EVALUATION OF POTENTIAL PALEOCHANNELS IN THE WASHITA ALLUVIUM AND TERRACE AQUIFER, OKLAHOMA

By

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Bachelor of Science in Geology

Oklahoma State University

Stillwater, Ok

2014

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 2020

EVALUATION OF POTENTIAL PALEOCHANNELS IN

THE WASHITA ALLUVIUM AND TERRACE

AQUIFER, OKLAHOMA

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ACKNOWLEDGEMENTS

First and foremost, I would like to acknowledge my adviser and mentor, Dr. Todd Halihan. Not only has your profound understanding of the world around us changed my life, but your life lessons have benefited me more than I could ever describe. I am extremely fortunate to continue to work with such a brilliant and charismatic leader. I would also like to thank my committee members Dr. Jim Puckette and Dr. Javier Vilcaez Perez for their expertise and guidance.

I would also like to acknowledge my former boss and good friend Chris Neel, thank you for always making me think about things in as many different ways as we could come up with. I learned a great deal from working with you. I am greatly appreciative of all of the help in the field from my colleagues and friends from the Oklahoma Water Resources Board including; Byron Waltman, Jacob Hernadez, Jon Sanford, Derrick Wagner, Sean Hussey, and Alan LePera. Thanks for all the hard work and good times!

Name: KYLE SPEARS

Date of Degree: DECEMBER, 2020

Title of Study: EVALUATION OF POTENTIAL PALEOCHANNELS IN THE WASHITA ALLUVIUM AND TERRACE AQUIFER, OKLAHOMA

Major Field: GEOLOGY

Abstract: Aquifers comprised of alluvium are often an important source of water for industrial, municipal, and environmental purposes. To best manage and protect these complex hydrogeologic systems, a comprehensive evaluation is needed to monitor and predict their response to stress. Electrical Resistivity Imaging (ERI) was used to image the subsurface architecture of the Washita Alluvium and Terrace aquifer in western Oklahoma up to 110 meter deep. This technique was applied to evaluate the geometry and hydraulic properties of the deposits, and integrated these data with limited well data available in the area.

The Washita Alluvium and Terrace aquifer overlies Permian-age bedrock, forming a boundary detectable by ERI. Previous investigations suggest the alluvial deposit was approximately 36 meters deep. The ERI data suggest a previously unknown paleochannel, up to 90 m deep is present in each of four cross section datasets that run perpendicular to the stream with lengths between 0.83 and 1.95 kilometers. The interpretation was supported by some limited deep borings in the area. The discovery of this deeper component of the aquifer demonstrates interpretations of these systems through traditional methods, such as correlating borehole information, can miss important features due to lack of spatially continuous information.

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CHAPTER I

INTRODUCTION

Quaternary alluvial aquifers are utilized worldwide as a stable, high volume reservoir of water resources (Davis, 1988). Quaternary alluvial aquifers are used throughout western Oklahoma as viable sources of fresh water where precipitation totals are much less than what they are in the eastern portion of the state. Communities in these areas tend to rely more on groundwater than surface water (OWRB, 2017). These systems are complicated to characterize for hydrogeologic purposes as the grain sizes in the systems can range from clay to boulders, generating a range of hydraulic conductivity values (Larkin, 1992). Additionally, these sediments accumulated in channels and overbank deposits in complicated three-dimensional structures that may connect in space (Scudder et al., 1995). In order to effectively manage these systems, an understanding of the three-dimensional variability of the aquifers is required (Durkin et al., 2015). The primary difficulty is that many of these systems have only been characterized at a low density of data, comprised of well data spanning miles of aquifer (Kent, 1982); comprehensive spatial evaluation of alluvial channels is necessary to better characterize the groundwater contained in these systems.

Traditional approaches to understanding these complex systems rely upon the installation of monitoring wells and the subsequent interpolation between them. This method provides useful information at discrete points, but inherently fails when trying to interpret complex structures existing between well locations. Traditional practices can be inadequate when trying to interpret alluvial systems which can change in composition significantly over a small area both vertically and horizontally. The scale at which some of the features exist can make them easily missed by the correlation of logs.

Tracer tests can be used to determine hydraulic connections between different features but provide little information on the geometry of the path traveled between the features (Berkowitz, 2002). Ground penetrating radar (GPR) is another method applied for evaluation of alluvial aquifers, but can be ineffective in areas where thick clay layers are present and limited in depth of investigation (Bowling, 2005). Another method used to characterize alluvial deposits is horizontal to spectral ratio (HVSR), a passive seismic method developed by USGS. This method is applied by measuring ambient seismic noise and resulting velocity data is used to determine depth to bedrock. This methodology is also limited in depth and areas where thick clay layers are present (Brown, 2013).

The Washita River in west-central Oklahoma flows over Quaternary alluvial deposits which provide groundwater primarily used for irrigation in this region. Geomorphology of the region is characterized by dendritic patterns of incised channels in Tertiary and Permian rock. The river channels trend overall in a northwest to southeast direction in conjunction with other predominant rivers and geologic features, including the axis of the Anadarko basin and the Wichita Uplift. The aquifer material is primarily composed of reworked sediments from the Tertiary age Ogallala

Formation, as indicated by the abundance of quartzitic material (Goss, 1972). Alluvium material is reported as being up to 79 meters (260 ft.) thick in well logs from the Oklahoma Water Resources Board Well Drillers' Database (OWRB). Groundwater quality is impacted by lower stratigraphic units containing evaporite beds such as dolomite ($CaMg(CO_3)_2$) and gypsum ($CaSO_4 \cdot 2H_20$), as well as anthropogenic activity on the surface such as agricultural practices and oil and gas mining.

Schipper (1983) modeled the furthest reach of the aquifer to the west in 1983 as part of a more comprehensive groundwater flow model that encompassed all four reaches of the aquifer (Kent et al., 1982). This study focuses on the hydrogeologic architecture of Reach 1of the alluvial aquifer, extending from the western Oklahoma border and continuing south to southeast to the municipality of Clinton, Oklahoma. The model was prepared for the Oklahoma Water Resources Board to determine the maximum annual yield and equal proportionate share for each reach of the aquifer. The model ran 20-year simulations resulting in a 2.18 acre-feet/acre equal proportionate share being set for the aquifer. Every hydrologic investigation conducted under this statute is to be updated after 20 years. It is critical to collect new field data sets to be able to improve the model by expanding our understanding of the system and testing hypotheses generated by the previous model.

Electrical Resistivity Imaging (ERI) is a surface geophysical method possible in nearly all field conditions and is a non-intrusive procedure, making it a preferred method of data collection over drilling to depth at a significant number of locations. This technique is based on the measurement of electrical resistivity of earth materials. Resistance [ohms] is a fundamental property of a volume of material and is defined as the material's resistance to the flow of electrical current

(Reynolds, 1997). In a volume of material with length (L) and cross-sectional area (A), the material's resistance will be proportional to the potential drop of an induced electrical current (V/I). Resistivity [ohm-m] is expressed as a resistance across a distance making it independent of material geometry (Reynolds, 1997). Resistance (R) and resistivity (ρ) can be expressed by the following equations (Reynolds, 1997):

$R = V/I$ (ohms – Ω) (Ohm's Law)

$\rho = V/I * A/L$ (ohm-meters – Ω-m)

This geophysical method is an effective approach for characterizing systems with high degrees of heterogeneity because ERI provides continuous, high resolution data. ERI has the ability to detect geologic structures, location and continuity of the water table, saturated and unsaturated zones, lithology boundaries, and geometry of subsurface sediments continuously in two dimensions (Crook, 2008). Using the roll along technique, ERI surveys can extend laterally over significant distances, while maintaining the same resolution as each individual survey. This methodology provides continuous two dimensional data across the domain, yet still requires confirmation drilling and sampling to further refine hypothesis based on integration of qualitative and quantitative datasets.

This thesis was initiated in collaboration with the Oklahoma Water Resources Board (OWRB) to better characterize the horizontal and vertical extents of the alluvial channel, and the overall geometry of the underlying bedrock surface to aid in the development of a groundwater flow model by the U.S. Geological Survey. Continuously imaging across most or all of the alluvial channel using a proprietary electrical resistivity imaging (ERI) technique, it is possible to determine features previously overlooked due to low data density. Of particular interest to this study is the potential existence of a deeper paleochannel below the overlying alluvial deposits. This would present a potential source of error in calibrating the model, which would not account for a significant volume of the aquifer, resulting in inaccurate storage estimates and geometry. Presence of a paleochannel in the WAT aquifer would be consistent with amalgamated fluvial systems described by Milliken et al. (2018).

Quaternary alluvial channels are particularly hard to characterize with wells alone due to the discontinuity of the channel forms along a linear geometry. Given the geologic history of the site and the limitations of previous investigations of the aquifer, it is possible the current understanding of the aquifer is inadequate. As a result of these conditions, attempts to simulate historical observations of water levels have been unsuccessful.

If the hydrogeological architecture of the Washita Alluvium and Terrace (WAT) aquifer consists of an underlying paleochannel, it likely exists at any point in the alluvial channel. ERI transects performed perpendicular to the trend of the alluvial channel would highlight a channel structure. This technology has the ability to resolve hydrogeologic features of this nature because the properties of the paleochannel would be apparent in the data as channel shaped electrical structures with consistent geometry, dimensions, and slope. While fluid and rock features aren't independent signals in the data, patterns of resistivity integrated with drilling and groundwater data can provide a much more complete understanding of the subsurface. To date, no studies have used subsurface imaging on this scale to characterize alluvial valleys of this magnitude. By scanning the subsurface on a kilometer scale basis it is possible to glean valuable insight by capturing a large area in one dataset.

CHAPTER II

SITE DESCRIPTION

Geography

The Washita River is located at the western edge of the North American interior lowlands, adjacent to the eastern Great Plains (Kottek et al., 2006). Beginning at the western border of Oklahoma with the Texas Panhandle, the alluvium and terrace deposits of the WAT aquifer traverse 150 km (93 mi) and cover 337.2 km^2 of Roger Mills and Custer counties in Oklahoma. This portion of the southwestern Great Plains Region is characterized by hummocky topography, created by gently rolling hills and dendritic canyons carved by meandering rivers and streams (Shipper, 1987). The alluvium filled channels and canyons in this region trend northwest to southeast across western Oklahoma.

Land-use data for the WAT aquifer were obtained from the CropScape database (National Agricultural Statistics Service, 2019). This database contains information about land-use characteristics at a 30-m resolution. Land uses overlying the total reported alluvium and terrace aquifer area of 337.2 km^2 (843,000 acres) were composed of crops (53.3%), pasture and shrubland (39.1%), forest (3.1 %), and wetlands (0.1%) (Fig. 1). The remaining land overlying the aquifer area was reported as surface water, barren regions, and developed land (4.4%) (Fig. 1). Winter wheat is the predominant crop grown over the aquifer, accounting for 67.4% of all the land area used for crops (Fig. 1). Other crops grown within the aquifer area include alfalfa and other types of hay (15.6%), cotton (9.7%), sorghum (2.2%), and the remaining 5.1% is comprised of various other crops and fallow or idle cropland (Fig. 1).

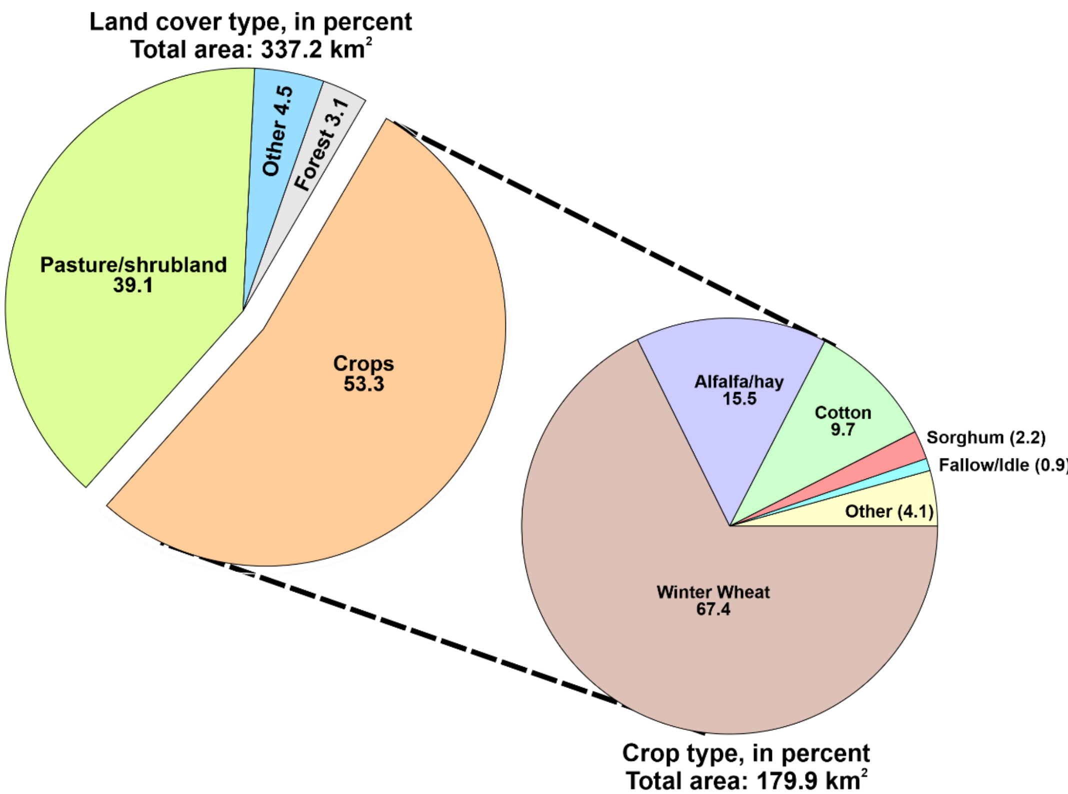

Figure 1: Land cover and crop types on the Washita Alluvium and Terrace aquifer, Oklahoma (data obtained from the CropScape database from the National Agricultural Statistics Service, 2019).

Climate

Climate in the Washita River basin is the result of its location at the western edge of the Interior Lowlands, adjacent to the eastern Great Plains of North America. This geographic boundary correlates with the climatic boundary between a mid-latitude dry steppe to the west and the humid subtropical climate to the east (Kottek et al., 2006). The proximity of the study area to this climatic boundary is reflected in the increase of average annual temperature from 14.4°C (58 ºF) to the west and 15.6°C (60 ºF) in the east. Average annual precipitation also varies from 609 mm (24 in) in the western end of the study area to 762 mm (30 in) in the eastern portion (Oklahoma Climatological Survey, 2017). Precipitation increases as the rain shadow effects of the Rocky Mountains to the west diminishes (Tortorelli, 1991).

Historical climate data were retrieved from six climate stations in west central Oklahoma, including stations Bessie, Butler, Cheyenne, Hammon, and Leedey (Table 1). Years with fewer than 9 months of data in the period of record were omitted from analysis. Bessie, Butler, and Cheyenne Oklahoma Mesonet stations have been recording daily precipitation and temperature data beginning in 1994. Monthly precipitation data from climate stations across the study area show the west to east increase in precipitation with the Cheyenne station consistently reporting less monthly precipitation totals than stations Bessie and Butler, to the east, except for the month of July (Fig. 2).

The National Weather Service (NWS) Cooperative Observer Program (COOP) provides historical climate data collected by local volunteers. Oklahoma COOP stations recorded precipitation data from 1920-2017 and temperature was recorded at the Hammon station from 1920-2004.

Historical mean-annual precipitation and wet and dry periods were determined using data from climate stations Leedey, Hammon, and Cheyenne (Fig. 3). Leedey collected daily rainfall continuously for 76-years, and the Hammon station recorded daily precipitation from 80 of 84 years during the period of record. The Cheyenne station was in operation from 1923-1975, 1980-1985, and 1987-1993. Climate data from these stations were analyzed, quality controlled, and summarized as part of this study of Reach 1 of the Washita basin. Average annual precipitation can vary greatly from year to year, with transitions from wet to dry periods as indicated by the red and blue areas, representing the 5-yr moving average for annual precipitation (Fig. 2). Recharge potential is greatest during May and June when average monthly precipitation is 100 to 110 mm (Fig. 3).

Roger Mills County has an average temperature of 14.4℃ (58ºF), ranging from average daytime highs of 35℃ (95°F) in July, to an average low of -6.1℃ (21ºF) in January (Oklahoma Climatological Survey, 2017b). Winds are predominantly from the south to southwest, averaging near 20.9 km/hr (13 mph) (Oklahoma Climatological Survey, 2017b). The Hammon COOP station is centrally located in the study area and recorded an average daytime high of 22.7℃ (72.9 °F), average daytime low of 7.3℃ (45.2°F), and an overall average of 16.05℃ (59.1°F). Data from the Mesonet stations also shows average annual temperature increases from west to east from 15.4℃ (59.7°F) at the Cheyenne station, to 15.6℃ (60.1°F) at the Butler station, and 16.1℃ (60.9°F) at the Bessie station.

Table 1. Data collection time periods of average annual precipitation at selected climate stations used in the Washita River aquifer. Locations of the climate stations used are shown on figure 1. Bessie is located 8.9 km south of the study area near Clinton, Oklahoma. [Data from Oklahoma Climatological Survey, 2017 and Mesonet stations, 2017. All units are mm per year.]

Station Name	Period of record[1]	Number of years	Period of record mean annual precipitation (mm)	1930-1988 mean annual precipitation (mm)	1989-2008 mean annual precipitation (mm)	2009-2014 mean annual precipitation (mm)
[1]Leedey (COOP)	1941-2017	76	619.76	587.36	683.26	523.24
[1]Hammon (COOP)	1920-2004	84	652.78	616.67	741.68	N/A
[1]Cheyenne (COOP)	1923-1993	70	589.28	581.29	551.18	N/A
Bessie (mesonet)	1994-2017	23	706.12	N/A	*759.90	533.40
Butler (mesonet)	1994-2017	23	693.42	N/A	*731.85	515.62
Cheyenne (mesonet)	1994-2017	23	685.80	N/A	*583.95	520.70
Mean of all stations			**657.86**	**595.11**	**658.71**	**523.24**

[1]Not continuous.

[*]Data begins in 1994.

