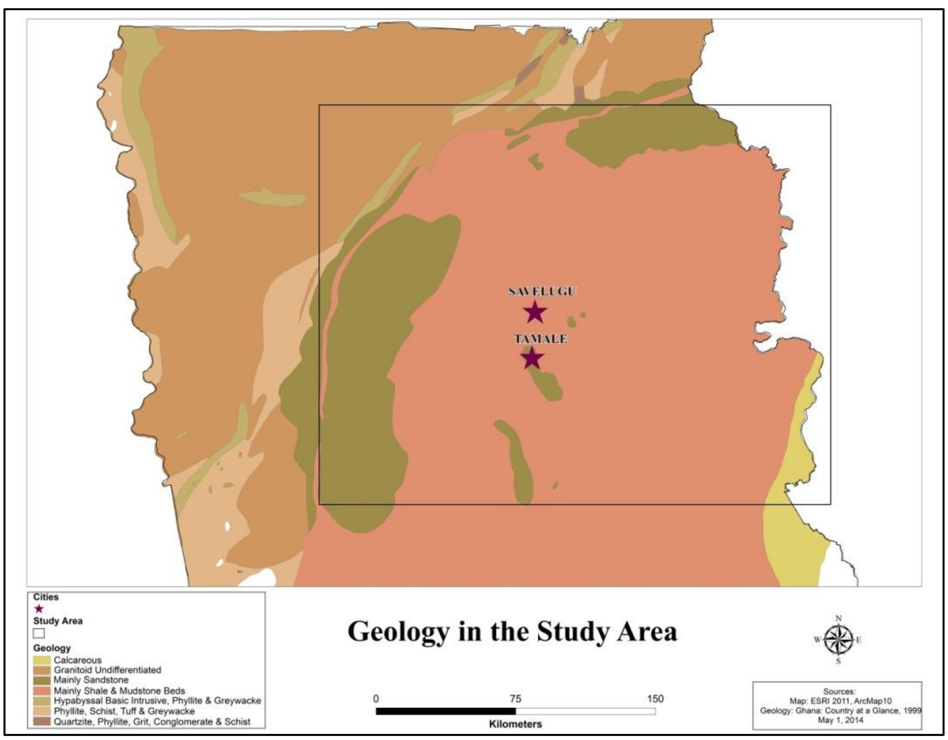


Figure 3. Geologic map of the Northern Region in Ghana. The study area is outlined in the Middle Voltaian Basin (Created in ESRI 2011, ArcMap 10; shapefile and geology from Ghana: Country at a glance, 1999).

Hydrogeology

Primary porosity in the Voltaian Basin is almost nonexistent due to high levels of consolidation and cementation, therefore, preferential groundwater flow paths are along the strike direction of fractures and the weathered portion of the Basin (Acheampong and Hess, 2000; Boadu et al., 2005; Lutz et al., 2007). Hydraulic conductivity has the potential to increase by several orders of magnitude over a short distance of a few meters (Boadu et al., 2005). Hydraulic conductivity values for fractured sandstone range between 0.01 and 3 m day^{-1} (Lutz et al., 2007). Transmissivity estimates from Kwei (1997), reported in Lutz et al. (2007), range from 1 to 30 m^2 day^{-1}. Aquifer test analysis in the Nabogo Basin, Northern Region report a transmissivity value of 13 m^2 day^{-1} (Lutz et al., 2007). In the Middle Voltaian unit recharge to the regional aquifer is estimated at 2 to 4% of the annual rainfall, while 86% of the precipitation is lost to high levels of evapotranspiration, and 10% to runoff (Teeuw, 1995).

Methods and Materials

The following sections will discuss the steps preformed throughout this project to achieve the desired objectives introduced in the introduction. Borehole drilling logs were collected and used to create a main database that consists of log locations, lithology descriptions, aquifer tests, and well construction. This data was evaluated for location accuracy before input into the borehole management package in RockWorks16 and 3Dand 2D maps created.

Data Collections

Borehole drilling logs from GI-WASH were captured electronically to create a database that serves as the foundation for input data into RockWorks16, a software to construct an interpolated 3D map of the regional lithology. The map is used to generate 2D cross sections in areas of interest and characterize the hydrogeologic framework throughout the region. Rockworks16 stores data including: location, coordinates, district/community name, and elevation; lithology at depth intervals in the borehole; stratigraphic intervals such as confining layers and aquifers; flow rate at intervals and final flow rate (yield); static and pumping water levels; symbol of the well which was defined as either wet or dry; and well construction. Borehole coordinates and elevation are the primary data needed for RockWorks16 to successfully read the other borehole information. Many logs were lacking these data and required manual input with the help of Ghana Survey Maps and ESRI's ArcGIS.

Data QAQC

Data quality control on the borehole drilling logs was conducted based on coordinate and elevation information, as many borehole logs were incomplete with respect to coordinates and elevation and had to be manually entered with the use of Ghana Survey Topography maps and ESRI's ArcGIS. The ArcMap portion of ArcGIS was used to validate and, when necessary, make adjustments to coordinates for each well. The location of each well was converted to a shapefile and overlain on the district map of the country. Each borehole location was checked to make sure it resided in the correct district reported on the original log. Logs without coordinates or incorrect coordinates that could not be accurately adjusted were removed from the dataset.

Missing elevation information was also updated using ArcGIS. Digital Elevation Models (DEMs) were not used for this process since they are only available at 90 m resolution, which is too course for this study. Instead, boreholes were plotted over a Ghana Geological Survey elevation contour map of the country. Missing elevation data were read from the contour map. In cases where the borehole did not place on a contour line, the closest elevation reported was used. In areas where multiple known elevations were closest, an average was taken.

The final database includes 879 borehole logs, which reflects those considered to have accurate coordinates and elevations. Assessing coordinate locations and elevation data was the only metric put into place to evaluate the quality of borehole logs before input into RockWorks16. Detailed information varied between logs, but due to the large study area it was decided that as many available logs as possible were used to create cross sections in RockWork16 to minimize the interpolation of the regional hydrogeologic framework.

Aquifer Characterization

The next step was to normalize the data reported in the drilling logs by standardizing the lithologic descriptions. Diverse expertise of the various drilling crews results in variability of the quality and the level of detail reported in the geologic units penetrated, and the possibility of several descriptions given for one sediment unit (Dumedahand and Schuurman, 2008). To standardize the descriptions and capture the main lithology attributes used in the logs, 11 categories were created using methodology modified from Dumedahand and Schuurman (2008) and Ross et al. (2003). The literature reviewed indicated that groundwater is most commonly found in fractures, therefore, lithology categories were focused around fracture characteristics as a dominant attribute.

The Middle Voltaian Basin mainly consists of sandstone, siltstone, mudstone, and shale, which are the main lithologies recorded on the logs. A few logs that included granite and associated minerals were lumped into a granite category. Typically an interval at the top of the borehole was recorded as top soil, which may consist of clay or laterite. Each lithology was classified into one of the 11 categories shown in Table 1. Fracturing was described by moderately or highly fractured reported in the logs. Slightly and no fractures were categorized as non-fractured. These standardized categories were used to compare lithology type to final yield values reported at completion of the borehole.

Table 1. Eleven dominant lithology types

1	Topsoil		
2	Sandstone	7	Fractured Sandstone
3	Mudstone	8	Fractured Mudstone
4	Silstone	9	Fractured Silstone
5	Shale	10	Fractured Shale
6	Granite	11	Fractured Granite

Specific capacity and transmissivity were calculated from 140 borehole drilling logs that contained aquifer test data. Aquifer tests were run for one time interval ranging between one and six hours. In cases where a time was not recorded two hours was used, as that is the standard GI-WASH methodology (Samuel Edusei, personal communication, 2013). Specific capacity is the yield of the well divided by the drawdown (Equation 1 [Fetter, 2001]). This value was used to calculate transmissivity. Equation 2 taken from Fetter (2001) was used to calculate transmissivity for a confined aquifer through iteration and the calculated values of specific capacity:

$$SC = \frac{Q}{(ho-h)} \qquad \text{Equation (1)}$$

$$T = \frac{Q}{(h0-h)} \frac{2.3}{4\pi} \log \frac{2.25Tt}{r^2\, S} \qquad \text{Equation (2)}$$

where: *SC* is specific capacity calculated in *T* m^2 day^{-1}, *T* is the transmissivity calculated in m^2 day^{-1}, *Q* is the discharge in m^3 day^{-1}, *t* is time of 1 day, *r* is the radius of the pumping well which is 0.06 meters, h_0-h is the drawdown in m, and *S* is the storativity. A value of 0.001 was used for storativity as reported in Driscoll (1986) for confined aquifers.

Comparison Analysis

The dominant lithology represented at the aquifer interval was recorded for each log. The aquifer interval refers to the interval between the depth to water and the final depth of the borehole. Depth to water is recorded on each log during the borehole drilling process. In all cases where the borehole intersects water during the drilling process, the yield is measured at depth intervals from the first depth to water recording to the end of the borehole. If the aquifer interval spanned over multiple lithology descriptions, the most frequent lithologic unit and most frequent degree of fracturing was determined the dominant lithology. The dominant lithology for the aquifer interval was then used for comparisons with the final output yield for the purpose of assessing favorable lithologic units for drilling purposes.

Boxplots were constructed to visually display normalized yield values for each lithology category with the goal to assess lithological units best for developing groundwater. The following assumptions were made in comparing yield for each borehole and lithology type:

- Each well was constructed with the same well casing diameter.
- Methodology for measuring yield from the borehole was standardized during well construction.

The aquifer interval length was used to normalize the yield for each well. Yield was divided by the aquifer interval length to obtain a yield value per meter of aquifer interval. Boxplots were constructed for each lithology category and normalized yield values. These graphs are used to visually compare lithology favorability for increased well yields (Appendix 8.1).

Cross Section Development

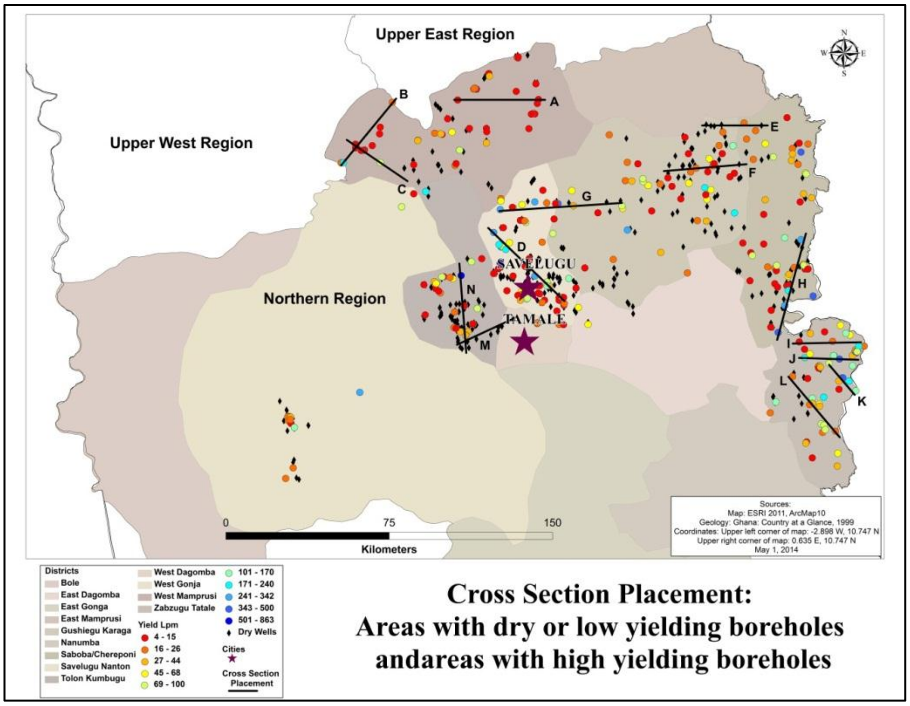
Rockworks16 was used to visualize the lithology across the study basin. Rockworks was chosen to develop cross sections that will represent the entire study. The software chosen to act as the borehole manager and develop regional sub-surface maps had to meet several requirements: user friendly interface; easy to import and export data, as well as update the data base; capability to interact with ArcGIS and Google Earth; a detailed visual output for the 3D map and 2D cross sections; and has the ability to add additional information such as water quality data. RockWorks16 met all of these requirements. Several limitations, however, became apparent when interacting with this software and the study area's data. First is the limitation of scale. For this particular project, the study area spans the majority of the Northern region and maps 879 boreholes. When including borehole locations in the 3D map and 2D cross sections, wells appear to be on top of each other and are illegible. This issue may be eliminated by decreasing the size of the study area, but for the purpose of this project that was not an option. The next limitation is the interpolation method. Boreholes are clustered in certain areas and scattered in other areas throughout the domain space. In cases where boreholes are scattered, large amounts of interpolation in the sub-surface lithology occurs. It is also a limitation that the 2D cross sections are developed from the 3D interpolated map, instead of going through a separate interpolation method at the smaller cross section scale.

A 3D solid model of interpolated lithology was generated in RockWorks16 and smaller cross section profiles were extracted from the 3D lithology map to better define the regional hydrogeologic framework and isolate areas of interest. Lithology profiles were created for four west-to-east cross sections and four north-to-south cross sections over the entire domain area. Smaller cross sections were generated in areas that have proven difficult for successful well drilling, clusters of dry or low yielding wells, and areas of high yields (Figure 4).

Two dimensional profiles of the water level were plotted on each area of interest cross section using the Water Level Table in RockWorks16. Visual connections can be made to which lithologies contain water. The interpolated aquifer model is constructed from interval depths recorded down the borehole that contain water. Limited spatial and temporal data necessitated the following assumptions for purposes of constructing these cross sections:

- The aquifer reported in the drilling logs is continuous and confined.
- Depth to water recorded during the drilling process was at the same time of year for each well to eliminate variation in water table levels from the wet and dry season.

This method of displaying the aquifer profiles yields several limitations in the visual output and accuracy of aquifer locations. The depth to water is interpolated across the lithology profile and connected to the next depth to water profile on the closest well so the aquifer can appear to be above ground. One reason for this appearance is that the data set includes dry wells and the aquifer profile may be connecting to the next wet well. Another reason is that the 2D lithology and aquifer profiles are made from a 3D map. The swath from which the 2D profile is created may consist of data above or below the profile line which can give the illusion that the aquifer profile is above ground.



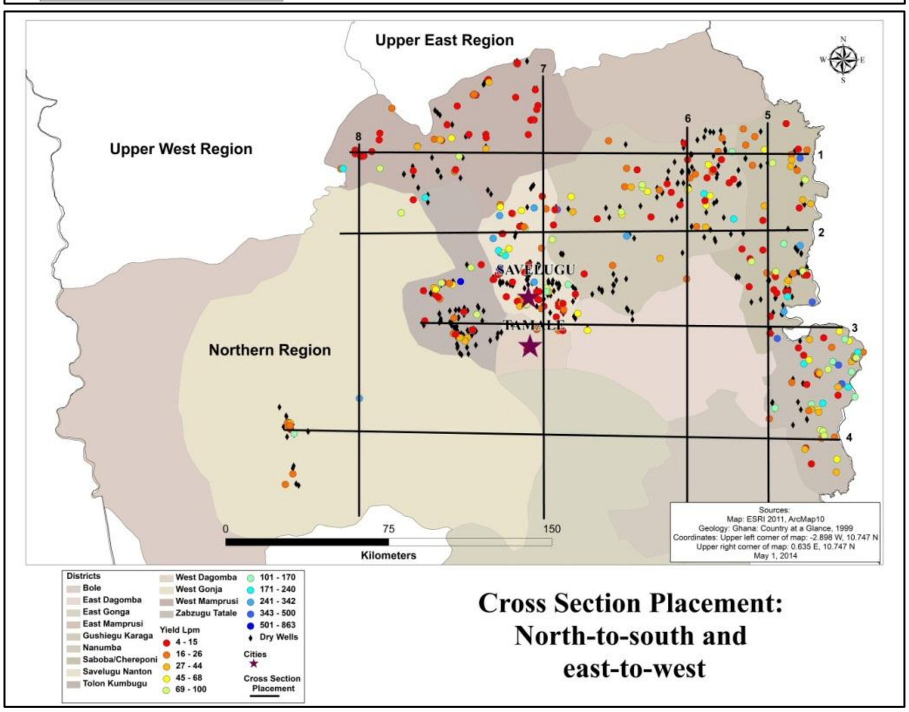


Figure 4. Top: cross section placement in areas of interest that display clusters of wet, dry, and high and low yielding wells. Bottom: cross section placement west-to-east and north-to- south to characterize the entire region (Created in ESRI 2011, ArcMap 10; shapefile and geology from Ghana: Country at a glance, 1999).

Results

Transmissivity ranges from less than 1 to 5414 m^2 day^{-1}, averaging 90 m^2 day^{-1} and a median value of 7.54 m^2 day^{-1}. Specific capacity ranges from less than 1 to 1348 m^2 day^{-1}, averaging 24 m^2 day^{-1} and median of 2.68 m^2 day^{-1}. Over half of the well logs recorded were dry, 368 of the 879 wells were considered wet and developed. For GI-WASH, a wet well is defined as 19 m^3 day^{-1} (13 L min^{-1}) or greater (Samuel Edusei, personal communication, 2013).

The minimum, maximum, average, and median yield of the wet wells are 5.8, 1243, 92, and 32 m^3 day^{-1}, respectively. Minimum, maximum, average, and median total depth of wet wells is 25, 76, 40, and 37 m, respectively. Out of the 368 wet wells, 299 were drilled into lithological units that were characterized as being fractured. This implies that 81% of the wet wells have screened intervals in a fractured rock. Of the entire 879 borehole drilling logs 53% of all wells were drilled into lithological units that were characterized as being fractured.

Boxplots were constructed to compare yield to lithology types. A boxplot graphically displays the distribution of the data set (Helsel and Hirsch 2002). In summary, the mid line is the median of the data and the upper and lower quartile lines display where the bulk of the data points reside. The upper quartile line indicates 75% of the data is equal to or less than this line, and the lower quartile line indicates 25% of the data is equal to or less than this line. The whiskers or straight lines extending from the box represent the maximum and minimum data values. The asterisks display outliers in the data. Each plot was constructed to compare all lithologic categories, and the same lithologies fractured and non-fractured. On the y-axis is the normalized yield value and the x-axis is lithology type. Two wells had final yield values of 1,242 (863 L min^{-1}) and 1,080 m^3 day^{-1} (750 L min^{-1}), which were categorized as outliers and removed from the dataset for easier visualization of the data (Figure 5). Individual fractured and non-fractured boxplot graphs are included in Appendix 8.1.

