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HYDROGEOLOGIC CHARACTERIZATION OF THE ANTLERS FORMATION AND AQUIFER IN SOUTHERN AND SOUTHEASTERN OKLAHOMA

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HYDROGEOLOGIC CHARACTERIZATION OF THE ANTLERS FORMATION AND AQUIFER IN SOUTHERN AND SOUTHEASTERN OKLAHOMA

A THESIS APPROVED FOR THE
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Abstract

The Cretaceous-aged Antlers Formation crops out in several counties just north of the Texas border in southern and southeastern Oklahoma. The Antlers is composed of sands, conglomerates, clays, and limestones that lie unconformably over Paleozoic rocks, which forms the Antlers Aquifer, the fourth largest aquifer in Oklahoma in terms of storage volume. There have been no hydrogeologic investigations of the aquifer since a 1992 USGS report that estimated the hydraulic conductivity to range from 0.87–3.75 ft/day. In the absence of comprehensive studies of the Antlers, the goals of this study were to examine existing depositional models of the Antlers and understand the geologic controls on the aquifer's hydraulic properties in Marshall, Johnston, and Carter Counties. Field investigations included observations of lithologies and outcrop characteristics. Samples were collected from numerous locations that were spatially distributed throughout the study area. Laboratory studies included grain-size analyses, which were used to estimate hydraulic conductivity of the Antlers.

Based on field observations, the previously postulated depositional environment of deltaic and alluvial fan deposits that transitioned into fluvial environments appears to be reasonable. Sample collection and laboratory analyses resulted in grain size distributions for 35 samples from 10 outcrops. Hydraulic conductivity of the samples ranged from 1.19–198.86 ft/d using the Hazen method. Specific capacity data analysis and slug testing were completed to compare the subsurface hydraulic conductivity (0.11–31.38 ft/day) to the properties computed for

outcrop material. The large range of hydraulic conductivities using the Hazen Equation is consistent with the highly variable lithology observed in the field. The results of the specific capacity tests and slug tests have a larger range and higher values than previous conceptual models and reports on the Antlers. Based on observed outcrop characteristics, laboratory analyses, and field (well) test results, this study shows that a more heterogeneous Antlers is present in the surface and subsurface with a broader range and higher average hydraulic conductivity than was previously reported.

Chapter 1: Introduction

1.1 Overview

Water availability (i.e., quantity) and quality are both important for municipal and domestic water supplies. Geologic and climatic conditions affect water supplies that are derived from groundwater systems. In some regions, such as in the midcontinental United States, the ever present threat of drought makes it especially important to understand groundwater availability and how geologic variability impacts groundwater recharge and supply.

This study focuses on the Cretaceous-aged Antlers Formation and Antlers Aquifer in southern and southeastern Oklahoma. The Antlers Aquifer has the fourth largest storage volume of the aquifers in the state of Oklahoma (Table 1), but it has not been well characterized. Few previous studies have been published on the formation and aquifer, and there have been no detailed studies on small-scale, sedimentologic and hydrogeologic characteristics of the Antlers. The goals of this study are to better understand the geologic characteristics and variability of Antlers outcrop material, and correlate with subsurface hydrogeologic properties, where possible, using a combination of field and laboratory investigation methods.

Table 1: Storage volumes (in acre-feet) of Oklahoma aquifers (from OWRB, 2012)

	Aquifer	Storage (Acre-Feet)
1	High Plains (Ogallala)	90,590,000
2	Rush Springs	79,838,000
3	Central Oklahoma	58,583,000
4	Antlers	53,570,000
5	Roubidoux	43,029,000
6	Boone	33,751,000
7	Pennsylvanian	26,382,000
8	El Reno	18,750,000
9	Vamoosa-Ada	14,931,000
10	North Central Oklahoma	14,250,000
11	East Central Oklahoma	13,940,000
12	Woodbine	12,630,000

1.2 Study Area

The Antlers is located in south-central and southeastern Oklahoma, and crops out on the surface in nine counties along the borders with Arkansas and Texas (Figure 1). Eastern Carter, southern Johnston, and northern Marshall Counties were selected as the primary study areas because outcrop materials for the Antlers were accessible and would potentially yield an adequate number of vertical and lateral exposures. Numerous water wells were also completed in the Antlers Aquifer in this region, which provide an opportunity to characterize hydrogeologic properties of the Antlers.

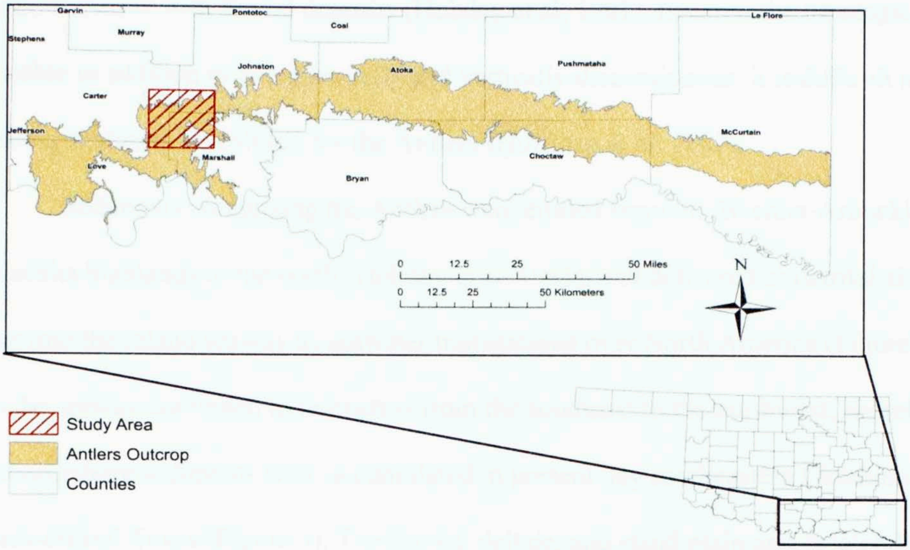

Figure 1: Locations of Antlers outcrops in southern and southeastern Oklahoma

Chapter 2: Background

Based on the 2010 U.S. Census, approximately 67,687 people live within the boundary of the Antlers Aquifer in Oklahoma (US Census Bureau, 2010). The largest population that uses water from the Antlers is the town of Durant in Bryan County with a population of 15,856. Madill (3,770) in Marshall County, and Tishomingo (3,034) in Johnston County are the largest towns within the study area.

2.1 Geologic Setting

The Antlers is lower Cretaceous (Aptian to Albian) in age and has been interpreted as a mixture of non-marine and transgressive, marine sediments that were deposited when the inland Cretaceous seaway covered central North America. The lower part of the Antlers is composed of deltaic sequences and the upper part is shallow marine with fluvial deposits (Hobday et al, 1981). Because the lithologies are variable in addition to being laterally and vertically discontinuous, it is difficult to make a stratigraphic column for the Antlers (Huffman et al, 1987).

Sediments comprising the Antlers were eroded from the Wichita-Arbuckle-Ouachita highlands to the north (Hobday et al, 1981), and delivered as detrital alluvial fans into the inland seaway as seawater transgressed over North America (Figure 2). As the seaway continued to transgress from the southeast to the northwest, shoreline and nearshore sediments were accumulated in present day southeastern Oklahoma and north-central Texas (Figure 3). The fluvial, deltaic, and stand plain unit is laterally equivalent to the Trinity Group in Texas (Hobday et al, 1981).

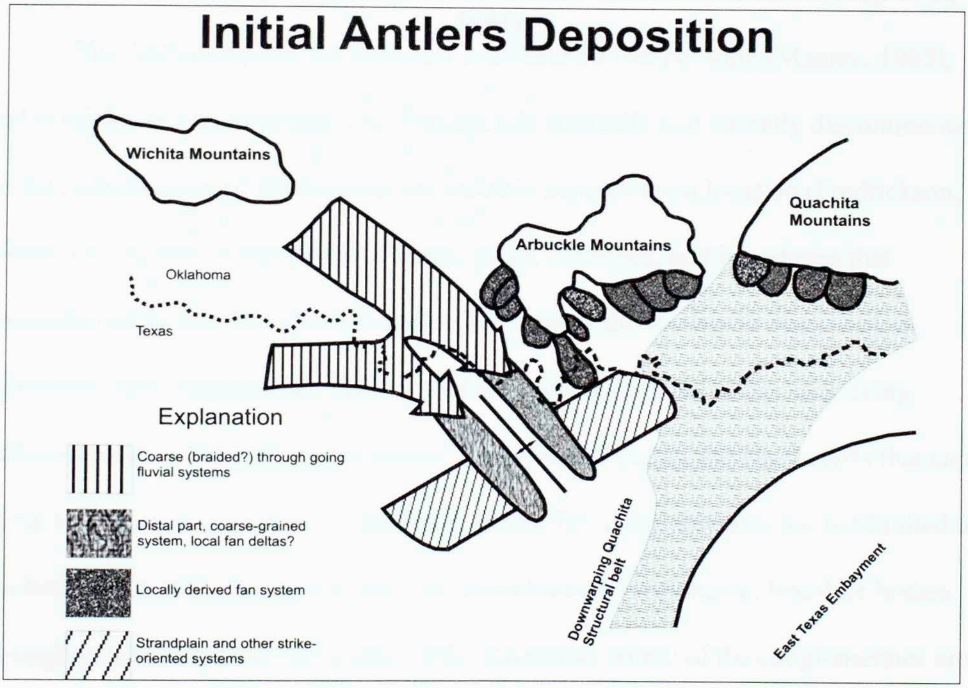

Figure 2: Initial deposition of the Antlers (modified from Hobday et al, 1981)

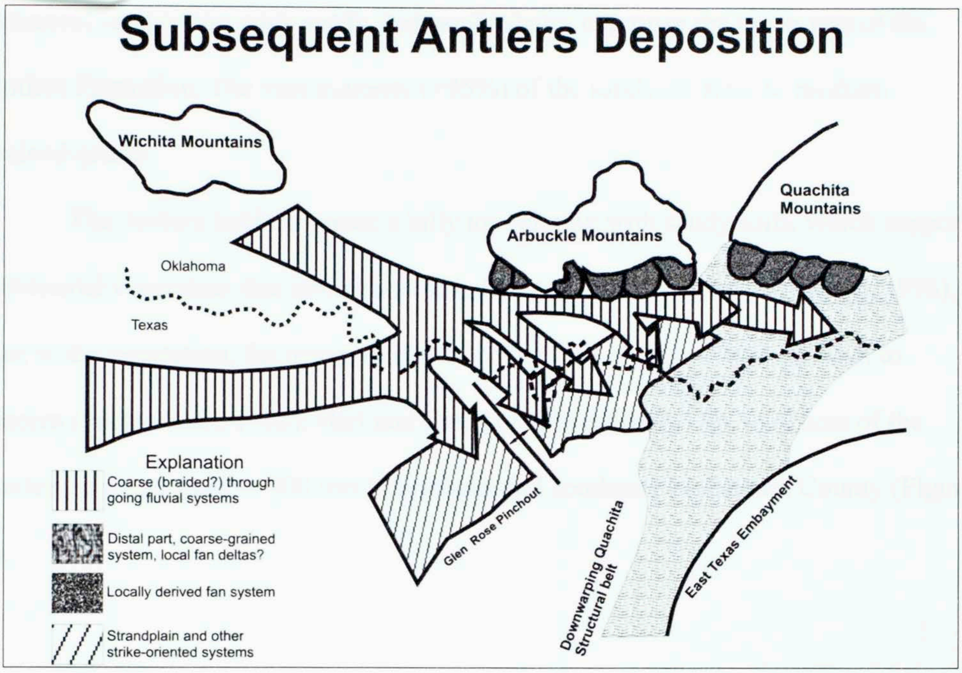

Figure 3: Subsequent deposition of the Antlers (modified from Hobday et al, 1981)

The Antlers dips to the southeast at around 50 feet per mile (Manley, 1965), and is thicker in the southeast. The formation is vertically and laterally discontinuous, so the compositions of the deposits are variable depending on location (Fredrickson, 1965). The Antlers is composed of sands, clays, siltstones, and limestones that uncomformably overlie Paleozoic rocks. The base of the Antlers is composed of limestones and conglomerate pebbles that are probably related to the underlying Paleozoic rocks. The pebbles are mainly composed of quartz and chert clasts that can be up to 7.5 cm in diameter (Fredrickson, 1965). The conglomerates are not limited to the basal units of the formation; they are also observed as elongate, lens-like bodies throughout the rest of the lower part of the formation. Many of the conglomerates are cemented with opaque, white cement that forms a hard, glassy quartz arenite. Carbonized wood has also been found in the lower parts of the formation. Poorly cemented sandstones, pack sands, and sandy shales comprise the upper part of the Antlers Formation. The vast majority (>95%) of the sands are fine- to medium grained quartz.