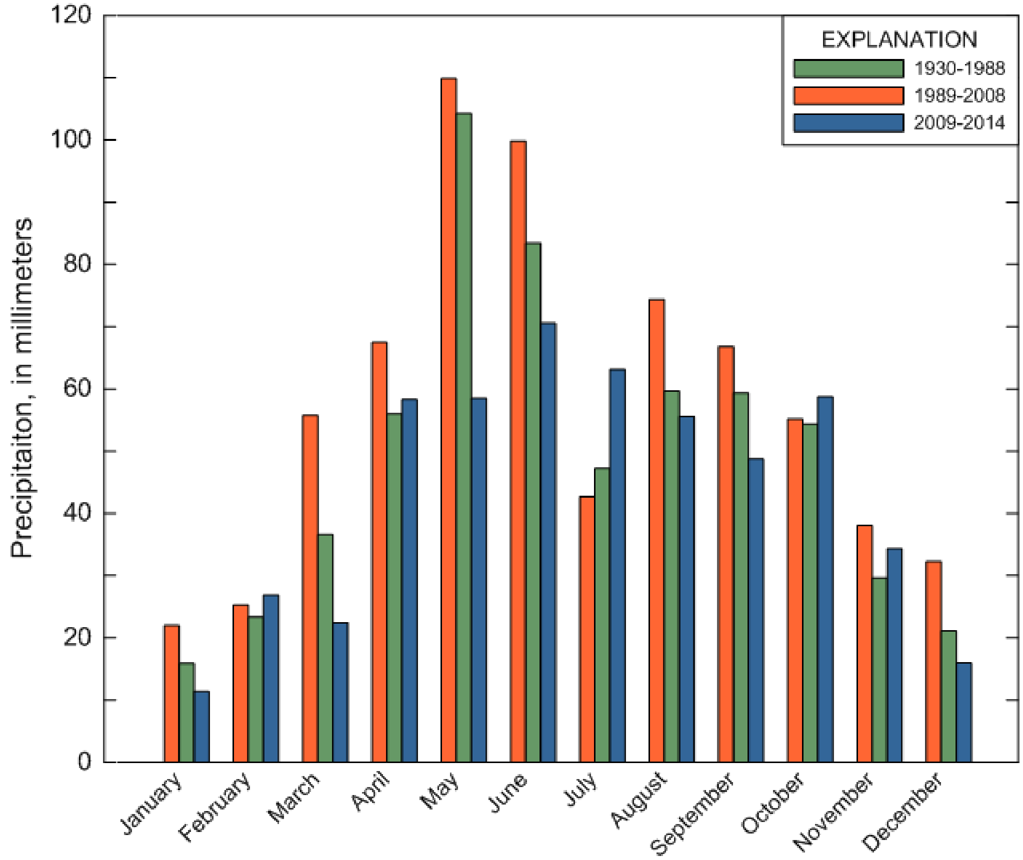

Figure 2: Average monthly precipitation over different time periods. The time periods include 1930-1988, 1989-2008, and 2009-2014 for cooperative observer stations Cheyenne, Hammon, and Leedey.

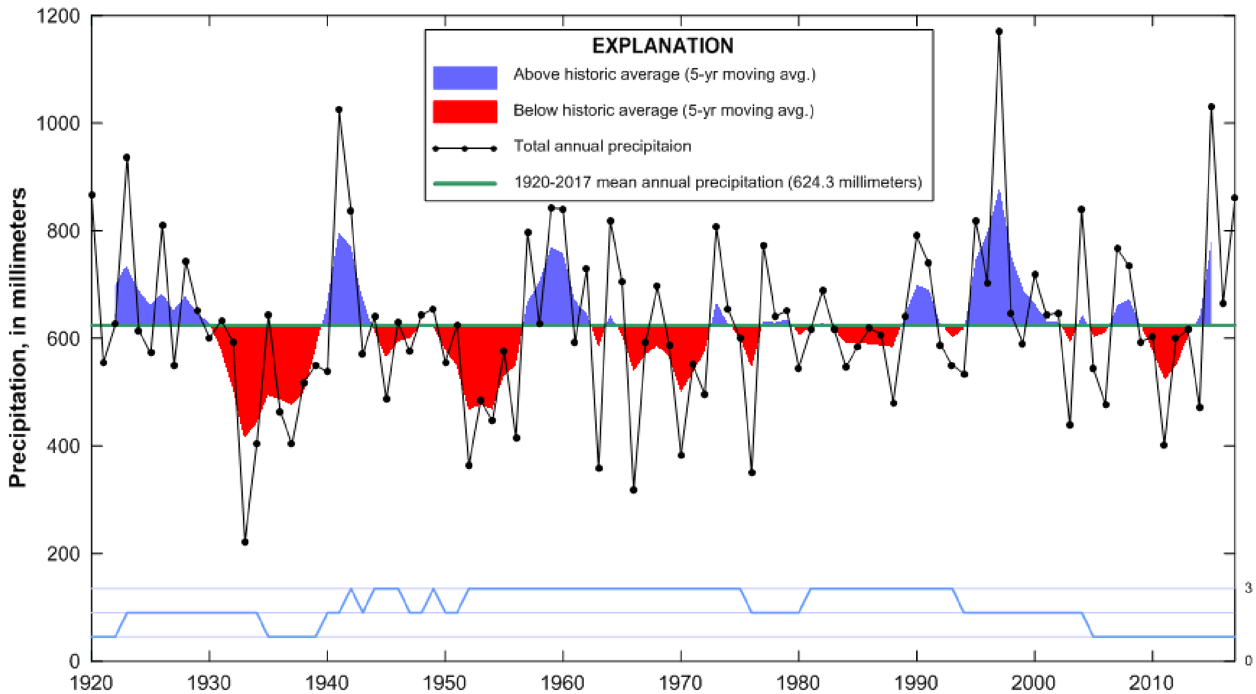

Figure 3: Precipitation trends over the WAT aquifer. Average annual precipitation (black dots), 5-yr weighted average (blue/red), and overall mean annual precipitation (green line) recorded from 1920-2017 for National Weather Service (NWS) Cooperative Observer Stations (COOP) at Cheyenne, Hammond, and Leedey.

Geology

The overall geologic setting of the WAT aquifer can be described in terms of lithology, stratigraphic sequence, depositional history, and geologic structure. Each formation's general characteristics are described in stratigraphic sequence as drilled from youngest to oldest. These stratigraphic units were deposited during and after the formation of the Anadarko basin which is described in section 3.2.2. Geologic structures prominent in the region are described in the following section.

Stratigraphy

Quaternary Alluvium

The valley formed by the Washita River is filled with Quaternary aged fluvial deposits consisting primarily of reworked sediments from the Tertiary age Ogallala Formation, as indicated by the plethora of quartzitic material (Goss, 1972; Fig. 4). The resulting sediments range in size from clay to boulders. These are tan, gray, and white in color, and can be red stained due to the high iron content of the parent Permian material in the valley walls. Sediments in the alluvial channel are primarily silica rich, being derived from weathering of uplifted granite to the west and south. Edges of the valley are overlain by terrace deposits from recently weathered sides of Permian bedrock outcrops, formed by mechanical and chemical weathering. Terrace deposits are comprised of unconsolidated sand, silt, clay, gravel, and some volcanic ash overlying modern floodplains. Mapped alluvium thickness ranges from 0 to over 61 m (200 ft) (Kitts, 1959). However, alluvium thickness can be greater where paleochannels may exist, which are typical in this depositional setting (Milliken et al., 2018).

Tertiary

The Tertiary age Ogallala Formation is described as fine to medium grained partially cemented layers of sand, with interbedded silt, clay, gravel, volcanic ash and caliche (Kitts, 1959). Thin layers of sandstone are poor to moderately cemented by calcium carbonate. Ogallala sediments are tan, brown, light gray, and white in color, and range from 0-107 m (350 ft) in thickness (Kitts, 1959).

Permian

Underlying the Quaternary and Tertiary formations are Permian strata, which are referred to collectively as “red beds” due to cementation of the sediments by iron oxide (Becker, 1997) (Fig. 4). These formations were deposited by fluvial processes and are divided into two groups, the Foss Group and Whitehorse Group (Hart, 1978) (Fig. 6). The Foss Group consists of the Doxey Shale, which is a blocky, red and maroon siltstone, and silty shale (Fig. 6). The lower formation of this group is the Cloud Chief, up to 122 m (400 ft) in thickness. It is composed of red, brown, and orange shale with interbedded fine to medium grain cross-bedded sandstone and siltstone, with intermittent evaporite beds (Johnson, 1978). The Moccasin Creek formation is an evaporite bed, either gypsum or dolomite, and marks the boundary between the Foss Group and the Whitehorse Group (Fig. 6). The Rush Spring Formation lies at the top of the Whitehorse Group. It is composed of red fine-grained silty sandstone with interbedded claystone and gypsum, and is locally cross-bedded (Fay, 1962).

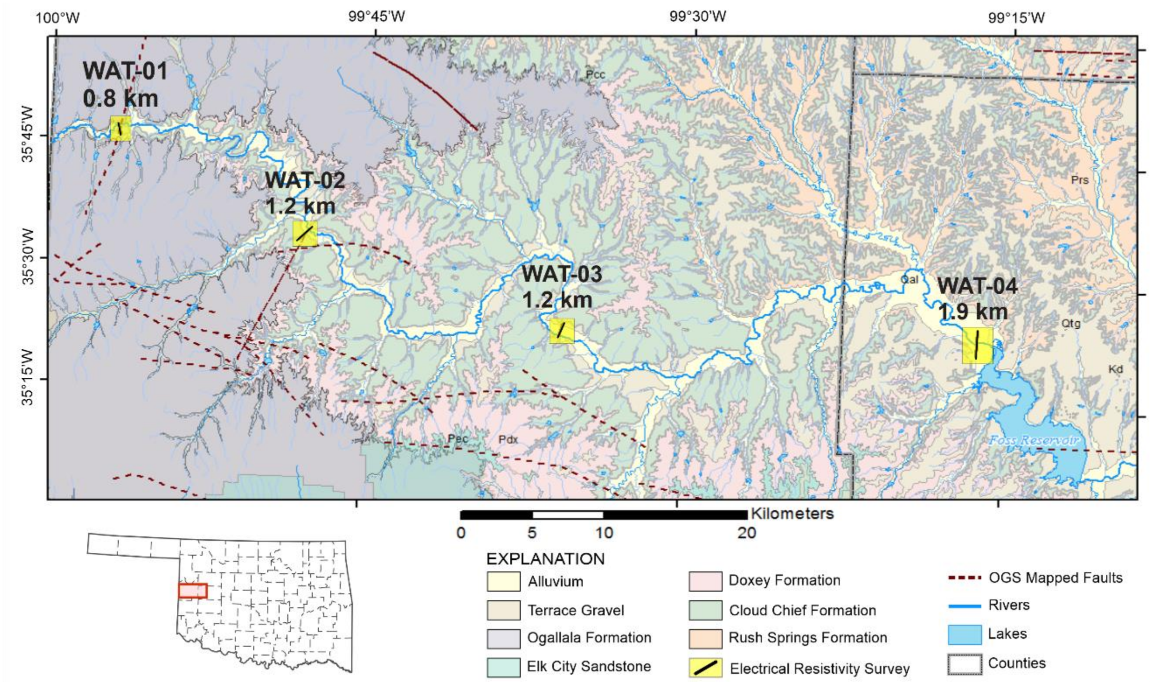

Figure 4: Surficial geologic units of the study area (OGS, 2005) showing location of electrical resistivity surveys, their lengths, and mapped faults by the Oklahoma Geological Survey (OGS, 2016). Inset map of Oklahoma in lower left illustrates the location of the study area.

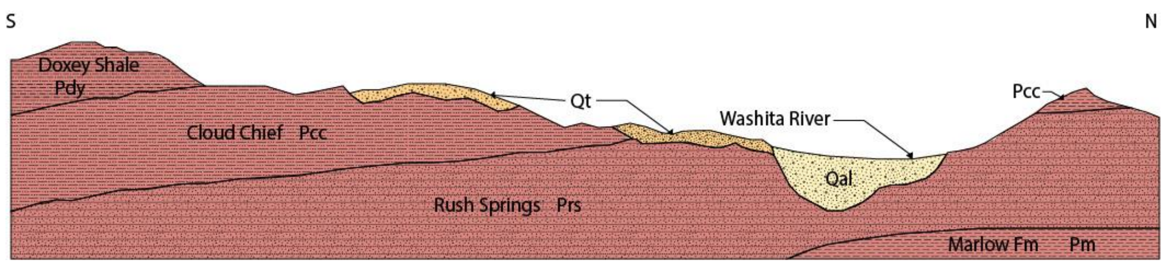

Figure 5: Geologic cross section of the WAT aquifer modified from Fay, 1978.

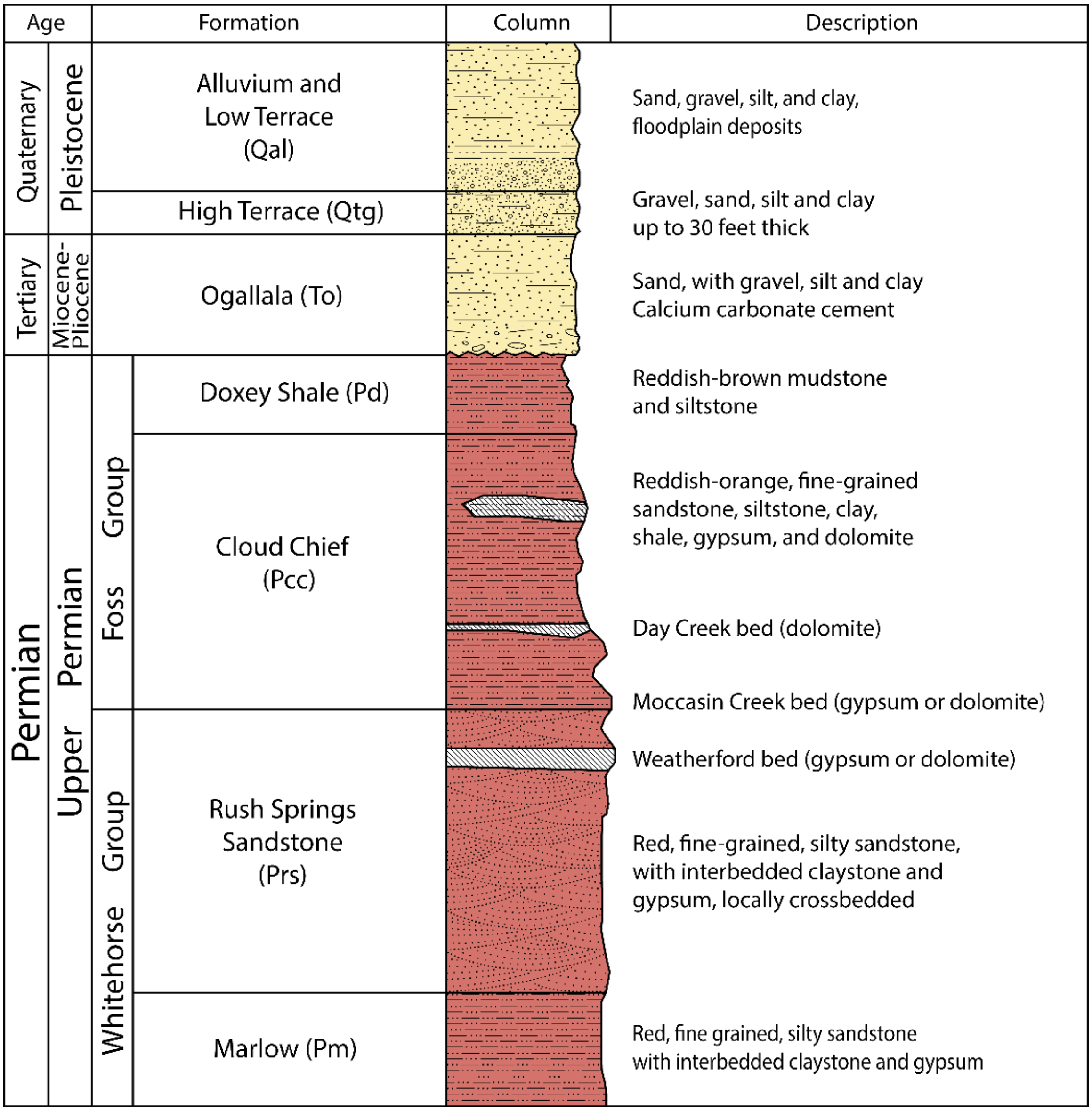

Figure 6: Stratigraphy column showing geologic units of the of the WAT aquifer study area modified from Schipper, 1986.

Depositional History

Formation of Anadarko Basin

The Anadarko basin has a long and complex geologic history, beginning in the late Proterozoic (Perry, 1989) when the Southern Oklahoma Aulocogen (SOA) started to form. The basin began as a reaction to the initial collision of the southern continental margin of Paleozoic North America with the Gondwana paleo continent, and possibly an intervening microplate (Perry, 1989). The development of the Anadarko basin is the result of subsidence and tectonically controlled faults. During the Cambrian period, the structural setting resembled a failed arm of a plate tectonic triple junction associated with rifting (SOA). The Anadarko Basin formed at this time when fault blocks lifted basement rocks above sea level to form the SOA, the Wichita mountains, and Arbuckle mountains (Perry, 1989).

The basin continued to form into the Permian before filling with carbonates, evaporites, and detrital material (Zabawa, 1976). The region was near the equator during this time and the depositional environment was an equatorial epeiric sea. Later in the Permian, as the area continued to be uplifted, conditions oscillated between wet and dry. By the end of the Permian, drier conditions persisted. Much of the study area underwent an erosional period during the Triassic and Jurassic periods, due to the region being positioned above sea level (Johnson, 1989). This period of erosion was abbreviated at the start of the Cretaceous and through the Tertiary, when piedmont sediments were transported from the west as a result of the Laramide Orogeny (Lyons, 1978). The area was being uplifted during the Triassic and Jurassic periods, resulting in erosional forces dominating over deposition.

During the late Cretaceous, 70 to 80 million years ago until 35 to 55 million years ago, the Laramide Orogeny caused extensive uplift in the Rocky Mountains region resulting in a large supply of sediment from the west (Kitt, 1959). This resulted in much of the west-central Great Plains being covered by a large apron of alluvial deposits (Kitt, 1959).

Following the Tertiary period, deposition in western Oklahoma occurred predominantly along rivers in the forms of alluvium, terrace, and flood plain deposits. During the Pleistocene epoch, transitions from glacial to interglacial conditions resulted in depositional events, as melting glaciers transported large sediment loads to the region. Resulting sedimentary deposits from deposition over the course of the Pleistocene are up to 1,524 m (5,000 ft) thick (Kitt, 1954). In the study area, Pleistocene deposits range from 0-107 m (350 ft) in thickness.

Structure

Structural features parallel to the trend of the Washita River alluvium in this region, include the Wichita megashear system, axis of Wichita-Amarillo uplift, and axis of Anadarko basin (Fig. 4). Several prominent streams including the North Fork of the Red River, Canadian River, and North Canadian River have parallel trends to the aforementioned structural features (Fig. 4). The Anadarko basin resulted from the SOA, which formed as a failed rift arm during the early Cambrian (Pruatt, 1975). Zones of weakness in this region originally formed during this time and have been the primary influence of subsequent tectonic stress (Zabawa, 1976). The Cordell faulted fold belt, which bounds the frontal Wichita Mountains on the north end, has existed since the Devonian period and is the primary structural feature in the region. The fold belt is primarily made up of northwest trending normal faults, intersected by offsetting north trending faults, resulting in a complex network of horsts and grabens (Zabawa, 1976). The WAT aquifer crosses over the Sayre Graben, upthrown North Block, and Cordell Graben. Normal faults measured by Zabawa et al. (1976), were found to dip north-northeast 75 degrees or more, while reverse faults dipped 61-75 degrees northeast. Zabawa et al. (1976) mapped 7 anticlinal folds and 2 synclinal folds, with 2 synclinal folds and 4 anticlinal folds trending northeast and plunging 8-10 degrees northeast. Seismic data collected by the GHK company and interpreted by Zabawa (1976) were used to delineate horst and graben structures, and were compared to lineaments seen in Earth Resources Technology Satellites (ERTS) imagery. Many of the apparent northwest-southeast lineaments were over 20 km in length and their locations are coincident with inflections in the subsurface structural contour maps, indicating deep seated faults that are expressed subtly at the surface (Zabawa, 1976).

Hydrogeology

Water Use

Groundwater use is permitted by the OWRB based on the 1978 water law and the Oklahoma Comprehensive Water Plan (OCWP) (Oklahoma Water Resources Board, 2012). OWRB groundwater use data from 1967-2015 overlying the study area were retrieved and analyzed for this study (Table 2). Permitted groundwater users in Oklahoma are required to submit annual reports on their water-use. Reporting of annual groundwater use has not been required for domestic water wells, agricultural use less than 6.17 ML (5 acre-feet per acre per year ([acre-ft/acre]/yr), or irrigation applied to fewer than 3 acres (Oklahoma Water Resources Board, 2014). Prior to 1980, water use reports only required farmers to record crop type, frequency of irrigation, and number of acres irrigated. Following 1980, irrigators were required to include the number of applications and the inches of water per application (Oklahoma Water Resources Board 2014), which allows for the volume of water used to irrigate to be calculated directly.