In the drilling process, depth to water is recorded and yield is measured until the final depth of the borehole is reached, and a final yield is reported. The reason for comparing lithology and yield within the aquifer interval length is to better characterize the aquifer. For the entire data set the average length of the aquifer interval is 13 m. Maximum and minimum lengths are 46 and 3 m, respectively.

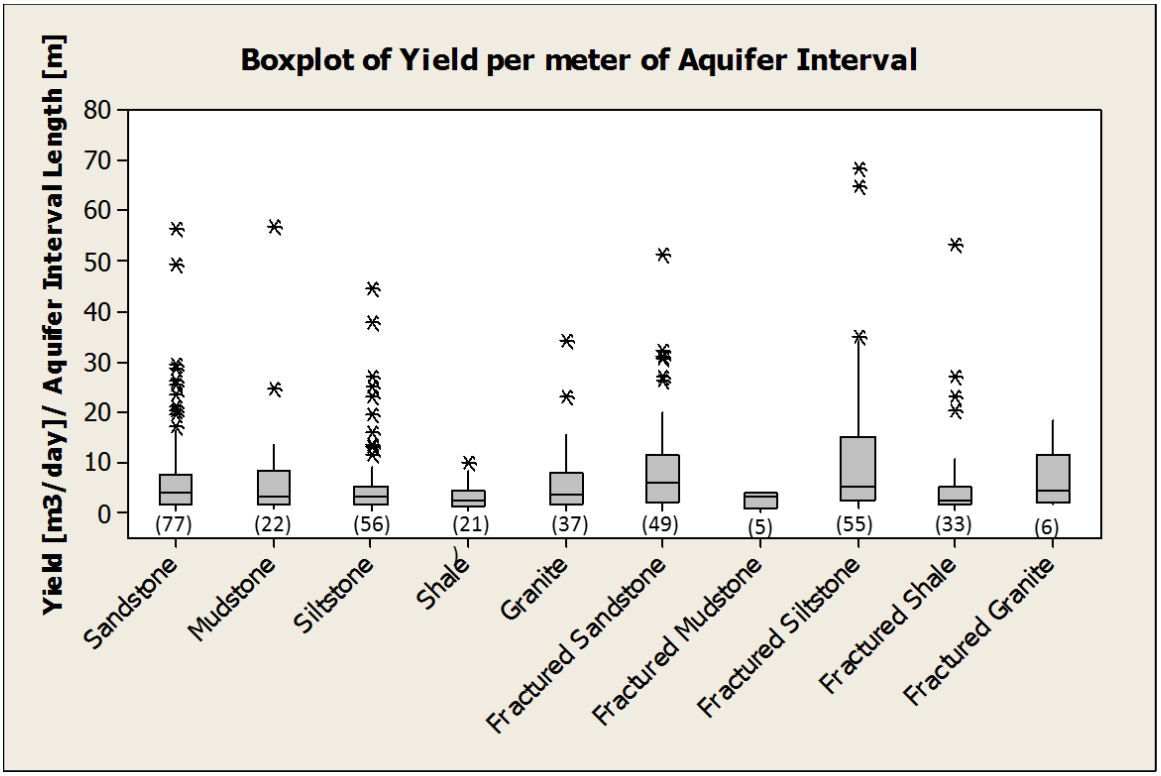
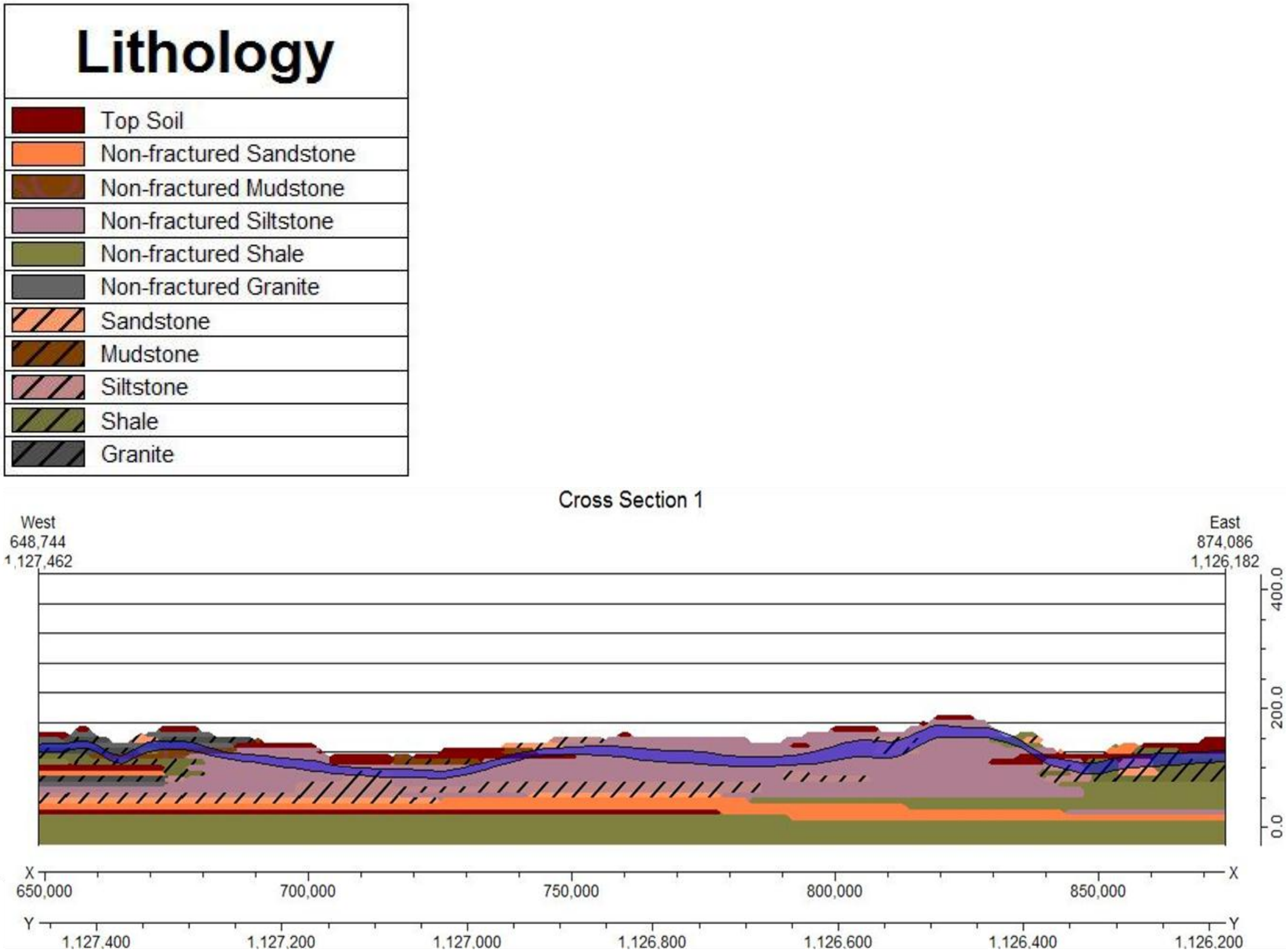


Figure 5. Boxplot comparing standardized lithology types to normalized yield values. Yield was normalized over the aquifer interval reported during borehole development. The plot visually displays which lithology types tend to produce higher yield values.

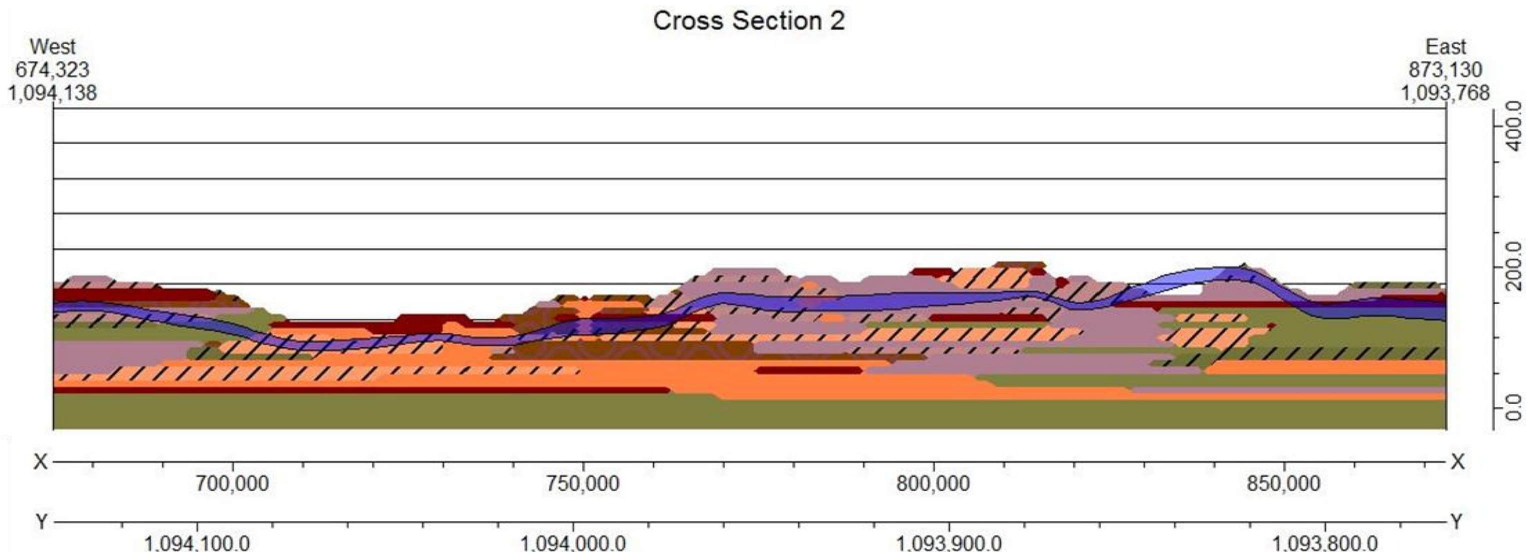
Visual comparisons between all lithology types and normalized yield values are made from the boxplot figure. Comparison of the distribution of fractured versus non-fractured lithologies shows that fractured sandstone, siltstone, shale, and granite have a higher upper quartile line, indicating 75% of the data points have a higher yield, than that of their non-fractured counterparts. The boxplot of yield per meter of aquifer interval length for fractured sandstone, siltstone, and granite shows the highest median and upper quartile lines compared to the other lithology types. The median value for all three lithology types is 5 m^3 day^{-1} and the upper quarter line values are 12, 15, and 12 m^3 day^{-1}, respectively. Non-fractured granite, sandstone, and mudstone have median values of 4, 4, and 4 m^3 day^{-1}, and upper quartile lines of 8, 6, and 11 m^3 day^{-1}, respectively. Fractured sandstone, siltstone, and granite and non-fractured granite, sandstone, and mudstone produce higher normalized yield values than the other lithology types.

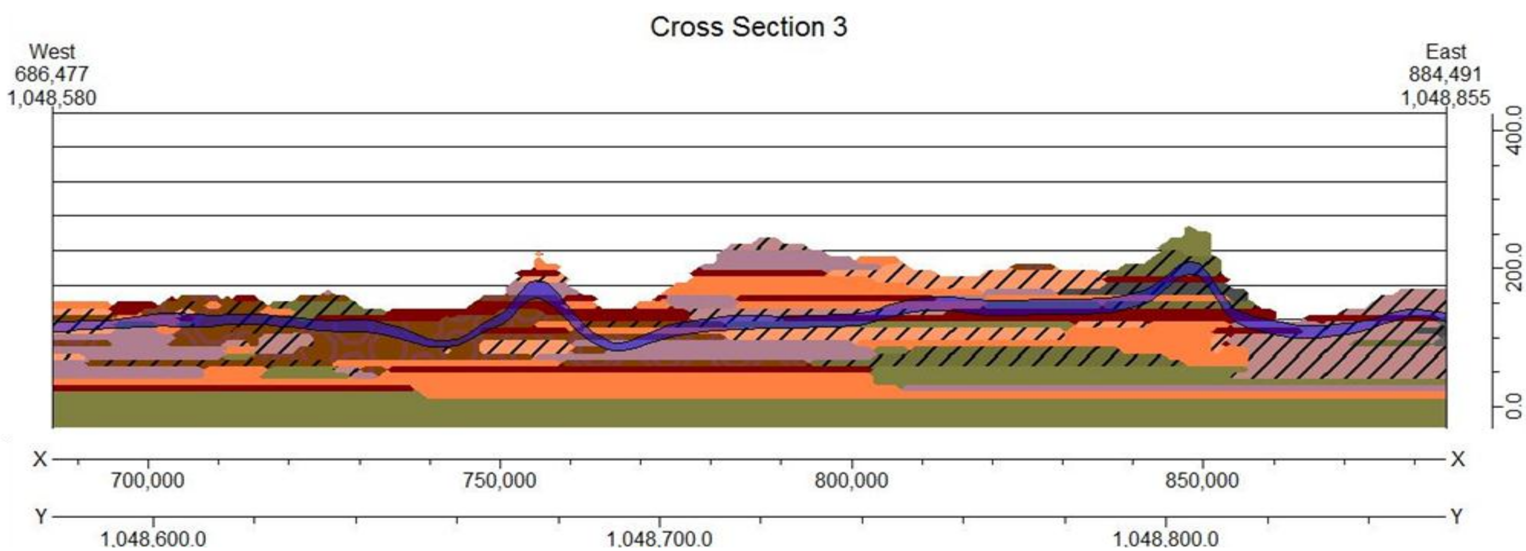
Cross sections of the Northern Region were drawn west-to-east, north-to-south, and in areas of particular interest, for instance where drilling success rates have been low, yield values reported are either low or high, and where demand is more urgent. Figure 6 divides the region into four sections from the west-to-east capturing boreholes in each profile line. Cross section 4 has the most interpolation from the west-to-east direction due to limited and poorly spaced boreholes. Figure 7 separates the region into four sections from the north-to-south direction. The majority of boreholes are found in the northern portion of the study domain compared to sparse boreholes in the southern portion of the domain. For this reason a large amount of error and interpolation expected on the southern end of each cross section.

Figure 8 displays cross sections in areas where clusters of dry wells, low yielding wells, or high yielding wells are found. Cross sections A, B, C, E, F, I, M, and N are drawn in areas where larger groups of dry or low yielding wells are drilled. Cross sections E, F, M, and N are drawn in areas that have proven difficult to find water for the drilling crews. High yielding wells are found in the Zabzugu-Tatale district located along the eastern border of Ghana. Cross sections D, G, H, J, K, and L are drawn in areas where high yielding wells are drilled. It is predicted that these cross sections along with spatial distributions visually displayed in ArcGIS can gain insight into areas of preferential drilling. Depth to water reported in the drilling logs was plotted on each cross section for an interpolated indication of aquifer location.



Lithology
Top Soil
Non-fractured Sandstone
Non-fractured Mudstone
Non-fractured Siltstone
Non-fractured Shale
Non-fractured Granite
Sandstone
Mudstone
Siltstone
Shale
Granite
Cross Section 1
West
648,744
1,127,462
East
874,086
1,126,182
400.0
200.0
0.0
X
650,000
700,000
750,000
800,000
850,000
X
Y
1,127,400
1,127,200
1,127,000
1,126,800
1,126,600
1,126,400
1,126,200
Y


Cross Section 2
West
674,323
1,094,138
East
873,130
1,093,768
400.0
200.0
0.0
X
700,000
750,000
800,000
850,000
Y
1,094,100.0
1,094,000.0
1,093,900.0
1,093,800.0


Cross Section 3
West
686,477
1,048,580
East
884,491
1,048,855
400.0
200.0
0.0
X
700,000
750,000
800,000
850,000
Y
1,048,600.0
1,048,700.0
1,048,800.0