The Antlers tends to create a hilly topography with sandy soils, which supports substantial vegetation that covers and obscures potential outcrops (Holtzman, 1978). Due to the vegetation, the actual thickness of the formation has been difficult to discern (Fredrickson, 1965). Hart and Davis (1981) estimated the thickness of the Antlers to range from 0–900 feet in northern and southeast McCurtain County (Figure 5).

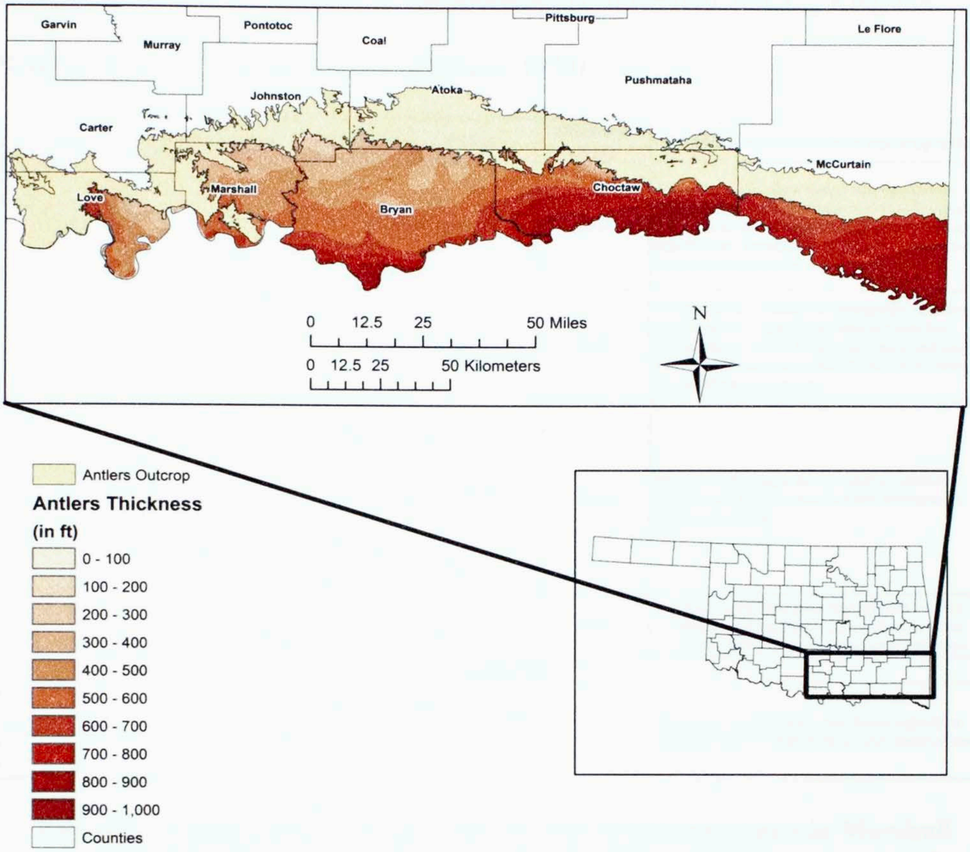

Figure 4: Locations of Antlers outcrops and approximate thicknesses of the formation in southern and southeastern Oklahoma (modified form Hart and Davis, 1981)

A stratigraphic column of the overlying and underlying formations is shown in Figure 5. Above the Antlers is the Goodland Limestone, a light gray, fine crystalline wackestone (Bridges, 1979), of the Fredricksburg Group. This contact appears to be conformable, and the thickness of the Goodland ranges from 20–55 feet (Huffman et al, 1975). The Goodland acts as a low permeability barrier and a vertical confining unit when present over the Antlers (Morton, 1992). The formation under the Antlers is the Mississippian-age Sycamore Limestone. In southern Marshall County, the

Cretaceous units are interrupted by the southeast-northwestern trending Kingston Syncline and the Preston Anticline (Bridges, 1979).

Age	Series	Group	Formation, Member	Thickness (feet)	Lithology and water-bearing properties
Cretaceous	Comanchean	Fredricksburg Group	Kiamichi Formation	35-40	Black, fissile clay shale with scattered siltstone lenses; 1-foot bed of siltstone near middle; thin interbeds of yellow -gray, fossiliferous limestone near the top, forming the "shell beds" composed of abundant *Texogrypaea navia*
			Goodland Limestone	15-25	White, massive, biomicritic limnestone; weathers gray to yellow ; upper beds weather into thin curved plates ; lower beds argillaceous and locally nodular; Walnut facies with *Ceratostreon texanum* at base of some exposures
		Trinity Group	Antlers Formation, Sandstone Facies	200-600	White to dull-orange, fine to medium-grained quartz sand; locally cross-bedded; ferruginous, with lenses of clay
			Antlers Formation, Baum Limestone Member	0-13	Upper part; light gray, fine grained, micritic limestone. Lower part: pale-yellow to white, coarsely crystalline conglomeratic limestone
Unconformity					
Mississippian	Oseagean-Meramecian		Sycamore Limestone	100+	Massive to thick-bedded, very finely crystalline blocky limestone, slightly shaly and sandy at base

Figure 5: Stratigraphic column of the Lower Cretaceous units in Marshall County. Thicknesses are not to scale. (modified from Huffman et al, 1987)

The majority of recent studies on the Antlers in Oklahoma focused on the dinosaurs and other vertebrate fossils found in the formation. Studies of the geology and hydrogeology in southern and southeastern Oklahoma include a 1979 Bryan County report and a 1987 Marshall County report by the Oklahoma Geological Survey (OGS), a 1981 report by Hart and Davis of the OGS on the hydrogeology of the aquifer, and a 1992 report by Robert Morton in cooperation with the U.S. Army Corp of Engineers describing a simulation of groundwater flow. There have been no published reports on the Antlers hydrogeology since the 1992 Morton paper.

2.2 Hydrogeologic Setting

The Antlers Aquifer is the fourth largest aquifer in Oklahoma, in terms of total water storage, with approximately 53.5 million acre-feet of water in storage (OWRB, 2012). While the area that depends on water from the aquifer is not very populated, there are some municipal water suppliers that rely on the Antlers. Unconfined on the surface, the younger Goodland Limestone (and sometimes the Baum Limestone) acts as a confining unit while the older Paleozoic strata form the lower confining unit for the Antlers (Morton, 1992). The saturated thickness of the aquifer ranges from 0 ft near the northern boundary of the aquifer to more than 2,000 ft about 25–30 miles south of the Red River in Texas (Morton, 1992).

2.2.1 Rainfall

Southern and southeastern Oklahoma has a semi-humid to humid climate with hot summers and mild winters (Hart and Davis, 1981). According to the Oklahoma Climatological Survey (OCS), the rainfall ranges between 38.85 in/yr in Love County to 52.02 in/yr in McCurtain County. On average, southeastern Oklahoma has the highest annual precipitation in the state of Oklahoma (OCS, 2015). The greatest amount of rainfall occurs in April and May, with the lowest amount in December and January (Hart and Davis, 1981).

2.2.2 Recharge

Groundwater recharge to the Antlers was estimated to range from 0.8–3.0 in/yr, with an average of 1.7 in/yr (Morton, 1992). Recharge is primarily a function of the soil type; for example, loose, sandy, and loamy soils will generally have higher recharge rates than more clay-rich soils. Hart and Davis (1981) estimated that the recharge rate may be as high as 6.0 in/yr in some parts of the Antlers outcrop.

2.2.3 Discharge

The outcrop area of the Antlers is drained by several major tributaries of the Red River including the Little Kiamichi, Muddy Boggy, Blue, and Washita Rivers (Hart and Davis, 1981). Morton (1992) suggested that most of the discharge from the Antlers Aquifer occurs as baseflow to streams, upward leakage, or pumpage. While there is little information about the discharge rates, Hart and Davis (1981) measured rates from 0.4–5.2 cubic feet per second (cfs) at four locations during the fall and winter of 1975–1976.

2.2.4 Hydraulic Conductivity

Hart and Davis (1981) conducted 21 aquifer tests in five locations across the aquifer. From these measurements, hydraulic conductivity values were estimated to be from 0.87–3.75 ft/day. Numerous clay layers are present in the formation; however, they are not continuous, allowing the sands to be hydraulically connected.

2.3 Previous Studies

Despite being a major source of water in these localities, surprisingly little is known about the formation itself. To date, there have been no comprehensive geological studies on the formation. The term "Antlers" was first proposed in 1894 to describe the base of the Cretaceous system in Indian Territory (now Oklahoma). Similar sands had been previously described in 1887 as "Dinosaur Sands". The name "Antlers" was selected because of the outcrops that were located near the town of Antlers in Pushmataha County. The terms Trinity, Paluxy, and Antlers were used interchangeably until 1957, when Paluxy was assigned to the sandstone-shale facies that are equivalent to the Walnut clay. Since that time, the Antlers has been considered to be equivalent to the uppermost Trinity and lower Fredricksburg Groups in Texas (Huffman et al, 1975).

The OGS has published bulletins identifying the geology and mineral resources of Bryan (Huffman et al, 1978), Choctaw (Huffman et al, 1975), Marshall (Huffman et al, 1987), and Love (Fredricksen, 1965) Counties. In each publication, the Antlers' etymology, geology, and mineral resources are briefly described. The thickness of the Antlers was estimated in each bulletin because there were no identified locations that exposed an entire vertical section of the formation.

Manley (1965) analyzed the clay mineralogy and defined four distinct major mineral zones: a lower, mixed layer illite-montmorillonite zone with an origin in the Ouachita Mountains to the northeast, a montmorillite-illite-kaolinite zone derived from the Ouachita and Arbuckle Mountains, a montmorillonite zone derived from the Anadarko Basin, and a kaolinite zone that was possibly derived from the Appalachian and Wichita Mountains.

White (1977) used geochemical analysis and field investigations to complete a study of the uranium potential of the Antlers. The study established evidence for the existence of a uranium deposit in the Antlers; however, the deposit(s) was not located, nor was the size of the deposit postulated.

Descriptions and maps of the Cretaceous geology and stratigraphy were prepared for the northwestern (Holtzman, 1978) and southern (Bridges, 1979) parts of Marshall County.

Hobday et al (1981) described, based on outcrop and subsurface studies, the structural controls on non-marine deposition of the Antlers. Their study was focused on the Antlers and stratigraphically equivalent deposits in north and central Texas. The study suggests that various pulses of tectonic activity in the early Cretaceous created alluvial fans that originated in the Wichita-Arbuckle highlands in Oklahoma. Later, streams from the Wichita paleoplain, to the west, brought in the sands that dominate the formation. Coarser sediments most likely originated from the Wichita, Arbuckle, and Ouachita Mountains. They also estimated the maximum thickness of the Antlers to be 985 ft (300 m) in the subsurface of Texas.

Hart and Davis (1981) from the OGS worked in conjunction with the U. S. Geological Survey (USGS) to complete a study that broadly described the hydrogeology of the Antlers. Based on their measurements and data analyses, they estimated recharge rates, discharge rates, and hydraulic conductivities of the aquifer. They also established potentiometric surface, base, top, thickness, and average sand content maps for the formation. Chemical analyses indicated that the water in the northern areas of the formation was of higher quality (i.e., lower total dissolved solids concentrations) than water in the southern portions of the aquifer, and suitable for human consumption. Most wells in the Antlers were able to yield 20–100 gallons per minute (gpm) from the aquifer, but poor well design allowed for small sediment particles to enter through the perforations, often leading to pump failures. More properly designed wells could withdraw water at a rate of 1,700–2,500 gpm. The storage for the aquifer was estimated to be about 44.6 million acre-ft. This was the first (and to date, the last) hydrogeologic study of the Antlers Formation and Antlers Aquifer.