The OWRB also reports water use by category for uses including power, industrial, mining, commercial, agriculture, fish and wildlife, and recreation. These accounted for little to no use in this aquifer (Table 2). Temporary permits are also issued by the OWRB for short term use of groundwater, expiring after three months. There were 145 temporary permits issued in the study area, almost entirely for oil and gas drilling, with a combined total reported use of 1,761 ML/yr (1,428 ac-ft/yr) from 1992 to 2017 (OWRB, 2017). During this time the most temporary permits for groundwater use in a given year was 1 ML/yr (5 ac-ft/yr) in 2012, all of which was for oil and gas drilling.

Data from 245 groundwater-use permits were analyzed and total annual use categorized by type for 1967-2015 for the study area. Nearly 98% of the total groundwater use reported was for irrigation, while other uses of groundwater in the study area include public supply, mining, and agriculture. Mean annual total groundwater use for the period of record, 1967-2015, was 7,498 ML/yr (6,079 ac-ft/yr). From 1967-1980 average annual use increased to 8,867 ML/yr (7,189 ac-ft/yr). During this period, eight of thirteen years recorded precipitation totals below the 76-year mean. There was a brief rise in use from 1994-1996 ranging from 4933 ML/yr (4,000 ac-ft) to nearly 9,867 ML/yr (8,000 ac-ft/yr); interrupted by above average rainfall in 1997 and reported groundwater use declined to 2,305 ML (1,869 ac-ft/yr).

Groundwater use steadily increased from 5,817 ML/yr (4,716 ac-ft/yr) in 2008 to over 12,335 ML/yr (10,000 acre-feet) in 2013 and 2014. This increasing trend in groundwater usage is likely due to several consecutive years of drought conditions during this time. The following year the study area received over 1,016 mm (40 in.) of precipitation and reported groundwater use decreased over 6,167 ML/yr (5,000 ac-ft/yr) from the previous year. These trends suggest periods with below average precipitation typically corresponds to higher amounts of reported groundwater use. In this semi-arid region, where drought conditions can last over a decade, it is imperative to have a comprehensive and accurate understanding of this freshwater resource so that it can be effectively managed.

Table 2. Reported annual groundwater-use statistics for the Washita alluvium and terrace aquifer, Oklahoma, 1967-215.

Period	Mean annual reported groundwater use, in ML/year (and percentage), by type					
	Agriculture	Irrigation	PWS	Mining	Other	Total
1967-1980	0	8861	7	0	0	8868
	0	100	0	0	0	100
1981-1993	0	4909	46	1	0	4957
	0	99	1	0	0	100
1994-2003	3	5516	242	5	155	5921
	0	93	4	0	3	100
2004-2015	3	9032	67	28	116	9246
	0	98	1	0	1	100
1967-2015	1	7171	80	8	60	7321
	0	98	1	0	1	100

Streamflow

Groundwater from the WAT aquifer discharges as baseflow to the Washita River and its tributaries, according to stream flow data collected using a FlowTracker handheld ADV (acoustic doppler velocimeter) in December 2017. Streamflow was measured to be 0.17 cubic meters per second (cms) (6.14 cubic feet per second (cfs)) just east of the Oklahoma border, 0.18 cms (6.52 cfs) where WAT-01 crossed the river, and increases to 0.47 cms (16.72 cfs) approximately 33 km downstream (Fig. 7), indicating gaining conditions.

The contribution of groundwater to the river varies seasonally. Long sections of the river channel are encompassed by cotton wood forests, which act as large pumps, taking up water during spring and summer months. According to 1970-1979 data from discharge station 3242 (Carr et al., 1976) just upstream from Foss Reservoir, total dissolved solids averaged 1,712 mg/L during winter months, and 1,086 mg/L during summer months. This suggests that base flow contribution is higher during the winter months when less precipitation is received and trees are dormant; during summer months there is more surface runoff and TDS values are dampened.

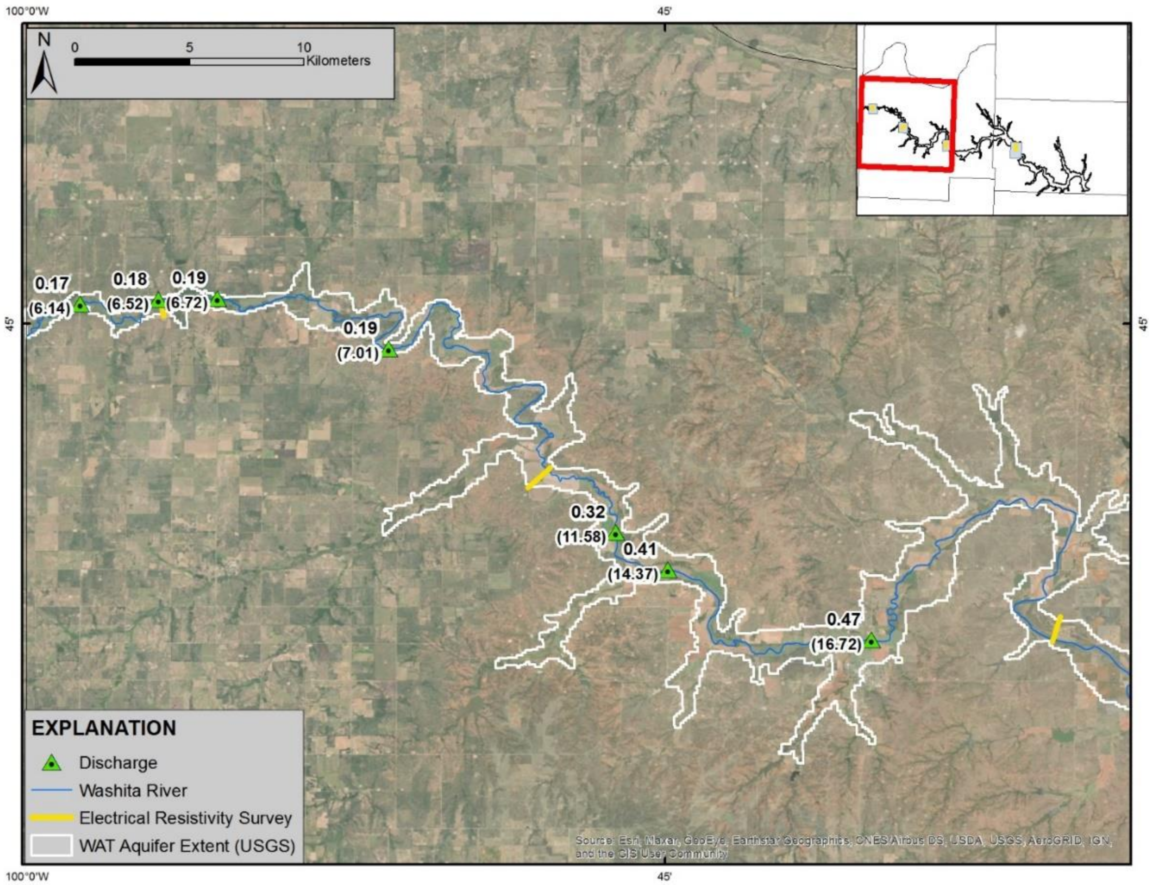

Figure 7: Map showing in-situ streamflow measurements in cubic meter per second (cubic feet per second) along the Washita River.

Water Quality

Groundwater samples for water quality analysis were collected from 13 wells throughout the aquifer by OWRB staff in 2013 as part of the Groundwater Monitoring and Assessment Plan (GMAP) (OWRB, 2013) (Fig. 8). Data from these samples were investigated for the purpose of this thesis. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) are the predominant cations, with some sodium (Na^{+}) and potassium (K^{+}) present, with mean hardness being 1,643 mg/l (Table 3). Anions present in the water samples collected, in order of concentration, were sulfate (SO_4^{2-}), bicarbonate

(HCO_3), and chloride (Cl^-) (Table 3). Total dissolved solids (TDS) of the samples collected from the aquifer reported a mean of 2,752 mg/l, with a maximum of 3,650 mg/L and a minimum of 1,760 mg/L (Table 3). The full range of TDS in this dataset is brackish meaning electrical signals are expected to be more electrically conductive than freshwater or low porosity rock. The Oklahoma Water Resources Board (OWRB) has defined fresh water as less than 5,000 mg/L TDS, meaning water in the aquifer is considered fresh.

Mean pH for of the aquifer was determined to be 7.3, with a maximum of 7.6 and a minimum of 7.3. Mean groundwater temperature across the aquifer was 20℃ and ranged from 18.2℃ to 23.7℃ (Table 3). The Ogallala is composed of fine to coarse grained alluvial deposits and conglomerates weakly cemented by calcium carbonate. Presence of calcium carbonate cementation is represented in the Piper Plot (Fig. 9) with the samples plotting in the calcium carbonate zone. Results from the GMAP water quality sampling program suggests the water type for the WAT aquifer is predominantly calcium sulfate (Fig. 10), with some samples being calcium, sodium, and magnesium sulfate. Calcium concentrations decrease from west to east as the presence of the Ogallala diminishes.

The Clinton Hydrologic Atlas (Carr et al. 1976) includes water quality data from two wells in the WAT aquifer. The 58 m (190 ft) deep well, northwest of Cheyenne, was reported as having 3,450 mg/L TDS with the main constituents being calcium (Ca^{2+}), magnesium (Mg^{2+}), and sulfate (SO_4^{2-}). The second well, located approximately 10 km (6.2 mi) east of Cheyenne, Oklahoma, is 39 meters (128 ft) deep and had 2,920 mg/L of TDS, with the same primary cations and anion. The Clinton Hydrologic Atlas (Carr et al. 1976) also included a summary of 15 water chemistry analyses. The summary reported an average TDS of 2,850 mg/L, hardness (Ca and Mg) of 1,700 mg/L, and average sulfate (SO_4^{2-}) concentration of 1,700 mg/L. Water quality data for the Rush Springs Sandstone is very similar in chemistry and concentration.

The similarity between water quality of the alluvium and underlying bedrock indicate that they are likely hydraulically connected. Groundwater in the WAT aquifer is characterized by elevated concentrations of total dissolved solids (TDS), hardness, and sulfate. This reflects the contribution of groundwater from Permian age rock formations including the Doxey Shale, Cloud Chief, and Rush Springs. Concentrations of calcium, magnesium, and sulfate are elevated due to dissolution of evaporative layers of gypsum ($CaSO_4 \cdot 2H_20$) and dolomite ($CaMg(CO_3)_2$). Quality of runoff water that may infiltrate into storage near the surface can impact the alluvial groundwater under certain conditions.

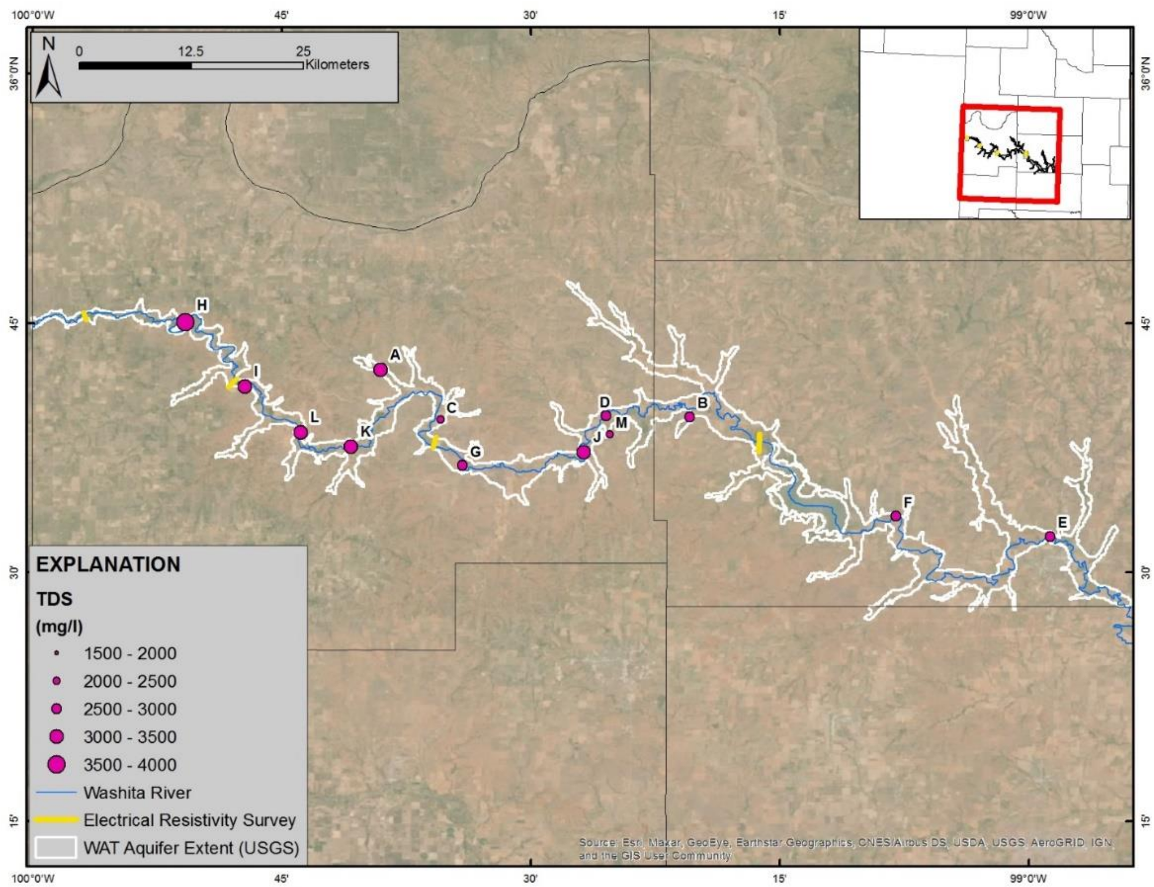

Figure 8: Map of the study area showing locations of groundwater quality sampling done by the OWRB groundwater monitoring and assessment plan (GMAP) program and TDS concentrations.

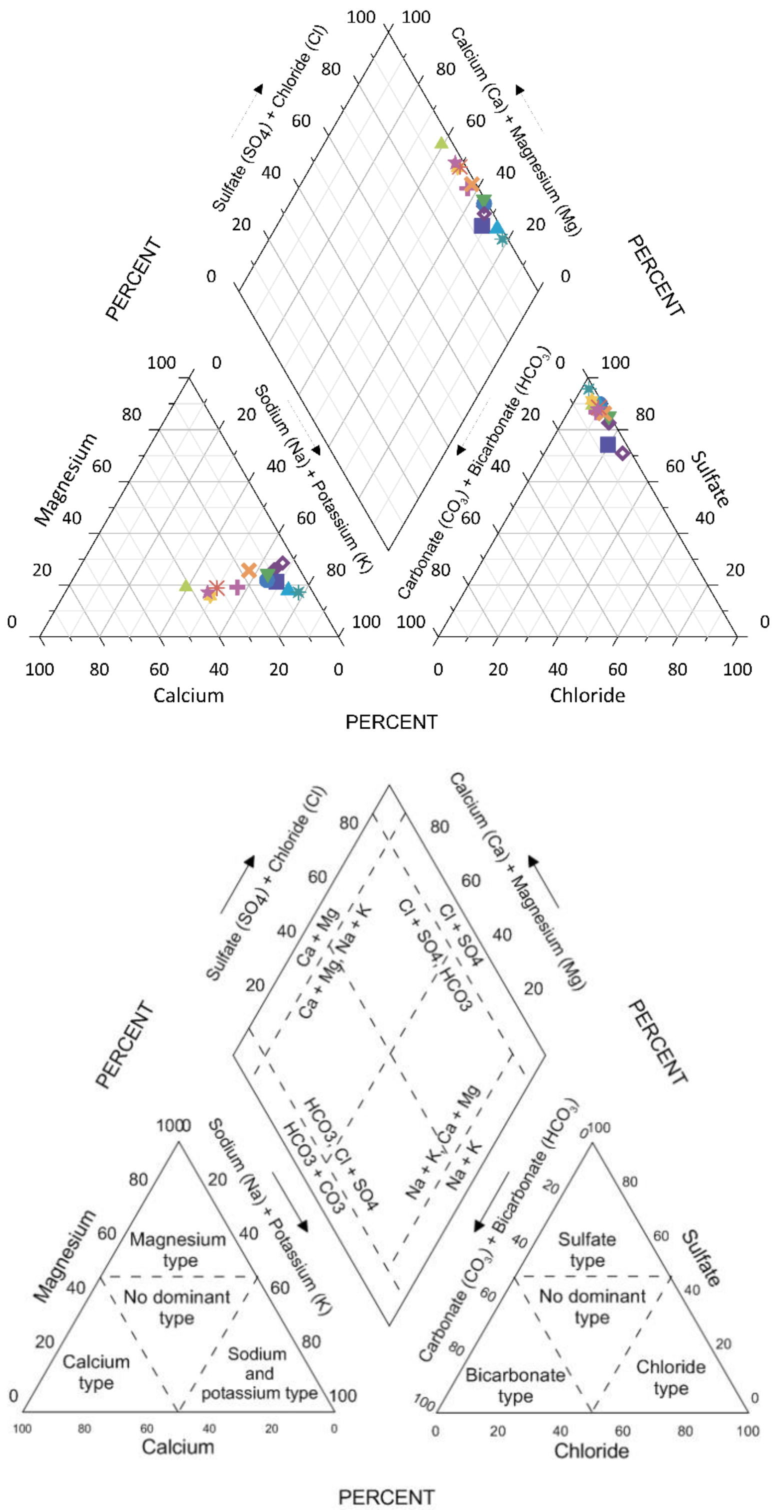

Figure 9: Piper plot of water quality data collected by the OWRB groundwater monitoring and assessment program (GMAP, 2013) plan.

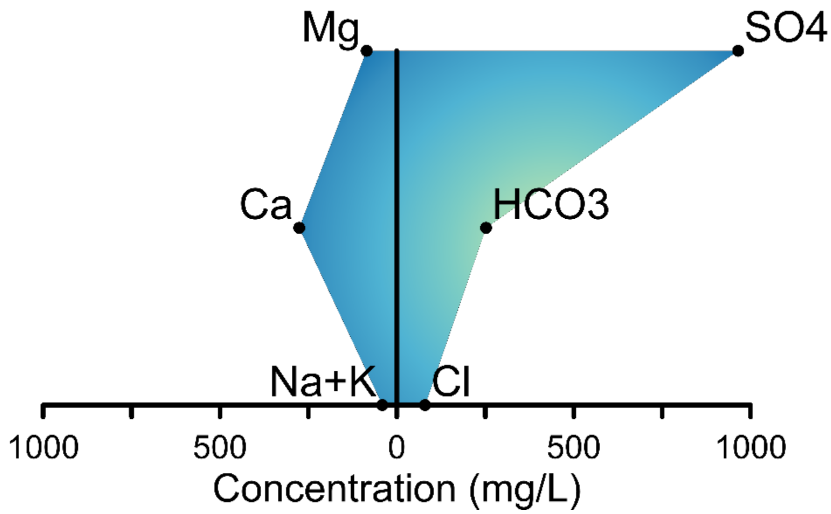

Figure 10: Representative Stiff plot of data from OWRB groundwater monitoring and assessment plan (GMAP, 2013) groundwater quality data showing relative concentrations of anions and cations in groundwater wells from the Washita alluvium and terrace aquifer.