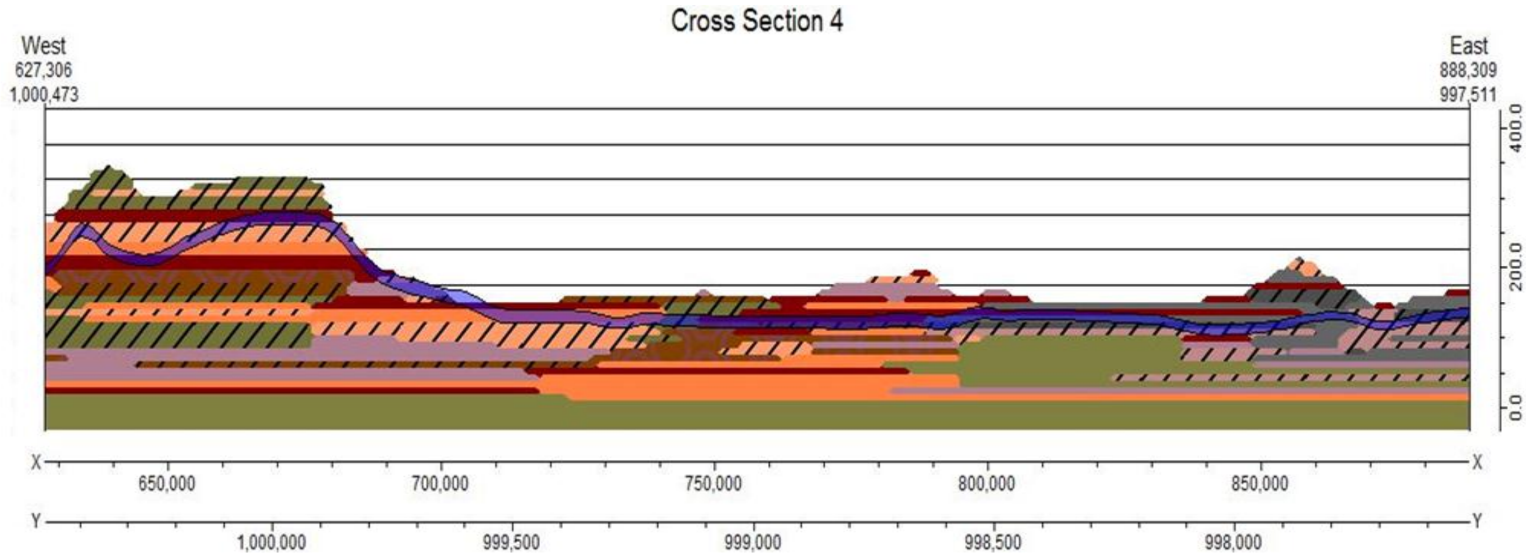
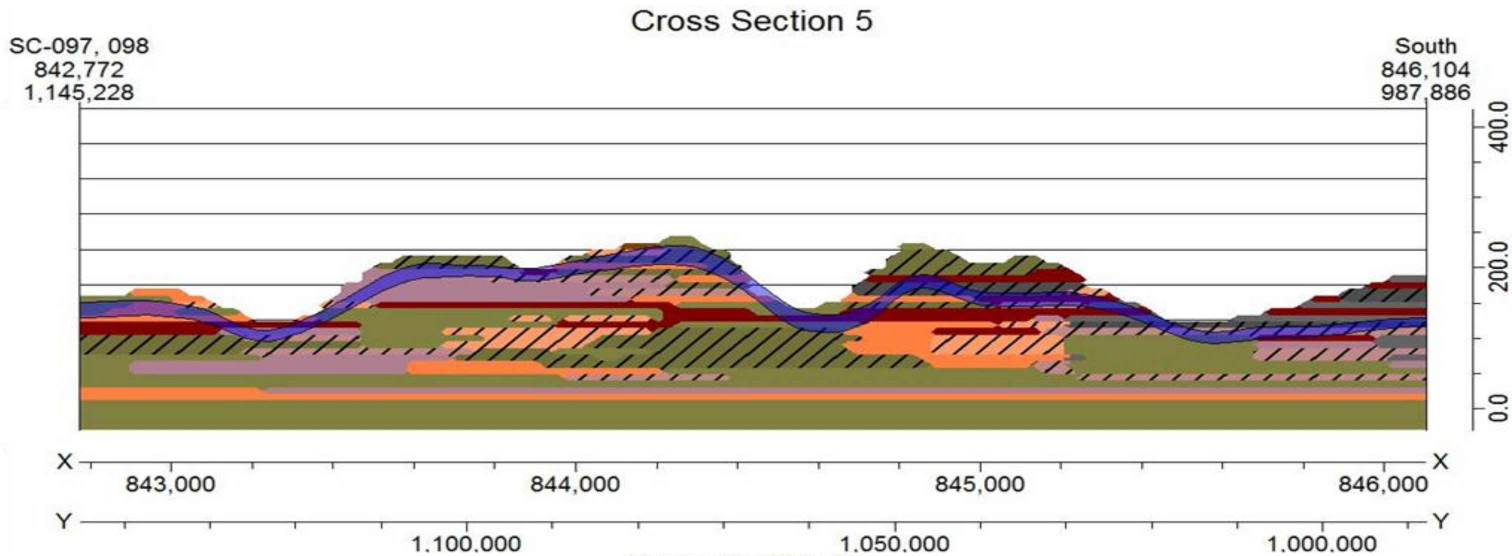
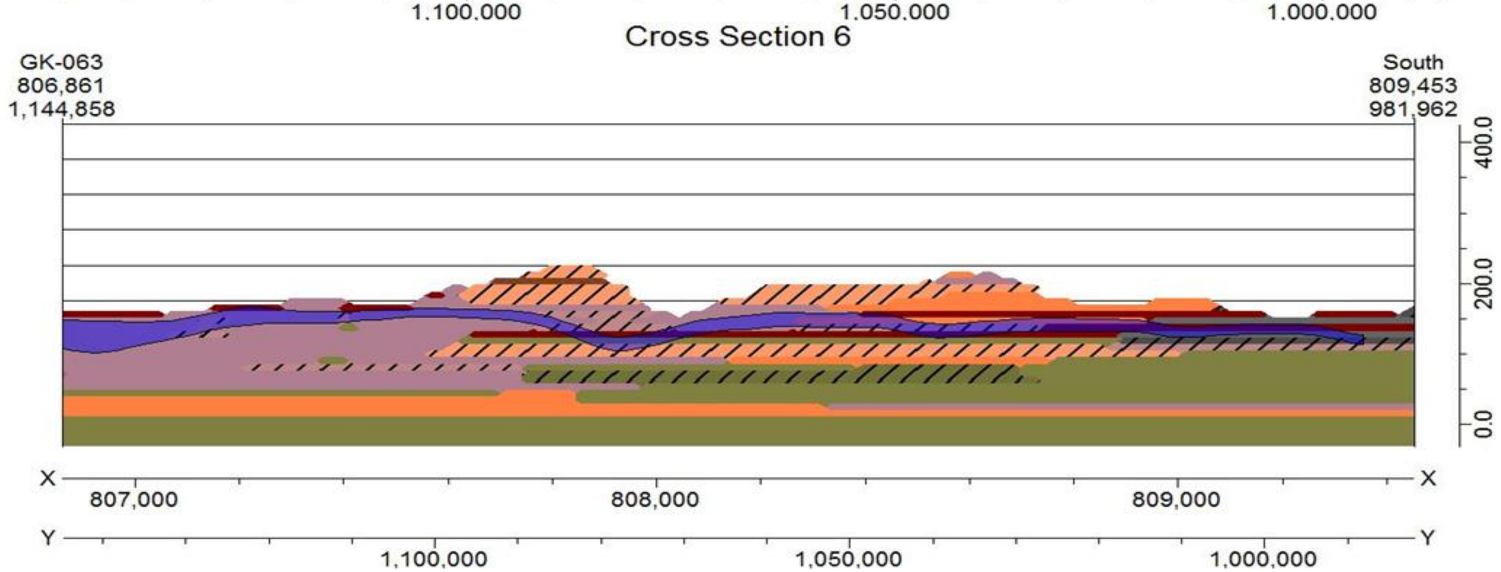
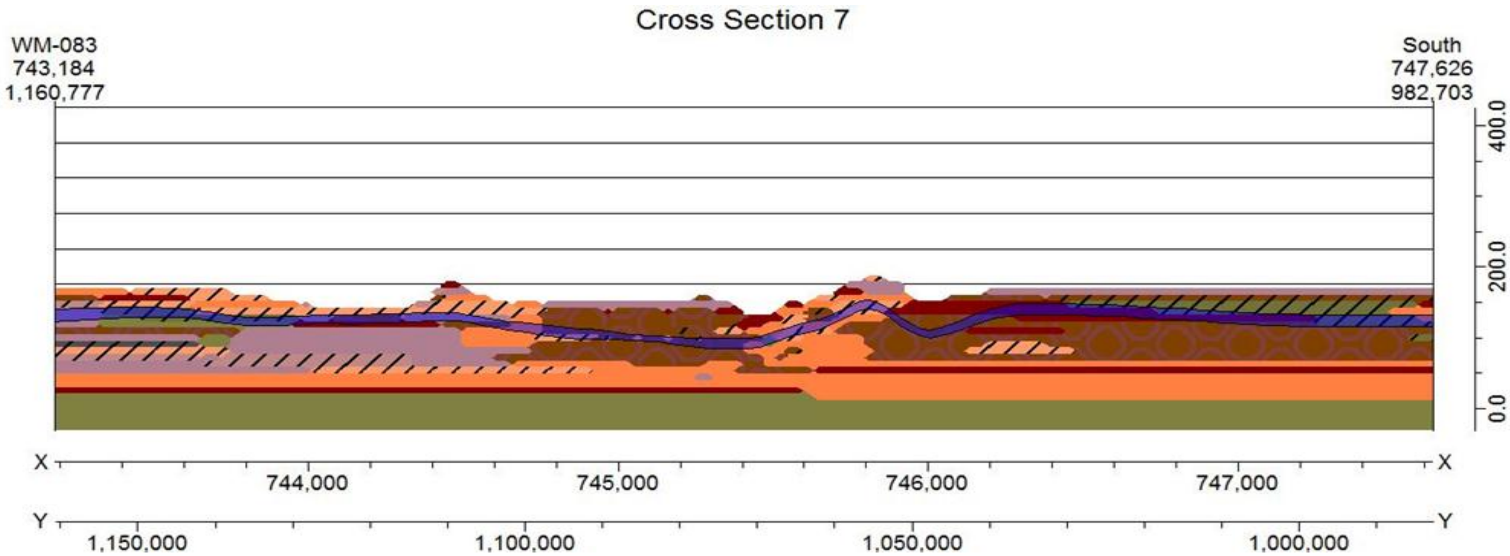


Figure 6. Four cross section profile draw in the west-to-east direction that divide evenly dividing the study domain for an overall horizontal representation of the study domain. The blue line running through the profile is the interpolated aquifer profile. The coordinates in the upper left and right corners of the profiles are reported in UTM Zone 30, x-easting and y-northing. The x and y profiles on the x axis are the coordinates reported across the lithology profile. The vertical tick marks on the y-axis is the elevation reported in meters (Rockworks16, 2013).


Cross Section 5
SC-097, 098
842,772
1,145,228
South
846,104
987,886
400.0
200.0
0.0
X
843,000
844,000
845,000
846,000
X
Y
1,100,000
1,050,000
1,000,000
Y


Cross Section 6
GK-063
806,861
1,144,858
South
809,453
981,962
400.0
200.0
0.0
X
807,000
808,000
809,000
X
Y
1,100,000
1,050,000
1,000,000
Y



Cross Section 7
WM-083
743,184
1,160,777
South
747,626
982,703
400.0
200.0
0.0
X
744,000
745,000
746,000
747,000
X
Y
1,150,000
1,100,000
1,050,000
1,000,000
Y

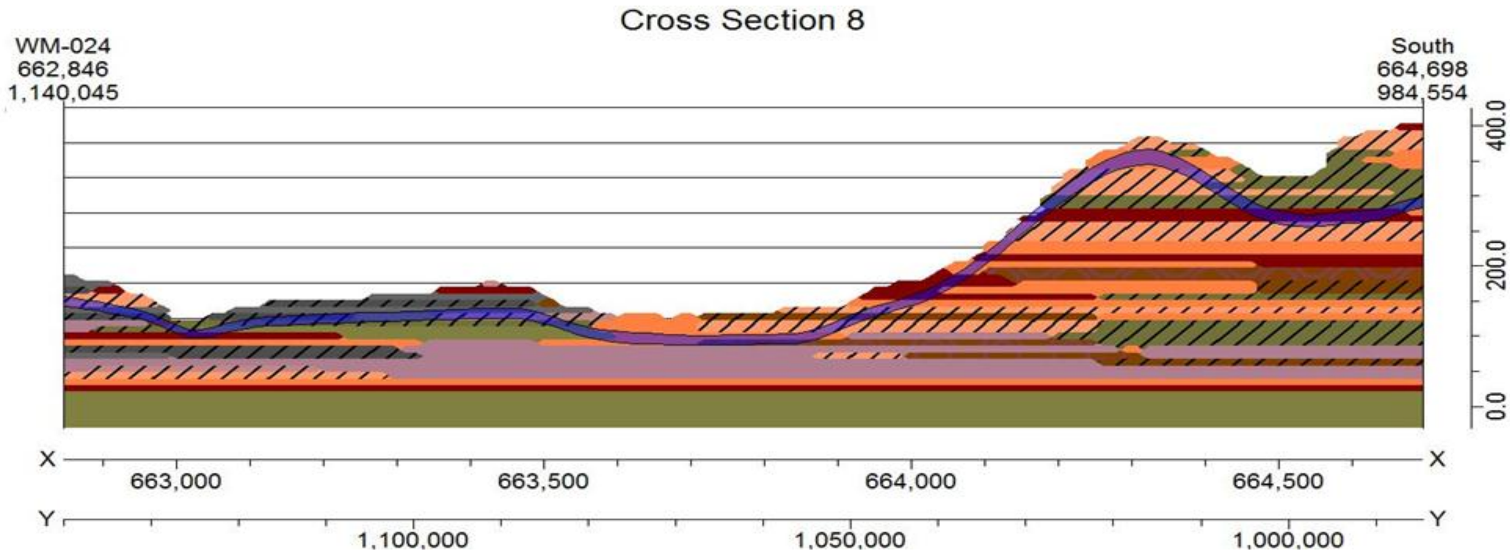
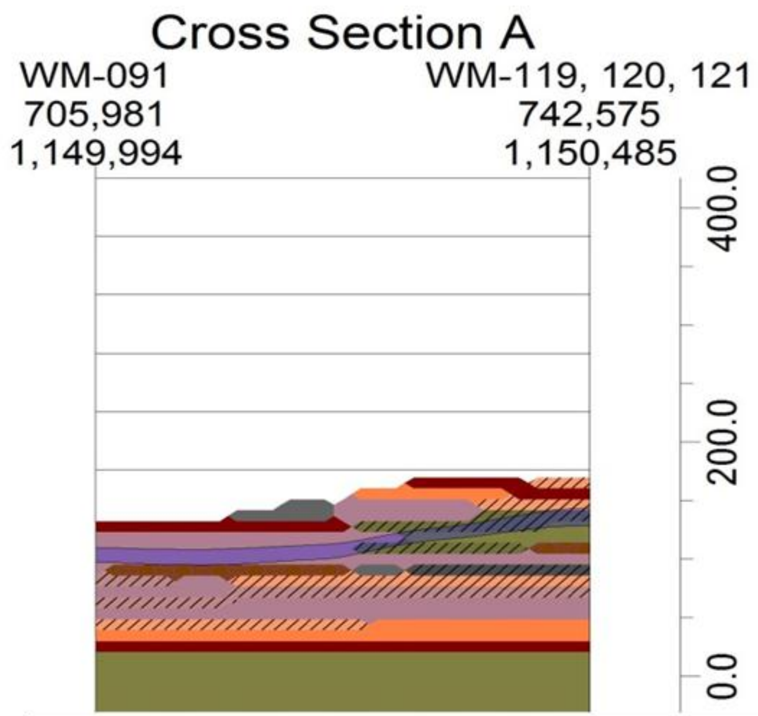
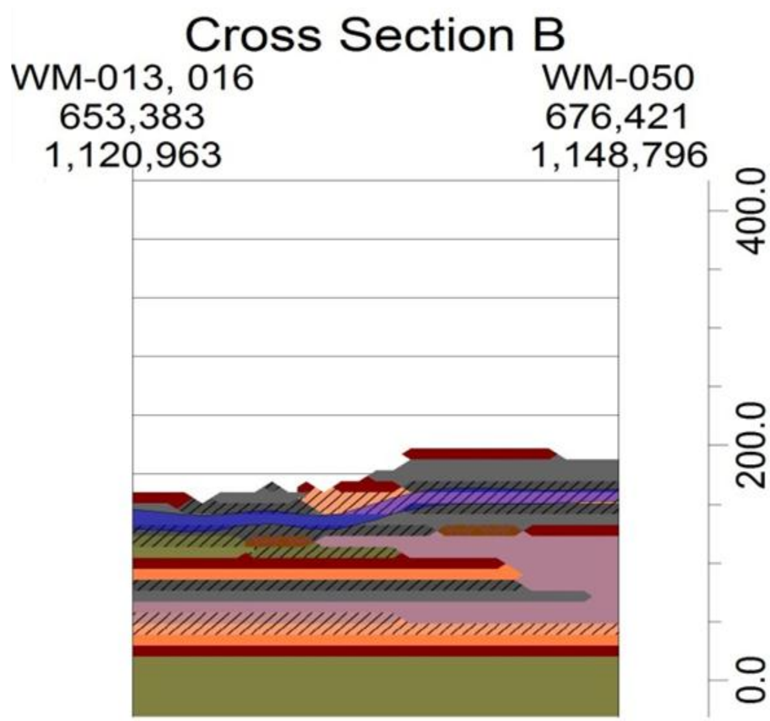


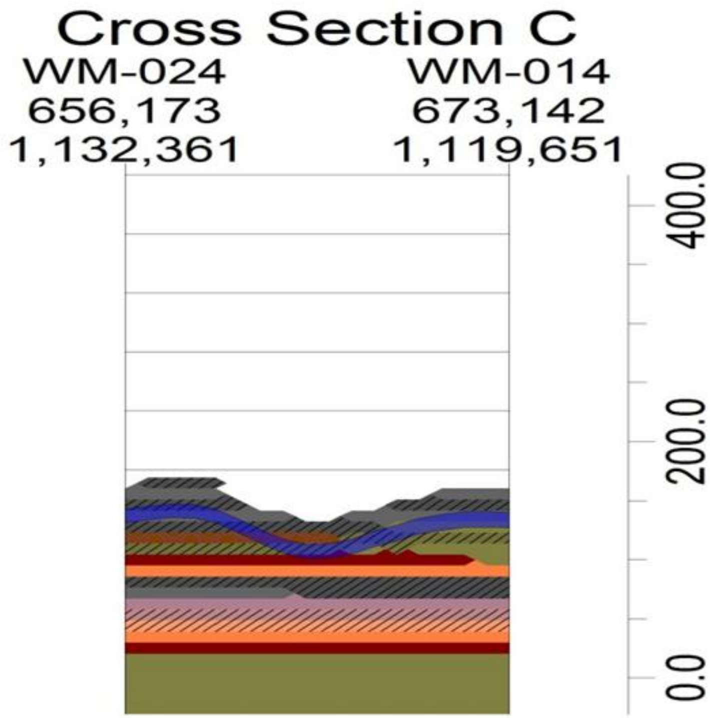
Figure 7. Four cross section profiles drawn in the north-to-south direction dividing the study domain evenly. These four cross sections gain an overall vertical representation of the hydrogeology in the study domain. The blue line running through the profile is the interpolated aquifer profile. The coordinates in the upper left and right corners of the profiles are reported in UTM Zone 30, x-easting and y-northing. The x and y profiles on the x axis are the coordinates reported across the lithology profile. The vertical tick marks on the y-axis is the elevation reported in meters (RockWorks16, 2013).