Morton (1992) simulated ground-water flow in the aquifer using data from the previous hydrogeology study as well as by collecting water well and stream information throughout southern and southeastern Oklahoma. The study area was divided into two distinct zones that were distinguished by differences in groundwater flow properties. The study area was then represented using model cells, and each cell was populated with average hydraulic properties for those locations. The model simulations indicated that the majority of the aquifer was in a steady state, with the only exceptions being the very northern areas. Based on conservative projections for population and groundwater withdrawals from the aquifer, Morton (1992) had few concerns about long-term water availability from the Antlers.

After the Morton (1992) groundwater simulation study, the majority of published papers about the Antlers examined vertebrate fossils that were discovered in the formation. These include some very large terrestrial dinosaurs such as *Acrocanthosaurus atokensis* (Currie and Carpenter, 2000), *Dienonychus antirrhopus* (Brinkman et al, 1998), and *Sauropoesiden proteles* (Wedel et al, 2000), which was one of the largest sauropods ever studied. Fish, amphibians, and early mammals were among the other fossils that were studied (Cifelli et al, 1997).

2.4 Objectives

While many of the previous studies described various aspects of the Antlers Formation and aquifer, to date, there has not been a comprehensive study relating the geology of the formation to the hydrogeologic properties of the aquifer. Thus, the primary goals of this study are to conduct a detailed analysis of the geologic material and hydrogeologic properties of the Antlers Formation and Antlers Aquifer. If possible, this study will observe the outcrop sedimentary characteristics of the formation to confirm or modify the current depositional model.

Previous reports have observed high variability in sediment sizes, from clays to conglomerates. The previously reported hydraulic conductivities have a seemingly small range. It is the hypothesis of this study that the actual range is much larger. This will be tested using three methods of calculating hydraulic conductivity: the Hazen Equation, slug tests, and specific capacity tests.

Chapter 3: Methods

3.1 Selection of Study Area

3.1.1 Reviewing Previous Publications

A study area was selected by reviewing previously published studies and county reports for the presence of large vertical and horizontal exposures. Pictures, descriptions, and locations of outcrops were examined to define areas that were adequate for field investigations.

3.1.2 Interpreting Topographic Maps

Prior to any trips to the study area, topographic maps were obtained from the OGS and USGS. These maps were examined for topographic characteristics that might be indicative of usable outcrops. Locations that showed steep slopes, due to erosion by a river or stream, or roads cutting into hillsides were prospective sites for adequate exposed sections of the formation.

3.1.3 Examining Satellite Imagery

Satellite imagery was also utilized to identify possible study locations. The area was examined, using Google Earth©, for indications of accessible outcrops. These included non-vegetated areas, quarries, or sites that exhibited white- or yellow-colored surface soil or sediment; possibly indicating sands on the surface. Pins were placed on these locations and noted on maps that were later used for field reconnaissance.

3.1.4 Conducting Field Reconnaissance

Southern Johnston and northern Marshall Counties were selected as the most suitable for field investigation after reviewing previous publications, topographic maps, and satellite imagery. Field trips were taken to this area to confirm that an adequate number of outcrops were accessible for field investigation. Subsequent trips were conducted to collect data and samples for laboratory analysis.

3.2 Collect Outcrop Samples

One of the goals of this study was to investigate the spatial distribution of hydraulic properties. This was accomplished by sampling outcrops from multiple quadrangles and counties within the Antlers outcrop area.

3.2.1 Identifying Adequate Outcrops

Adequate outcrops were defined as sites that had enough vertical and horizontal exposure (~10 feet wide to over a quarter of a mile) to exhibit lithologic changes. Outcrop naming conventions are as follows: "Name of the Quadrangle where the site is located" "Outcrop Number". "Outcrop sub number" "Lithologic Unit" "Distance from the base of the outcrop". For example: "Mansville 2.2 Unit #3, 12 ft." is a sample that was located in the Mansville quadrangle, it was the second outcrop visited in the quadrangle, it is the second vertical section that was measured, the third unit from the base of the outcrop, and was collected 12 feet from the base of the outcrop. The outcrop number and sub number do not have any spatial information; instead, the numbers indicate the chronological order in which the outcrops were visited.

3.2.2 Recording Outcrop Characteristics

Characteristics of the outcrops were recorded prior to the collection of samples including the location of the outcrop, dimensions, color(s), sedimentary structures, lithological descriptions, thicknesses, spatial relationships, and any other noteworthy features. Photos were taken, from multiple angles, at every outcrop.

3.2.3 Distinguishing Lithologic Units

Lithologic units were defined by characteristics such as changes in lithologies, the end of repeating layers, changes in grain sizes, or other distinct features. All justifications for distinguishing units were noted in the field.

3.2.4 Collecting Samples

Samples were collected from every lithologic unit after removing the weathered surface to obtain a representative sample. Sediment was removed and collected into a plastic bag that was labeled with the site name.

3.3 Analyze Grain Size of Samples

3. 3.1 Preparing Samples

Samples were organized into three categories, based on estimated grain sizes, including clay-rich, sand-rich, and conglomeratic. Because clay-rich samples were cohesive, they formed clumps that were hard to separate, whereas the sand-rich and conglomeratic samples were less cohesive and easily separated when dry.

No dispersants were used during this study because preliminary tests showed that the particles could be separated using a (non-chemical) physical process. Because of the cohesiveness of clay-rich samples, a wet-sieving process was needed to separate clumps that would otherwise clog the coarse sieves. This required water and a longer time to separate the grains, as well as a longer drying period. To prepare samples for wet sieving, clay-rich samples were put into a one liter container with a cap to better separate the clay grains from each other. Several pebble-sized rocks were added to the container and it was filled halfway with water. The container was then vigorously shaken for several minutes, during which water and pebbles facilitated the separation of grains from each other.

3.3.2 Sieving Samples

The grain-size distributions of the outcrop samples were derived from sieve analyses completed using six stainless steel Fieldmaster™ sieves having a broad range of mesh sizes. Sieves included #5 Mesh with 4000μ (-2 Φ) openings, #10 Mesh with 2000μ (-1 Φ) openings, #35 Mesh with 500μ (1 Φ) openings, #60 Mesh with 250μ (2 Φ) openings, #120 Mesh with 125μ (3 Φ) openings, #230 Mesh with 63μ (4 Φ) openings, and a pan at the base to catch grains smaller than 63μ that pass through the #230 Mesh.

The sieves were stacked on top of each other prior to any sample being prepared so that the sample could be immediately poured onto the top sieve. The sieves were stacked with the pan on the bottom, followed by the smallest opening (i.e., #230 Mesh or 63 μ opening) in ascending order until the largest opening (i.e., #5 Mesh or 4000 μ opening) was on top.

After shaking, the clay-rich samples were poured onto the coarse mesh sieve at the top of the stack to begin the wet-sieving process. During wet sieving of clay-rich samples, the bottom pan was checked to ensure that it was not filling with water. If the bottom pan was nearly filled with water, then the entire stack was placed into an aluminum pan that was labeled "<63 μ". The sieves were then removed from the sieve pan so that any grains that passed through the bottom mesh would be collected. Once the sieves were removed, the sieve pan was dumped into the <63μ aluminum pan. The pan was then placed back under the sieves and the sieving continued.

Sand-rich or conglomeratic samples did not require wet sieving to separate the grains. Samples were poured onto the top mesh for the sand-rich and conglomeratic samples that were dry, and then the cap was added. With the cap on, the stack of meshes and the bottom pan were manually shaken for approximately five minutes. Sand-rich and conglomeratic samples were poured onto the top sieve and passed through the sieves using a combination of manual shaking of the sieve set and manual breaking of minor clumps. A small amount of water was sprayed onto the samples to help separate the sand and conglomeratic grains during the shaking process.

For all samples, the finest three sieves (250μ, 125μ, and 63μ) with sediments had water continuously sprayed on them and swirled to separate the finest grains. Three aluminum pans were labeled "125μ", "63μ", and"<63μ". After sieving was completed, any of the contents of the sieves or pan were poured into the corresponding pan.

3.3.3 Drying Samples

Sieved samples were placed in an aluminum pan and dried in a Blue M Electric Company Stabil-Therm Constant Temperature Cabinet that was set at about 170°C. After the sample was sufficiently sieved, the #5 Mesh (4000μ) through the #120 Mesh (125μ) were removed and placed on top the oven to dry with the ambient heat emanating from the unit. This allows both the sieves and their contents to dry using the ambient heat emanating from the oven. The two pans containing contents of the #230 Mesh (63μ), and Fines pan (<63μ grains) were placed inside the oven (as it could only hold two pans). Special attention was given to ensure that the sieves were placed on the oven right side up and in a sturdy location so that the sieves would not fall. For clay-rich sample pans, the drying process could take up to six hours to complete.

3.3.4 Measuring Mass of Samples

Samples were not weighed (i.e., massed) prior to sieving because any mass from water in the sample would be removed in the drying process. Prior to any measurements, the mass of the plastic bags, sieves, and aluminum pans were noted so that their masses could be subtracted from the total mass of the sample and its container.

Samples were not removed from their container after they were dried. The container (either the sieve itself or an aluminum pan) was placed on a Denver Instrument TR 603D Electronic Balance with a mass sensitivity of ±0.001 g (i.e., ±1.0 mg). Mass was recorded after the scale reading stabilized, the mass of the empty container was subtracted resulting in the mass of the sample in the container.

This process was repeated until the mass was measured for all grain sizes in the sieves and pans. The contents of the sieves and pans were collected into two bags: one with all the grains over 63μ and another bag with grains less than 63μ. The bags with clay-sized or smaller particles were separated in case a Laser Particle Size Analyzer (LPSA) would be used.

The two bags were weighed at the same time, and then the mass of the bags was subtracted to calculate the mass of the entire dried sample. The masses of all the different sized grains were summed and divided by the final weight of the dried sample. This was done to ensure that there was no loss of sediment. If the difference of the weights was more than 5%, the process from 3.4.2 to 3.4.3 was repeated.

3.3.5 Displaying Results

As the samples were being weighed, the mass of the contents in each container were logged. These data were then imported into Microsoft Excel. The category that the sample was originally assigned to (clay-rich, sand-rich, or conglomeratic) was noted. The location, unit, unit location information, and final dried weight (in grams) of the sample were added to the spreadsheet. Percentages of each particle size were calculated by dividing the weight of the particles from the total mass of the sample, Eq. (1):

$$\frac{M_S}{M_{Total}} * 100 \qquad \text{Equation (1)}$$

where, M_S is the mass of the grains in the sieve, and M_{total} is the mass of the entire sample.

The grain-size distribution was defined by subtracting the percentages of each size, from the >4000μ sieve to the <63μ sieve. Table 2 shows an example calculation for grain-size distribution of the McMillan 1.1 Unit #1 (1ft).

Table 2: Example calculation for grain-size distribution

Location McMillan 1.1 Unit #1 (1ft)	
Dried Weight (g)	177.911
Grain Size%	
>4000 Microns	0.000
2000-4000 Microns	0.000
500-2000 Microns	0.071
250-500 Microns	0.333
125-250 Microns	39.730
63-125 Microns	44.970
<63 Microns	14.545
Sum	99.649
Finer than %	
>4000 Microns	100.000
2000-4000 Microns	100.000
500-2000 Microns	99.929
250-500 Microns	99.595
125-250 Microns	59.866
63-125 Microns	14.896
<63 Microns	0.351

A chart of the grain-size distribution was made for each sample by plotting "% Finer Than" on the y-axis versus "Grain Size (In Phi)" on the x-axis. Each grain-size distribution curve was symbolized using a color that represented the category to which they were assigned during sample preparation; whereby orange was used for clay-rich, green was used for sand-rich, and red for conglomeratic samples.

3.3.6 Estimating Hydraulic Conductivity

Hydraulic conductivity of the samples was calculated using the Hazen equation (Millham & Lowes, 1995), Eq. (2):

$$K = C(d_{10})^2 \qquad \text{Equation (2)}$$

where K is hydraulic conductivity (ft/d), C is a dimensionless constant that is based on the sorting and grain size of the sediments (Table 1), and d_{10} is the size at which 10% of the sample was finer (mm).