Table 3. Summary statistics of groundwater-quality data for 13 samples collected from the Washita alluvium and terrace aquifer (OWRB GMAP, 2013).

	Mean	Min	Max	25 Percentile	50 Percentile	75 Percentile
Temp (° C)	20	18.2	23.7	18.75	19.27	20.63
pH	7.3	7	7.6	7.08	7.37	7.42
TDS (mg/l)	2752.3	1760	3650	2390	2780	3190
SC (mS/cm)	3004.1	2096.2	4073.3	2605.2	2889.4	3485.9
Hardness (mg/l)	1642.6	1088	1916	1618	1686	1790
Alkalinity (mg/l)	165.3	35.4	264	139	177	205
ORP	242	202.4	279	223.45	244.5	261.75
DO (mg/l)	1.7	0.3	4.9	0.43	0.94	2.2
Al (mg/l)	25	25	25	++	++	++
NH_3 (mg/l)	0.2	0.1	0.7	0.05	0.05	0.33
Sb (ug/l)	0.5	0.5	0.5	++	++	++
As (ug/l)	3.2	1.6	5.2	1.9	2.8	4.5
Ba (ug/l)	13.6	2.5	38.2	10.5	11	11.6
Be (ug/l)	++	++	++	++	++	++
HCO_3 (mg/l)	203.2	43.4	325	171	217	252
B (ug/l)	922.6	33.2	2070	548	833	1120
Br (ug/l)	306.7	236.0	433	268	301	352
Cd (ug/l)	0.3	0.3	0.25	++	++	++
Ca (mg/l)	361.1	258.0	534	328	364	372
$CaCO_3$ (mg/l)	++	++	++	++	++	++
Cl (mg/l)	48.5	15.1	99.7	28.1	37.3	65.1
Cr (ug/l)	3.7	2.5	18	++	++	++
Co (ug/l)	2.5	2.5	2.5	++	++	++
Cu (ug/l)	2.5	2.5	2.5	++	++	++
F (mg/l)	0.1	0.1	0.2	0.1	0.1	0.22
N (mg/l)	2.4	0	18.7	0.025	0.4	2.71
Fe (ug/l)	289.4	10	1120	25.8	109	643
Pb (ug/l)	2.5	2.5	2.5	++	++	++
Mg (mg/l)	126.9	85.6	172	117	124	136
Mn (mg/l)	206.6	8.4	761	13.4	141	318
Hg (ug/l)	++	++	++	++	++	++
Mo (ug/l)	4.6	2.5	10	2.5	5.1	6
Ni (ug/l)	++	++	++	++	++	++
P (mg/l)	0.02	0	0.06	0.007	0.019	0.028
K (mg/l)	2.8	1.8	4	2	2.4	3.6
Se (ug/l)	5.4	5	10	++	++	++
SiO_2 (mg/l)	21.2	8.9	41.6	13.3	17.5	25.9
Ag (ug/l)	++	++	++	++	++	++
Na (mg/l)	130.3	15.1	365	38.9	71.2	238
SO_4 (mg/l)	1693.5	890	2300	1450	1800	2000
U (ug/l)	9.5	0.5	40.7	3.4	7.7	11.3
V (ug/l)	18.6	2.5	37.6	12.3	14.9	24.9
Zn (ug/l)	13.3	2.5	93.8	2.5	13.3	38.9

++, analyses were below analytical detection limit and statistics could not be estimated

Specific conductance is in microsiemens per centimeter at 25°C

Aquifer Parameters

Oklahoma Groundwater Law, section 1020.5, requires hydrologic investigations be conducted for all major groundwater basins in Oklahoma so that a maximum annual yield of freshwater to be produced can be determined. A groundwater flow model for the aquifer from the Oklahoma-

Texas state line to Clinton, Oklahoma, was constructed in 1983 (Schipper, 1986) for this purpose. The WAT aquifer was modeled as a shallow unconfined aquifer with an average depth to water of 5 meters (17 ft) and an average saturated thickness of approximately 36 meters (120 ft). Specific yield is a dimensionless term defined as the volume of water an unconfined aquifer releases per unit surface area of the aquifer per unit decline of the water table. Values for specific yield of the aquifer ranged from 0.2 to 0.3 (Schipper, 1986). Transmissivity of the alluvial deposits, the rate at which water flows through an area of the aquifer, calculated by Schipper (1983), varied from 4,000 gallon per day/foot (gpd/f) to 70,000 gpd/ft with an average of 28,600 gpd/ft. Variability of transmissivity results from irregular saturated thickness, porosity, and composition of sediments. Throughout most of the study area the alluvium is underlain by Permian age Cloud Chief, Doxey, and Rush Springs formations, which have much lower porosity and permeability and were considered the base of the aquifer.

Resistivity Site Descriptions

Four sites for electrical resistivity imaging (ERI) were chosen based on geology, geomorphologic characteristics, channel width, space from other surveys, and accessibility. Electrical resistivity surveys are named in sequence from west to east as WAT-01 to WAT-04.

WAT-01 Washita Battlefield National Historic Site, Black Kettle Grasslands – 5/5-5/6/2017

The western most survey (WAT-01), was conducted on the Washita Battlefield National Historic site in the Black Kettle Grasslands in Roger Mills County, Oklahoma (Fig 11). The survey had a total line length of 830 m with a heading of 167°. The survey consisted of two individual surveys (A and B) 550 m in length, each consisting of 56 electrodes with 10 m spacing, giving an image depth of 110 m (360.9 ft). The first segment started at the north end of the survey atop exposed Permian bedrock and headed southeast through alluvium deposits, across the river, and through more alluvium. The alluvium is fine- to medium-grained, well sorted tan sand. The riparian zone extended approximately 40 m on either side of the river. Shrubs were present on top of the Permian red beds. South of the river, the line traversed through nearly 200 meters of open grassland before going back into wooded areas. The mapped alluvial deposits are approximately 350 meters in width where the survey was conducted. The electrical resistivity survey began atop weathered Ogallala sand 56 meters northwest of the study area boundary, over exposed friable red siltstone and fine-grained sandstone from the Cloud Chief Formation, and crossed over 350 meters of Quaternary alluvium deposits before returning to the top of the Ogallala across the river valley. The survey transect intersected a fault at a 40° angle at approximately 500 meters.

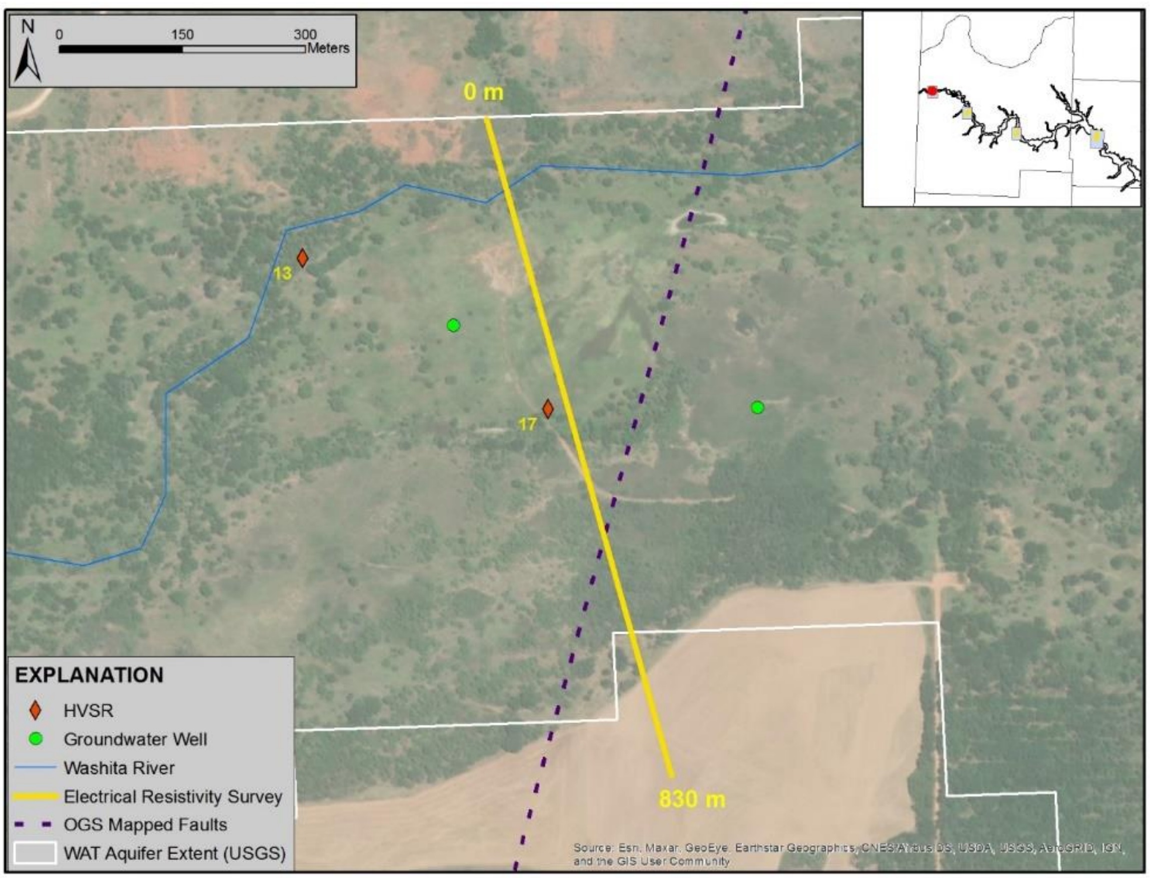

Figure 11: Site map showing location of electrical resistivity survey WAT-01 Washita Battlefield National Historic Site, Black Kettle Grasslands, nearby groundwater wells, OGS mapped faults, and USGS HVSR depth to bedrock measurements in meters, and Washita alluvium and terrace aquifer extent determined by the USGS

WAT-02 Private Property – 11/4-11/5/2016

Survey WAT-02 is located on farmland overlying the aquifer 14 km (9 mi) northwest of Cheyenne, Oklahoma (Fig. 12). This resistivity line consists of six 330-meter segments (A-F) with 6-meter spacing, resulting in an image 66 meters (216 ft) deep with a total length of 1,170 meters. The line started at the corner of an abandoned oil drilling pad, and headed northwest across a dry creek bed and into open pasture. The survey line continued through pastures for over 800 meters before going into sand terraces with shrub cover, through the river, and back into terrace deposits. The mapped width of Quaternary deposits at this site is 763 meters; however, the full 1,170 meters of survey was over sand deposits. The OGS fault map shows the termination of a fault near the center of the survey transect.

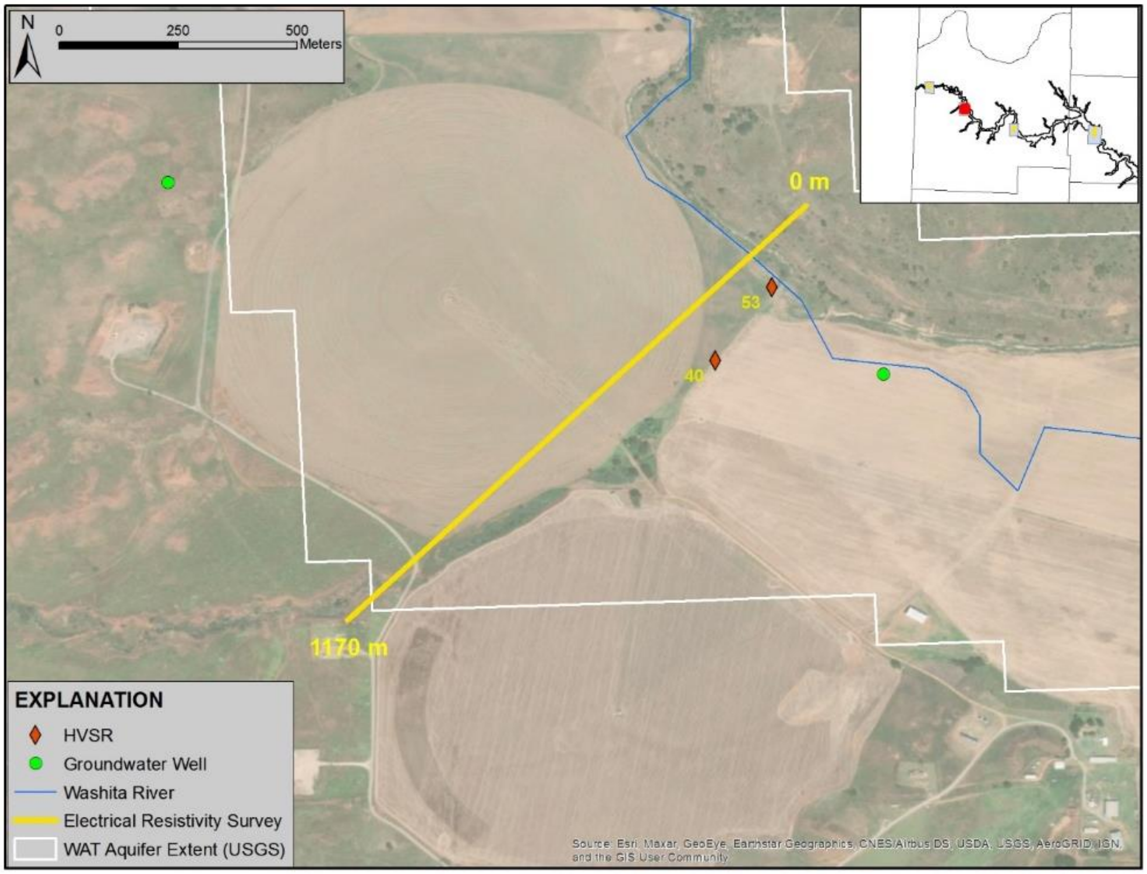

Figure 12: Site map showing location of electrical resistivity survey WAT-02, nearby groundwater wells, and USGS HVSR depth to bedrock measurements in meters, and Washita alluvium and terrace aquifer extent determined by the USGS

WAT-03 Private Property – 12/9-12/10/2016

Survey WAT-03 was conducted on farmland 7 km (4.35 mi) northeast of Cheyenne, Oklahoma (Fig. 13). The survey began 1 km north of the Washita River and extended 1.1 km (0.68 mi) at a heading of 195° consisting of four segments (A-D), each 440 meters in length. The lines were set up with 8-meter spacing giving an image depth of 88 meters (288 ft). The aquifer is mapped as 716 meters (2,349 ft) wide at this location. The survey began in grassland with sandy soil, before crossing into wooded areas and over sand dunes, crossing over a wheat field, into the riparian zone over the river, and back out of the riparian zone. Just past the south end of the survey, the gypsum from the Cloud Chief Formation was exposed along the east west trending hillside.

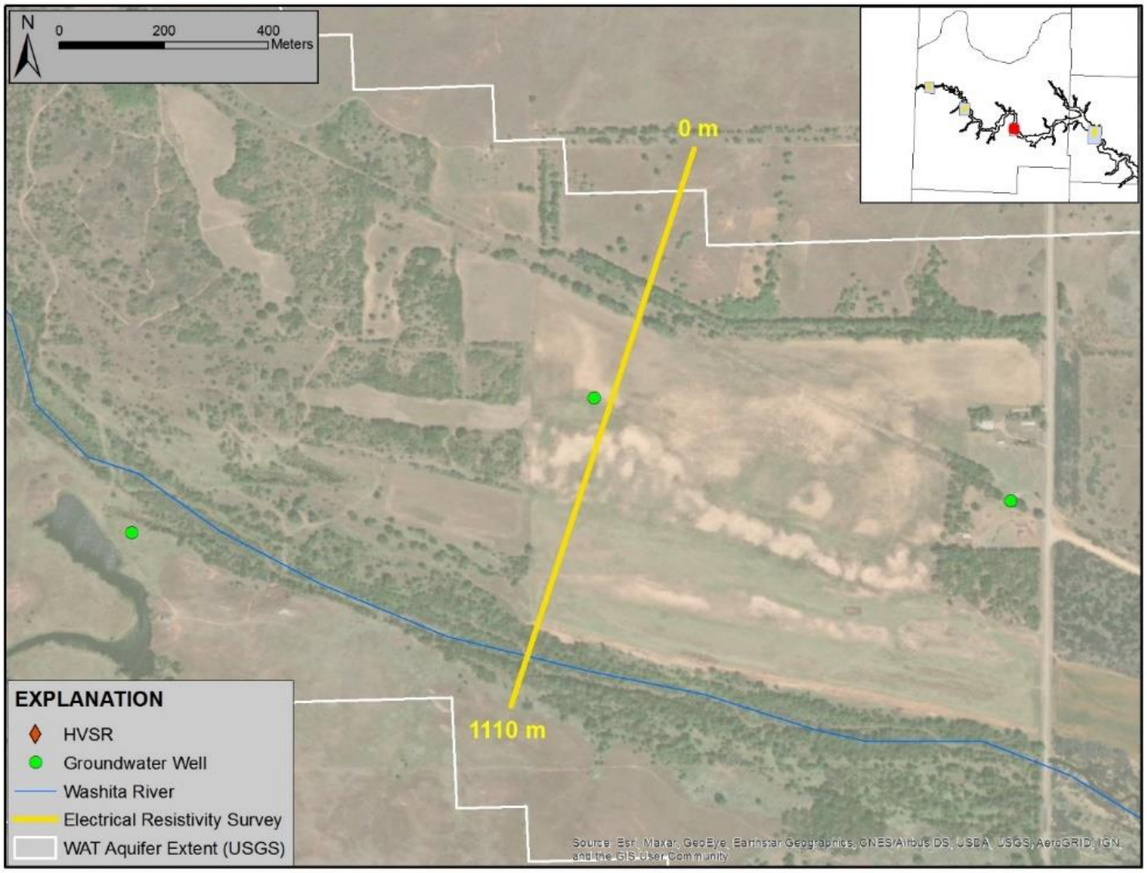

Figure 13: Site map showing location of electrical resistivity survey WAT-03, nearby groundwater wells, and USGS HVSR depth to bedrock measurements in meters, and WAT aquifer extent determined by the USGS.

WAT-04 Washita National Wildlife Refuge – 2/28-3/1/2017

Survey WAT-04 crosses the Washita River near its entrance to Foss Lake. The line begins at the southwest corner of intersection OK highway 33 and county road 2090, east of Hammon, Oklahoma, and extends 1.95 km at a heading of 181.5° (Fig. 14). This survey consisted of 6 segments, each 550 meters in length; electrode spacing was 10 meters, resulting in an image depth of 110 meters (360.8 ft). The aquifer boundary widens to 2,762 meters (9,061 ft) in the area where this survey was conducted. It begins on sandy soil and continues over sand dunes with sporadic vegetation, before crossing into a cottonwood forest. The survey transect continues through the cottonwood forest and terminates in open farmland.