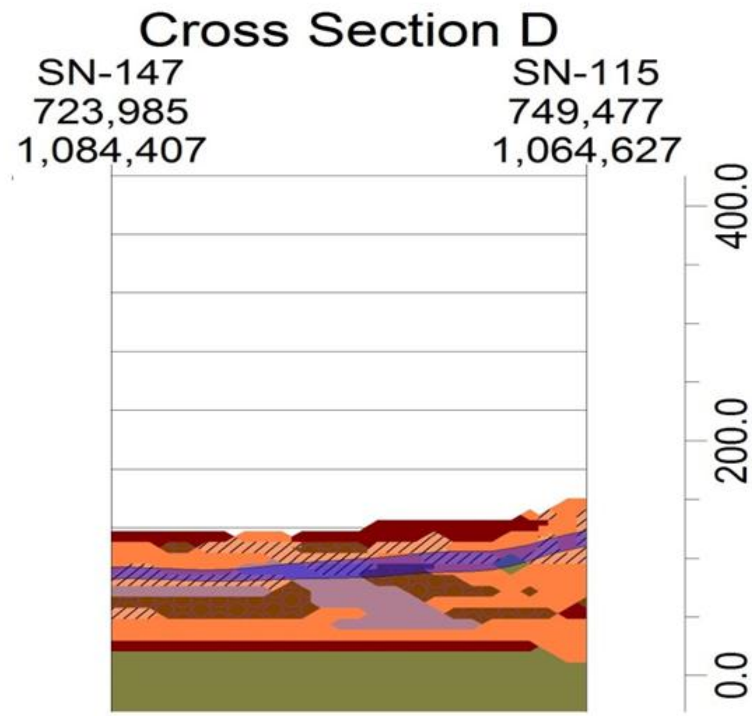


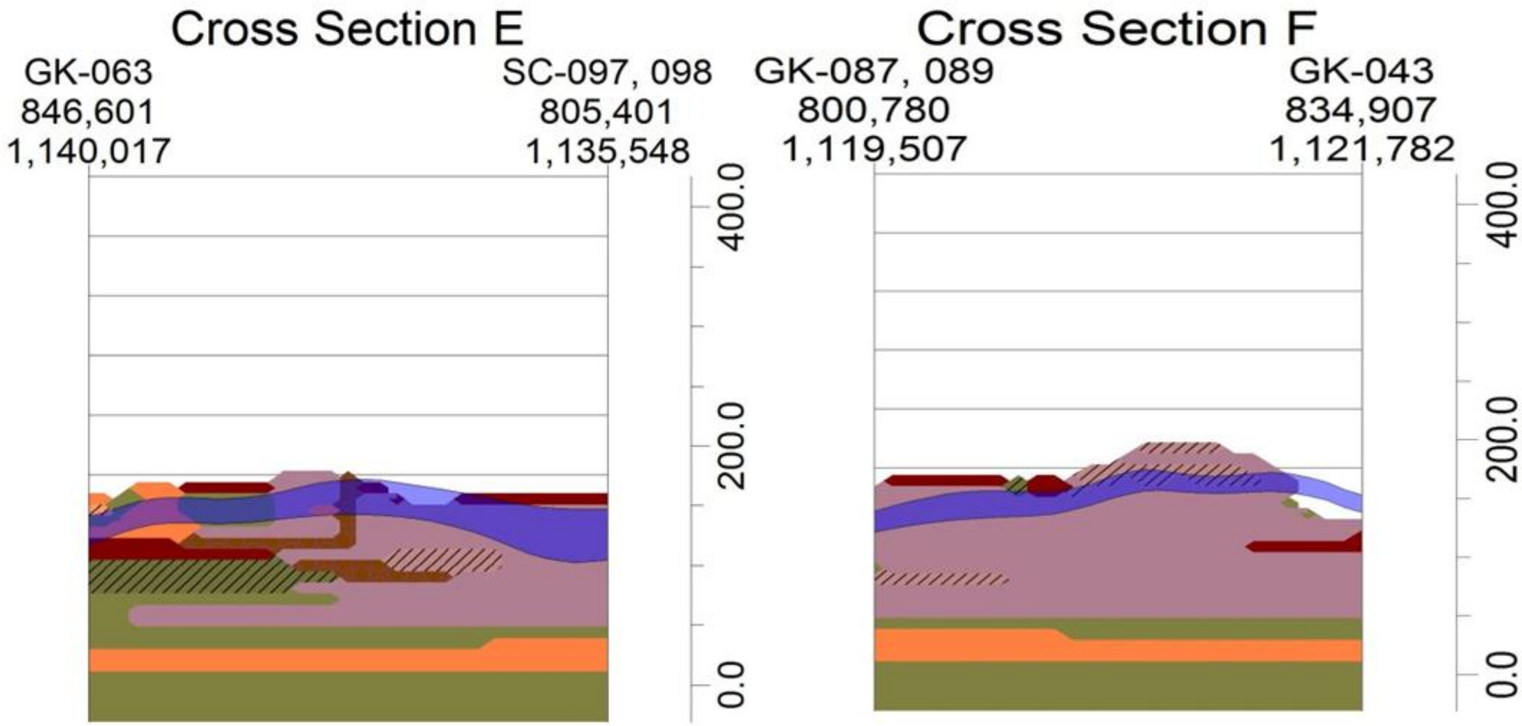
Cross Section A
WM-091
705,981
1,149,994
WM-119, 120, 121
742,575
1,150,485
400.0
200.0
0.0

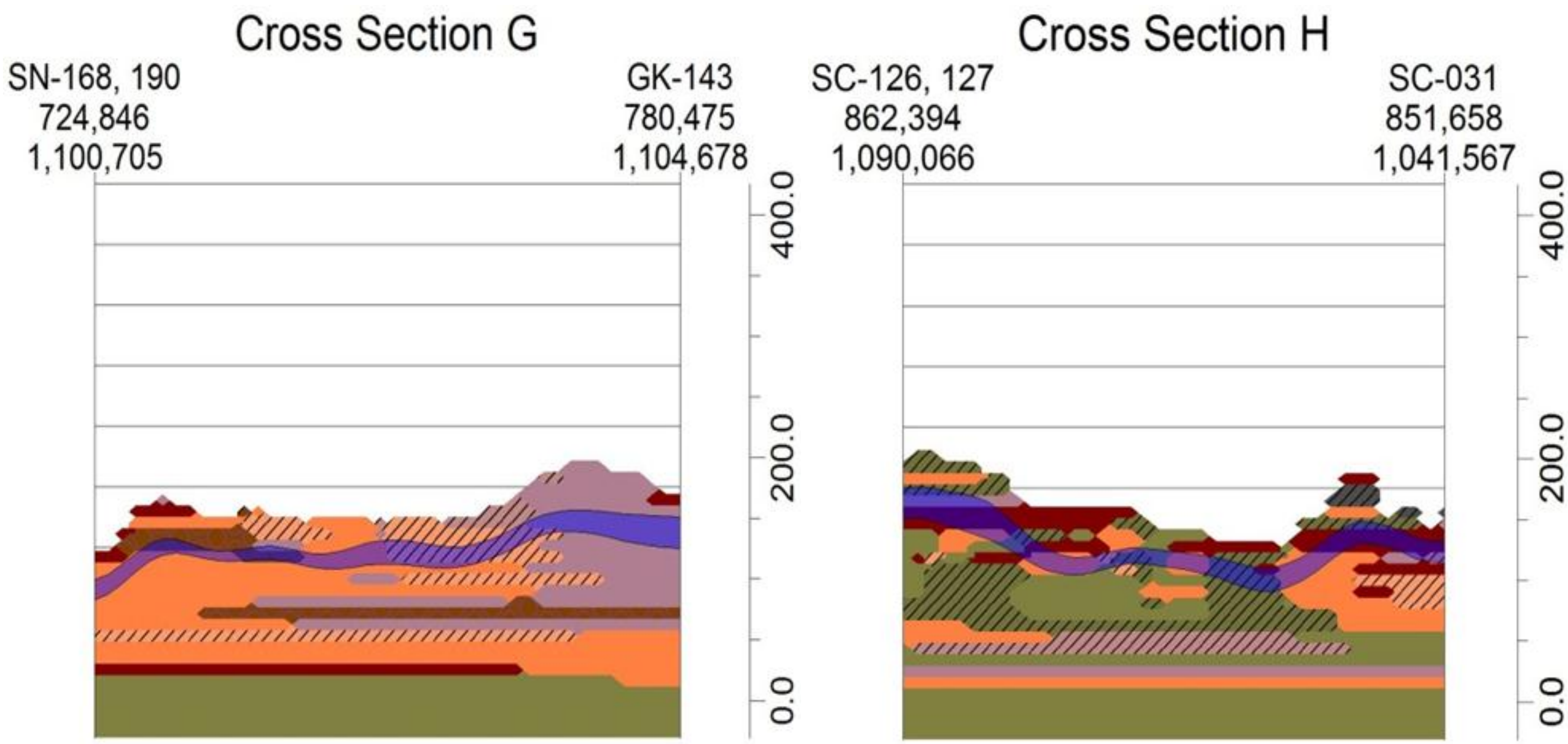


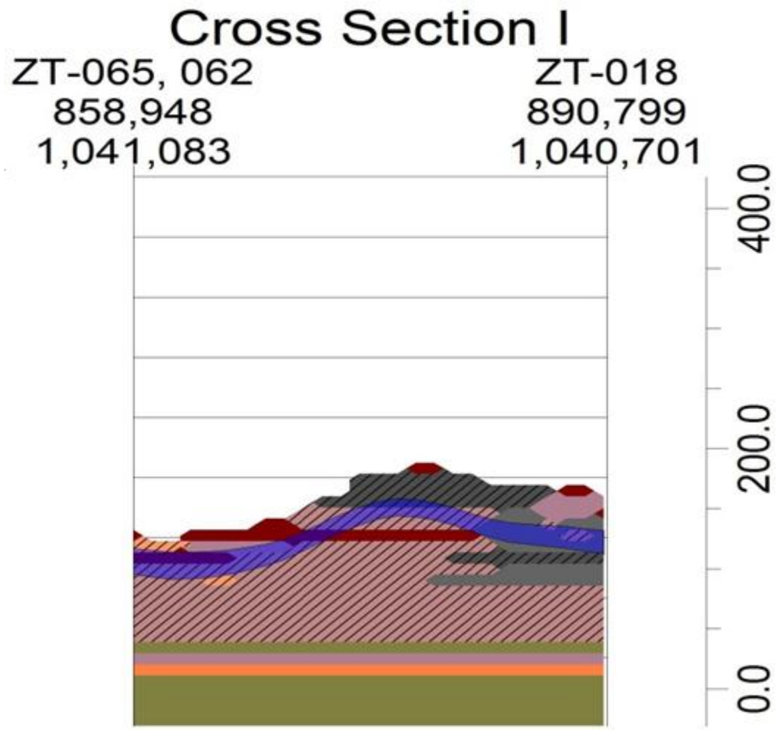
Cross Section B
WM-013, 016
653,383
1,120,963
WM-050
676,421
1,148,796
400.0
200.0
0.0

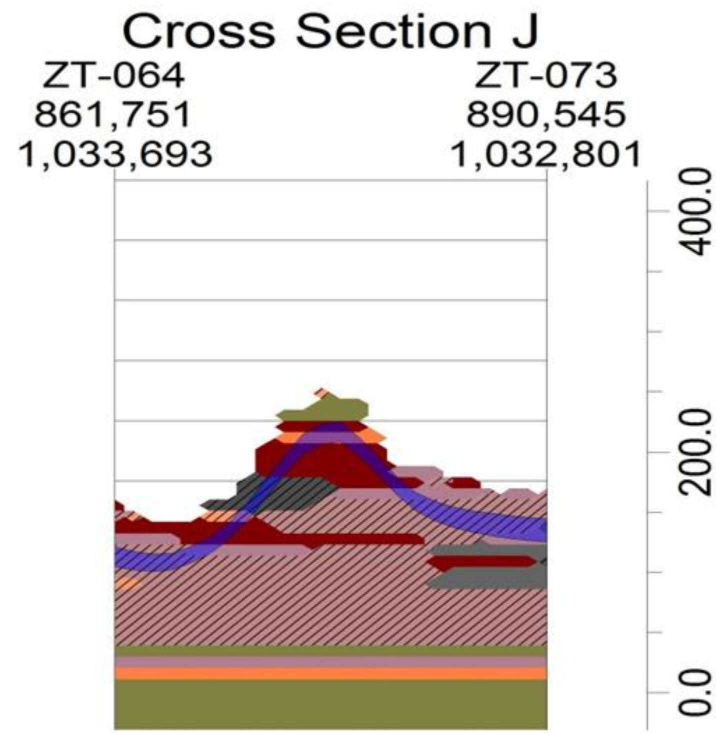

Cross Section C
WM-024
656,173
1,132,361
WM-014
673,142
1,119,651
400.0
200.0
0.0

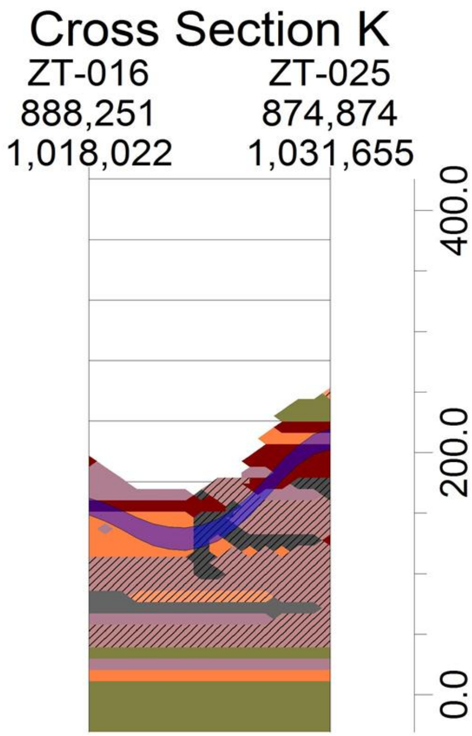

Cross Section D
SN-147
723,985
1,084,407
SN-115
749,477
1,064,627
400.0
200.0
0.0

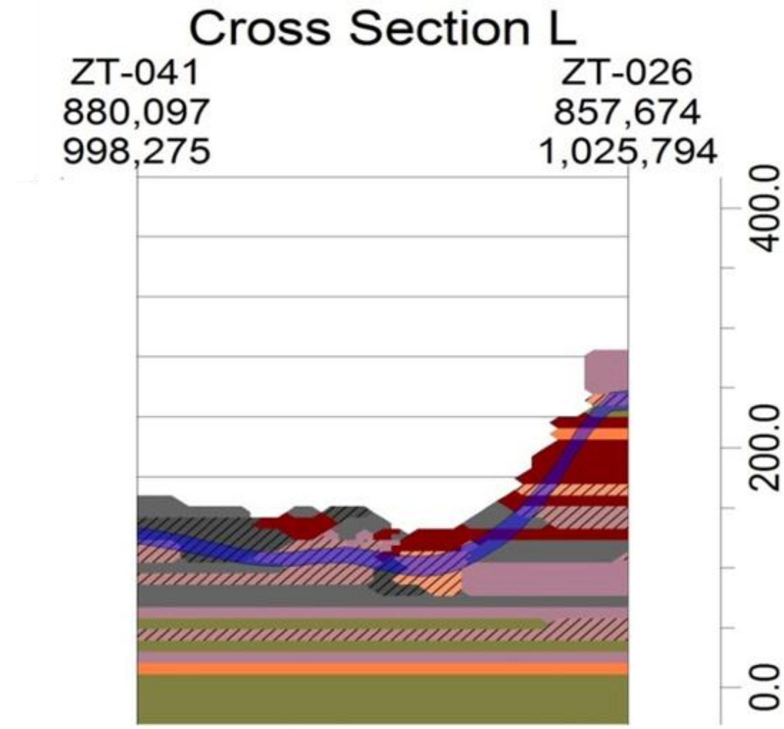

Cross Section E
GK-063
846,601
1,140,017
SC-097, 098
805,401
1,135,548
400.0
200.0
0.0
Cross Section F
GK-087, 089
800,780
1,119,507
GK-043
834,907
1,121,782
400.0
200.0
0.0


Cross Section G
SN-168, 190
724,846
1,100,705
GK-143
780,475
1,104,678
400.0
200.0
0.0
Cross Section H
SC-126, 127
862,394
1,090,066
SC-031
851,658
1,041,567
400.0
200.0
0.0


Cross Section I
ZT-065, 062
858,948
1,041,083
ZT-018
890,799
1,040,701
400.0
200.0
0.0


Cross Section J
ZT-064
861,751
1,033,693
ZT-073
890,545
1,032,801
400.0
200.0
0.0


Cross Section K
ZT-016
888,251
1,018,022
ZT-025
874,874
1,031,655
400.0
200.0
0.0


Cross Section L
ZT-041
880,097
998,275
ZT-026
857,674
1,025,794
400.0
200.0
0.0

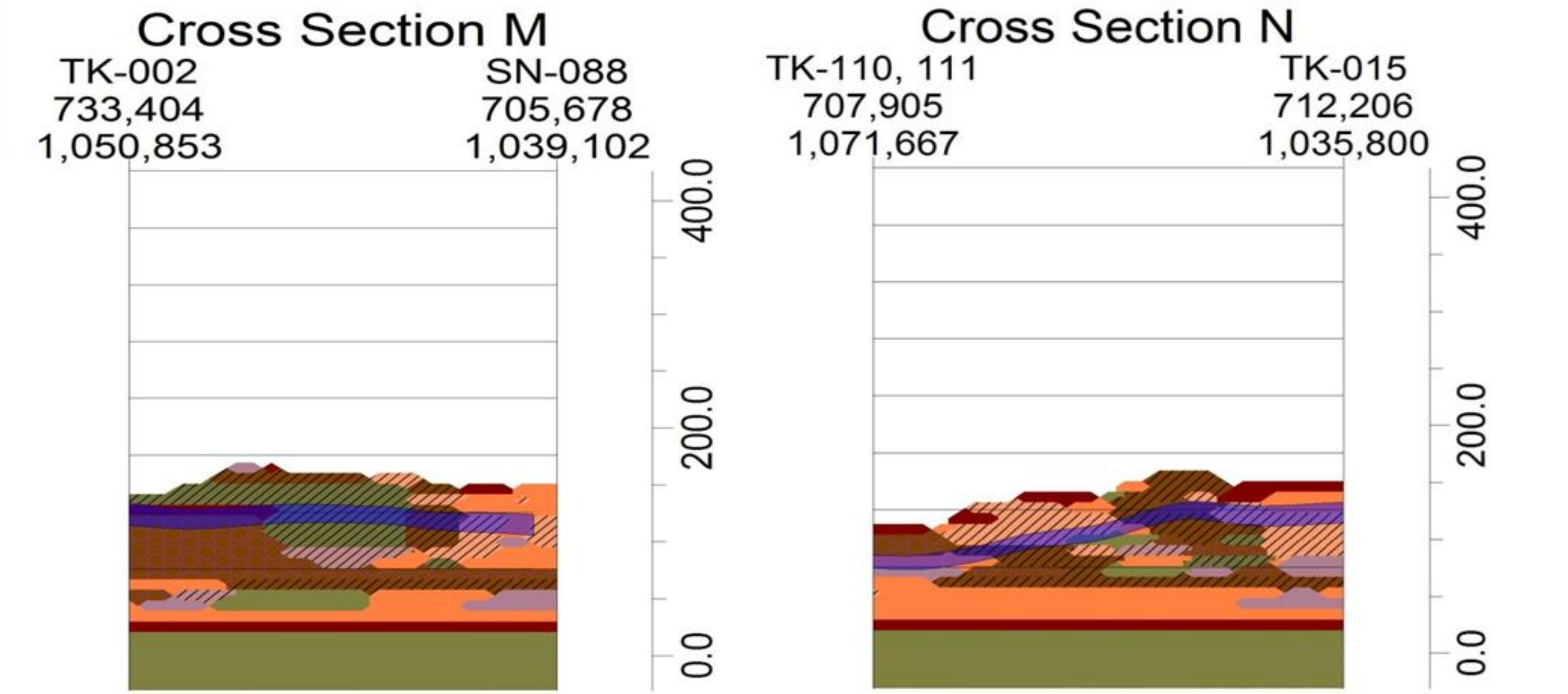


Figure 8. Smaller cross section profiles that represent areas of interest. Areas of interest include ares of clustered dry wells, low yielding wells, or high yield wells. The blue line running through the profile is the interpolated aquifer profile. The coordinates in the upper left and right corners of the profiles are reported in UTM Zone 30, x-easting and y-northing. The vertical tick marks on the y-axis is the elevation reported in meters (RockWorks16, 2013).