Table 3: Table of values of C (modified from Fetter, 2000)

Grain Size and Sorting	Values for C
Very fine sand, poorly sorted	40–80
Fine sand with a lot of fines	40–80
Medium sand, well sorted	80–120
Coarse Sand, poorly sorted	80–120
Coarse sand, well sorted, clean	120–150

Table 4: Table of values that relates the effective size of the finest 10% of sediments (modified from West, 1995)

Material	K (cm/sec)	Effective Size, d_{10} (mm)
Uniform coarse sand	0.4	0.6
Uniform medium sand	0.1	0.3
Clean, well-graded sand and gravel	0.01	0.1
Uniform, fine sand	4 x 10-3	0.06
Well-graded, silty sand and gravel	4 x 10-4	0.02
Silty sand	1 x 10-1	0.01
Uniform silt	5 x 10-5	0.006
Sandy Clay	5 x 10-6	0.002
Silty Clay	1 x 10-1	0.0015
Clay (30–50% clay size)	1 x 10-7	0.0008

The value of d_{10} was estimated by examining the plot of "% Finer Than" on the y-axis versus "Grain Size (in Phi)" on the x-axis, and estimating the grain size, in phi, where the curve crosses the 10% gridline. Grain size in phi is converted to millimeters using the formula (Krumbein, 1938):

$$D(mm) = 2^{-phi}$$

There is no established method for estimating C. For this project, C was estimated using Table 3. C is higher for larger or well sorted grains, and lower for finer or poorly sorted grains. For this study, C values of 40–80, 80–150, and 180 were used for clay-rich, sand-rich, and conglomeratic samples, respectively.

Once d_{10} and C were estimated for the sample, hydraulic conductivity was calculated in cm/s using the Hazen equation, Eq. (2) and converted into ft/day before computing minimum, mean, median, maximum, and quartiles of the hydraulic conductivity values.

3.4 Measure Subsurface Hydraulic Properties

One of the primary objectives of this study was to measure hydrogeologic properties of the Antlers Formation and Aquifer. The properties of the aquifer can be assessed most directly by conducting tests on existing groundwater wells completed in the Antlers.

3.4.1 Identifying Potential Slug Test Sites

Slug tests involve an "instantaneous" displacement of water in a well and measurement of the rate of response of the water level to the displacement. Slug test data are analyzed to calculate hydraulic conductivity of the aquifer. For this study, slug tests were completed with one-inch diameter (six feet in length) or two-inch diameter (three feet in length) "slugs" that were constructed from solid PVC cylinders. A "falling-head" slug test was used to monitor the change in water level after instantaneously submerging a slug below the static water level, and a "rising-head" slug test was used to monitor the change in water level after instantaneously removing the slug from the water column.

A well that would be suitable for a slug test would need to be in good hydraulic connection with the aquifer, be deep enough for the slug to be fully submerged in the water, have an opening that is large enough for a one or two inch diameter slug to be submerged below the static water level, away from any active pumping sources so that the displacement and recovery results are not skewed. The OWRB's well database was queried to identify suitable (i.e., meeting the criteria described above) slug test sites within the study area.

3.4.2 Performing the Slug Test

After arriving to each well site identified for slug testing, the following procedure was used:

1. Measure inner-diameter of the well casing
2. Measure height of the well casing and designate the measuring point (MP) of the well (i.e., north facing point of the well casing)
3. Measure depth to the static water level using an electronic water-level indicator (i.e., Solinst device)
4. Measure the temperature (°C) and the conductivity (microSiemens per cm or μS/cm) of the well water using the electronic water-level indicator.
5. Set up a pressure transducer (i.e., In-Situ Level Troll 500s® with pressure limits of 30 or 100 psi) for a test using the manufacturer's software interface (i.e., Win-situ). Several steps are necessary for set up including specifying a test name such as *WellNumber_WellName*, creating a new log such as *WellNumber_WellName_DateOfTheTest_Slug*, inputting well

information, and specifying the time interval for data collection (for this study, 500 milliseconds).

6. Submerge a pressure transducer 10 ft or more below the static water level and secure at the surface using a pre-measured rope or chord
7. Monitor the water level, using the pressure transducer and software interface, until it returns to the initial static level
8. Fully and instantaneously submerge the slug below the static water level, which is when the pressure transducer begins to collect data for the falling-head slug test
9. Monitor the water level, using the pressure transducer and software interface, until it returns to the initial static level
10. Instantaneously remove the slug from the water column, which is when the pressure transducer begins to collect data for the rising-head slug test
11. Monitor the water level, using the pressure transducer and software interface, until it returns to the initial static level
12. Manually stop data collection, using the software interface, after the falling-head and rising-head slug tests were completed, and download data onto the laptop
13. Raise pressure transducer back to the surface, disconnect, and place back into its containers.
14. Clean wellhead and equipment before moving to another site.
15. Repeat steps 1–14 at each accessible well

Information about the construction of the well itself is important to the analysis of the slug test data. If the information provided by the OWRB did not document screened intervals or depths of the screens, then a borehole camera was lowered into the well. An Inuktun CrystalCam camera was used for this study. The camera was connected to a 500ft cable, which was connected to a monitor indicating the length of cable that was removed from the spool. Length was reset (i.e., zeroed) by pushing the plus (+) and minus (-) buttons on the unit to initiate the menu on the monitor, then using the minus button to scroll down the menu to length. By selecting zero length, the length on the monitor read 0.0. The camera chord was then pulled out of the spool and the camera lowered into the well. As the camera was being lowered, the monitor was observed to identify the characteristics of the well. Special attention was given to the depths and lengths of screened intervals and if the well casing ended before the base of the well. The camera was lowered until it reached the total depth (TD) of the well or until the camera reached a depth of 500ft (i.e., maximum length of cable).

3.4.3 Analyzing Slug Test Data

Slug test data files were opened in Excel, and then the time and depth to water columns were copied and pasted into a worksheet of the Grapher™ 10 program (by Golden Software). High displacement corresponding to the beginning of the falling-head slug tests and low displacement corresponding to the beginning of the rising-head slug tests were apparent when displaying the data in Grapher. The maximum value of displacement was selected in Grapher and used to calculate displacement relative to the static water level at any time, t.

Aqtesolv™ (by Rockware) was used to analyze the slug test data. The dimensions for the calculations were selected in Aqtesolv, with length (L) in ft, time (T) in sec, and hydraulic conductivity (K) in ft/day. Observed initial displacement H(0) is the maximum displacement caused by the insertion or removal of the slug in the well. The static water column height (H) is equal to the level depth to water to the base of the aquifer. If the well is not deep enough to reach the base of the aquifer, then the depth to the base was specified as equivalent to the total depth of the screened/open interval of the well. For the purposes of this analysis, the well coordinates are not required to be entered.

The saturated thickness of the aquifer (b) is the same as H in the previous step in unconfined aquifers. The Kv/Kh (Kv = vertical hydraulic conductivity, Kh = horizontal conductivity) value was set to 0.1 because this is a typical value for the anisotropy ratio in a sedimentary aquifer.

The depth to the top of the well screen (d) is the depth at which the slotted intervals in the well begin, which was obtained from the well completion report submitted to OWRB or via visual inspection of the well with the downhole camera. The length of the well screen (L) is the length of the well that has perforations. The transducer depth is the height of the column of water above the transducer, which is calculated by multiplying the static pressure (in psi) by 2.31 to convert to feet of water.

The radius of the well casing [r(c)], radius of the downhole equipment [r(eq)], inside radius of packer [r(p)], radius of the well [r(w)], and outer radius of well skin [(r(sk)] were entered. Since the same downhole equipment was consistently used throughout this study, r(eq) was 0.03ft. Unless the well completion report had the construction information, r(p) was assumed to be 0 and r(sk) was assumed to be equal to r(w).

Assumptions were applied including that the frictional (viscous) well loss was zero, and effective porosity, n(e), was 0.25. For slug tests completed in an unconfined section of the aquifer, the Bouwer-Rice (1976) method was used to correct for effective casing radius.

3.5 Analyze Specific Capacity Test Data

Specific capacity tests are conducted by well drillers to evaluate the productivity of a newly completed well. Drillers pump a well for a known period of time at a constant rate, while the drawdown is recorded. Properties of the aquifer, such as hydraulic conductivity, can be estimated by the change in water level (i.e., drawdown) over the duration of pumping. Specific capacity test results are recorded on some OWRB well logs. The logs contain the initial depth to water prior to the start of the test, pumping rate, duration of the test, and the drawdown of the water level in the well.

Hydraulic conductivity (K) and transmissivity (T) were estimated using Aqtesolv's specific capacity test calculator (http://www.aqtesolv.com/forum/transcap2.asp). The calculator uses a modified version of the Cooper and Jacob (1946) solution for flow into a well in a confined aquifer, expressed by Eq. (3):

$$\frac{Q}{S_w} = \frac{T}{0.183\log\left(\frac{2.25Tt}{r_w^2 S}\right)} \qquad \text{Equation (3)}$$

where Q is constant rate discharge (ft^3/d), r_w is well radius (ft), S is storativity (dimensionless, assumed to be 0.17 [Morton, 1992]), S_w is drawdown in the well (ft), T is the transmissivity (ft^2/d), and t is time (days).

Eq. (3) can be rearranged and solved for T, as shown in Eq. (4).

$$(1)\ T = 0.183\frac{Q}{S_w}\log\left(\frac{2.25Tt}{r_w^2 S}\right) \qquad \text{Equation (4)}$$

OWRB records include pumping rate in gpm, which must be converted to cubic feet per day (ft^3/d), whereby 1 gpm = 192.5 ft^3/d. The well radius (r_w) is reported in inches and must be converted into feet. Since T is on both sides of the equation, the calculator uses techniques such as successive approximation to solve for T.

Transmissivity (T) must be divided by the saturated thickness of the aquifer to estimate hydraulic conductivity (K) at the location of the well. Thickness of the aquifer is assumed to be height of the water column above the bottom (i.e., TD) of the well, which is equivalent to the actual aquifer thickness at wells that fully penetrate the aquifer. This information is available in the construction section on the well logs.

Chapter 4: Results

4.1 Field Results

4.1.1 Outcrop Locations

10 outcrops were identified and described. The majority of outcrops are located on stream embankments or hills that were excavated to construct roads. The terrain is relatively flat so, generally, limited exposures are available on the small hills in the study area. Exposures adjacent to streams provided the best access to outcrop material; therefore, the majority of samples were collected on stream embankments. Road cuts had the smoothest exposures and tended to be the best areas for maintaining sedimentary structures. Figure 5 shows the distribution of outcrops that were visited.

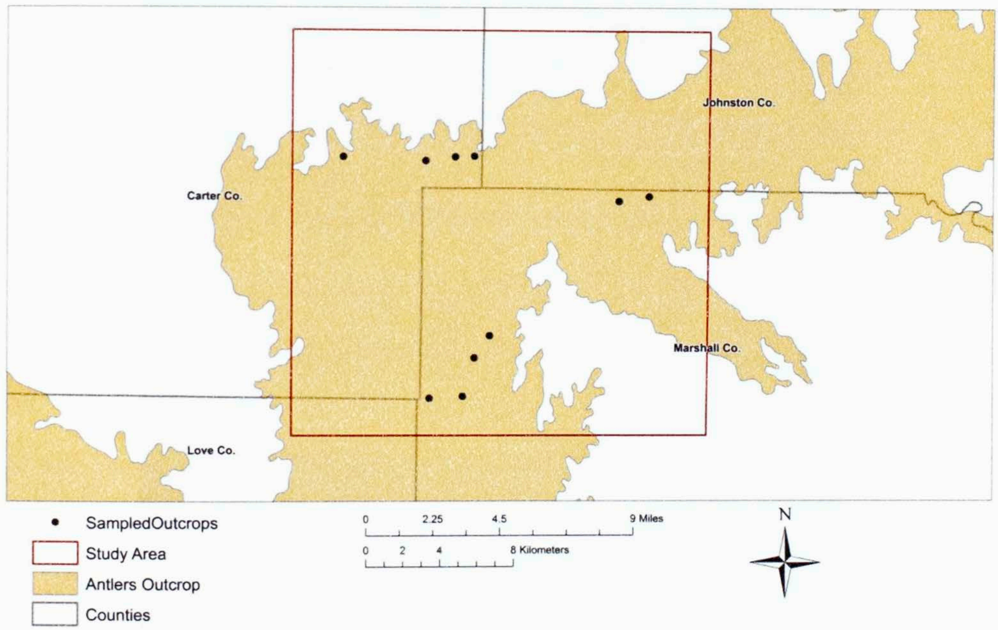

Figure 6: Locations of visited and sampled outcrops in Marshall, Johnston, and Carter Counties

4.1.2 Outcrop Characteristics

The stream outcrops were up to 50 feet tall and exposed the formation for the entire vertical face. The Antlers Formation was exposed for a long distance, up to one-quarter mile, at the McMillan #1 location. Stream banks were generally eroded so that there was a gradual slope near the top of the embankment, but a nearly vertical face below. Figure 7 shows one of the largest stream exposures observed. Hill exposures were far less common, and the exposure was usually inadequate to accurately describe the formation.