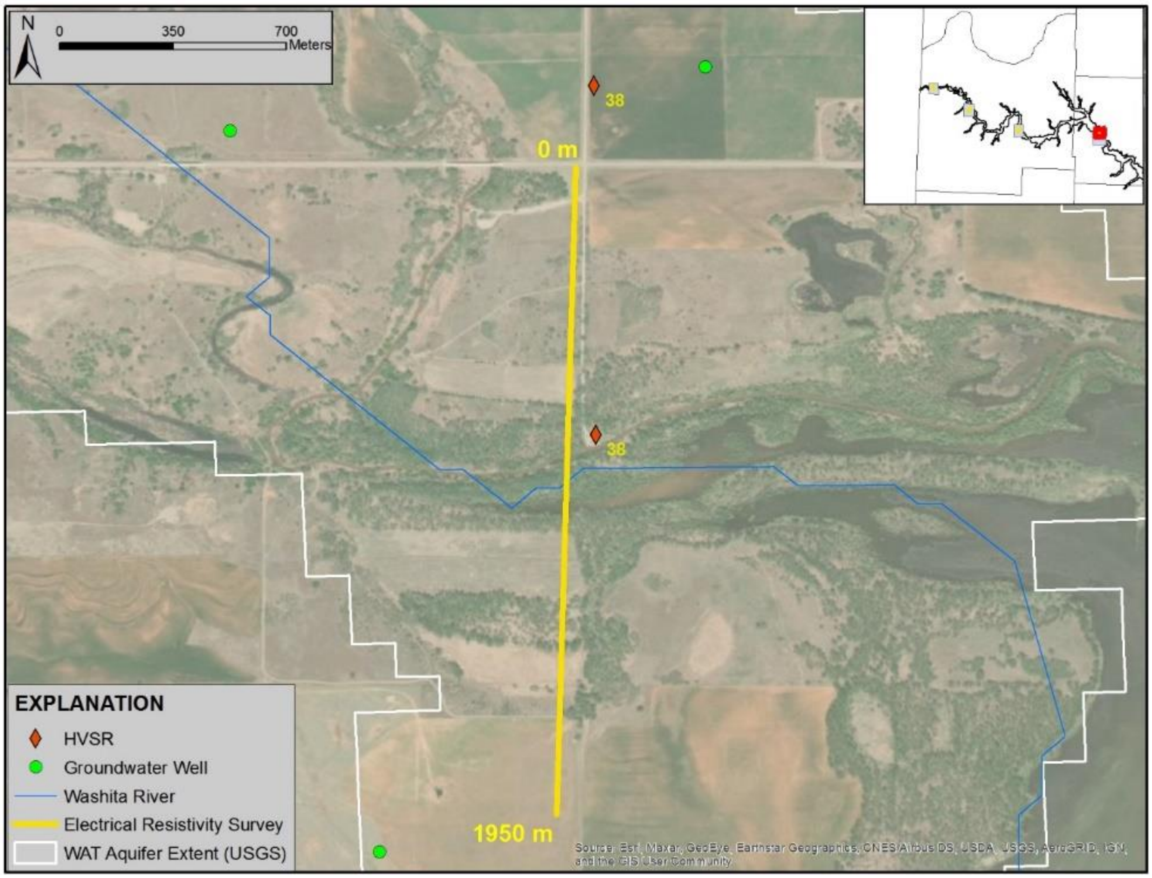

Figure 14: Site map showing location of electrical resistivity survey WAT-04 Washita National Wildlife Refuge, nearby groundwater wells, and USGS HVSR depth to bedrock measurements in meters, and Washita alluvium and terrace aquifer extent determined by the USGS.

CHAPTER III

METHODS

Field methods were conducted to acquire new data and were subsequently integrated with existing historical data to evaluate hydrogeology of the WAT Aquifer. Existing data included historical well data for the region, a hydrologic atlas containing geology and hydrogeology related maps and tables, mapped faults by the Oklahoma Geological Survey (OGS), water quality data sampled from groundwater wells in the aquifer, water use data for the aquifer, in-situ streamflow data, hydraulic profiling, and horizontal to vertical spectral ratio (HVSR) data. Field data acquisition included the collection of resistivity data along four separate kilometer-scale transects perpendicular to the orientation of the alluvial valley and land surveying of topography and other relevant features. Additionally, slug testing in an existing well was conducted near transect WAT-01. Resulting datasets were integrated with historical data to develop an updated and improved conceptual model of the aquifer, to evaluate a potential buried valley, and determine potential sources of irregularities in the existing numerical model of the aquifer.

Available Historic Data

An online database of lithology logs recorded by groundwater well drillers' across Oklahoma has been created and maintained by the Oklahoma Water Resources Board (OWRB, 2017). This database contains location data for groundwater wells, water levels, and reported lithology logs. Data from 485 groundwater wells were queried based on their proximity to the Washita River.

Wells within 1 km of the WAT aquifer boundary in either direction reporting alluvium and terrace deposits were used for analysis. The locations for these groundwater wells were entered into a GIS geodatabase and analyzed in ESRI's ArcMap 10.1 (Appendix E1). Of the 485 groundwater well lithology logs used in this study, 14 wells located within the channel boundaries reported coarse sand, gravel, and boulder deposits at depths greater than 36 meters (131 ft), including 3 wells in Roger Mills county shown in figures 21 A&B. Fewer wells are drilled near the inner portions of the channel due to uneven terrain, large sand dunes, and thick vegetation. Borings drilled by the Army Corps of Engineers for use in the construction of Foss Dam were also used to assess lithology of the channel.

Work from previous groundwater investigations of the aquifer were reviewed for the purpose of this study. Referenced materials include "Results of Computer Modeling of Alluvium and Terrace Deposits Along the Washita River, Southwestern Oklahoma, for Water Supply Capability" (Kent et al. 1978), "Evaluation of Aquifer Performance and Water Supply Capabilities of the Elk City Aquifer in Washita, Beckham, Custer, and Roger Mills Counties, Oklahoma" (Kent et al. 1982), and "A Ground-Water Management Model for the Washita River Alluvial Aquifer in Roger Mills and Custer Counties, Oklahoma" (Schipper, 1986). "Hydrologic Atlas 5 of the Clinton Quadrangle", prepared by Jerry Carr and DeRoy Bergman of the USGS in 1976, provided geologic and hydrogeologic data for the region.

Land Survey Data Acquisition

Topographic data were collected using a Trimble Pathfinder Pro XR receiver with an integrated radio beacon to determine real-time positions and elevations at each electrode along ERI survey transects. Real time kinetic (RTK) positioning data were collected at one second intervals for at least 60 seconds within 7.6 cm (3 in.) horizontal precision and 91.4 cm (36 in.) vertical precision. Resulting location data were post processed using data from nearby CORS Clinton, OK station. The WGS-84 coordinate system was used to collect positions in units of latitude and longitude and elevation was recorded in meters above sea level in reference to the NAVD88 datum. Positions and their elevations were used to create topographic profiles for the electrical resistivity images. Individual resistivity data sets were modeled with their respective topographic profiles. In addition, groundwater wells and surficial geologic contacts near the ERI transects were surveyed for geospatial analysis.

Resistivity Data Acquisition

Electrical resistivity data were collected on four transects over 11 field days, from June 2016 to May 2017. Three of these transects took two days each to complete. Due to field and equipment complications, one site required 5 days of field work before acquiring a satisfactory data set. Site locations were spaced 22.5 km (14 mi) to 35.4 km (22 mi) apart, range from 0.83 km (0.5 mi) to 1.95 km (1.2 mi) in length, and were based on alluvial mapping and landowner access. Depth of investigation ranged from 66 meters (216 ft) to 110 meters (360 ft) below land surface.

The four locations were selected to evaluate consistency in the interpretation as the transects went from the most upgradient location near the Texas border (WAT-01) to the most downgradient line near Foss Dam (WAT-04). The lines were placed orthogonal to the modern stream (Fig. 4). In order to cross the stream, electrodes were placed in the stream bed as the stream is shallow and only one or two electrodes were in the stream on individual transects.

Individual electrical resistivity surveys were conducted using 56 electrodes with 6, 8, or 10-meter spacing between electrodes. Larger spacing in between electrodes results in a deeper image with lower resolution; resolution of the images is equal to one-half of the electrode spacing. To image a larger portion of the alluvium and terrace deposits without decreasing resolution, a roll-along method was employed. This method is conducted by starting a successive ERI survey transect at the midway point of the previous survey transect, using the same number of electrodes for each transect and equivalent electrode spacing. Roll along transects can extend as far as desired laterally, within the limitations of terrain or accessibility. This arrangement is also beneficial for ensuring data quality by overlapping portions of data collection.

A generator was used as a power source to supply 110 volt AC power for data acquisition. An Advanced Geosciences, Inc. (AGI) power converter unit was used to change the 110V output from the generator to 12V power to the resistivity instrument. An AGI SuperSting 8-channel resistivity meter, a switch box, and electrode surface cables were used to collect apparent resistivity data. The Halihan/Fenstemaker method was utilized for acquisition and processing of the field data (OSU OIP, 2004; Halihan et al., 2005). Inverted datasets are product of the electrical measurements and do not include any additional data that would alter the inversion.

Resistivity Data Analysis

Resulting data from resistivity inversion modeling were exported in an X, Y, R grid in a trapezoidal shape, where X is the lateral distance along the survey transect, Y is the elevation in meters above sea level, and R is the resistivity in ohm-m. The trapezoid grid of electrical resistivity data was color contoured on each individual data set from the 19 separate electrical resistivity datasets collected along the four transect lines. Images from a “roll along” series were combined using a mosaic tool in Surfer using data averaging on image overlaps to create continuous images of the subsurface resulting in four final datasets (Figures 15-18).

In order to delineate the geometry of the contact between Quaternary fluvial sediments and the underlying Permian bedrock, resistivity data collected for this study were analyzed to evaluate the electrical profiles for evidence of channel boundaries vertically and horizontally. Single resistivity profiles can be isolated and plotted at specific X and Y locations to assess the presence of an electrical gradient change along a single dimension. Select locations along the resistivity images were chosen based on their distance along the transect (X) to assess vertical variability in resistivity (R) across the dataset to evaluate the bottom of the channel. Specific elevations (Y) were selected throughout the dataset to plot one-dimensional horizontal profiles of resistivity (R) to investigate approximate location of the sides of the channel. Resistivity across the interpreted channel area is generally lower for all four datasets, however, clear channel boundaries were not particularly distinct. In order to more precisely determine the lateral edges of the channel, first order derivatives (Laplacian Edge Detection) were also plotted to determine locations of 0 crossings (De Pasquale, 2019) (Fig. 19A-D & 20A-D).

First order derivative functions were applied to the resistivity data grids vertically and horizontally to provide a consistent measurement for changes in electrical properties across the full data sets. Resulting images were used to determine subsurface boundary conditions both vertically and horizontally (Appendix 1). Color contouring of the resistivity data was reevaluated after these analyses to better represent the interface between alluvial deposits and bedrock by highlighting this boundary in the updated color scheme.

Results from the Laplacian Edge Detection (De Pasquale, 2019) analyses suggested a boundary could be delineated using a range of resistivity of 21-23 ohm-m. Classed post maps were generated using values of 21 and 23 ohm-m and were utilized to draw the boundary between the alluvium and the bedrock. The depth of the alluvial aquifer was compared against the literature value of 36 meters of aquifer thickness. The depth of the interpreted incised channel was evaluated for all four transects and plotted against the stream distance. This plot was used to evaluate the consistency of the results between the datasets. An estimate of incised channel width was also developed by measuring the width at the half depth of the channel. An area for the interpreted incised channel was also estimated for each transect.

Slug Test

To determine hydraulic parameters such as hydraulic conductivity and transmissivity of the aquifer near WAT-01, a series of slug tests were conducted in a well 20 meters west of the center of the electrical resistivity transect. A slug test is a controlled field experiment in which a change in hydraulic head is induced in order to observe the subsequent return to static water level (Butler, 1998). Due to the lack of wells suitable for slug testing in the study area, this was the only location slug testing could be performed. Inertia slug tests are conducted by lowering a solid cylinder of a known volume gently into the water column where the top of the "slug" is just below the water table surface while recording water levels with a Win-situ 500 water level troll. When the water levels return to static conditions, the "slug" is carefully removed and the recovery time to static conditions of the water table is recorded. These are generally described as falling-head and rising-head tests. Resulting curves are then fit to mathematical models to determine properties such as hydraulic conductivity and transmissivity. The well tested was constructed as a monitoring well for the Black Kettle Grasslands and water levels are monitored by the U.S. Geological Survey Oklahoma Water Science Center. The well is 18 m (60 ft) deep with a 12.7 cm (5 in) inner casing diameter and is screened from 12 – 18 m (40 – 60 ft) (OWRB well drillers database). The recorded lithology is described as “sand & gravel” from 0-15 m (0-50 ft) and the remaining 3 m (10 ft) is described as brown clay. Four total tests were conducted at the well, two falling-head and two rising-head tests. The first set of slug tests was done with a 5.08 cm diameter by 0.9 m long slug, and the second set of tests was done with a 7.62 cm diameter by 0.9 m long slug. Each test took around 6 to 7 min to return to static water level. Further slug testing was not possible due to limited number of observation wells in the region and limited access to wells located on private land which generally had pumps installed.

Data Integration

For the purpose of this study, data from a variety of sources and methods was integrated to provide a more comprehensive conceptual model of the aquifer. Integrated data collected in the field for this study included 19 electrical resistivity images and slug testing at one well. Data obtained from databases for analysis included groundwater use data, groundwater well lithology logs, groundwater quality data, and GIS data for mapped faults from the Oklahoma Geological Survey (OGS). Maps and other data from Oklahoma Hydrologic Atlas 5 were also incorporated (Carr et al. 1976). Data provided by the USGS included hydraulic profiling testing data from one well, and horizontal to vertical spectral ratio (HVSR) data at three of four locations ERI was performed (USGS, 2017). Most of the aforementioned data sets were compiled into a geodatabase and analyzed using ArcMap 10.1 (Appendix E1).

Groundwater well logs within 1 km (0.62 mi) of the study area boundary were queried for analysis of depth to bedrock across the study area. Lithology logs associated with queried borings were analyzed for approximate depth to bedrock. Depth to bedrock was determined by identifying lithology logs where red colored shale, siltstone, and sandstone were encountered below tan or brown colored sediments. This color change and lithology is the typical indication of the depth to the Permian bedrock interface.

Hydraulic Profiling Testing results from the WAT aquifer 5 km northwest of WAT-04 demonstrate significant vertical variability of hydraulic conductivity values from 4.5-27 m (15-90 ft) below the surface (Appendix 2). This is likely the result of the complexity of fluvial deposits, which can have abrupt changes in porosity and permeability over short distances. Hydraulic conductivity was highest from 4.6-7.6 m (15-25 ft) and (65-70 ft) below land surface. According to nearby lithology logs from the OWRB well drillers' database, these higher zones of hydraulic conductivity are related to discontinuous intermittent coarse sand and gravel deposits.

The U.S. Geological Survey collected horizontal to vertical spectral ratio (HVSR) measurements across the WAT aquifer during the same period as electrical resistivity surveys were conducted. The HVSR method is a passive seismic approach that does not receive a powerful enough signal for penetrating through thick clay layers, which are known to be present in the alluvial deposits. Field staff from the USGS Oklahoma Water Science Center coordinated HVSR measurements with locations of electrical resistivity surveys. HVSR data did not show a clear trend for depth to bedrock. Resulting HVSR data recorded a minimum depth to bedrock of 11 m, maximum of 53 m, and an average of 30 m.

CHAPTER IV

RESULTS

Resistivity Data

Results of this study evaluate the resistivity data obtained at each of the four cross sections of the alluvial channel. Integrated resistivity and well data are presented relative to interpreted geologic and hydrogeologic controls for the WAT aquifer. All four transects showed a shallow electrically conductive zone extending from the surface to approximately 36 meters deep. This conductive zone likely represents brackish groundwater in the alluvial aquifer. Deeper conductive features were also observed in all four transects. The results will present the data from each transect, followed by the evaluation of integrated patterns for the four transects.

Electrical resistivity transect WAT-01 is the furthest west, where the alluvium deposit is thinnest laterally (Fig. 4). The transect consists of two 550 meters long electrical images overlapping at the midpoint for a total of 830 meters in transect length (Fig. 11). Electrode spacing for these lines was 10 meters, resulting in an image depth of investigation of 110 meters (360 ft). Electrical resistivity values ranged from 5 ohm-m to 219 ohm-m across the two datasets (Fig. 15A). The image shows the top 36 m are more conductive with the majority of values below 24 ohm-m with the exception of dry terrace deposits at ~500 meters and ~700 meters laterally (Fig. 15A). Below 36 meters electrical resistivity values are 23 ohm-m and greater, except for the center of the image between 320 and 430 meters laterally, where resistivity values are in the same range as the overlying alluvial aquifer (0 – 21 ohm-m). This portion is below the Quaternary alluvium and terrace deposits in elevation, extending to approximately 90 meters below the surface. Lateral boundaries were determined by assessing zero crossings occurring at approximately 320 meters and 430 meters laterally, which corresponds to the location of the 21 - 23 ohm-m zone of electrical resistivity (Fig.15).

Electrical resistivity transect WAT-02 is approximately 22 km (36 mi) down gradient from WAT-01, where terrain is flatter and the surface alluvium deposit is more than twice the width of WAT-01 (Fig. 4). Transect WAT-02 consists of six 330-meter long electrical images each overlapping starting at the midpoint of the previous line for a total transect length of 1.17 km (0.73 mi). Each image utilized 6-meter electrode spacing, resulting in an image depth of 66 meters (216 ft). Electrical resistivity values range from 4 ohm-m to 117 ohm-m across the six datasets. The most electrically conductive part of the image is along the top 36 meters of the image ranged from 0-21 ohm-m. Similar to WAT-01, the top 36 meters are largely conductive, ranging from 4 ohm-m to 21 ohm-m. This is likely resulting from the abundance of fine grain material and groundwater with elevated TDS. The NE side of the image, 0 - 320 meters, is also within this range of resistivity, but extends downward 66 meters (216 ft), through the bottom of the image. From 320 meters onward, below 36 meters is relatively more resistive, ranging from 23 ohm-m to over 50 ohm-m. A highly conductive zone, ranging in resistivity from 4 ohm-m to 21 ohm-m (Fig. 15B), illustrates a channel shaped electrical structure with its center approximately 260 meters from the NE end of the image. Lateral boundaries of the channel shaped electrically conductive anomaly were delineated by corresponding 21-23 ohm-m band of electrical resistivity with zero crossings in the horizontal derivative resistivity profiles (Fig. 21B).

Transect WAT-03 is approximately 33 km down gradient from WAT-02 where the surface alluvium deposit is slightly narrower than WAT-02 and exhibits rougher terrain. This transect consist of four 440 meters long electrical images each overlapping starting at the midpoint of the previous line for a total transect length of 1.1 km (0.68 mi). Each image was conducted using 8-meter electrode spacing, yielding an image depth of 88 meters (288 ft). Electrical resistivity values ranged from 0.04 ohm-m to over 10,000 ohm-m, making it the most electrically resistive transect of the four. Resistivity below the alluvium was 23 ohm-m and higher, and is likely more resistive due to abundance of gypsum beds, some of which are exposed at the surface. Consistent with the other two datasets is an electrically conductive feature (0 - 21 ohm-m), which drops down through the lower part of the image below the alluvial channel on the surface. This channel shaped conductive feature has steeper walls on its sides and is approximately 250 meters (820 ft) in width, making its geometry similar to that seen in WAT-01. Lateral boundaries were evident in the zero crossings in first and second order derivatives of resistivity across the domain at an elevation of 505 meters (Fig. 21C). As with the other two datasets, the Laplacian Edge Detection correlated with the 21-23 ohm-m band in the electrical imagery (Fig. 20A-D and 21A-D).