Discussion

Transmissivity values reported in the literature are much lower than the values calculated from Equation 2. On average, for the Upper and Middle Voltaian Basin, transmissivity reported in the literature is 13 m^2 day^{-1}, but the extent of area over which this average was calculated is unknown. Transmissivity values from the Nabogo Basin range between 1 and 30 m^2 day^{-1}. Nabogo basin is a small basin located slightly north of Savelugu. This study's project area spans over a large area, therefore, a larger range in transmissivity is acceptable. The boxplot figures reveal higher median and upper quartile lines for fractured sandstone, siltstone, and granite and non-fractured granite, suggesting these lithology types are more favorable for producing higher yield values. This statement is consistent with findings reported in the literature that fractured sandstone areas are most favorable for groundwater development.

Three hundred and sixty eight boreholes in the 879 boreholes logs database were developed into wet wells. This is a 42% success rate based on these finding. A statistic reported in 1996 states a 55% success rate in drilling wet boreholes (Sander et al., 1996). The borehole logs from which this statistic reported in the literature was calculated from are unknown. The borehole logs used in this study span from 2002 to 2010 and do not represent every borehole drilled by GI-WASH; therefore the 42% success rate may not be representative of the overall drilling success rate.

The Voltaian Sedimentary Basin is approximately 3,000 to 4,000 m thick and the average depth of each borehole is approximately 48 m. A detailed representation of the entire basin formation is not represented in these relatively shallow cross sections due to limited data with depth. In order to properly characterize the basin and make decisions based on the preferential depth to drill, experimental boreholes drilled deeper would be necessary. Borehole drilling logs from boreholes drilled deeper than 100 m may exist with other agencies that may have experimentally drilled deeper boreholes.

Depth to water in each borehole was plotted using the aquifer profile for each cross section. This displays a general thickness and location of the aquifer in which each well is drilled into. As already discussed, several assumptions are made when representing the aquifer in this manner. The first is that there is one confined and continuous aquifer throughout the basin. Based on the literature, boreholes are drilling into fractures. In some cases boreholes are not drilled into fractures and yield water, based on this observation we do not rule out the assumption that a continuous or confined aquifer exists. The second assumption is that all boreholes were drilled in the same season. Large variation in water table depth is present in this area due to heavy monsoonal rains followed by a long drought period (Akudago et al., 2009). Some wells were drilled during high water table levels and others in the dry season when the water table has dropped; seasonal variation in water table level is not represented in this study.

Large amounts of error are assumed in cross section interpolations for areas that span locations where few wells occur. This project incorporated all available data. Future data collection in the Northern Region can reduce the amount of error that may be reported in these cross sections, and provide a better understanding of the hydrogeologic framework.

The focus of this project was to present a preliminary understanding of the regional hydrogeology in the Northern Region. This project presents the utility of RockWorks16 and its usefulness in generating cross sections from borehole log data for use in improving drilling success rates. The database used to create a regional hydrogeologic map was constructed from borehole drilling logs collected only from GI-WASH. Other non-governmental agencies (NGOs), and the government of Ghana have drilled in the Northern Region and the addition of their borehole logs would help complete these cross sections for a better representation at the regional scale, and potentially reduce error or uncertainty.

Conclusions

The information used to create cross sections of the Northern Region is the foundation for a more robust study of hydrogeology in this region to ensure sustainable groundwater development. An electronic database of all available borehole drilling logs from GI-WASH did not exist at the start of this project. Collecting these data and organizing them in a way that was useful for input into RockWorks16 and ArcGIS was the first and most time consuming task. The main goals of this study were to collect and validate borehole drilling logs, construct a database, compile available data for trasmissivity and specific capacity calculations, and make connections between lithology and available yield. An ancillary goal was to evaluate the usefulness and visual outputs of RockWorks16 for use in other WVI projects. These goals were achieved throughout the project and serve as the basis for more comprehensive analyses. Future work would entail entering more borehole drilling logs from GI-WASH, and collecting more logs from other NGOs, and the government of Ghana. Additional information is likely to decrease the level of error reported in the regional scale hydrogeologic map due to large interpolation across the study area. Additional borehole logs and aquifer test data would allow not only more accurately constructed hydrogeological maps but also more calculations on the aquifer for better characterization of the regional groundwater source and promote sustainable development.

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5.0 Summary

A database of 879 borehole drilling logs was constructed in Excel and imported to RockWorks16. The borehole drilling logs were collected from the Northern Region in Ghana throughout the Voltaian Basin. Lithologies reported in the drilling logs were standardized into 11 categories focused around fractured and non-fractured lithology units. RockWorks16 was used to create a 3D solid model of the regional hydroegologic framework and 2D profile cross sections focused on areas of interest: four west-to-east regional scale cross sections and four north-to-south regional scale cross sections. Review of available literature suggests that rock type and especially fractures control the location of groundwater and groundwater yield, therefore, these units were the focus for the lithology standardization. This regional solid model and cross sections should provide the start to more insight to the regional hydrogeologic framework to improve drilling success rates.

One hundred forty well logs contained aquifer test data needed to calculate transmissivity and specific capacity of the aquifer. Yield for all constructed wet wells was normalized by dividing it by the aquifer interval length. The normalized yield values were plotted using a boxplot graph format for each standardized lithological unit. A visual comparison was made between each lithology and normalized yield values. Fractured sandstone, siltstone, and granite showed the highest median, maximum, and upper quartile lines for normalized yield values. Non-fractured granite, sandstone, and mudstone produced the highest median, maximum, and upper quartile line for normalized yield compared to all other non-fractured lithology units. Based on several assumptions and limited available data it appears that fractured sandstone, siltstone, granite, and non-fractured granite, sandstone, and mudstone are most likely to produce the highest yield values when drilled into.

There is a need to collect more borehole drilling logs to gain a better spatial representation of the entire Northern Region. Additional aquifer test data are also needed to better characterize the aquifer throughout the basin. Large amounts of interpolation error are present in the cross sections that span the entire study area due to spatial distribution of borehole logs. Even though large amounts of error may be present in the overall 3D map of the hydrogeologic framework of the basin, and in each cross section, this information will serve as the basis for future analyses as more data are added to the database.

6.0 Conclusions

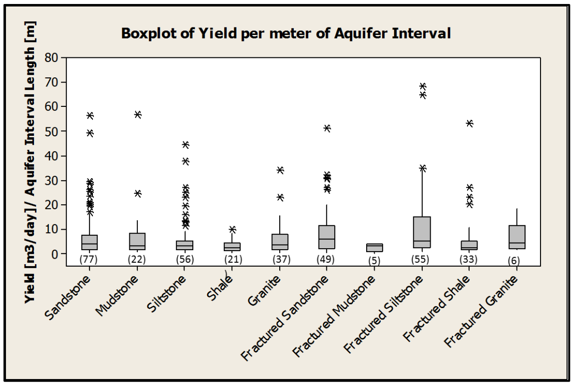
The information used to create cross sections of the Northern Region is the foundation for a more robust study of hydrogeology in this region to ensure sustainable groundwater development. A database of all available borehole drilling logs from GI-WASH did not exist at the start of this project. Collecting this data and organizing it in a way that was useful for input into RockWorks16 and ArcGIS was the first and most time consuming task. The main goals of this study were to collect and validate borehole drilling logs, construct a database, compile available data for trasmissivity and specific capacity calculations, and make connections between lithology and available yield. An ancillary goal was to evaluate the usefulness and visual outputs of RockWorks16 for use in other WVI projects. These goals were achieved throughout the project and serve as the basis for more comprehensive analyses. Future work would entail entering more borehole drilling logs from GI-WASH, and collecting more logs from other NGOs, and the government of Ghana. Additional information is likely to decrease the level of error reported in the regional scale hydrogeologic map due to large interpolation across the study area. Additional borehole logs and aquifer test data would allow not only more accurately constructed hydrogeological maps but also more calculations on the aquifer for better characterization of the regional groundwater source and promote sustainable development.

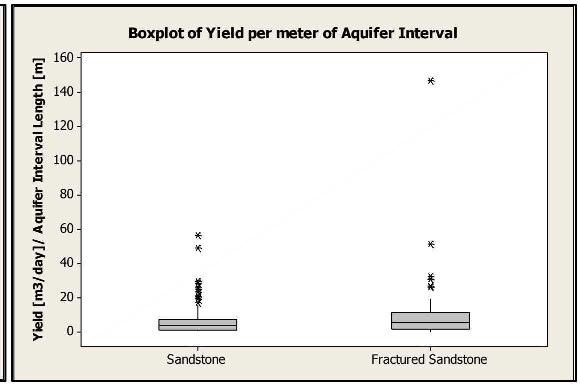
7.0 Recommendations

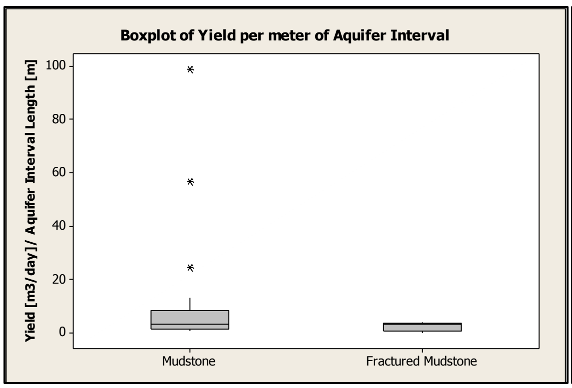
It is recommended that any currently available and future drilling logs be added to the GI-WASH Rockworks16 database. This will decrease the error in the interpolated 3D map and cross sections. This information can then be used to determine where and how deep to drill future wells to increase drilling success rates and well yields. Future analysis may also include more aquifer test data and a better understanding of aquifer recharge, hydraulic conductivity, transmissivity, and specific capacity for a regional water budget. The long term goal of this study is to contribute a continuous geologic framework that is representative to the heterogeneous complex geology of the basin to construct a three-dimensional groundwater/surface water flow model.

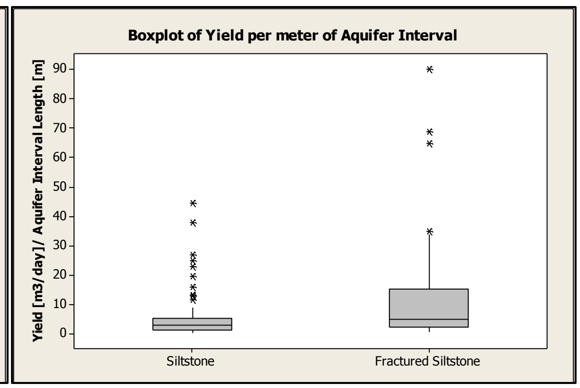
8.0 Appendix

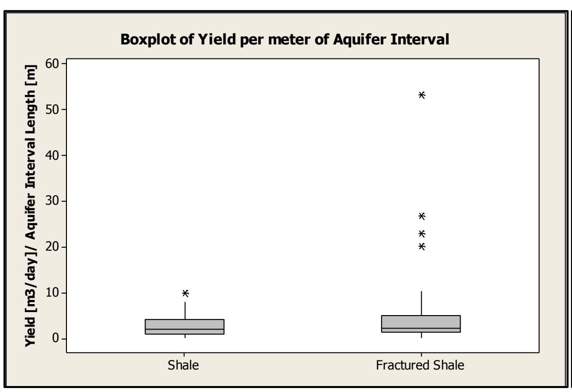
8.1. Boxplots

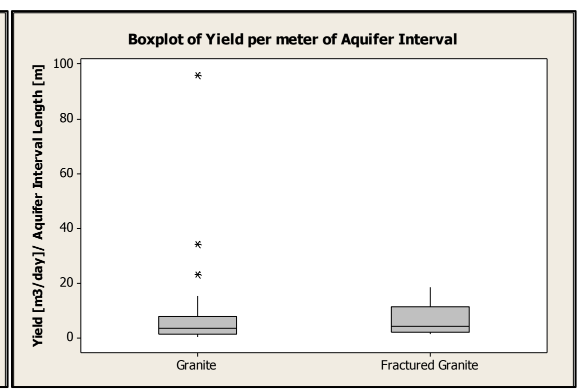


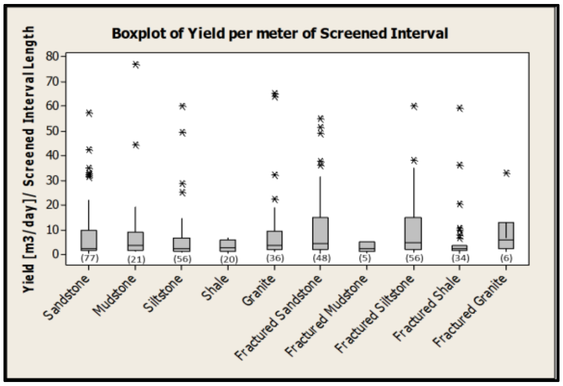


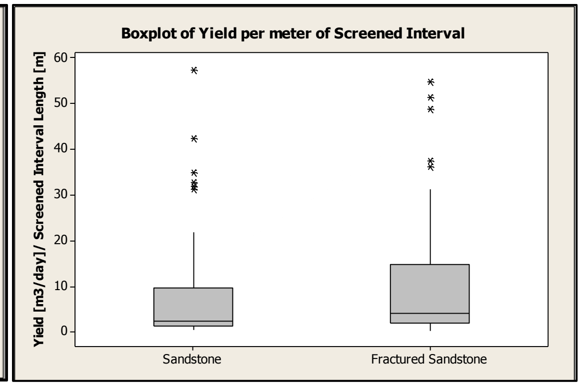


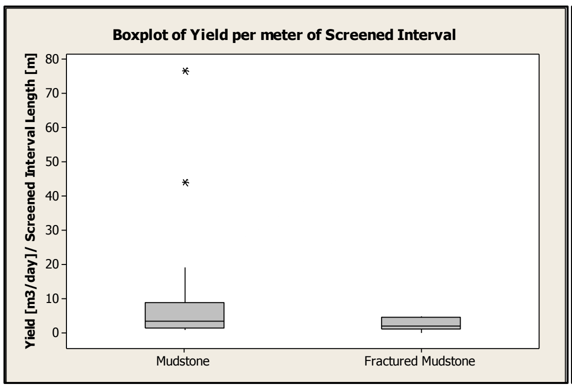


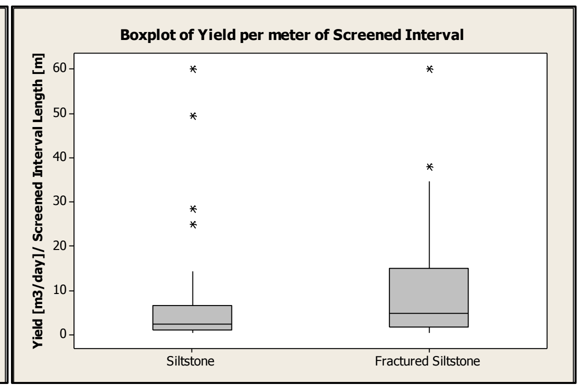


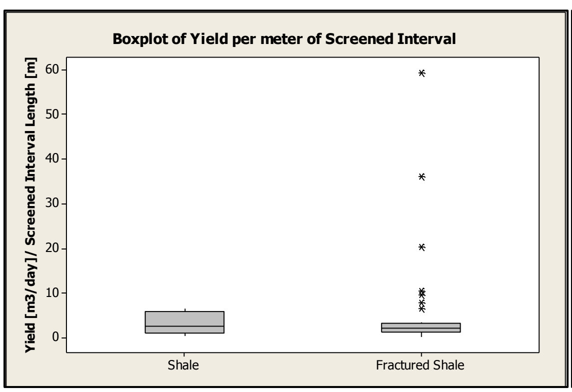


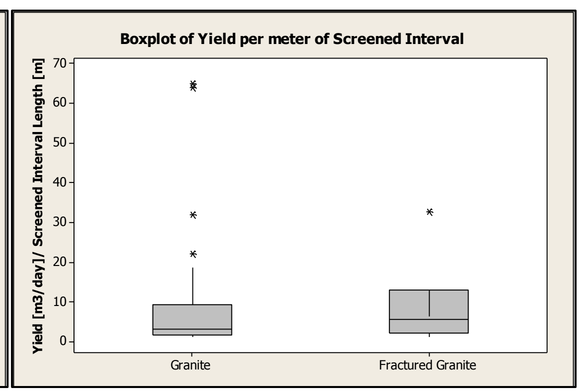

Boxplot of Yield per meter of Screened Interval
Yield [m3/day]/ Screened Interval Length
80
70
60
50
40
30
20
10
0
(77)
(21)
(56)
(20)
(36)
(48)
(5)
(56)
(34)
(6)
Sandstone
Mudstone
Siltstone
Shale
Granite
Fractured Sandstone
Fractured Mudstone
Fractured Siltstone
Fractured Shale
Fractured Granite