Figure 7: Antlers Formation in the Little Hauani Creek, just outside the town of McMillan in Marshall County.

4.1.3 Lithologies

Sand units were prevalent in the outcrops, and were predominated by yellow to white, and very-fine to fine grained, well sorted, and rounded to subrounded quartz. The vast majority (>95%) of the Antlers outcrop material was composed of uncemented quartz sands that commonly showed some iron staining. Iron appears to act as a cement and a coating, which created units of red to orange sand that formed "benches" (Figure 8) indicating greater resistance to weathering than the overlying units. Iron nodules (Figure 9) up to two inches in diameter were observed where iron was present. These nodules were red-brown to black, circular concretions that were far more durable than any other lithologic unit.

The Mansville #1(Figure 10) exposure was exceptional because it was composed of only mud or clay. Clays, including red, green, and greenish blue colors, were present in both lenses and layers. Clay layers were generally blocky, greenish units with little to no sand content.

The McMillan #1 exposure was exceptional because it was comprised of conglomeratic material (Figure 11). The conglomerates occurred in lenses that were one to two feet wide and six inches thick. The grains were orange to black, with clasts up to one inch in diameter.

Figure 8: Iron cemented bench (layer with the shovel) from McMillan #4.

Figure 9: Iron nodules from McMillan #4.

Figure 10: Manville #1 outcrop.

Figure 11: Conglomerate unit from McMillan #1

Calcareous concretions were observed in 4 outcrops. These concretions ranged from pebble-sized (4–64 mm diameter) to 76 mm (~3 in) elongated (i.e., low sphericity) boulders that were white in color and resembled bones.

The Ravia #1 exposure was composed mainly of clay-sized grains, but also had large gypsum crystals. The gypsum crystals were up to 4in elongated, clear crystals that littered the entire outcrop. The gypsum did not appear to originate in the outcrop. At this time the origin of the gypsum is unknown.

4.1.4 Sedimentary Structures

Horizontal layering, cross-bedding, clay and conglomerate lenses, and iron staining were all observed in the Antlers Formation outcrop material. Contacts between sedimentary units ranged from gradual to sharp. Horizontal layering was the most commonly observed sedimentary structure, with layers of the Antlers showing little or no dip.

Cross bedding (Figure 12) was commonly observed in sand-rich units. These cross beds were generally unidirectional, but bidirectional beds dipping E-SE were observed at the McMillan #5 exposure.

Figure 12: Cross bedding from McMillan #5.4

Iron appeared to partially cement or lithify the outcrop material in many locations. These units weathered less than units with no noticeable cement, and formed bench-like features. Rounded iron nodules, up to an inch in diameter, were also present in iron-rich locations. The nodules were much more indurated than any other sedimentary structure observed in this study.

4.1.5 Fossils

Petrified wood specimens, ranging in size from 0.25–6.00in in length, were observed in the Antlers Formation at numerous locations. Petrified wood specimens observed during this study appear to be of only one type of tree (i.e., same species). There are no previously published reports that identify petrified wood in this area.

One small fossilized bone was found just outside the town of McMillan among a pile of small rocks, and it was not in situ. While it is not possible to determine the type of animal the bone belongs to, with its size and large capillary openings, it is possible that it comes from a medium sized terrestrial creature.

4.2 Laboratory Results

4.2.1 Grain Size Distributions

The grain size distributions from the Antlers outcrop are shown in Figure 13.

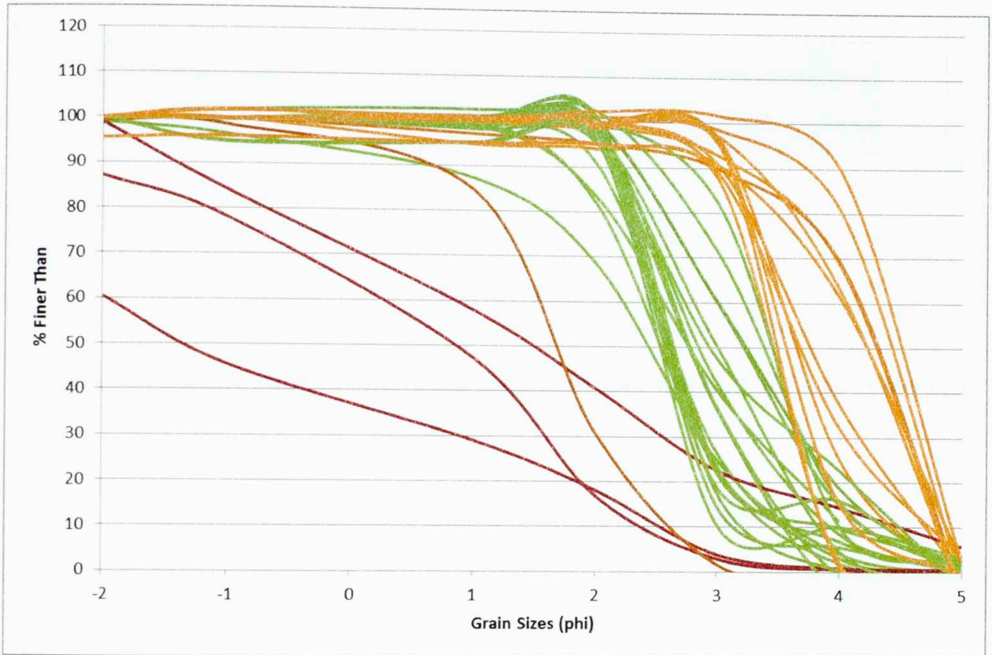

Figure 13: Grain size distributions for samples collected from Antlers Formation outcrops. Colors are based on the dominant grain size in the sample; orange is clay-rich, green is sand-rich, and red is conglomeratic.

The d_{10} for all clay-rich and sand-rich samples were between 3 phi (0.125 mm) and 5 phi (0.0313 mm). These results indicate that the finest 10% of grains in the Antlers Formation are silts to very-fine sands.

4.2.2 Hydraulic Conductivity from Grain-Size Distributions

A summary of estimated hydraulic conductivities, using d_{10} from grain-size analyses and the Hazen equation, are shown in Figure 14. Hydraulic conductivity was estimated for a total of 35 samples that were sieved, which resulted in hydraulic conductivities with a minimum value of ~1.19ft/day, mean of ~27.19 ft/day, median of ~9.11 ft/day, and maximum of ~198.86 ft/day.

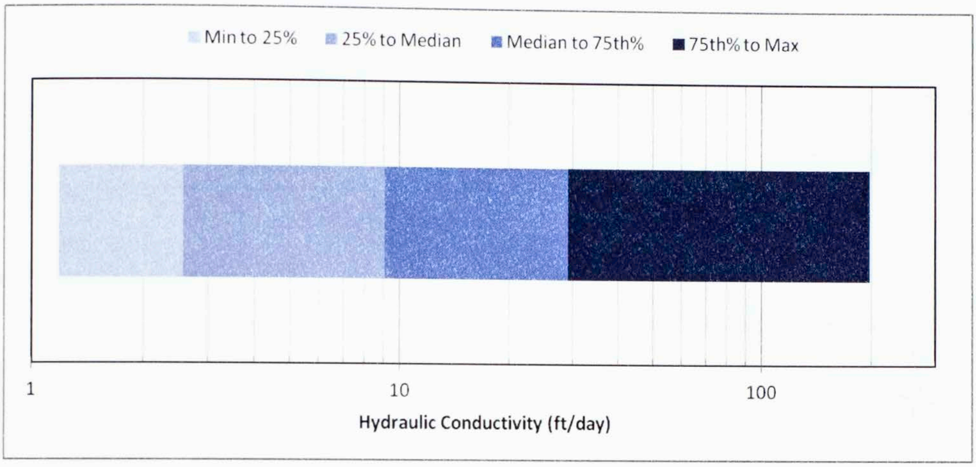

Figure 14: Distribution of hydraulic conductivities calculated from grain size distributions.

4.2.3 Hydraulic Conductivity from Slug Tests

The range of hydraulic conductivities from analyzed slug tests is shown in Figure 15. The minimum value was 3.901 ft/day and the maximum was 9.041 ft/day.

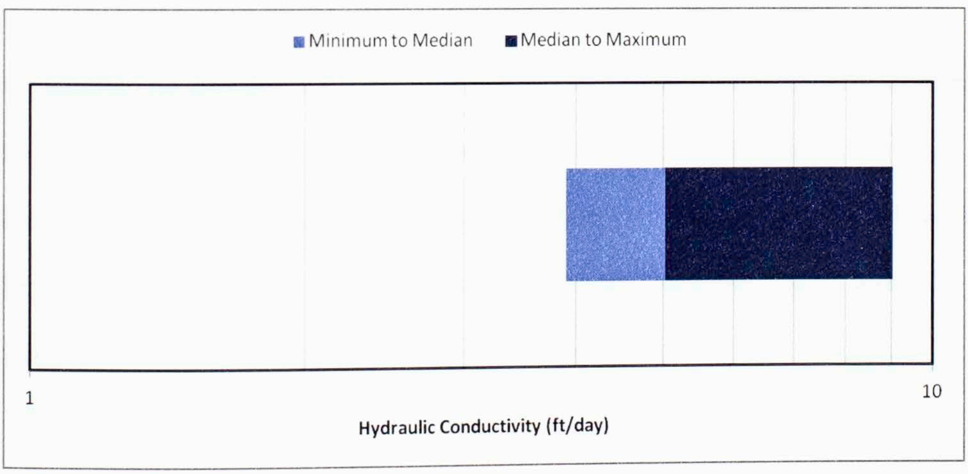

Figure 15: Hydraulic conductivity results from slug tests.

4.2.4 Hydraulic Conductivity from Specific Capacity Tests

A map of the analyzed specific capacity tests locations are shown in Figure 16.

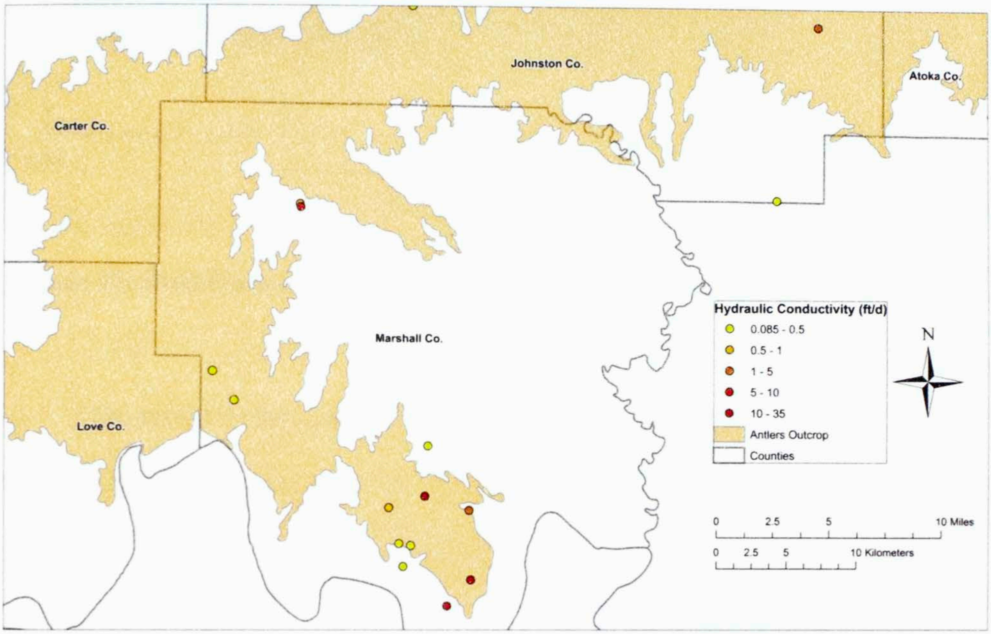

Figure 16: Locations and calculated hydraulic conductivities of specific capacity tests that were analyzed from wells completed in the Antlers Aquifer.