Transect WAT-04 is approximately 35 km (21.7 mi) down gradient from WAT-03, where the channel widens as it enters into Foss Lake (Fig. 4). This transect consists of six 550-meter long electrical images each overlapping and starting at the midpoint of the previous line for a total transect length of 1.95 km (1.2 mi), yielding an image depth of 110 meters (360 ft). Electrical resistivity ranged from 4 ohm-m to 49 ohm-m, making it the most conductive of the four datasets; however, the image does include the same conductive anomaly geometry observed in the previous three transects. A channel shaped conductive feature approximately 410 meters (1,345 ft) wide, with electrical resistivity ranging from 0 ohm-m to 21 ohm-m, extends downward to approximately 90 meters (295 ft) below land surface (Fig. 19A&B). Lateral boundaries were determined by correlating the 21 -23 ohm-m band of resistivity with Laplacian Edge Detection (Fig. 21A-D). The northern half of the transect shows multiple vertical conductive (15 - 24 ohm-m) features extending towards the bottom of the image. Overall increase in electrical conductivity for this image could be related to change in underlying bedrock from the Cloud Chief Formation to the Rush Springs Formation, which is considered a major bedrock aquifer by the Oklahoma Water Resources Board. The increased width and depth of the conductive channel shaped anomaly in this location is likely a result of the WAT aquifer merging into the Rush Springs aquifer.

Well Data

Groundwater well data from 485 well lithology logs from the OWRB Well Drillers' database were analyzed to interpret lithology of the aquifer. Of the 300 well logs in the aquifer, 14 reported coarse sand, gravel, and boulders at depths ranging from 55-77 m (180-252 ft). These groundwater wells are typically irrigation wells and are essentially in a random spatial distribution. Disregarding wells in the tributaries, there are 196 wells along the main trunk of the alluvium channel. This suggests that sampling the alluvium at random with wells yields a 7% chance of encountering a potential paleochannel feature.   Twenty kilometers northwest of Cheyenne, Oklahoma, there is a group of 5 wells with lithology logs that demonstrate a bedrock geometry similar to the channel-shaped electrical structures apparent in the ERI datasets (Fig. 22A & B). Wells 2812, 2813, and 2808 don't encounter "red beds", and report gravel and boulders at depths ranging from 56.4 m – 68.6 m (185 ft – 225 ft) below land surface. Speaking with a local well driller, drill rigs would experience refusal at depths greater than 70 m where they encountered large boulders, which were described as likely being quartzite and granite. Interpolation of the lithology reported in the logs produces an average aquifer thickness of ~36 m, with some indications of a paleochannel. However, wells closer to the river do not report encountering bedrock and are sparse due to accessibility limitations of a drill rig.

Average hydraulic conductivity for groundwater well 90854 was determined to be $4.0x10^{-5}$ m/s (Table 4). Curve matching of the slug test data fit the Bowers-Rice (1976) model for unconfined aquifers (Appendix E2). These values are within the range for hydraulic conductivity of fine to medium sand determined by Schwartz and Zhang (2012). It is likely that the hydraulic conductivity values were dampened due to the well screen being 3 meters in clay and 3 meters in sand and gravel.

The groundwater flow model for Reach 1 of the aquifer developed by Schipper (1986) found the average saturated thickness of the aquifer to be approximately 36 meters, using lithology logs from the OWRB Well Driller's database. This boundary is also evident in the electrical imagery across the alluvial deposits where the paleochannel isn't present (Figures 16-19). The electrical structure of this portion of the alluvial deposits are more conductive near the surface, suggesting shallow groundwater is likely more conductive due to influence from anthropogenic activity, abundance of fine-grained material, and runoff over exposed Permian bedrock. This inverted salinity gradient is also observed in individual wells with EC readings from USGS monitoring well 90854 (Table 5). Values for electrical resistivity are slightly higher in the deeper portion of the paleochannel indicating the groundwater contains lower TDS and less fine grain material, suggesting the lower portion of the paleochannel is composed of courser grained material as corroborated by OWRB well drillers' logs (Fig. 22B).

The boundary between the aquifer and underlying Permian bedrock is not a distinct boundary. These bedrock formations are less competent, friable, and saturated providing very little electrical contrast between the aquifer and underlying bedrock resulting in a small range of resistivity values across the datasets. Leonard (1958) determined that the bedrock hydraulic gradient was toward the river, indicating that some volume of groundwater is added to the alluvium through upward leakage. All four of the electrical resistivity transects contain vertical conductive features at depth, which are interpreted to represent zones where groundwater is entering the alluvial deposits from the underlying bedrock. This adds to the body of evidence that they are hydraulically connected.

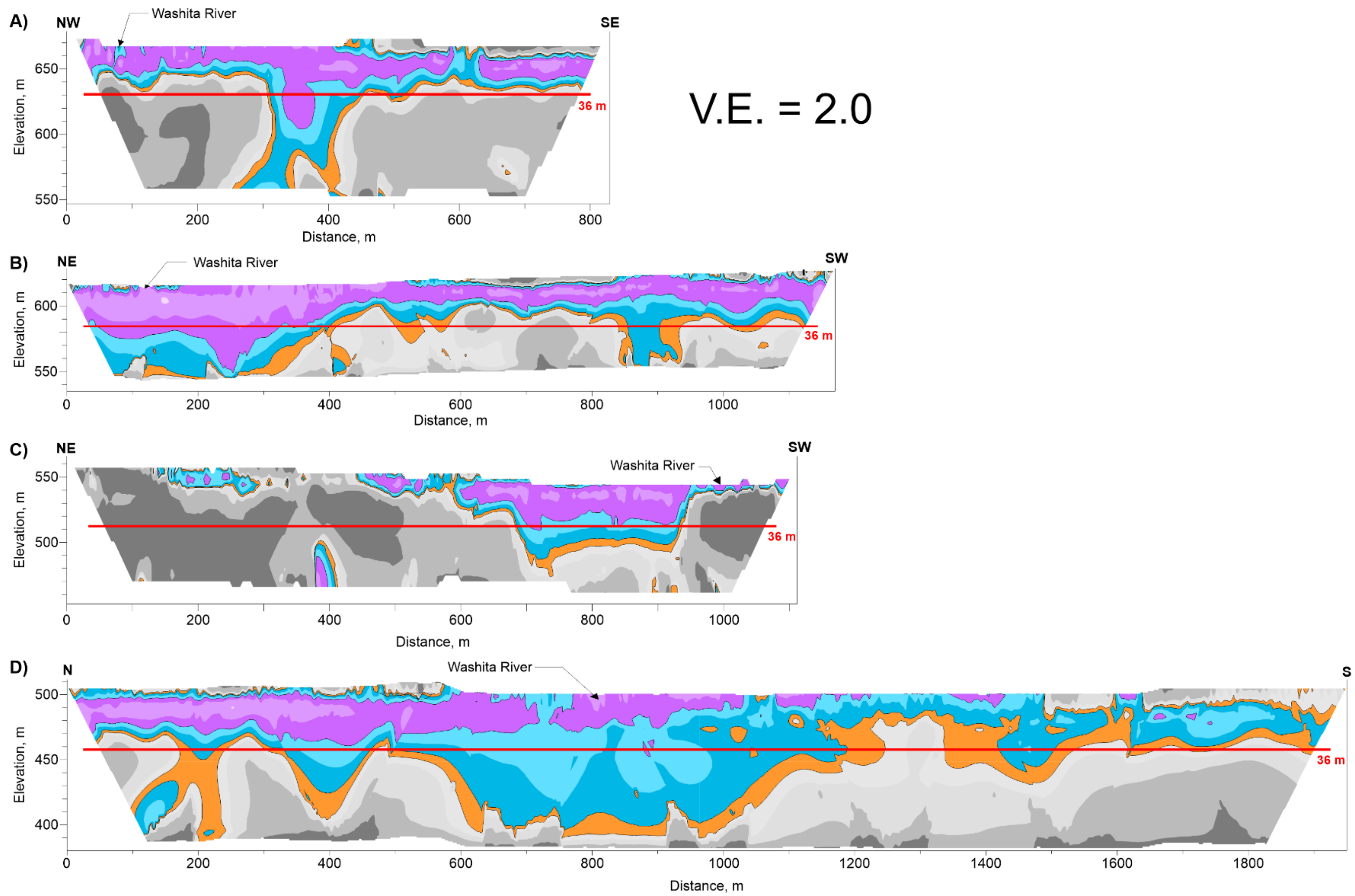

Figure 15 A): Mosaic of Electrical Resistivity Imaging (ERI) results for WAT-01. B): Mosaic of Electrical Resistivity Imaging (ERI) results for WAT-02. C): Mosaic of Electrical Resistivity Imaging (ERI) results for WAT-03. D): Mosaic of Electrical Resistivity Imaging (ERI) results for WAT-04. Base of alluvium denoted by red line located 36 m bgs.

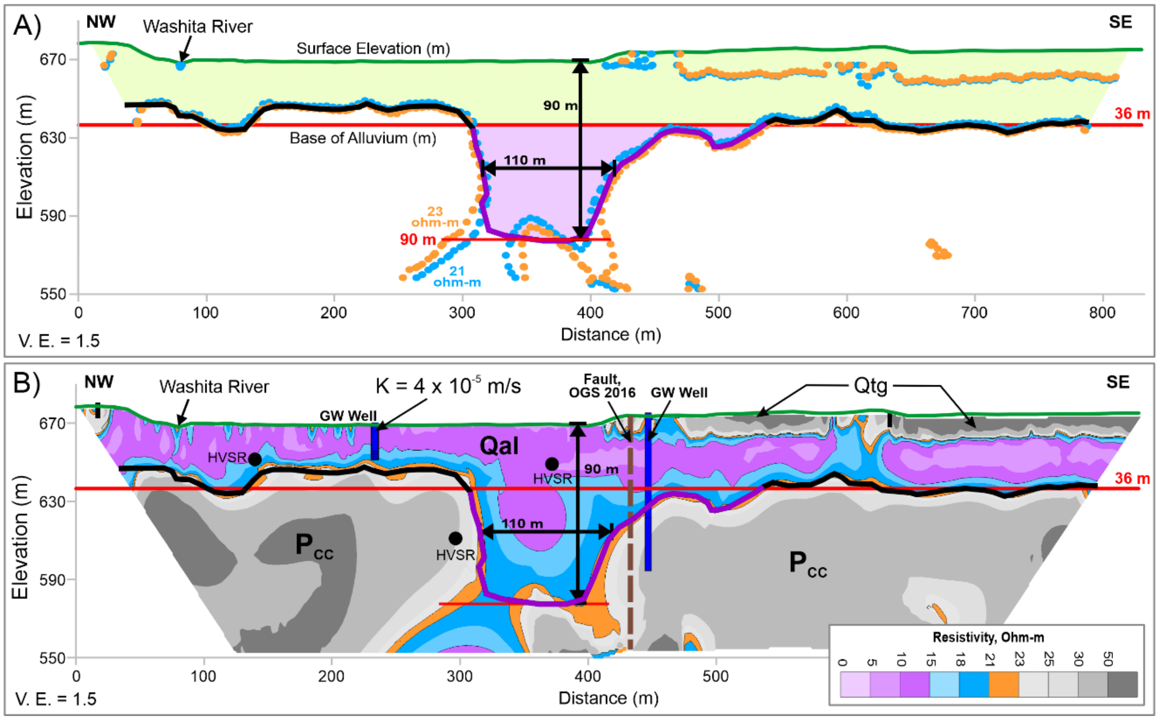

Figure 16 A): Upper and lower geometry of the aquifer delineated by ERI data at WAT-01 B): Delineated geometry of the aquifer overlaid on electrical data.

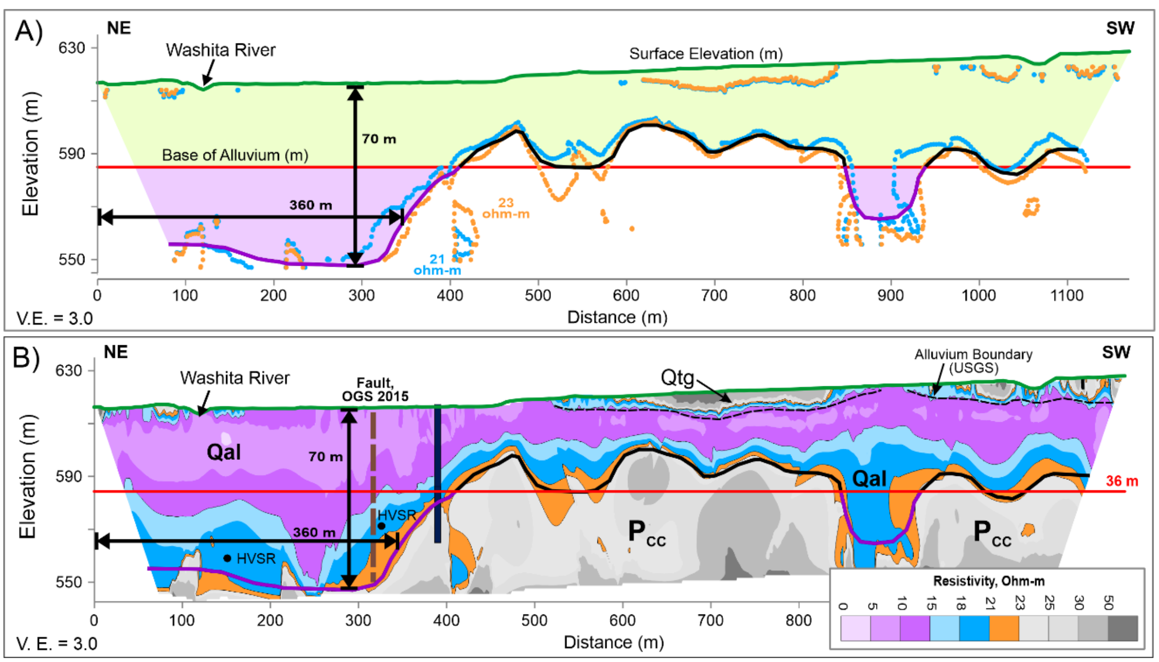

Figure 17 A): Upper and lower geometry of the aquifer delineated by ERI data at WAT-02 B): Delineated geometry of the aquifer overlaid on electrical data.

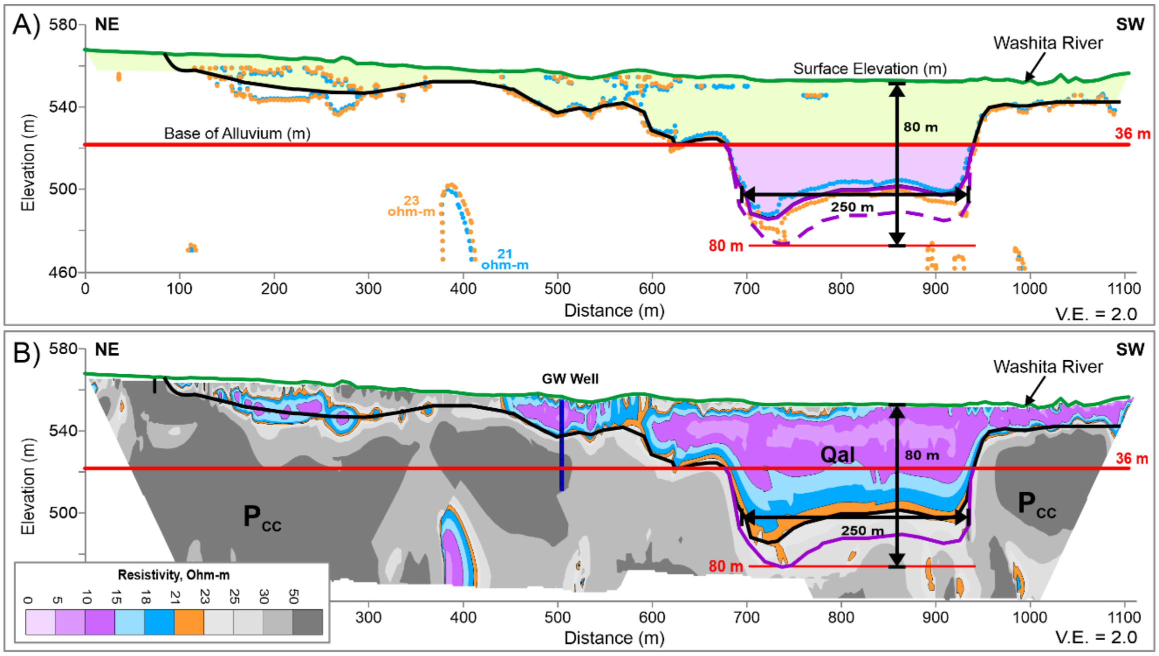

Figure 18 A): Upper and lower geometry of the aquifer delineated by ERI data at WAT-03 B): Delineated geometry of the aquifer overlaid on electrical data.

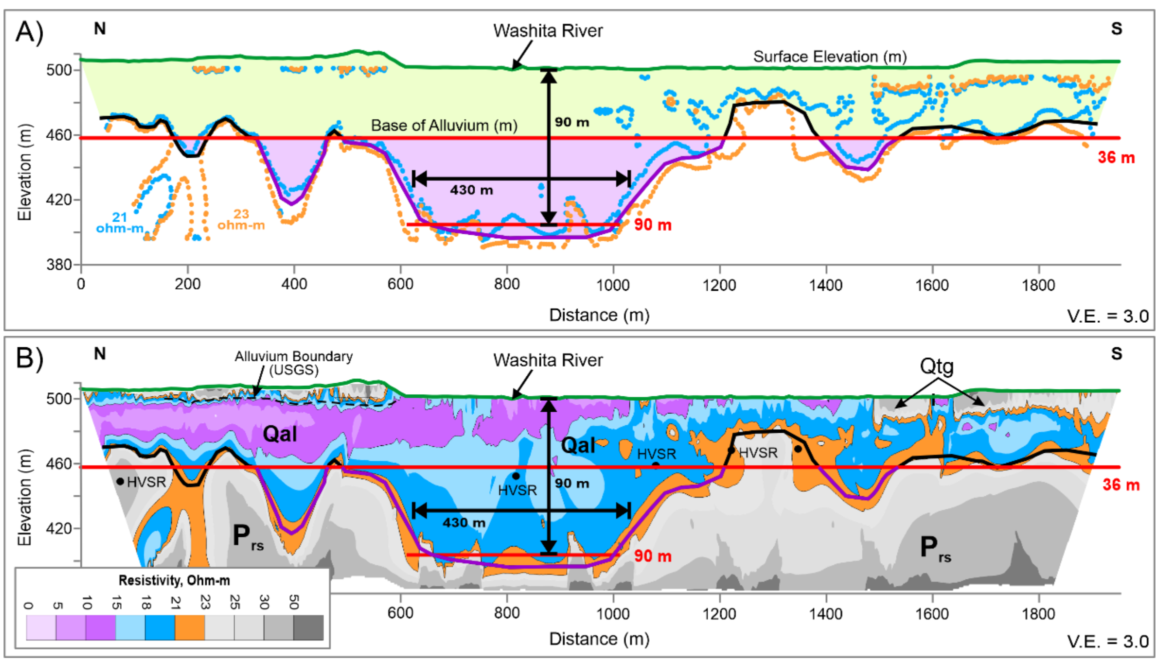

Figure 19 A): Upper and lower geometry of the aquifer delineated by ERI data at WAT-04 B): Delineated geometry of the aquifer overlaid on electrical data.

Table 4. Summary of slug test results for USGS monitoring well 90854.

Test	Test Type	Slug Dia. (cm)	K (m/s)	T (m^2/s)
A	Rising Head	5.08	2.70E-05	2.29E-03
B	Falling Head	5.08	3.93E-05	3.34E-03
C	Rising Head	7.62	3.95E-05	3.36E-03
D	Falling Head	7.62	5.41E-05	4.60E-03

Table 5. Summary of electrical conductivity (EC) measurements in wells across the aquifer taken using a Solinst TLC meter.