Boxplot of Yield per meter of Screened Interval
Yield [m3/day]/ Screened Interval Length [m]
60
50
40
30
20
10
0
Sandstone
Fractured Sandstone


Boxplot of Yield per meter of Screened Interval
Yield [m3/day]/ Screened Interval Length [m]
80
70
60
50
40
30
20
10
0
Mudstone
Fractured Mudstone

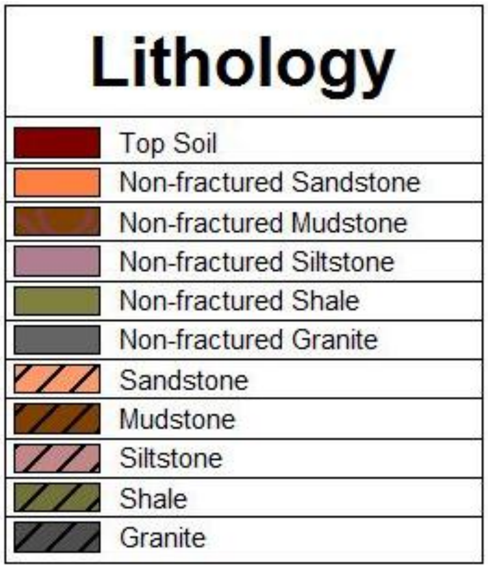

Boxplot of Yield per meter of Screened Interval
Yield [m3/day]/ Screened Interval Length [m]
60
50
40
30
20
10
0
Siltstone
Fractured Siltstone

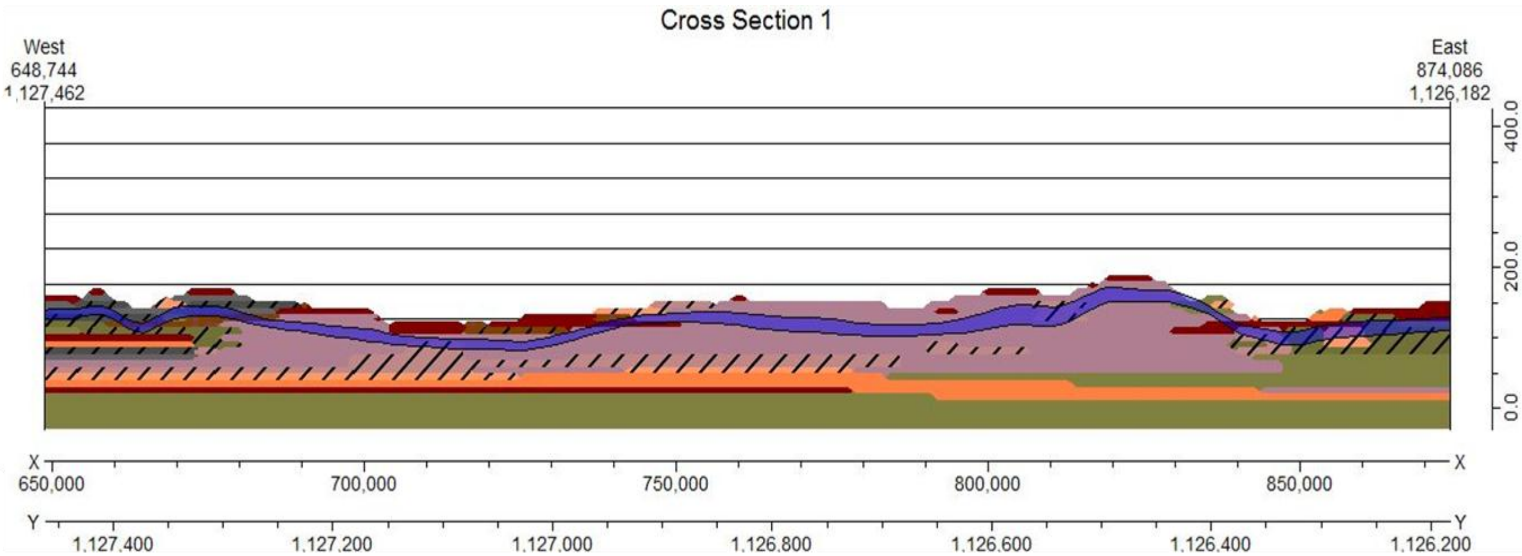

Boxplot of Yield per meter of Screened Interval
Yield [m3/day]/ Screened Interval Length [m]
60
50
40
30
20
10
0
Shale
Fractured Shale

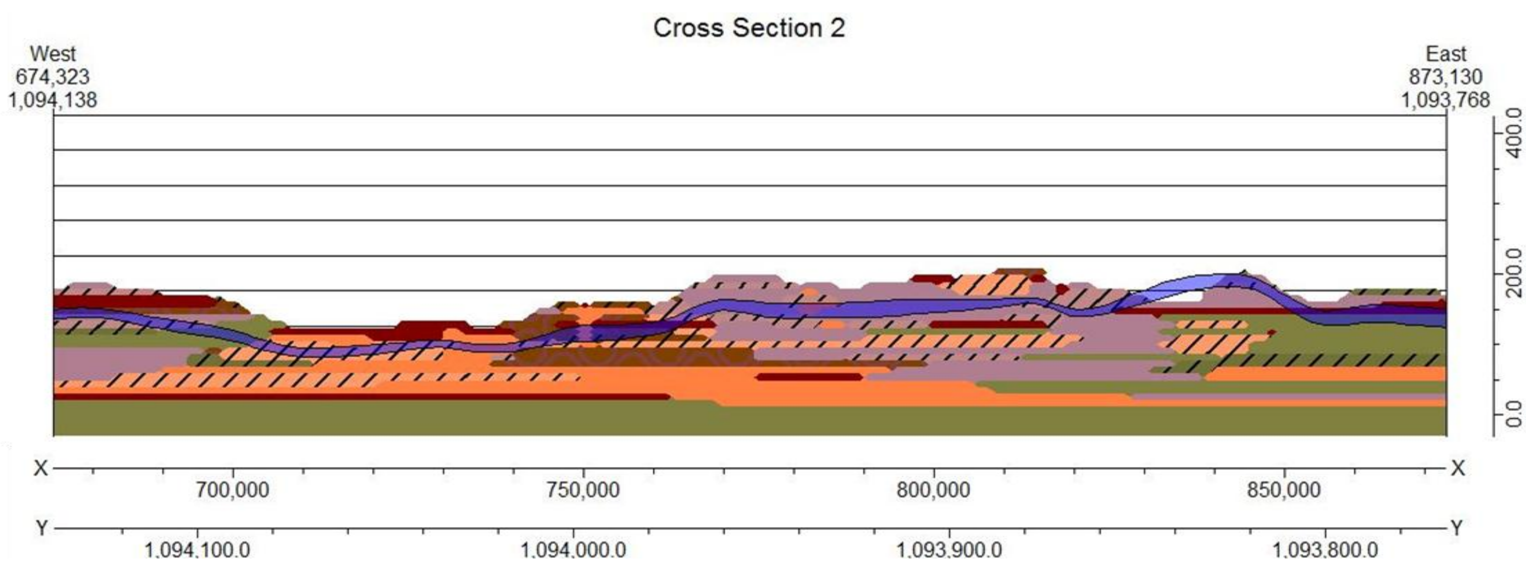

Boxplot of Yield per meter of Screened Interval
Yield [m3/day]/ Screened Interval Length [m]
70
60
50
40
30
20
10
0
Granite
Fractured Granite

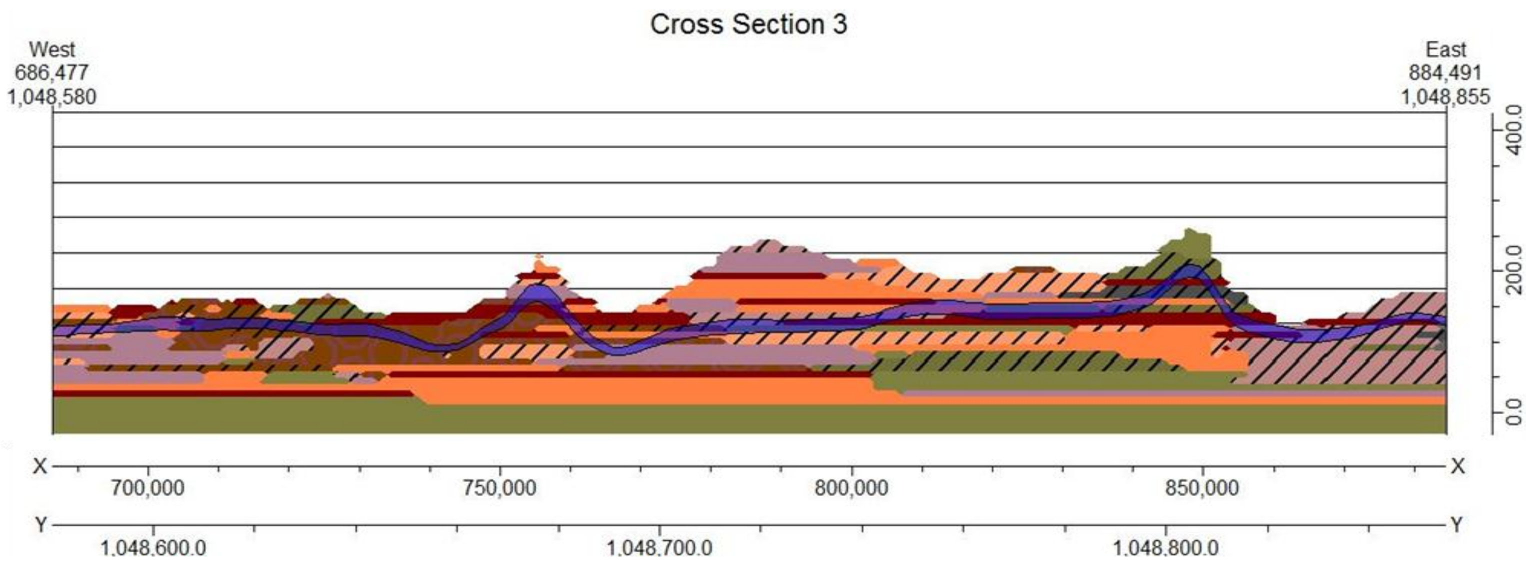
8.2. Cross sections

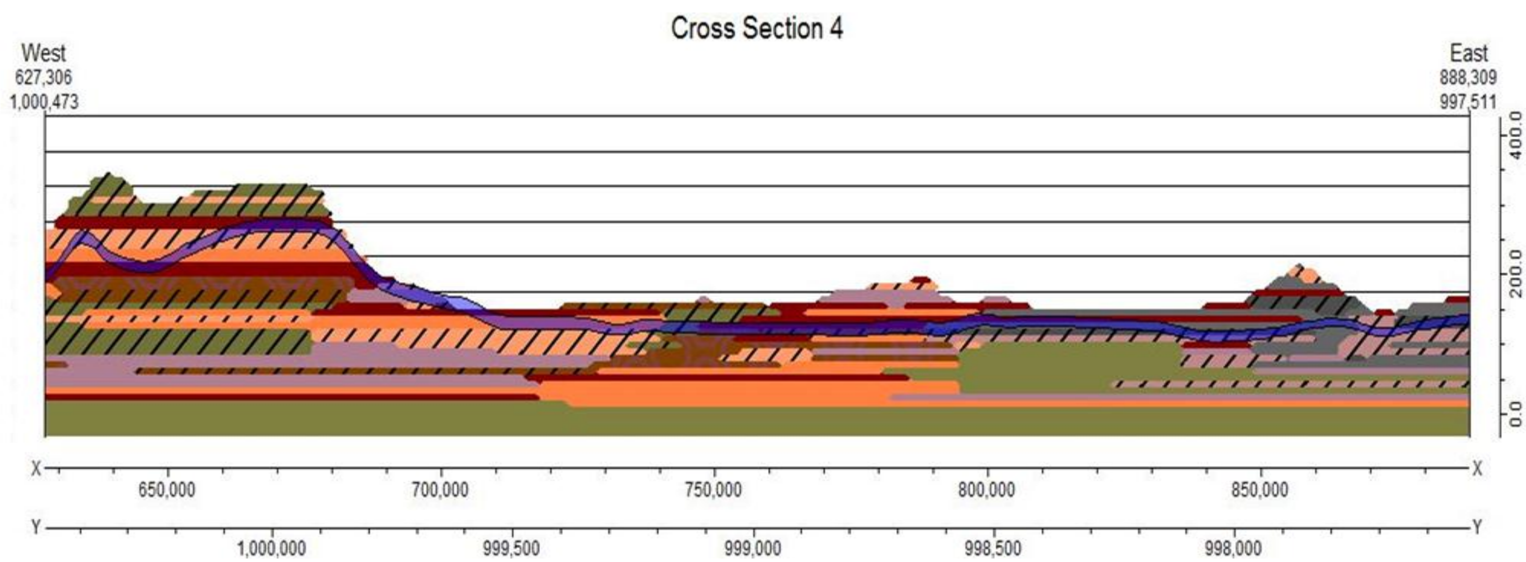
8.2.1. West to East



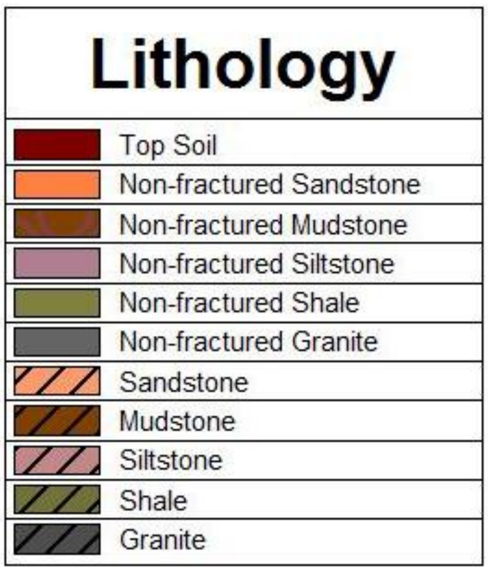

Cross Section 1
West
648,744
1,127,462
East
874,086
1,126,182
400.0
200.0
0.0
X
650,000
700,000
750,000
800,000
850,000
X
Y
1,127,400
1,127,200
1,127,000
1,126,800
1,126,600
1,126,400
1,126,200
Y

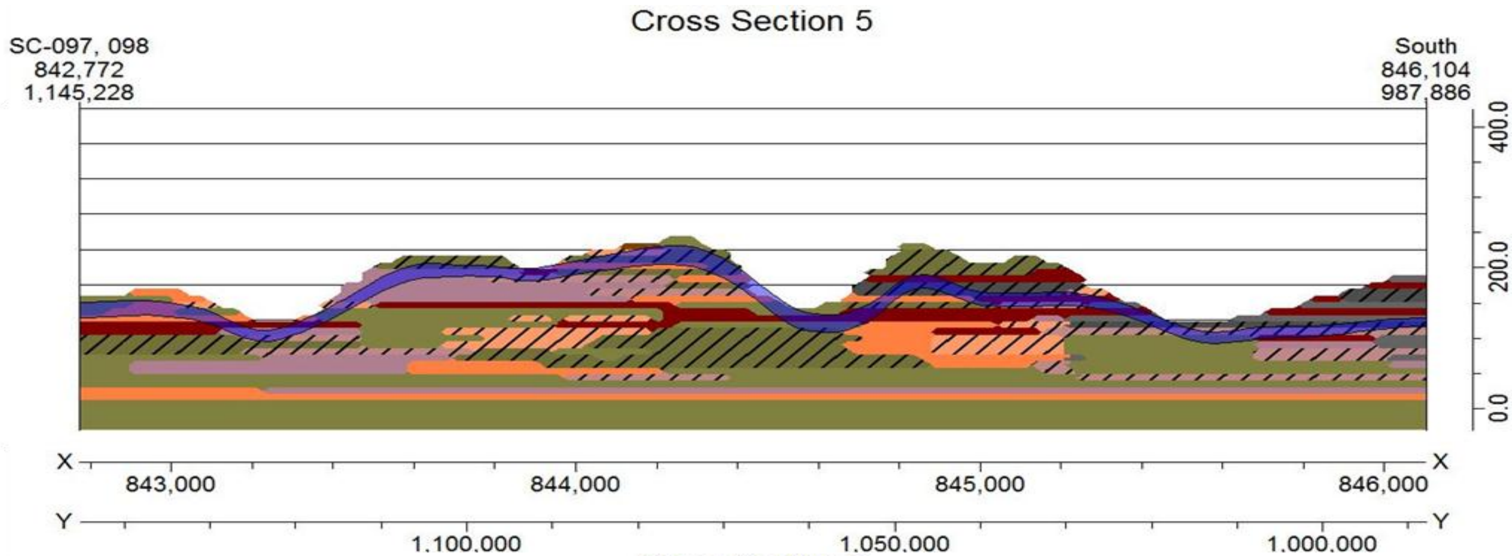

Cross Section 2
West
674,323
1,094,138
East
873,130
1,093,768
400.0
200.0
0.0
X
700,000
750,000
800,000
850,000
X
Y
1,094,100.0
1,094,000.0
1,093,900.0
1,093,800.0
Y