Hydraulic conductivity was calculated from 33 specific capacity tests. Four tests reported no drawdown. Others were not included because of potentially incorrect data. 18 tests were used for this study. The equation to calculate hydraulic conductivity cannot be used if there is no drawdown, as division by zero would occur. The minimum value was 0.11ft/day, the mean was 6.91 ft/day, the median was 0.71 ft/day, and the maximum was 31.38 ft/day, as shown in Figure 17.

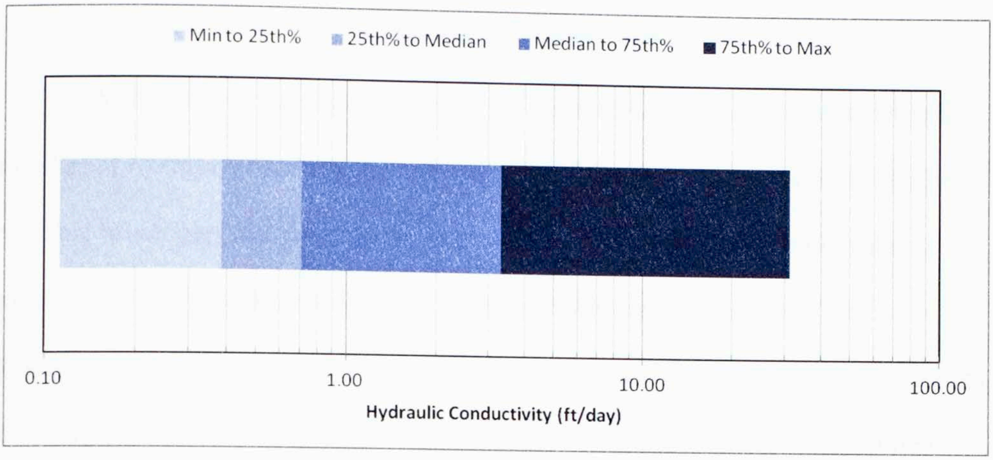

Figure 17: Distribution of hydraulic conductivity values calculated from specific capacity tests.

The results of the calculations from the grain size distribution estimates, slug tests and specific capacity tests compared to each other are shown in Figure 18.

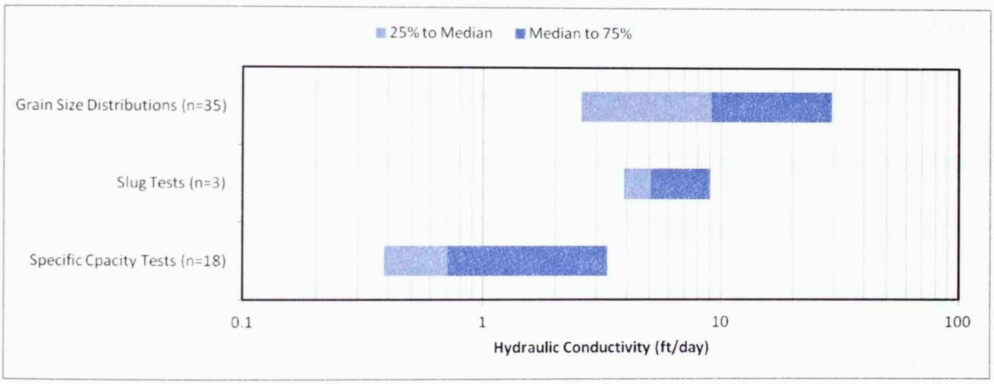

Figure 18: Hydraulic conductivity results of grain size distribution, slug tests, and specific capacity tests.

Chapter 5: Discussion

Previous hydrogeologic studies of the Antlers Aquifer resulted in a limited number of hydraulic conductivity measurements from the aquifer. With the highly variable lithologies that occur in the formation, it is unlikely that a single value or small range of hydraulic conductivities would be adequate to represent the heterogeneities of the aquifer. Grain-size distribution and, hence, hydraulic properties can vary substantially over short distances (i.e., within a few miles) based on field data collection efforts made in this study.

Previous studies showed no evidence of lithification in the subsurface. While there is some petroleum activity, there is little information from petroleum well logs because coring is nearly impossible because of the lack of lithification. Even the units that have some degree of lithification are poorly indurated and the rocks that could be cored would not maintain their cemented nature during transport to the surface. None of the outcrops visited during field reconnaissance or sampling efforts exhibited exposures of the entire vertical section of the Antlers. While there were locations that presented a large section of the formation, it was impossible to accurately ascertain the thickness of the Antlers. The vegetation, even in the winter months, was too dense and prevalent to allow an entire section of the formation to be exposed.

As previously reported, the vast majority of the sediments were fine to medium-grained quartz sands. Only a couple of locations had any lithified units, and even those were so poorly cemented that the sample would nearly fall apart during transportation from the field. Clay-rich and silt-rich layers were also observed, and may extend over the entire outcrop or only exist in small lenses. It was apparent that the clay and silt layers were not continuous over the entire formation, as outcrops that were located close to each other would have varying amounts of clay content. This supports the previous observations that the clay layers are not connected, meaning that there are no impermeable barriers within the Antlers Aquifer.

Three regimes of flow velocities were identified in this study based on sediment size; high flow velocity (conglomerates), medium to low velocity (medium to fine sands), and very low velocity (silts and clays). The presence of cross bedding, as well as clay and conglomerate lenses supports the fluvial interpretation. With the sediments being relatively fine (medium sands and finer) in most of the study area, it is a reasonable interpretation that the sediments have been transported over a long distance from their origin. Some of the contacts with clay layers over sand layers indicate a rapid transition from proximal locations (sands) to more distal facies (silts and clays). The clay layers over the sand units suggest that the depositional environment could have quickly changed to deeper water or low energy environments. The observed conglomerate lenses indicate that there were local channels of higher energy.

Determining the depositional environment in the study area is difficult due to the lack of available outcrops. However, the observed sedimentary structures may be used to postulate potential environments. Cross bedding in most of the formation suggests that the Antlers was deposited in an area with fluvial influences. Lenses of conglomerates and clays suggest that there were channels of high and low energy after the deposition of the sands. Contacts ranged from gradual to sharp, indicating that deposition versus erosion transitioned very slowly or rapidly, at the respective contacts. Petrified wood indicates that the Antlers was deposited, at least partially, in an area that was conducive to plant life. Previously reported fossils include large animals that could only have lived in a terrestrial area. However, fish and other aquatic fossils have also been observed in the Antlers. Swartz (1990) identified fossils and trace fossils in the underlying Baum Limestone that indicate shallow marine and lacustrine deposits. These observations require that the depositional model include an environment that has flow regimes that range from high to low, is located in an area that can support both terrestrial and aquatic life over short distances, and can change rapidly or slowly.

Based on field observations, there is no evidence to conclude that the previously established deltaic and alluvial fan changing to a fluvial dominated depositional environment is incorrect. The fining upward sequences that were observed, along with the cross bedding and conglomerate lenses, are consistent with the alluvial fan depositional environment. Because of the lack of available outcrops, it is beyond the scope of this study to postulate the size or origin of the fans. However, the study area is likely in the more distal sections of the fan because of the lack of coarse grained sediments, which would be expected closer to the sediment source.

Above the clay lenses and conglomerates were more sand-dominated outcrops with more crossbedding. This supports previous observations that the upper part of the Antlers was more fluvial dominated.

The Washita river flows through southern Johnston County and northern Marshall County on its way to merging with the Red River on the border between Oklahoma and Texas, covering a large area with Quaternary sediments. Some of these sediments may overlay the extreme northern extent of the Antlers, either eroding or covering areas closer to the proposed origin of the alluvial fans in the Arbuckle Mountains.

The large (>2in diameter) chert nodules likely come from the Arbuckles to the north (Hobday et al, 1981). Chert has been reported in several county reports in southern and southeastern Oklahoma.

Gypsum has never been identified in the Antlers prior to this study. Evaporate minerals have not been previously documented in the Antlers or units directly overlying the Antlers. The origin of gypsum observed in Ravia #1 is unknown at this time.

Iron staining and cementation, observed in the Antlers, also have been previously reported (Huffman et al, 1987), but not studied in depth. The exact type of iron nodules and their origin are beyond the scope of this study. It should be noted that if iron is cementing and staining the sands of the Antlers in the subsurface as they are in several outcrops, then these could lead to differences in hydraulic conductivity and possibly water quality in the aquifer. Since this study did not investigate water quality, no observations on the potential effects of iron in the aquifer were considered.

Because of the high variability of grain size in the Antlers Formation (ranging from clays to conglomerates), d_{10} ranged over three orders of magnitude (0.031–0.125mm) with a corresponding hydraulic conductivity range of 1.19–198.86 ft/day. While there are clay lenses in the Antlers, there is no evidence to suggest that they are connected throughout the aquifer. The lowest values that were calculated by the Hazen equation represent these fine-grained layers. This means that there may be small areas of the aquifer that have such low hydraulic conductivities, but they are not a representation of the whole aquifer. The same can be inferred for the very high K values, which resulted from conglomeratic lenses that were only observed in McMillan #1. Because of this, it was hypothesized that the mean or median hydraulic conductivity calculated from the grain-size distributions would give an approximate value that would be expected in the aquifer. To confirm this, slug tests were conducted and specific capacity tests were conducted and analyzed to compare to the K values to the values calculated by the Hazen Equation.

The slug tests had a smaller range of hydraulic conductivities than the ones calculated by the Hazen Equation (3.9-9.0 ft/day), and the median was relatively close to the median that was estimated from the grain-size distribution calculations. The smaller range is to be expected, as the hydraulic conductivity is being calculated based on water moving in and out of the aquifer. The smaller range is a result based on the influence of all the lithologies near the well, so there could be both coarser and finer sediments that water has to flow through, but it is unlikely that water will experience only one of those extremes. Three tests were completed for this study, and it is likely that more tests would be able to more accurately determine the exact range of hydraulic conductivity values in the Antlers.

Hydraulic conductivity values derived from specific capacity test data were lower than expected. The high value of 31.38 ft/day and mean of 6.91 ft/day are well within ranges for unlithified sands (Schwartz and Zhang, 2003), but hydraulic conductivity at several wells was less than 1 ft/day. An examination of the well logs shows that the wells are within the Antlers Aquifer. These low values could, partially, be explained by data entry issues to the OWRB. The completion reports that are filled out by well drillers include any drawdown tests that were conducted. Often the data that is reported is questionable because drawdowns are very large or there is no draw down at all. To try and minimize the effect of incorrect data in this study, the original completion reports were inspected, and any reports that had questionable data were not included. Regardless of the method, the hydraulic conductivity values of 0.87 ft/day and 3.75 ft/day that were estimated by Hart and Davis (1981) are too low and not representative of the unconfined section of the Antlers that was examined in this study.

In this study, hydraulic conductivity of the Antlers outcrop and shallow subcrop in Johnston and Marshall Counties, OK was estimated to range from 0.11–198.86 ft/day. Hydraulic conductivity ranging over three orders of magnitude is indicative of a heterogeneous system consisting of clay to conglomeratic sized particles. Most locations are sand- dominated. However, there are locations that have high clay content or are completely composed of clay. Field observations support the previously proposed depositional model of deltaic and fluvial environments. These models also support the observed the large ranges of grain sizes as these environments would introduce the variable grain sizes that were observed. The influence of these ranges in grain sizes on the hydraulic properties can be seen in the grain size distributions. The range of hydraulic conductivities that were calculated in the slug tests and specific capacity indicate that while the aquifer is sand dominated, there are areas where the clay content restricts groundwater flow, and the results of the tests are more likely representative of the properties of the aquifer. The previously published ranges of hydraulic conductivity are too narrow and not representative of the aquifer as a whole.

Chapter 6: Conclusions

The Antler Formation is an early Cretaceous sedimentary unit that creates the Antlers Aquifer in southern and southwestern Oklahoma. Despite being a major source of groundwater, only a couple of hydrogeological studies have been conducted on the aquifer. The municipalities that use the Antlers for its groundwater are not very populated, so there is little concern of water running out during a drought. However, understanding the properties of the aquifer is important. These studies concluded that there were broad scale properties that could be interpolated for the entire aquifer. However, previous reports noted that there is a very large variability in grain sizes and their distributions throughout the formation, even over short distances. Because of this variability, it was hypothesized by this study that the ranges of hydraulic conductivity that were determined by the previous studies were not large enough to adequately characterize the entire aquifer.