Well	Depth (m)	SC (µS/cm)	Temp °C
90854	3.05	3440	14.6
90854	9.14	3463	15.3
90854	17.98	2782	16.1
N/A	8.23	1448	17.9
N/A	9.14	1482	18.1
N/A	12.19	1524	18.2
N/A	13.72	1505	18.4
2693	8.84	2875	18.2
2693	17.98	3115	17.3
2693	27.13	3118	17.2
2693	33.22	3120	17.2
2693	42.37	3150	17.2
2693	508.69	3700	16.3
WWR03	18.29	1687	18.3
WWR03	21.33	1687	18.2
WWR03	30.48	1697	18.2
WWR03	39.62	1790	18.2

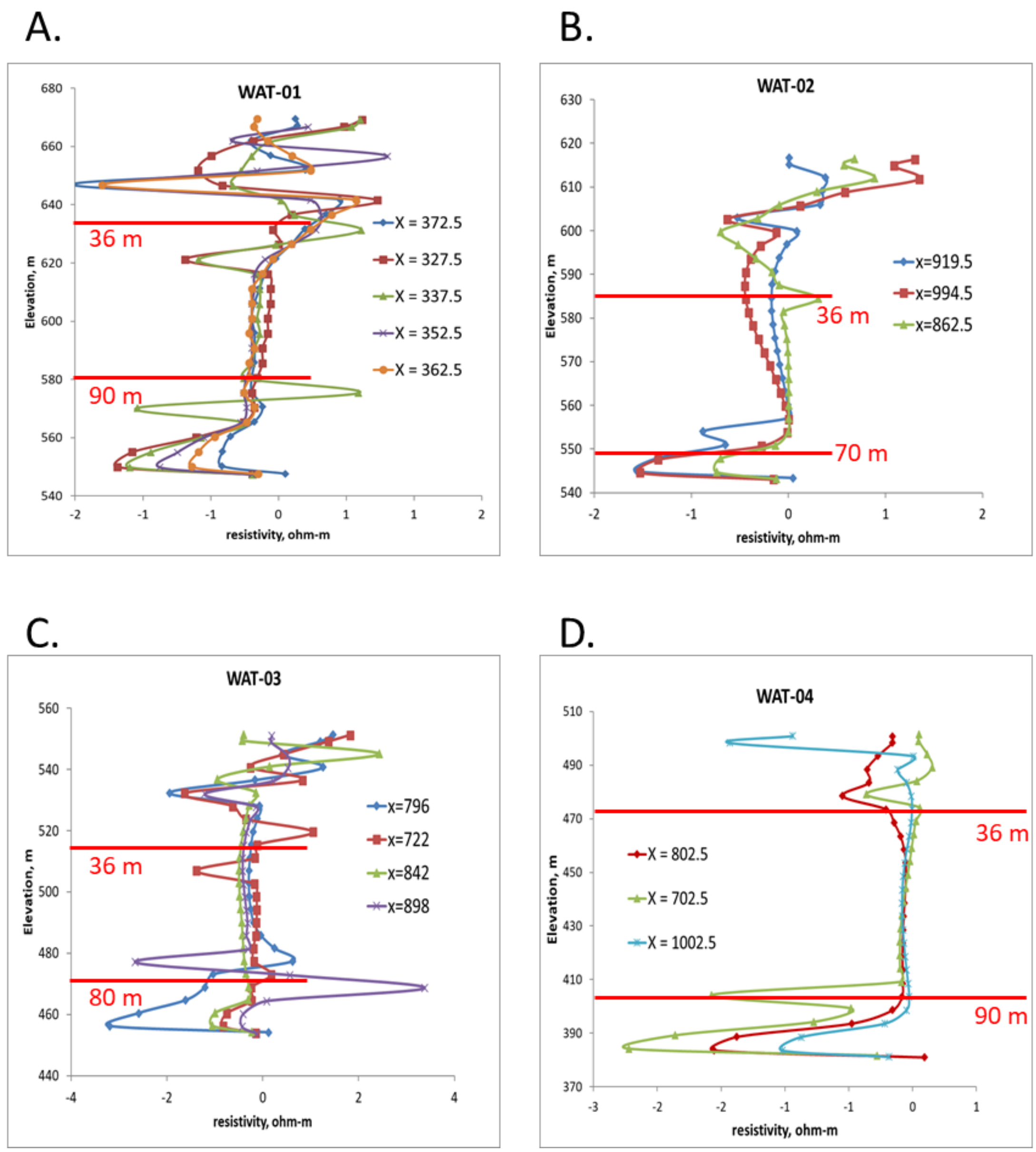

Figure 20: Vertical derivative of electrical resistivity in interpreted paleochannel, A: WAT-01, B: WAT-02, C: WAT-03, D: WAT-04. Estimations of bottom of paleochannel were chosen based off correlation of derivative 0 crossing with 21-23 ohm-m boundary.

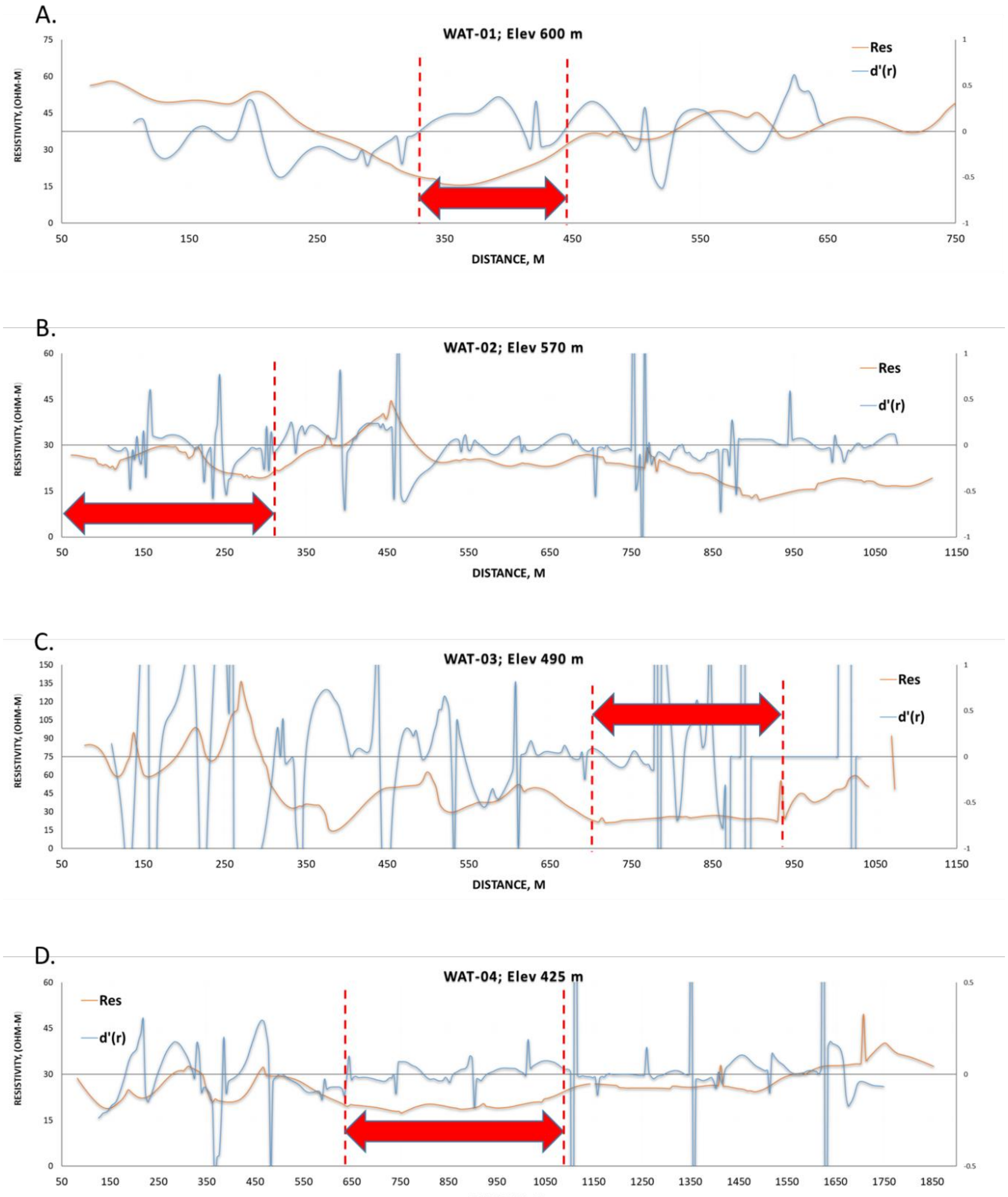

Figure 21: Horizontal resistivity profiles and first order derivative of resistivity profile across interpreted paleochannel A: WAT-01 B: WAT-02 C: WAT-03 D. WAT-04. Vertical red dashed lines indicate approximate lateral boundary of interpreted paleochannel.

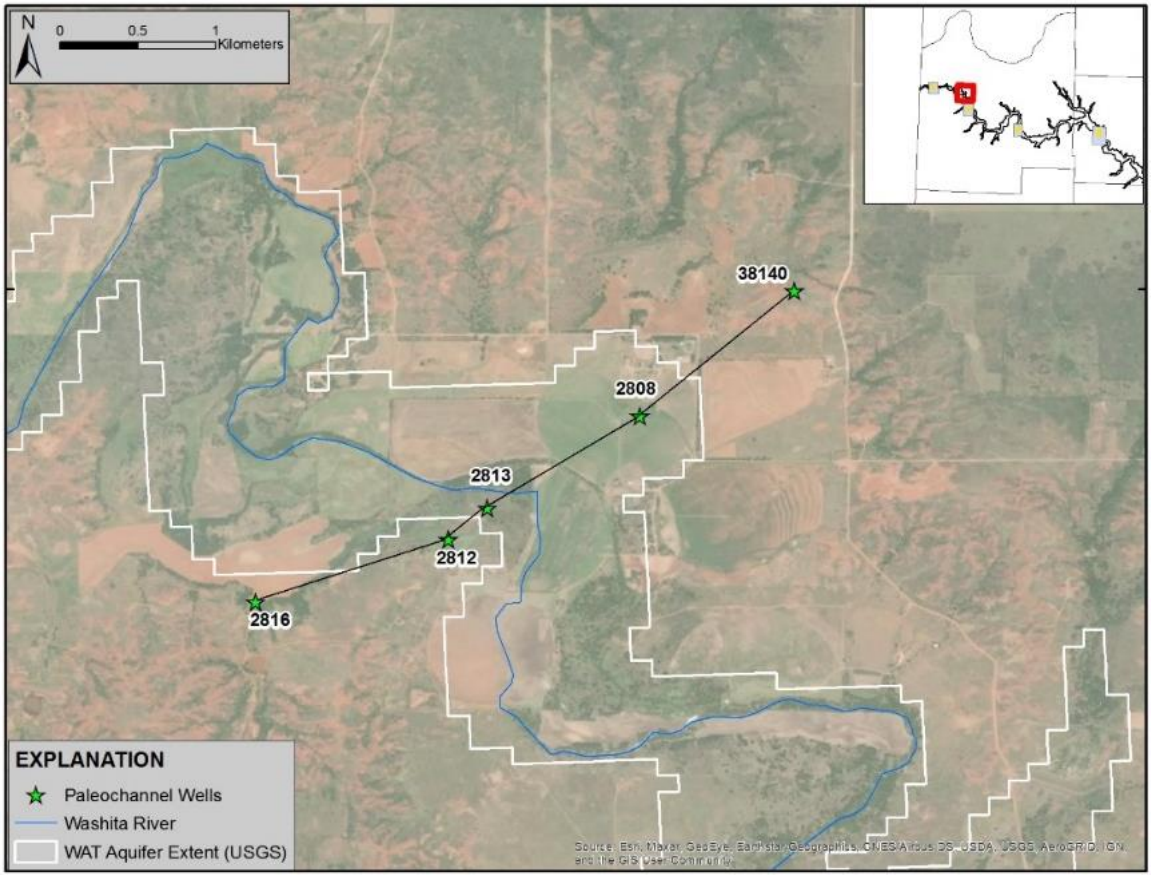

Figure 22A : Map of well locations used for correlation of bedrock surface.

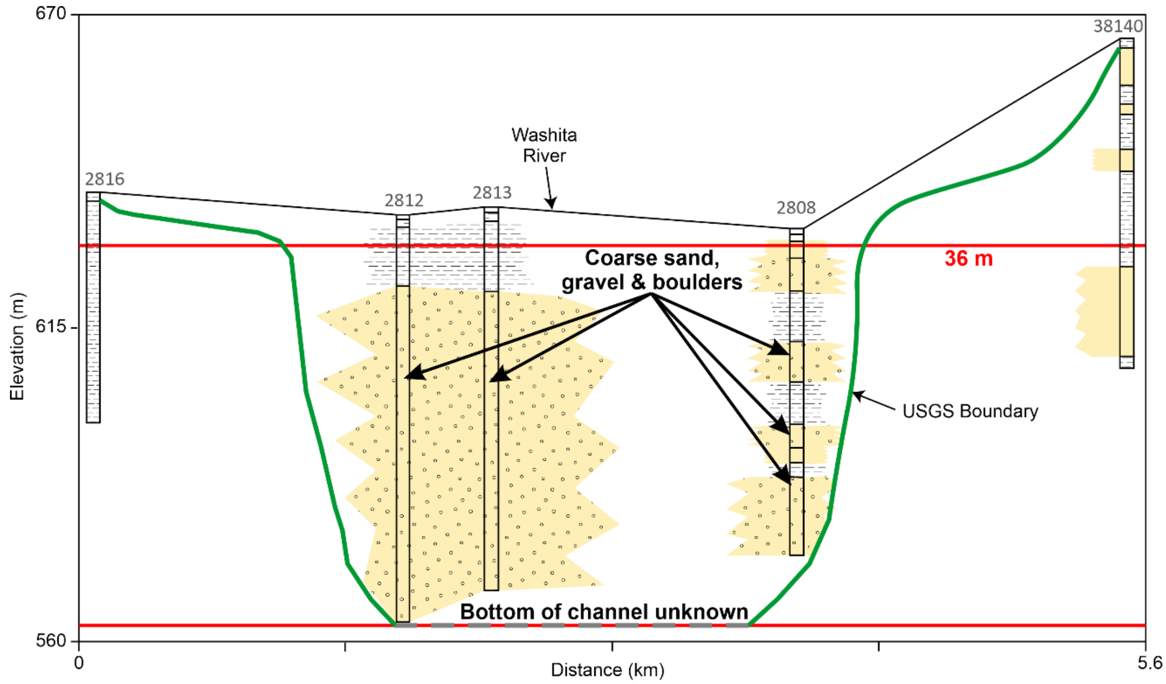

Figure 22B: Interpreted bedrock cross section NW of Cheyenne, Ok (Data from OWRB Well Drillers' Database).

CHAPTER V

DISCUSSION

Western alluvial valleys are considered among the most extensive and productive groundwater systems in North America (Davis, 1988). Much work has been done to characterize alluvial aquifers using seismic, GPR, and various electromagnetic techniques (Durkin et al. 2007, Gourry et al. 2003, Fradelizio et al. 2008, Baines et al. 2002, Bowling et al. 2005, Smith et al. 2006); however, these methods are limited in their ability to image to sufficient depths while maintaining adequate resolution (Gourry et al. 2003, Fradelizio et al. 2008, Baines et al. 2002). Studies such as Durkin et al. (2017) demonstrate the highly complex nature of alluvial systems and paleochannels using a combination of borehole geophysics and seismic data. A three-dimensional conceptual model of the meander belts in northeastern Alberta, Canada was developed to provide insight for interpreting these systems (Durkin et al., 2017). They characterized paleochannels 35 m to 50 meters deep and 475 meters to 1,180 meters wide. Channel and valley characteristics are determined by uplift and sediment rates, scales of river systems, modulation of sediment transfer, storage through incision, lateral migration and aggradation, proximity to river mouths, the influence of relative sea level change, and other marine processes (Blum, 2013).

In terms of uplift and sediment transport, the WAT aquifer parallels the trend of the Wichita uplift, which initiated early in the Pennsylvanian. Analysis of large-scale structural features in the region by Zabawa et al. (1976), indicated deeper faults are subtly expressed on the surface. It is possible the Washita paleovalley began to form during the Pennsylvanian and was further down cut and received large episodic influxes of sediments as a result of the Laramide orogeny, which began in the late Cretaceous (Perry, 1989). Structural features resulting from the Southern Oklahoma Aulacogen (SOA) could have provided the setting for the initial channel location (Zabawa, 1976). Material transported into the channel during this time would have been from the proximal Wichita Megashear Complex. If a deeper buried paleochannel does exist beneath the Quaternary Washita Alluvium and Terrace deposits it is likely comprised of such material. According to a handful of well log lithology descriptions and verbal communication with local drillers, large cobble and boulder size granite and quartzite are encountered at depths where Permian “red beds” would be expected.

In general, resistivity data demonstrate correlation with groundwater well lithology logs, which produce an average aquifer thickness of ~36 meters, and is an apparent boundary in the electrical imagery (Fig. 15A-D). Additionally, the presence of a deeper channel shaped conductive anomalous zone was detected in all four locations imaged (Fig. 16-19). The interpreted paleochannel is highlighted by an electrical structure apparent in all four locations consisting of an electrically conductive anomalous zone (0 - 21 ohm-m) with channel shaped geometry having variable width, but consistent depth and a longitudinal gradient consistent with the modern day stream channel. The channel-shaped feature appearing in all of the electrical datasets is within the same range of electrical resistivity (0 - 21 ohm-m) indicating it is composed of similar geologic material and groundwater chemistry, which are the two main drivers for controlling the electrical structure of the subsurface in this setting. The exception is the bottom of transect WAT-03, which was slightly more resistive at the base of the interpreted paleochannel (25-30 ohm-m). This small change in resistivity at the base of the paleochannel could represent an influx of fresher groundwater at this location as seen in TDS measurements from the aquifer (Fig. 8). Even though the resistivity value is slightly different, this is still where the vertical derivative zero crossing occurred (Fig. 20C) representing the rate of change in resistivity which is consistent with the other three transects (Fig. 20A-D). This pick for the bottom of the interpreted paleochannel at this transect is also provides a consistent slope of the base of the interpreted paleochannel with the base of the alluvial channel and the surface channel across the 110 km long study area (Fig. 23).

Electrical resistivity values are low in all data collected as a result of abundance of fine grain sediments and higher TDS groundwater from dissolution of evaporite layers in Permian bedrock. Electrical conductivity values vary vertically throughout the water column in some locations. For example, the bottom of USGS monitoring well 90854 (Fig. 15A) at 18 meters (59 ft), electrical conductivity was found to be 2,782 uS/cm and increased to 3,463 uS/cm in the upper portion of the water column (Table 5). This indicates there are fluids with different salinities mixing near the upper zones of the aquifer (Table 5). It also suggests there is an inverted salinity gradient, which is corroborated by the electrical structure seen in the upper portions of the aquifer being more electrically conductive than groundwater below it (Fig. 15A-D).

Other possible interpretations of the electrically conductive channel shaped feature in the imagery include a heavily fractured zone containing brackish groundwater, a mixing zone of different groundwater types, or simply an area with enhanced porosity. When considering the possibility of a heavily fractured zone containing brackish groundwater, it would be unlikely that it would have the variability in geometry from narrow to broad, as well as a consistent depth downgradient as seen in the electrical data (Fig. 16-19). Interpreting the electrically conductive zone apparent in all of the imagery as a mixing zone of waters with variable TDS wouldn’t account for the limited number of well logs that do encounter coarser material at depths greater than 36 meters. The integration of the various datasets suggests the most robust interpretation of this electrical feature is a paleochannel comprised of coarser material and less brackish groundwater.