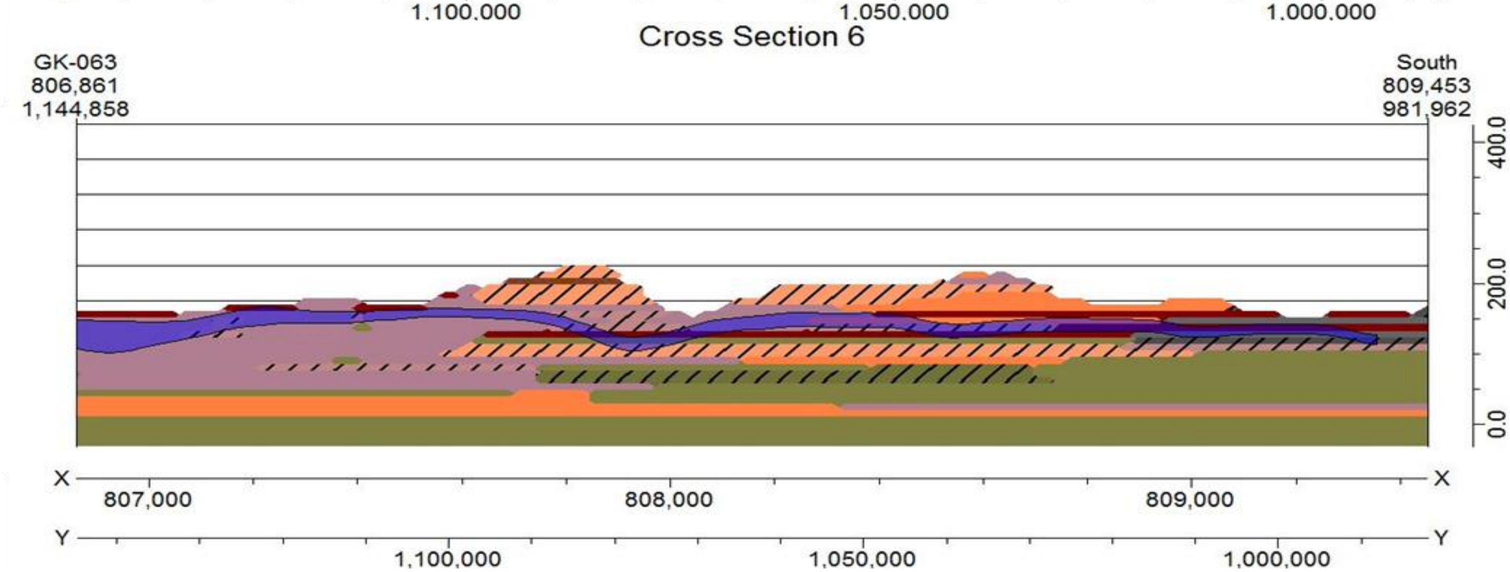

Cross Section 3
West
686,477
1,048,580
East
884,491
1,048,855
400.0
200.0
0.0
X
700,000
750,000
800,000
850,000
Y
1,048,600.0
1,048,700.0
1,048,800.0

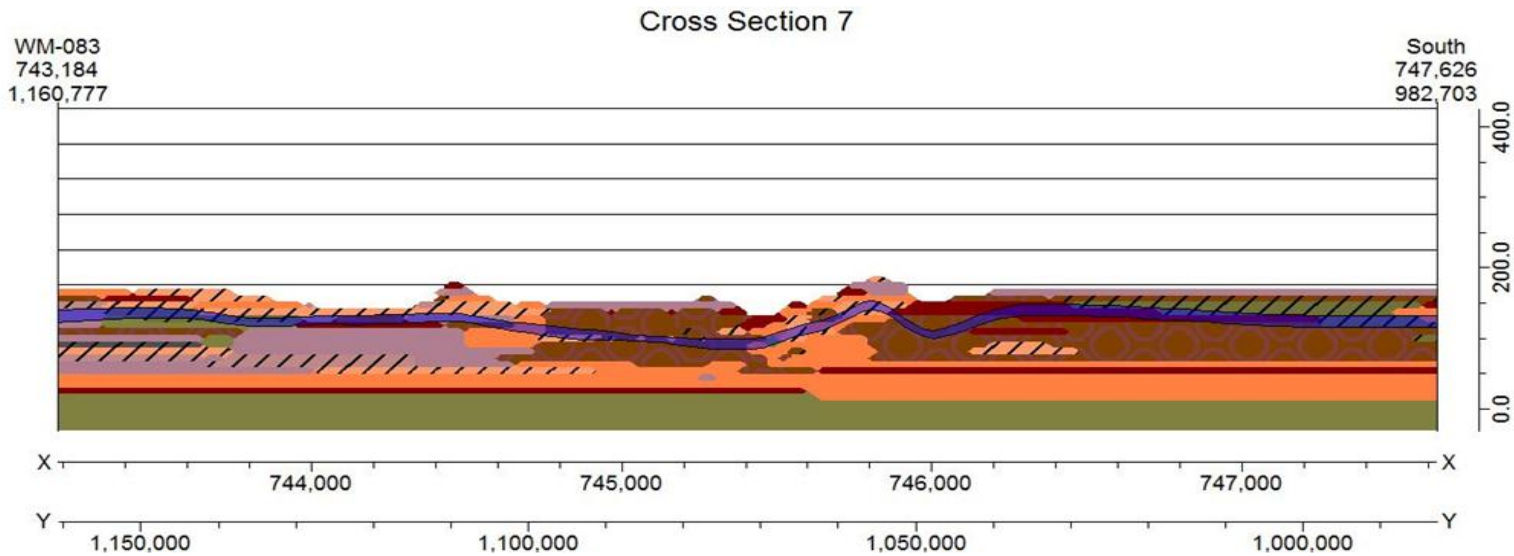

Cross Section 4
West
627,306
1,000,473
East
888,309
997,511
400.0
200.0
0.0
X
650,000
700,000
750,000
800,000
850,000
Y
1,000,000
999,500
999,000
998,500
998,000

8.2.2. North to South

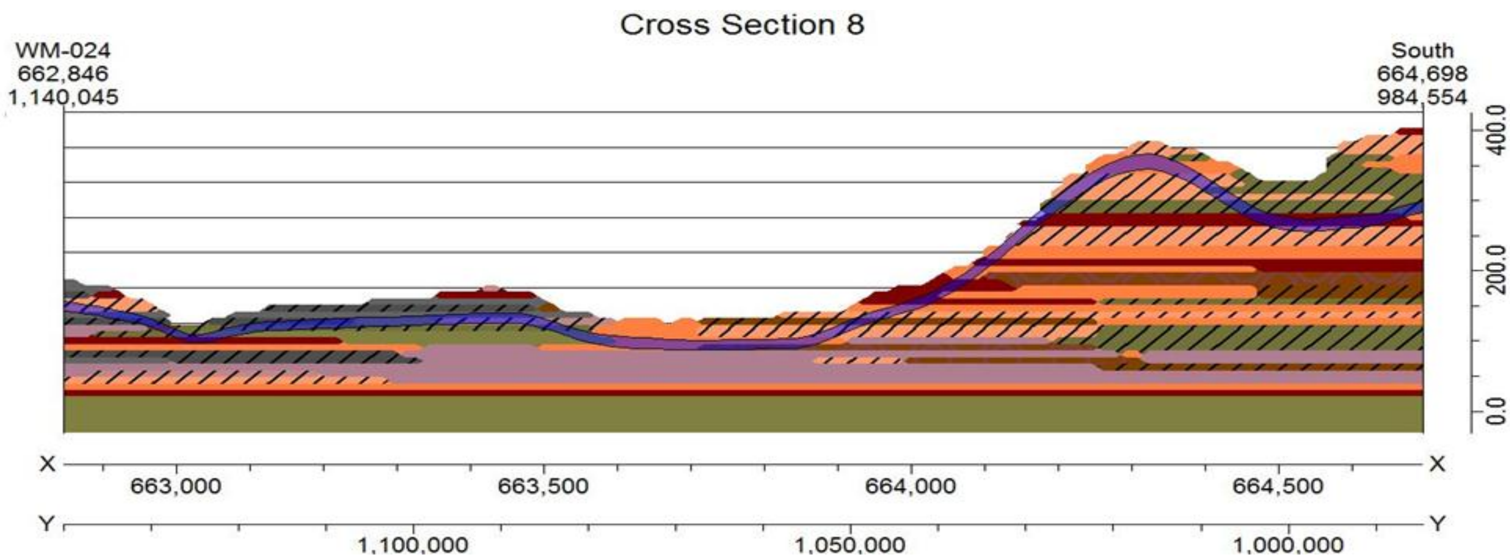



Cross Section 5
SC-097, 098
842,772
1,145,228
South
846,104
987,886
400.0
200.0
0.0
X
843,000
844,000
845,000
846,000
X
Y
1,100,000
1,050,000
1,000,000
Y

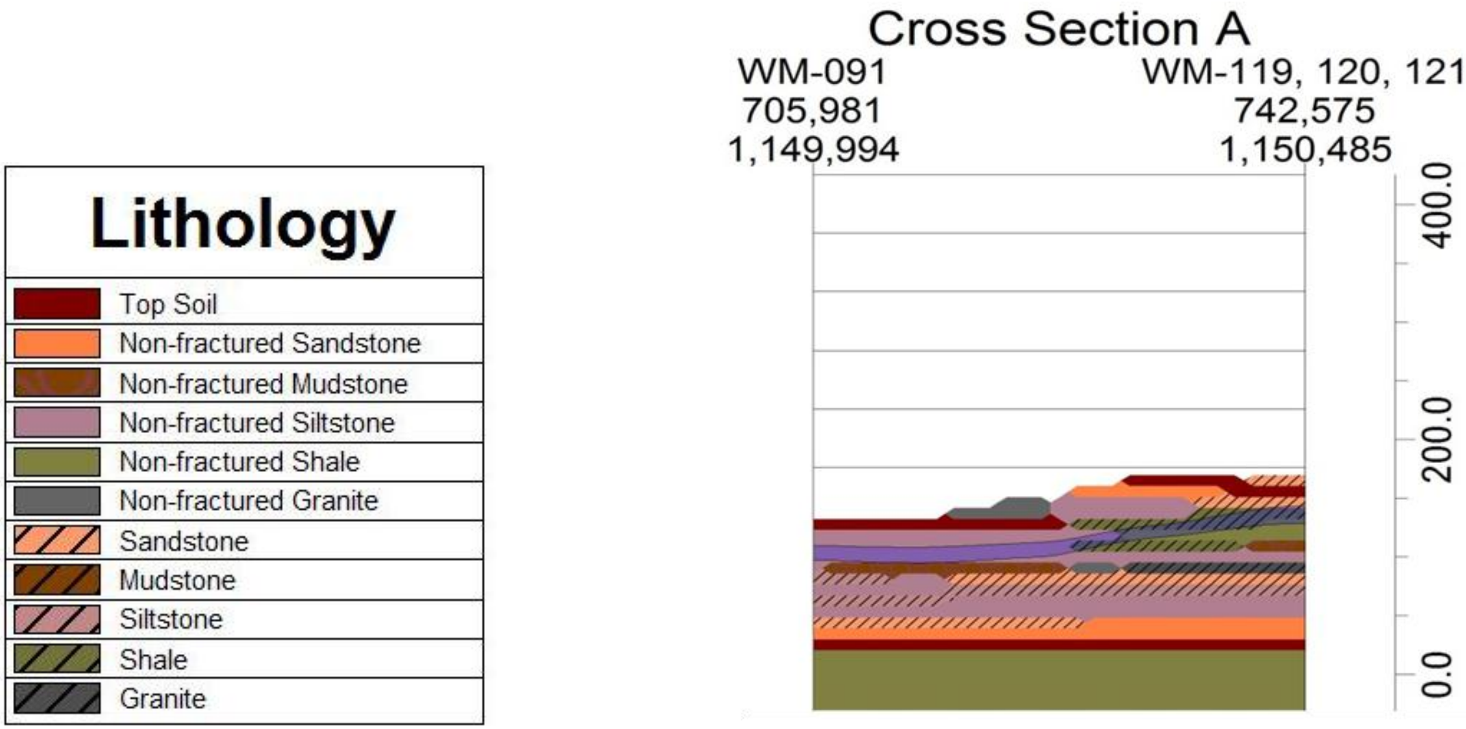

Cross Section 6
GK-063
806,861
1,144,858
South
809,453
981,962
400.0
200.0
0.0
X
807,000
808,000
809,000
X
Y
1,100,000
1,050,000
1,000,000
Y

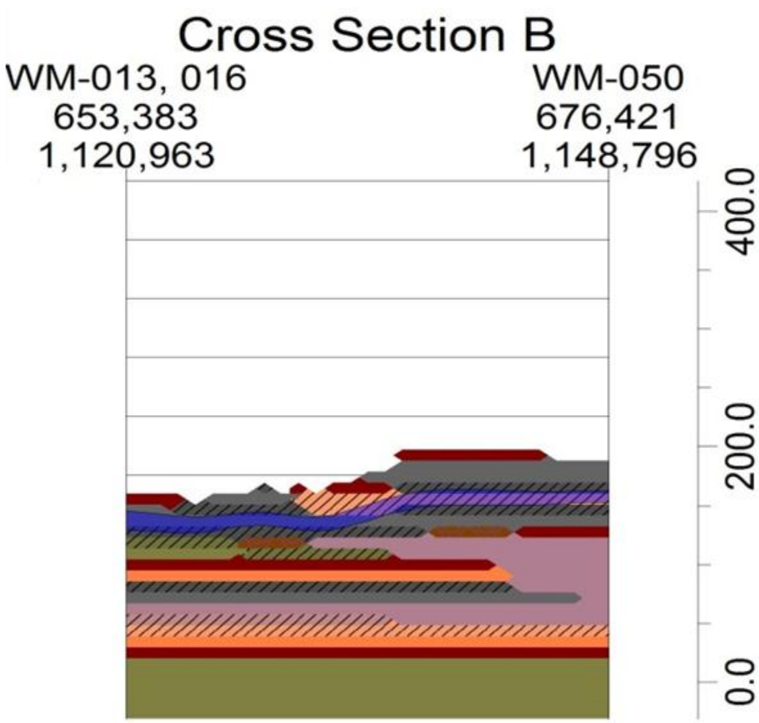


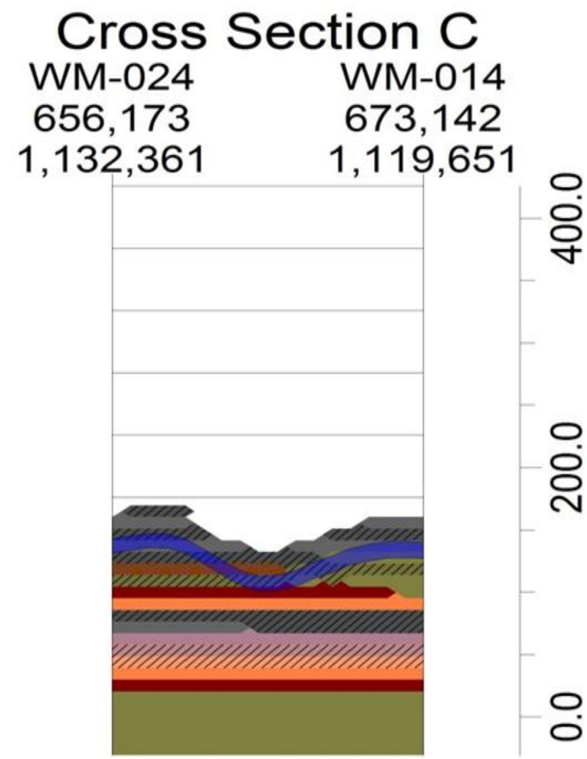
Cross Section 7
WM-083
743,184
1,160,777
South
747,626
982,703
400.0
200.0
0.0
X
744,000
745,000
746,000
747,000
X
Y
1,150,000
1,100,000
1,050,000
1,000,000
Y

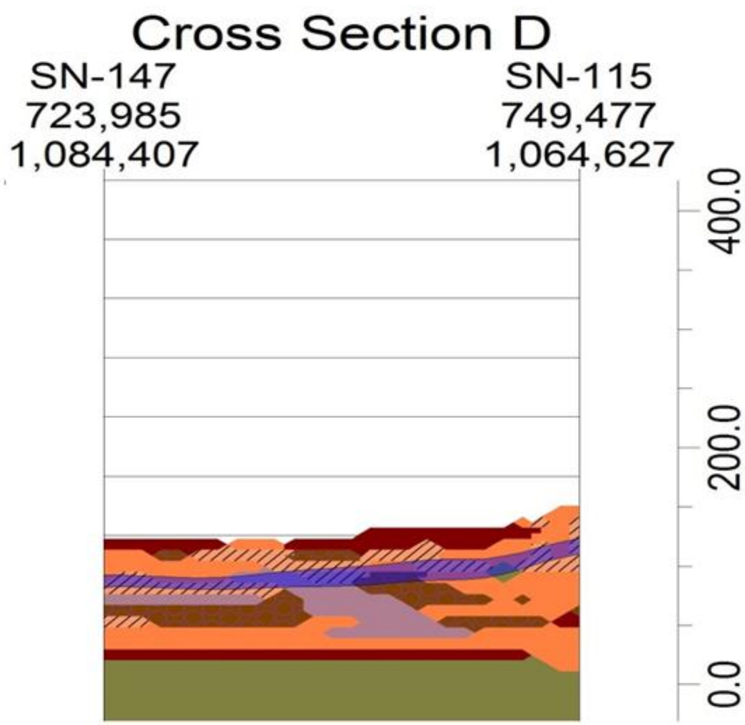

Cross Section 8
WM-024
662,846
1,140,045
South
664,698
984,554
400.0
200.0
0.0
X
663,000
663,500
664,000
664,500
X
Y
1,100,000
1,050,000
1,000,000
Y