Field investigations confirmed previously noted characteristics of Antlers outcrops. Heavy vegetation obscured most of the surface outcrop, making estimations of thickness impossible. The Antlers is composed mostly of sand, but much finer sediments and conglomerates were also observed. Most outcrops were nearly entirely composed of sand with minor amounts of silts and clays, but some locations were dominated (if not completely made of) clay. The clay units were not laterally continuous, even between outcrops separated by short distances, so there is no evidence that there are any hydraulic barriers in the aquifer. Sedimentary structures observed included horizontal bedding, cross bedding, clay and conglomerate lenses, and different contacts between beds. Sediments were both fining upward and downward throughout the formation. A depositional model would have to explain the large variance in sediment size and sedimentary structures. Because of these observations, there is no evidence to change or modify the current depositional model of alluvium fans.

Hydraulic conductivity was estimated through three different tests: the Hazen Equation, specific capacity test, and slug tests. The Hazen equation uses grain size distributions to mathematically estimate hydraulic conductivity. 10 outcrops were visited in eastern Carter, southern Johnson, and northern Marshall Counties. From these outcrops, 35 samples were collected and sieved. The calculated hydraulic conductivities were a minimum of~1.19ft/day, a mean of ~27.19 ft/day, median of ~9.11 ft/day, and maximum of ~198.86 ft/day. Three slug tests were completed and had a range of 3.901-9.041 ft/day. The calculated hydraulic conductivities from the specific capacity tests were a minimum of 0.11ft/day, the mean was 6.91 ft/day, the median was 0.71 ft/day and the maximum was 31.38 ft/day The majority of the hydraulic conductivities are within the ranges of sand dominated aquifers, but the large range of values indicates that finer sediments are influencing groundwater movement, although to a minor degree.

Previously reported ranges of hydraulic conductivity were 0.87–3.75 ft/day for the entire aquifer. Based on the results of the tests that were conducted in this study, this range is too small. While groundwater will probably not be influenced exclusively by the extreme small or large sediments in any one location, there will be influences from every sediment size. This study was conducted in a relatively small section of the Antlers Aquifer, and there was a very large range of hydraulic conductivities. It is likely that the rest of the aquifer is similar in this aspect.

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Appendix A: Grain Size Distribution Tables

Location	McMillan 1.1 Unit #1 (1ft)
Dried Weight (g)	177.91
Grain Size%	
>4000 Microns	0.00
2000-4000 Micron	0.00
500-2000 Microns	0.07
250-500 Microns	0.33
125-250 Microns	39.73
63-125 Microns	44.97
<63 Microns	14.54
Sum	99.65
Finer than %	
>4000 Microns	100.00
2000-4000 Micron	100.00
500-2000 Microns	99.93
250-500 Microns	99.60
125-250 Microns	59.87
63-125 Microns	14.90
<63 Microns	0.35

Location	McMillan 1.1 Unit #2 (2.5ft)
Dried Weight (g)	220.00
Grain Size%	
>4000 Microns	0.95
2000-4000 Micron	2.60
500-2000 Microns	9.20
250-500 Microns	18.68
125-250 Microns	43.82
63-125 Microns	20.61
<63 Microns	4.39
Sum	100.24
Finer than %	
>4000 Microns	99.05
2000-4000 Micron	96.45
500-2000 Microns	87.25
250-500 Microns	68.57
125-250 Microns	24.76
63-125 Microns	4.15
<63 Microns	-0.24

Location	McMillan 1.1 Unit #2 (4.5ft)
Dried Weight (g)	152.87
Grain Size%	
>4000 Microns	0.07
2000-4000 Micron	0.28
500-2000 Microns	0.69
250-500 Microns	15.40
125-250 Microns	43.29
63-125 Microns	28.95
<63 Microns	9.30
Sum	97.99
Finer than %	
>4000 Microns	99.93
2000-4000 Micron	99.65
500-2000 Microns	98.96
250-500 Microns	83.56
125-250 Microns	40.26
63-125 Microns	11.32
<63 Microns	2.01

Location	McMillan 1.1 Unit #3 (8ft)
Dried Weight (g)	187.17
Grain Size%	
>4000 Microns	0.00
2000-4000 Micron	0.00
500-2000 Microns	0.38
250-500 Microns	8.74
125-250 Microns	64.52
63-125 Microns	23.26
<63 Microns	3.15
Sum	100.06
Finer than %	
>4000 Microns	100.00
2000-4000 Micron	100.00
500-2000 Microns	99.62
250-500 Microns	90.88
125-250 Microns	26.35
63-125 Microns	3.10
<63 Microns	-0.06

Location	McMillan 1.1 Unit #3 (11ft)
Dried Weight (g)	182.32
Grain Size%	
>4000 Microns	0.00
2000-4000 Micron	0.03
500-2000 Microns	0.22
250-500 Microns	17.78
125-250 Microns	59.39
63-125 Microns	20.66
<63 Microns	1.63
Sum	99.71
Finer than %	
>4000 Microns	100.00
2000-4000 Micron	99.97
500-2000 Microns	99.76
250-500 Microns	81.97
125-250 Microns	22.58
63-125 Microns	1.92
<63 Microns	0.29

Location	McMillan 1.1 Basal Cong (5ft)
Dried Weight (g)	233.51
Grain Size%	
>4000 Microns	12.84
2000-4000 Microns	9.04
500-2000 Microns	30.87
250-500 Microns	30.40
125-250 Microns	13.96
63-125 Microns	2.32
<63 Microns	0.19
Sum	99.63
Finer than %	
>4000 Microns	87.16
2000-4000 Microns	78.12
500-2000 Microns	47.24
250-500 Microns	16.84
125-250 Microns	2.88
63-125 Microns	0.56
<63 Microns	0.37

Location	McMillan 1.1 Cong (9ft)	Location	McMillan 1.2 Basal Clay	Location	McMillan 1.2 Unit 2 4ft
Dried Weight (g)	194.74	Dried Weight (g)	175.77	Dried Weight (g)	182.36
Grain Size%		**Grain Size%**		**Grain Size%**	
>4000 Microns	39.52	>4000 Microns	0.00	>4000 Microns	0.00
2000-4000 Microns	14.89	2000-4000 Microns	0.00	2000-4000 Microns	0.00
500-2000 Microns	16.60	500-2000 Microns	0.00	500-2000 Microns	0.00
250-500 Microns	10.89	250-500 Microns	0.00	250-500 Microns	0.75
125-250 Microns	14.24	125-250 Microns	9.35	125-250 Microns	62.79
63-125 Microns	3.02	63-125 Microns	53.43	63-125 Microns	37.19
<63 Microns	0.23	<63 Microns	37.79	<63 Microns	1.85
Sum	99.39	Sum	100.56	Sum	102.58
Finer than %		**Finer than %**		**Finer than %**	
>4000 Microns	60.48	>4000 Microns	100.00	>4000 Microns	100.00
2000-4000 Microns	45.59	2000-4000 Microns	100.00	2000-4000 Microns	100.00
500-2000 Microns	28.99	500-2000 Microns	100.00	500-2000 Microns	100.00
250-500 Microns	18.10	250-500 Microns	100.00	250-500 Microns	99.25
125-250 Microns	3.86	125-250 Microns	90.65	125-250 Microns	36.46
63-125 Microns	0.84	63-125 Microns	37.22	63-125 Microns	-0.73
<63 Microns	0.61	<63 Microns	-0.56	<63 Microns	-2.58

Location	Mansville 2.1 E most 1ft	Location	Mansville 2.1 E of W outcrop 14ft	Location	McMillan 5.4 Unit #3 2ft
Dried Weight (g)	165.16	Dried Weight (g)	185.41	Dried Weight (g)	143.35
Grain Size%		**Grain Size%**		**Grain Size%**	
>4000 Microns	0.00	>4000 Microns	0.00	>4000 Microns	0.00
2000-4000 Microns	0.00	2000-4000 Microns	0.00	2000-4000 Microns	0.00
500-2000 Microns	0.58	500-2000 Microns	0.81	500-2000 Microns	1.08
250-500 Microns	0.48	250-500 Microns	1.66	250-500 Microns	2.85
125-250 Microns	82.84	125-250 Microns	31.20	125-250 Microns	56.37
63-125 Microns	16.97	63-125 Microns	55.54	63-125 Microns	33.39
<63 Microns	3.40	<63 Microns	13.96	<63 Microns	7.37
Sum	104.27	Sum	103.17	Sum	100.96
Finer than %		**Finer than %**		**Finer than %**	
>4000 Microns	100.00	>4000 Microns	100.00	>4000 Microns	100.00
2000-4000 Microns	100.00	2000-4000 Microns	100.00	2000-4000 Microns	100.00
500-2000 Microns	100.58	500-2000 Microns	100.81	500-2000 Microns	101.08
250-500 Microns	100.10	250-500 Microns	102.47	250-500 Microns	98.24
125-250 Microns	17.26	125-250 Microns	71.27	125-250 Microns	41.87
63-125 Microns	0.30	63-125 Microns	15.74	63-125 Microns	8.48
<63 Microns	-3.11	<63 Microns	1.77	<63 Microns	1.12

Location	McMillan 5.3 Unit 2 8ft	**Location**	Mansville 1 5ft	**Location**	Mansville 1 10ft
Dried Weight (g)	194.95	Dried Weight (g)	176.61	Dried Weight (g)	202.41
Grain Size%		**Grain Size%**		**Grain Size%**	
>4000 Microns	0.00	>4000 Microns	0.00	>4000 Microns	0.00
2000-4000 Micron	0.00	2000-4000 Micron	0.00	2000-4000 Microns	0.00
500-2000 Microns	0.00	500-2000 Microns	0.59	500-2000 Microns	0.52
250-500 Microns	0.01	250-500 Microns	0.61	250-500 Microns	1.26
125-250 Microns	39.90	125-250 Microns	2.63	125-250 Microns	6.45
63-125 Microns	41.37	63-125 Microns	17.79	63-125 Microns	24.36
<63 Microns	18.47	<63 Microns	82.23	<63 Microns	73.24
Sum	99.76	Sum	103.84	Sum	104.79
Finer than %		**Finer than %**		**Finer than %**	
>4000 Microns	100.00	>4000 Microns	100.00	>4000 Microns	100.00
2000-4000 Micron	100.00	2000-4000 Micron	100.00	2000-4000 Microns	100.00
500-2000 Microns	100.00	500-2000 Microns	100.59	500-2000 Microns	100.52
250-500 Microns	99.99	250-500 Microns	101.20	250-500 Microns	99.25
125-250 Microns	60.09	125-250 Microns	98.57	125-250 Microns	92.81
63-125 Microns	18.72	63-125 Microns	80.78	63-125 Microns	68.45
<63 Microns	0.24	<63 Microns	-1.44	<63 Microns	-4.79

Location	McMillan 1.2 Unit 4 top	**Location**	McMillan 5.3 Unit 3 15ft	**Location**	McMillan 5.3 Unit 1 3ft
Dried Weight (g)	166.79	Dried Weight (g)	207.66	Dried Weight (g)	183.57
Grain Size%		**Grain Size%**		**Grain Size%**	
>4000 Microns	0.65	>4000 Microns	0.00	>4000 Microns	0.00
2000-4000 Micron	0.82	2000-4000 Micron	0.00	2000-4000 Micron	0.00
500-2000 Microns	13.96	500-2000 Microns	0.26	500-2000 Microns	1.82
250-500 Microns	53.87	250-500 Microns	1.16	250-500 Microns	2.73
125-250 Microns	29.11	125-250 Microns	1.95	125-250 Microns	48.07
63-125 Microns	3.39	63-125 Microns	71.59	63-125 Microns	24.75
<63 Microns	2.76	<63 Microns	27.36	<63 Microns	25.57
Sum	104.56	Sum	102.32	Sum	102.95
Finer than %		**Finer than %**		**Finer than %**	
>4000 Microns	99.35	>4000 Microns	100.00	>4000 Microns	100.00
2000-4000 Micron	98.53	2000-4000 Micron	100.00	2000-4000 Micron	100.00
500-2000 Microns	84.57	500-2000 Microns	99.74	500-2000 Microns	98.18
250-500 Microns	30.70	250-500 Microns	98.58	250-500 Microns	95.44
125-250 Microns	1.59	125-250 Microns	96.63	125-250 Microns	47.37
63-125 Microns	-1.80	63-125 Microns	25.05	63-125 Microns	22.62
<63 Microns	-4.56	<63 Microns	-2.32	<63 Microns	-2.95

Location	McMillan 5.4 Unit #1 1ft
Dried Weight (g)	223.25
Grain Size%	
>4000 Microns	0.00
2000-4000 Micron	1.87
500-2000 Microns	0.67
250-500 Microns	2.15
125-250 Microns	18.23
63-125 Microns	72.10
<63 Microns	7.99
Sum	103.01
Finer than %	
>4000 Microns	100.00
2000-4000 Micron	101.87
500-2000 Microns	102.54
250-500 Microns	100.39
125-250 Microns	82.16
63-125 Microns	10.06
<63 Microns	2.07

Location	Mansville 2.1 Top of W 8ft
Dried Weight (g)	148.02
Grain Size%	
>4000 Microns	0.00
2000-4000 Micron	0.00
500-2000 Microns	0.02
250-500 Microns	4.07
125-250 Microns	13.29
63-125 Microns	27.23
<63 Microns	57.74
Sum	102.31
Finer than %	
>4000 Microns	100.00
2000-4000 Micron	100.00
500-2000 Microns	100.02
250-500 Microns	95.95
125-250 Microns	82.66
63-125 Microns	55.42
<63 Microns	-2.31

Location	McMillan 5.4 Unit #3 6ft
Dried Weight (g)	164.52
Grain Size%	
>4000 Microns	0.00
2000-4000 Micron	0.00
500-2000 Microns	1.09
250-500 Microns	2.77
125-250 Microns	85.86
63-125 Microns	0.20
<63 Microns	6.72
Sum	96.63
Finer than %	
>4000 Microns	100.00
2000-4000 Micron	100.00
500-2000 Microns	98.91
250-500 Microns	96.15
125-250 Microns	10.29
63-125 Microns	10.09
<63 Microns	3.37

Location	McMillan 5.4 Unit #3 8ft
Dried Weight (g)	216.18
Grain Size%	
>4000 Microns	0.00
2000-4000 Micron	0.00
500-2000 Microns	0.68
250-500 Microns	2.50
125-250 Microns	83.81
63-125 Microns	8.81
<63 Microns	3.96
Sum	99.36
Finer than %	
>4000 Microns	100.00
2000-4000 Micron	100.00
500-2000 Microns	100.68
250-500 Microns	98.18
125-250 Microns	14.37
63-125 Microns	5.56
<63 Microns	1.60

Location	McMillan 5.4 Unit #3 11ft
Dried Weight (g)	193.93
Grain Size%	
>4000 Microns	0.00
2000-4000 Microns	0.00
500-2000 Microns	0.59
250-500 Microns	2.90
125-250 Microns	75.93
63-125 Microns	11.97
<63 Microns	7.14
Sum	98.54
Finer than %	
>4000 Microns	100.00
2000-4000 Microns	100.00
500-2000 Microns	100.59
250-500 Microns	97.69
125-250 Microns	21.76
63-125 Microns	9.79
<63 Microns	2.64

Location	McMillan 5.1 Unit #1 1ft
Dried Weight (g)	183.83
Grain Size%	
>4000 Microns	0.00
2000-4000 Microns	0.00
500-2000 Microns	0.00
250-500 Microns	1.10
125-250 Microns	77.80
63-125 Microns	16.44
<63 Microns	6.69
Sum	102.03
Finer than %	
>4000 Microns	100.00
2000-4000 Microns	100.00
500-2000 Microns	100.00
250-500 Microns	101.10
125-250 Microns	23.30
63-125 Microns	6.86
<63 Microns	0.17

Location	McMillan 1.2 Unit 4 Congl 12.5	**Location**	McMillan 5.1 Unit #1 1ft	**Location**	McMillan 5.2 Unit #2 1.5ft
Dried Weight (g)	98.87	Dried Weight (g)	159.39	Dried Weight (g)	131.76
Grain Size%		**Grain Size%**		**Grain Size%**	
>4000 Microns	1.09	>4000 Microns	0.00	>4000 Microns	0.00
2000-4000 Microns	14.74	2000-4000 Microns	0.00	2000-4000 Microns	0.00
500-2000 Microns	22.25	500-2000 Microns	0.00	500-2000 Microns	0.00
250-500 Microns	17.16	250-500 Microns	0.00	250-500 Microns	1.12
125-250 Microns	18.16	125-250 Microns	2.92	125-250 Microns	3.61
63-125 Microns	8.15	63-125 Microns	34.09	63-125 Microns	80.16
<63 Microns	8.70	<63 Microns	67.40	<63 Microns	15.59
Sum	90.25	Sum	104.41	Sum	100.48
Finer than %		**Finer than %**		**Finer than %**	
>4000 Microns	98.91	>4000 Microns	100.00	>4000 Microns	100.00
2000-4000 Microns	84.17	2000-4000 Microns	100.00	2000-4000 Microns	100.00
500-2000 Microns	61.92	500-2000 Microns	100.00	500-2000 Microns	100.00
250-500 Microns	44.76	250-500 Microns	100.00	250-500 Microns	98.88
125-250 Microns	26.60	125-250 Microns	97.08	125-250 Microns	95.27
63-125 Microns	18.45	63-125 Microns	62.99	63-125 Microns	15.11
<63 Microns	9.75	<63 Microns	-4.41	<63 Microns	-0.48

Location	McMillan 3 #1 10 ft	**Location**	McMillan 3 Unit #2 14ft	**Location**	McMillan 5.1 Unit #1 1ft
Dried Weight (g)	177.01	Dried Weight (g)	184.96	Dried Weight (g)	205.36
Grain Size%		**Grain Size%**		**Grain Size%**	
>4000 Microns	0.00	>4000 Microns	0.00	>4000 Microns	0.00
2000-4000 Micron	0.00	2000-4000 Micron	5.04	2000-4000 Micron	5.25
500-2000 Microns	0.00	500-2000 Microns	0.30	500-2000 Microns	0.32
250-500 Microns	0.00	250-500 Microns	0.62	250-500 Microns	0.25
125-250 Microns	4.17	125-250 Microns	77.12	125-250 Microns	59.35
63-125 Microns	94.62	63-125 Microns	2.80	63-125 Microns	40.41
<63 Microns	3.14	<63 Microns	18.12	<63 Microns	0.51
Sum	101.93	Sum	104.00	Sum	103.93
Finer than %		**Finer than %**		**Finer than %**	
>4000 Microns	100.00	>4000 Microns	100.00	>4000 Microns	100.00
2000-4000 Micron	100.00	2000-4000 Micron	94.96	2000-4000 Micron	94.75
500-2000 Microns	100.00	500-2000 Microns	95.26	500-2000 Microns	95.06
250-500 Microns	100.00	250-500 Microns	95.88	250-500 Microns	95.32
125-250 Microns	95.83	125-250 Microns	18.76	125-250 Microns	35.97
63-125 Microns	1.21	63-125 Microns	15.96	63-125 Microns	-4.44
<63 Microns	1.93	<63 Microns	-2.16	<63 Microns	-3.93

Location	Ravia 2 Unit #2.2 25ft	**Location**	Ravia 1	**Location**	Ravia 2.1 25 ft
Dried Weight (g)	271.80	Dried Weight (g)	198.52	Dried Weight (g)	232.86
Grain Size%		**Grain Size%**		**Grain Size%**	
>4000 Microns	4.52	>4000 Microns	0.00	>4000 Microns	0.00
2000-4000 Micron	0.49	2000-4000 Micron	1.93	2000-4000 Microns	1.63
500-2000 Microns	0.87	500-2000 Microns	1.84	500-2000 Microns	0.80
250-500 Microns	0.02	250-500 Microns	2.31	250-500 Microns	0.54
125-250 Microns	4.38	125-250 Microns	0.69	125-250 Microns	11.35
63-125 Microns	29.60	63-125 Microns	11.95	63-125 Microns	56.89
<63 Microns	58.76	<63 Microns	87.28	<63 Microns	28.58
Sum	97.62	Sum	101.73	Sum	103.06
Finer than %		**Finer than %**		**Finer than %**	
>4000 Microns	95.48	>4000 Microns	100.00	>4000 Microns	100.00
2000-4000 Micron	95.98	2000-4000 Micron	101.93	2000-4000 Microns	101.63
500-2000 Microns	95.10	500-2000 Microns	100.09	500-2000 Microns	100.82
250-500 Microns	95.12	250-500 Microns	102.40	250-500 Microns	100.28
125-250 Microns	90.74	125-250 Microns	101.71	125-250 Microns	88.93
63-125 Microns	61.14	63-125 Microns	89.76	63-125 Microns	32.05
<63 Microns	2.38	<63 Microns	2.48	<63 Microns	3.46

Location	McMillan 5.3 Unit #1 2ft	**Location**	Mansville 1 18ft
Dried Weight (g)	137.04	Dried Weight (g)	139.40
Grain Size%		**Grain Size%**	
>4000 Microns	0.00	>4000 Microns	0.00
2000-4000 Microns	0.00	2000-4000 Microns	0.00
500-2000 Microns	0.00	500-2000 Microns	2.90
250-500 Microns	2.50	250-500 Microns	1.89
125-250 Microns	4.01	125-250 Microns	5.42
63-125 Microns	7.17	63-125 Microns	21.84
<63 Microns	87.06	<63 Microns	70.57
Sum	100.73	Sum	102.61
Finer than %		**Finer than %**	
>4000 Microns	100.00	>4000 Microns	100.00
2000-4000 Microns	100.00	2000-4000 Microns	100.00
500-2000 Microns	100.00	500-2000 Microns	97.10
250-500 Microns	97.50	250-500 Microns	95.22
125-250 Microns	93.49	125-250 Microns	89.80
63-125 Microns	86.32	63-125 Microns	67.96
<63 Microns	-0.73	<63 Microns	-2.61

Appendix B: Hazen Equation Results

Location	D10 Phi	mm	C	K(ft/day)
Mansville 1 10ft	4.81	0.035	40	1.44
Mansville 1 18 ft	4.82	0.035	40	1.42
Mansville 1 5ft	4.91	0.033	40	1.26
Mansville 2.1 E Most 1 ft	3.12	0.114	150	55.87
Mansville 2.1 Top of W most 8 ft	3.78	0.072	80	11.94
Mansville E of W outcrop 14ft	4.23	0.053	50	4.05
McMillan 1.1 Congl 9ft	2.53	0.172	180	152.13
McMillan 1.1 Unit #1 1ft	4.00	0.062	80	8.86
McMillan 1.1 Unit #2 4.5ft	3.64	0.080	150	27.46
McMillan 1.1 Unit #2 2.5ft	4.79	0.036	40	1.48
McMillan 1.1 Unit #3 (11ft)	3.43	0.093	150	36.86
McMillan 1.1 Unit #3 (8ft)	3.55	0.086	150	30.99
McMillan 1.1Basal Cong	2.34	0.197	180	198.86
McMillan 1.2 Basal Clay	4.75	0.037	40	1.56
McMillan 1.2 Unit #2 4 ft	3.66	0.079	150	26.56
McMillan 1.2 Unit #4 Cong	4.56	0.042	180	9.11
McMillan 1.2 Unit #4 Top	2.57	0.169	150	121.32
McMillan 3 Unit #2 14ft	4.38	0.048	50	3.27
McMillan 3 Unit #1 10 ft	3.86	0.069	80	10.72
McMillan 5.1 Unit #1 1ft	4.00	0.062	40	4.41
McMillan 5.1 Unit #1 1ft	3.66	0.078	150	26.52
McMillan 5.2 Unit #2 1.5ft	4.19	0.055	80	6.83
McMillan 5.2 Unit #2 1.5ft	4.14	0.057	50	4.54
McMillan 5.3 Unit #1 3ft	4.52	0.043	50	2.70
McMillan 5.3 Unit #3 15 ft	4.43	0.047	40	2.46
McMillan 5.3 Unit #2 8 ft	4.38	0.048	80	5.26
McMillan 5.4 Unit #1 1ft	3.86	0.069	80	10.72
McMillan 5.4 Unit #3 11ft	4.00	0.062	150	16.57
McMillan 5.4 Unit #3 2ft	3.98	0.064	80	9.17
McMillan 5.4 Unit #3 6ft	3.00	0.125	150	66.07
McMillan 5.4 Unit #3 8ft	3.13	0.115	150	55.87
McMillan 5.3 Unit #2 8ft	3.55	0.085	150	30.99
Ravia 1	4.95	0.032	40	1.188
Ravia 2 Unit #2.2 25 ft	4.87	0.034	40	1.33
Ravia 2.1 25 ft	4.78	0.036	50	1.88