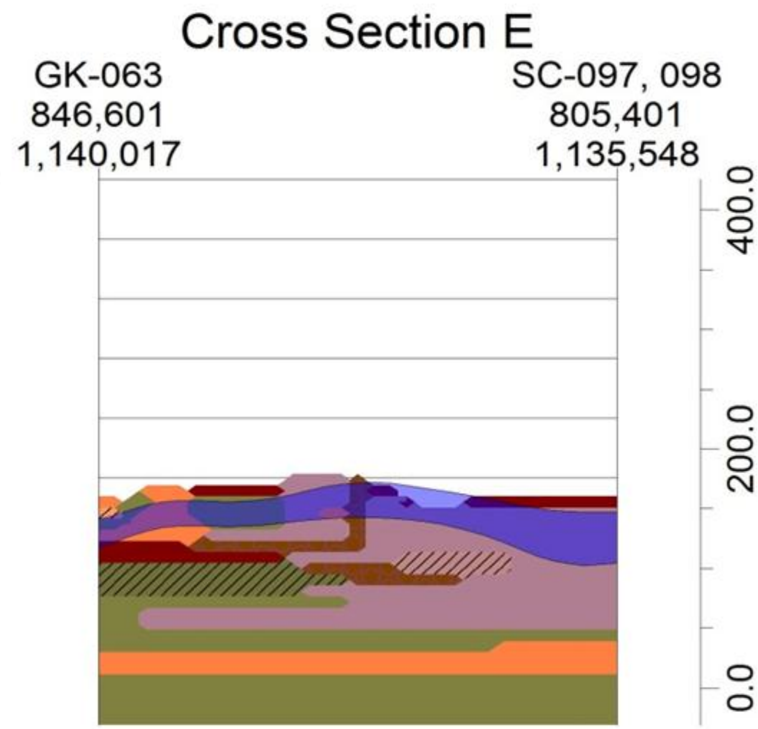
8.2.3. Areas of Interest

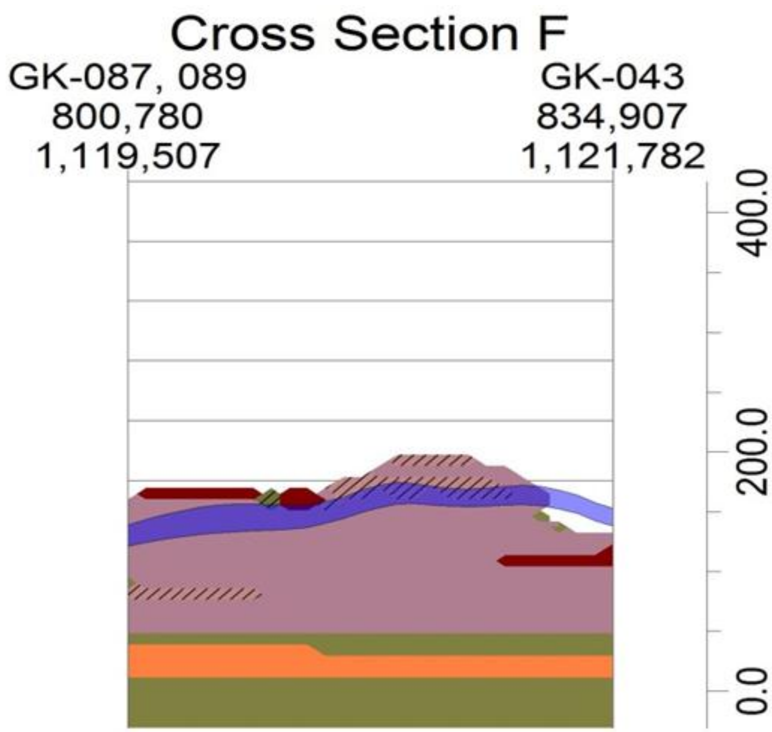


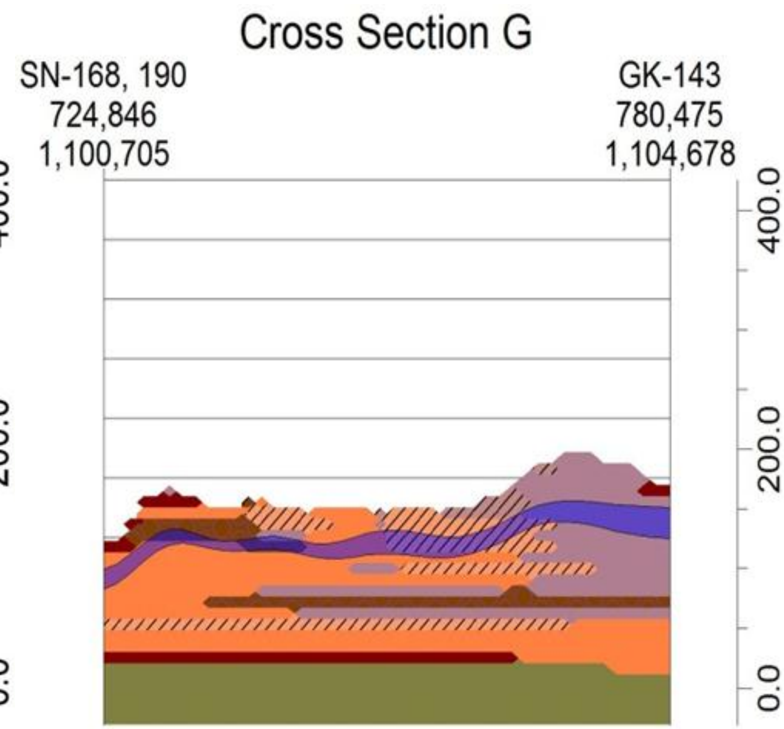

Cross Section B
WM-013, 016
653,383
1,120,963
WM-050
676,421
1,148,796
400.0
200.0
0.0

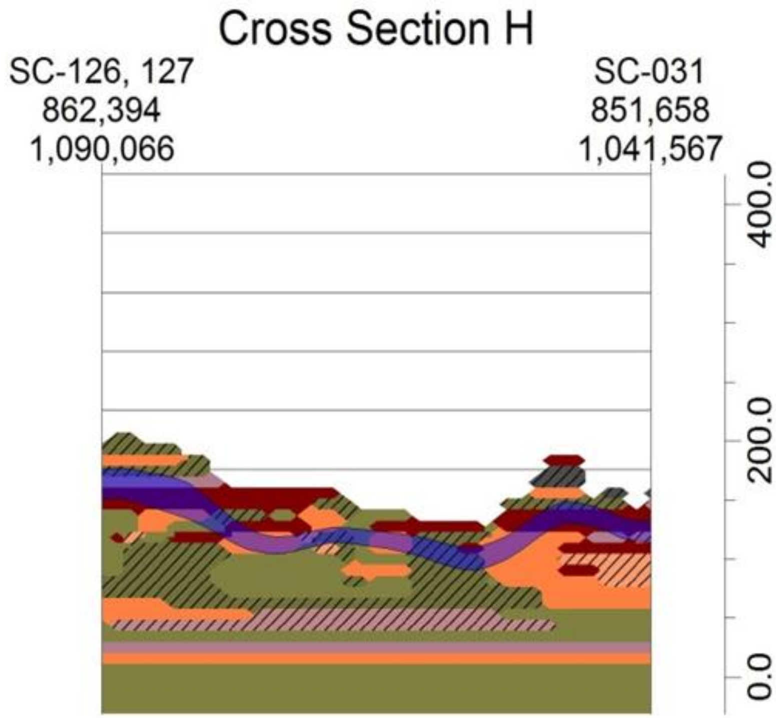

Cross Section C
WM-024
656,173
1,132,361
WM-014
673,142
1,119,651
400.0
200.0
0.0

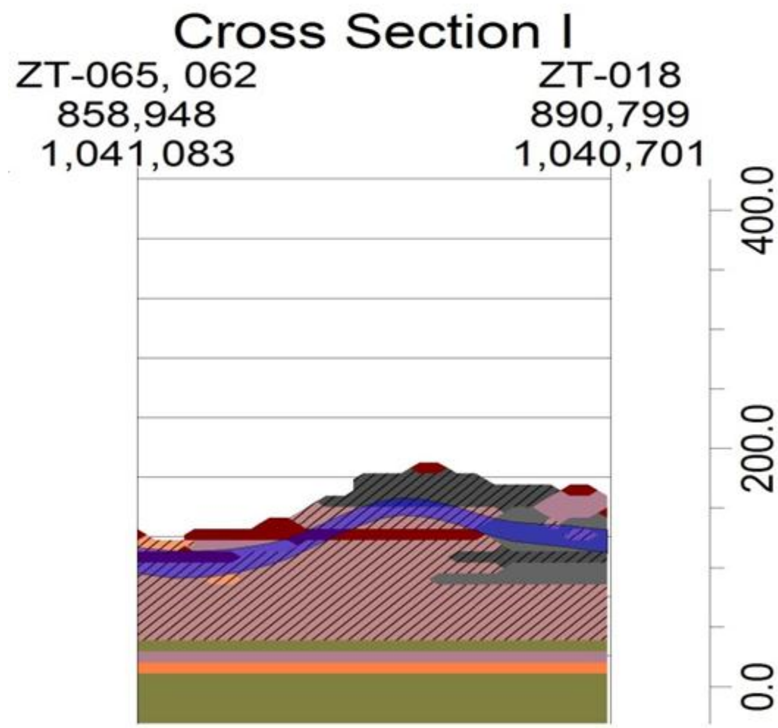

Cross Section D
SN-147
723,985
1,084,407
SN-115
749,477
1,064,627
400.0
200.0
0.0

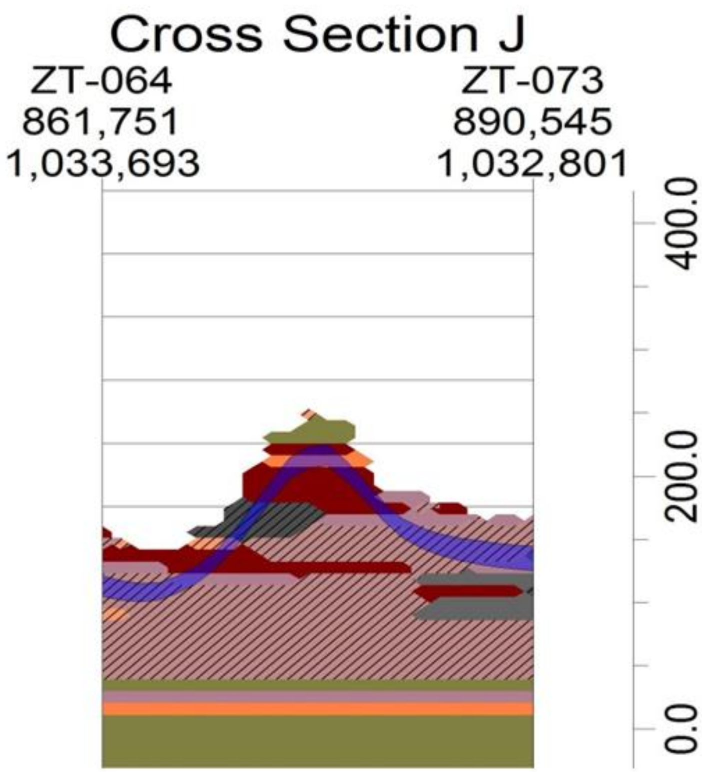

Cross Section E
GK-063
846,601
1,140,017
SC-097, 098
805,401
1,135,548
400.0
200.0
0.0

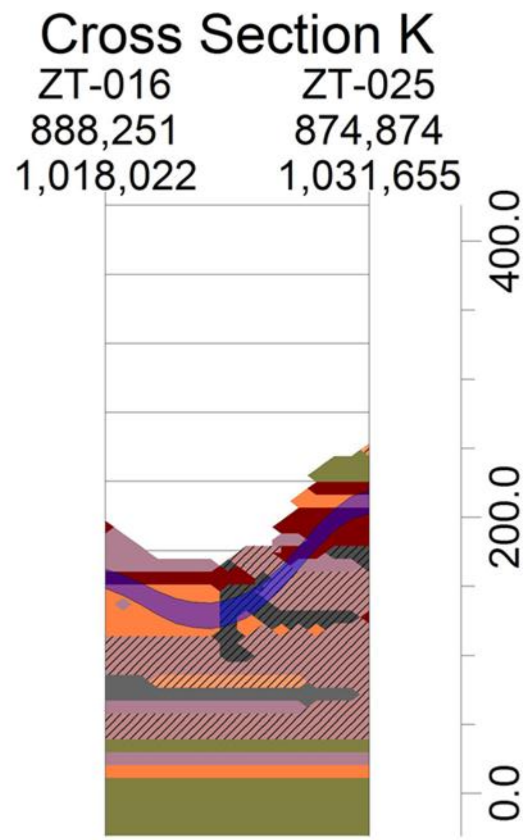

Cross Section F
GK-087, 089
800,780
1,119,507
GK-043
834,907
1,121,782
400.0
200.0
0.0

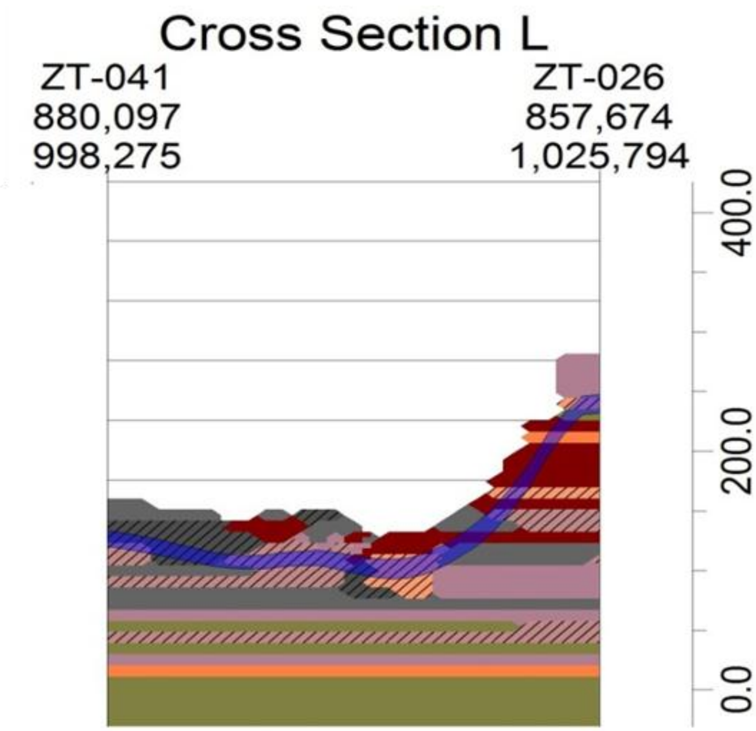

Cross Section G
SN-168, 190
724,846
1,100,705
GK-143
780,475
1,104,678
400.0
200.0
0.0

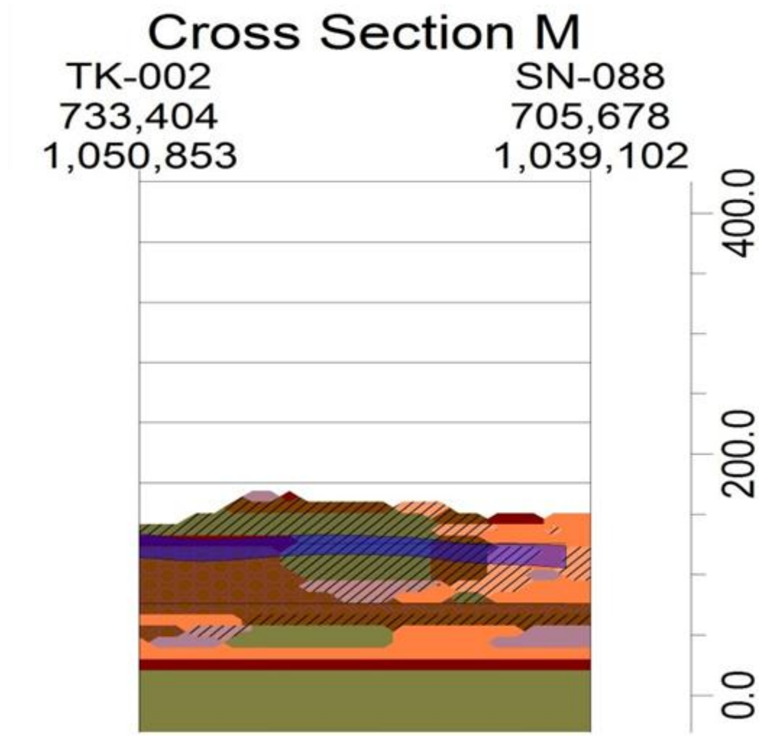

Cross Section H
SC-126, 127
862,394
1,090,066
SC-031
851,658
1,041,567
400.0
200.0
0.0

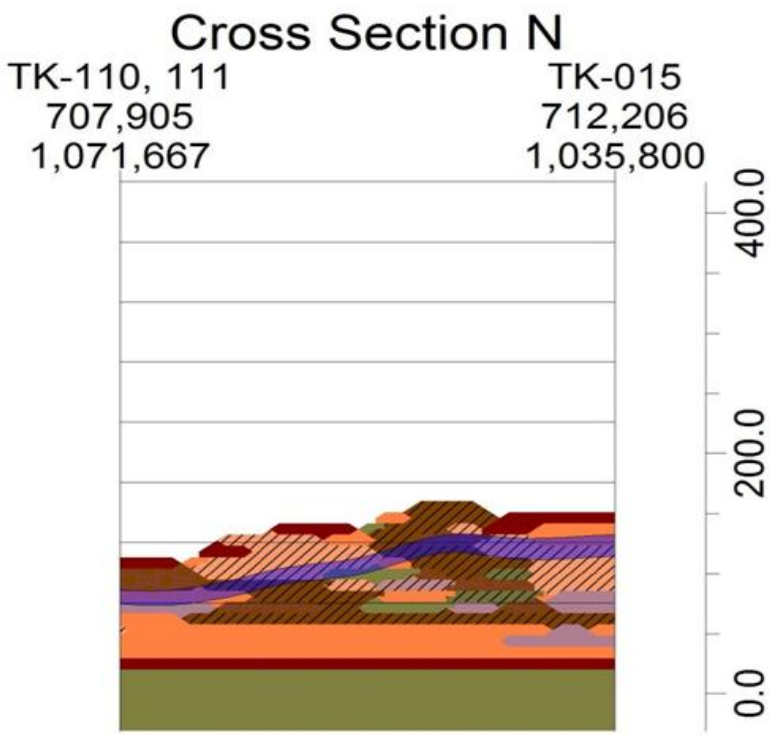

Cross Section I
ZT-065, 062
858,948
1,041,083
ZT-018
890,799
1,040,701
400.0
200.0
0.0


Cross Section J
ZT-064
861,751
1,033,693
ZT-073
890,545
1,032,801
400.0
200.0
0.0


Cross Section K
ZT-016
888,251
1,018,022
ZT-025
874,874
1,031,655
400.0
200.0
0.0


Cross Section L
ZT-041
880,097
998,275
ZT-026
857,674
1,025,794
400.0
200.0
0.0


Cross Section M
TK-002
733,404
1,050,853
SN-088
705,678
1,039,102
400.0
200.0
0.0


Cross Section N
TK-110, 111
707,905
1,071,667
TK-015
712,206
1,035,800
400.0
200.0
0.0

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