Elevation of the bottom of the interpreted paleochannel in the electrical imagery yields a down valley gradient of approximately 1.9 m/km. This is the same gradient of the modern Washita River on the surface, which measures out to be roughly 1.9 m/km over the study area (Fig. 23). WAT-01 (Fig. 16) and WAT-03 (Fig. 18) both show a narrower shaped conductive channel shaped anomaly ranging from 110 meters (360 ft) to 230 meters (754 ft) wide, while WAT-02 and WAT-04 have a broader shaped channel feature ranging from 320 meters (1,049 ft) to 430 meters (1,410 ft) (Fig. 17 & 19). The narrower channel geometry seen in WAT-01 is likely due to the channel being constrained by the presence of fault structures (Fig. 11). While there are no mapped faults near WAT-03, the similar geometry of the potential paleochannel to WAT-01 indicates the presence of faulting could be controlling the width of the potential paleochannel in this location as well. Several areas where beds of gypsum were exposed at the surface were observed by members of the field crew. The widest conductive channel shaped feature is found in WAT-04 (Fig. 19), which is located just upstream from where the Washita River enters Foss Lake (Fig. 4).

Geometry of the channel shaped conductive anomaly varies from steep and narrow, seen in WAT-01 and WAT-03, to broad and wide shown in WAT-02 and WAT-04, but maintains a uniform depth of approximately ~80 meters to ~90 meters below land surface (Fig. 16-19). Delineating the base of the paleochannel wasn't as clearly defined due to boundary conditions near the bottom of the dataset (Fig. 20A-D). Scale of the WAT aquifer proposed by this conceptual model (Fig. 24B) is consistent with paleovalley architecture of streams in the Texas Coastal plain proposed by Blum et al. (2013). Mixed bedrock-alluvial valleys are considered to be narrower and steeper than valleys incised in coastal plains and shallow marine settings (Blum, 2013).

Drainage area for the Washita River valley is approximately 20,400 km^2 (7,876 mi^2) and with a proposed channel depth of ~80-90 meters (262-295 ft), this would be consistent with Quaternary valley thicknesses in the region studied by Milliken et al. (2016) including western Texas and New Mexico. Ultimately the geometry of the interface between Quaternary alluvial deposits and underlying Permian bedrock was delineated in 4 locations by performing the following analysis:

1) Analyze first order derivative zero crossings of resistivity data in vertical orientation in select locations inside potential paleochannel (Fig. 20 A-D),
2) Analyze first order derivative zero crossings of resistivity data in horizontal orientation at select elevations near vertical center of potential paleochannel (Fig. 21 A-D), and
3) Determine from 1 and 2 what range of resistivity consistently correlates with these boundaries (Fig. 16-19).

The presence of an underlying coarser grained channel deposit is also demonstrated by the anomalous well logs reporting gravel and boulders below interpolated bedrock surfaces (Fig. 22A & B). From the 300 wells queried in the study area, ten locations with coarser grained material are reported in well logs at depths greater than 60 meters (196 ft) in the alluvial channel, and four additional wells report coarser material at depths equal to or greater than the upper 36-meter portion of the aquifer. This proportion of wells is expected as you have ~5-7% chance of encountering a feature 110 – 430-meter-wide feature over a 2 kilometer distance. This is significant given that a limited number of the wells queried are near the center of the channel where conditions are not favorable for drilling. This further illustrates the advantage of investigating these types of interfaces using a geophysical scanning approach with greatly increase your odds of detecting the feature that is the object of the investigation.

The set of wells used in figures 22 A&B are in an advantageous alignment, oriented semi perpendicular to the alluvium channel and indicate a deeper paleochannel similar to what is observed in all four of the ERI transects. The apparent width of the interpreted paleochannel in this figure appears significantly greater than the width observed in the electrical data due to the oblique intersection of the surface alluvial channel with the alignment of the wells. Ideally, ERI would have been performed at this location to allow direct comparison of electrical data to lithology logs; however, access to the properties associated with these wells was not granted.

Vertical conductive features outside of the interpreted paleochannel corroborated historical groundwater observations indicating upward leakage of groundwater from bedrock into the alluvium (Leonard, 1958). Major anions and cations from wells in the alluvial aquifer are similar to water chemistry data obtained from wells in Permian bedrock, further suggesting there is a significant hydraulic connection between the alluvial aquifer and the underlying bedrock (Carr, 1976). Vertical conductive zones (15 - 23 ohm-m) ranging from 50 meters to 200 meters wide in the electrical imagery indicate areas where enhanced hydraulic communication between bedrock and overlying alluvium may exist. Some of these features extend through the imagery, while others “bottom out,” possibly representing additional potential paleochannels associated with this alluvial aquifer.

Previous and ongoing modeling efforts for this portion of the WAT aquifer have considered the Permian age “red beds” underlying the Quaternary alluvium and forming the valley walls, as no flow boundaries (Kent et al. 1978, Schipper, 1986). Previous literature, groundwater chemistry, and electrical data all suggest there is significant hydraulic communication between the WAT aquifer and Permian strata. These formations consist of fractured siliciclastic layers loosely cemented by iron oxide and interbedded with evaporate layers such as gypsum and anhydrite. This geologic setting is favorable for potential for leakage between the aquifer and bedrock. To date, the WAT Aquifer has been modeled as being laterally and vertically constrained by Permian “red beds” which are described as having gently dipping sides with maximum depths of 50 m and an average depth of 36 meters. This characterization of the aquifer is likely incorrect based on electrical resistivity data and the limited deep borings encountering coarse material at depth (Fig. 22B). Modeling attempts to reproduce observed groundwater elevations may be difficult as the result of two inaccurate assumptions; first, there is limited to no hydraulic communication between the aquifer and underlying bedrock and second, a deeper buried paleochannel with increased porosity and hydraulic conductivity isn't accounted for. Both of these assumptions will result in underestimating aquifer storage, affecting the model's ability to accurately reproduce groundwater observations.

A rough estimation of the volume of groundwater contained in the interpreted incised portion of the aquifer's paleochannel can be determined from channel dimensions outlined in this study and an estimated porosity value. Taking the cross sectional area of the apparent paleochannel from each transect, multiplying it by the distance to the next image and adding the sections of the channel together, with an assumed porosity of 30%, yields a volume of 0.45 km^3 (364,821 acre-feet) of fresh groundwater.

Further investigation of the WAT aquifer hydrogeologic system with confirmation drilling should be performed based on selected targets from the electrical resistivity images. This process allows for more robust interpretations of the channel structure by providing information about the lithology, groundwater chemistry, as well as hydraulic parameters such as hydraulic conductivity, transmissivity, and storativity. Drilling along the images where the interpreted incised channel exists will confirm if the deeper portion of the paleochannel is composed of coarser material. Water sampling of these wells would determine if groundwater exhibits lower TDS than groundwater found in the upper portions of the alluvium, where it is electrically more conductive (0 – 15 ohm-m). Another method to further delineate the structure and hydrogeology of the deeper paleochannel is temporal electrical resistivity monitoring. Imaging the same locations at specified time intervals would further clarify the structure of the system and provide insight into how the hydrogeology changes over time in response to precipitation and water use.

If the current hypothesis about the existence of a paleochannel are supported by confirmation drilling data, it would suggest the potential for similar paleochannel features associated with other nearby rivers in the region. Rivers such as the Canadian to the north and North Fork of the Red to the south have parallel trends coincident with the orientation of major geologic structures such as the Wichita Megashear complex and axis of the Anadarko Basin (Zabawa, 1976).

To further investigate this hypothesis, a similar approach to this study should be conducted along aforementioned rivers. These all represent economically viable sources of fresh water across the region that are currently unknown. Based on the results of these studies a fruitful groundwater exploration effort could be characterizing alluvial channels in analogous geologic and geomorphologic settings, where deeper buried groundwater storage zones could exist.

Not only would these groundwater systems represent an economically viable source of fresh water, but they could be an ideal setting for aquifer storage and recovery (ASR) systems (Vanderzalm, 2011). The practice of storing and later recovering water from alluvial groundwater systems would be optimal where shallow water table conditions exist and there is significant storage and adequate yield. This practice in conjunction with temporal electrical resistivity monitoring would provide the most economic and robust methodology for storing, monitoring, and recovering fresh water as an alternative to surface reservoirs, where significant volumes of water are lost to evaporation.

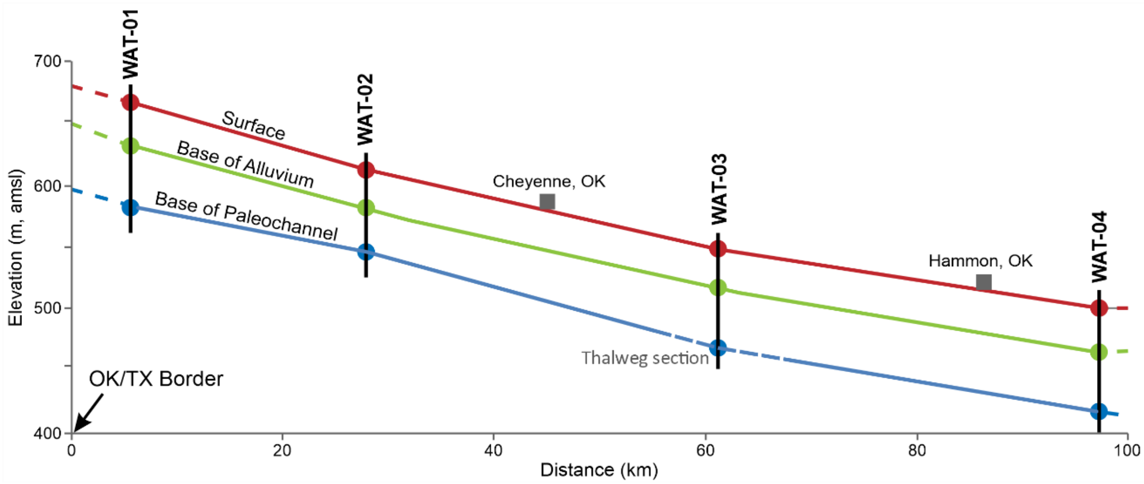

Figure 23: Washita Alluvium and Terrace thalweg section across the study area showing profile views of channel surface, base of alluvial deposits, and base of interpreted paleochannel relative to each other.

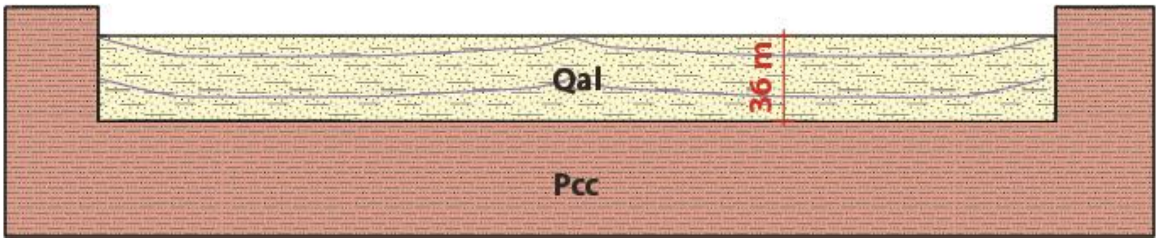

Figure 24A: Previous conceptual model of the aquifer showing typical alluvial aquifer overlying impermeable bedrock.

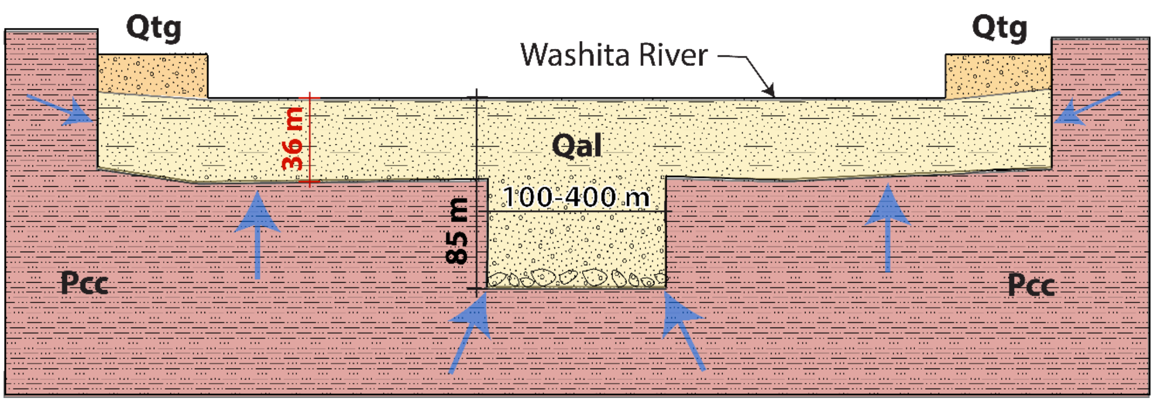

Figure 24B: New conceptual model after ERI investigation showing increased width, terrace deposits, and presence of buried paleochannel and flow lines demonstrating topographically driven lateral flow from upland areas and upward leakage from bedrock.

CHAPTER V

CONCLUSIONS

Electrical resistivity data and well data were evaluated for an approximately 110-kilometer (68 mi) section of the WAT aquifer in Oklahoma starting at the border with Texas to evaluate the aquifer geometry. Integration of these data resulted in a conceptual model of the WAT aquifer which includes two primary components. The first, a shallow fine-grained aquifer that extends from the surface to 36 meters (118 ft) below land surface updated from existing literature. The second, is a deeper buried paleochannel that extends to a depth of up to 90 meters (295 ft) below land surface with a narrower width than the shallower aquifer. High resolution ERI provided the data density required to tie together other sparse data available into a conceptual model of the aquifer that more adequately characterizes the groundwater system.

Previous field evaluations and groundwater modeling of the WAT aquifer derived an average thickness of 36 meters (118 ft), consisting of abundant fine-grained sediments and brackish water. The existing model was found to be consistent with electrical resistivity data collected orthogonal to the modern stream channel. This zone is more electrically conductive (0-15 ohm-m) than an aquifer with fresh water in a fine-grained alluvial system. The ER data for this interface at approximately 36 meters (118 ft) depth demonstrated a variable surface at the ~36-meter (118 ft) horizon with intervals that were shallow and deeper, but roughly along the 36-meter depth (Fig. 16-19).

Integrated data also indicate the presence of a deeper paleochannel system associated with the WAT aquifer extending to depths of approximately 80-90 meters (Fig. 16-19). Lithology logs from groundwater wells in the alluvium and terrace aquifer reported coarse grained alluvial deposits at depths greater than 36 meters, supporting the existence of a paleochannel. Local well drillers also reported refusal at depths of up to 60 meters due to encountering large “boulders” described as granite or quartzite, supporting the possibility of the existence of a deeper coarse grained paleochannel below the modern day stream deposits. The ER data highlights this interpreted paleochannel feature by delineating the geometry of zones of lower resistivity with characteristics consistent with an alluvial paleochannel. The channel presents as a more conductive zone at depth similar to the shallow aquifer. While logging data in the zone reports coarser-grained material, the ER signal is interpreted as related to the somewhat brackish water located in the aquifer.

More robust methods for characterization of alluvial aquifers is especially important in semi-arid regions such as western Oklahoma, where surface water resources can be limited and during drought periods, when demand for groundwater use increases. Evidence from this study suggests the presence of a deeper, coarser-grained paleochannel with an approximate storage capacity of 0.45 km^3 (360 acre-feet) over the approximately 110 km stretch of aquifer. Further investigations of the paleochannel could confirm aquifer dimensions and test the use of the aquifer for the benefit of the region.

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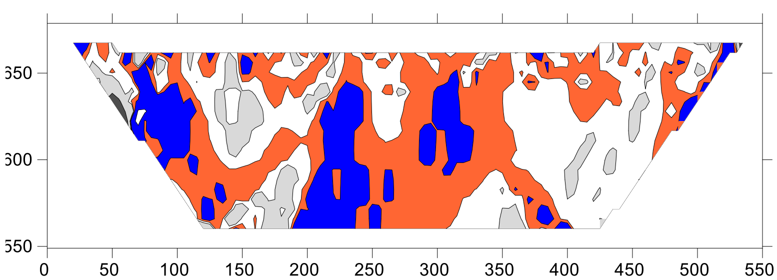
APPENDICES

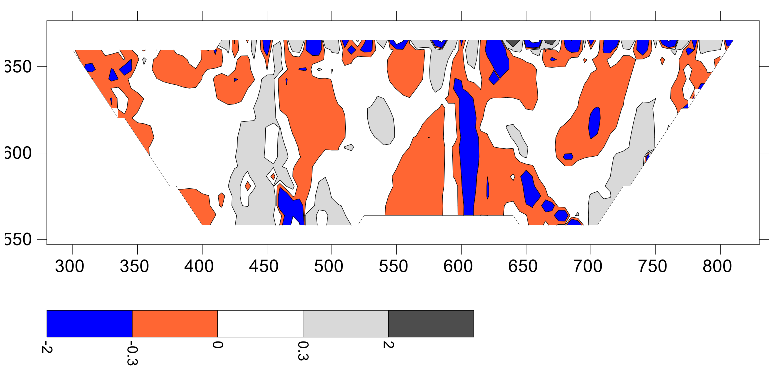
Appendix 1: Color contoured image of first order derivative based grids of electrical resistivity data

WAT-01A and WAT-01B – horizontal orientation

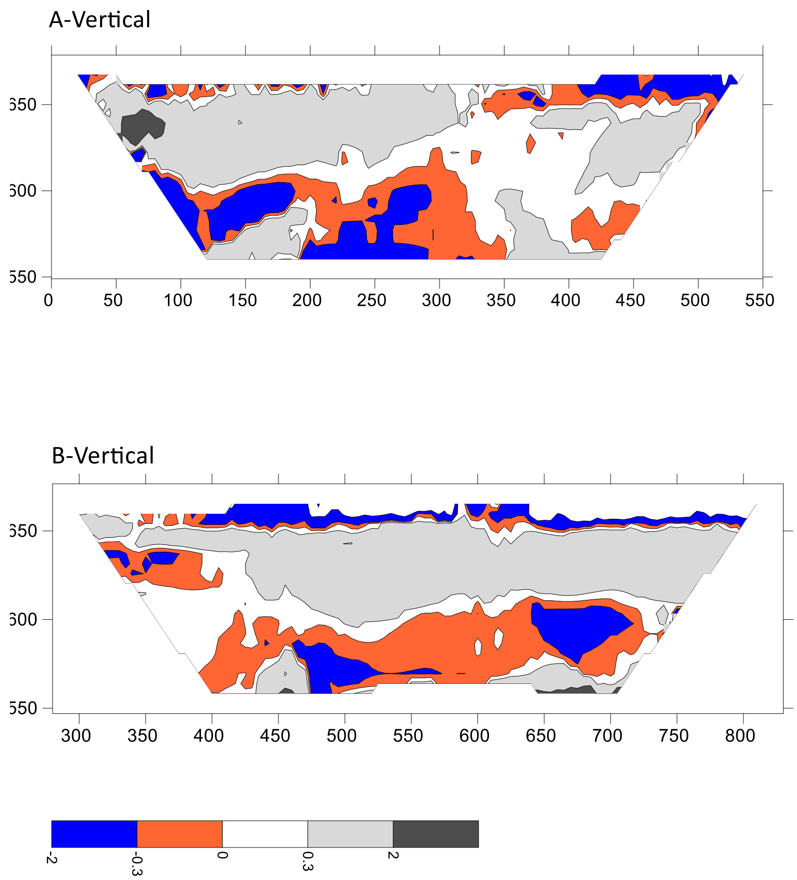
A-Horizontal



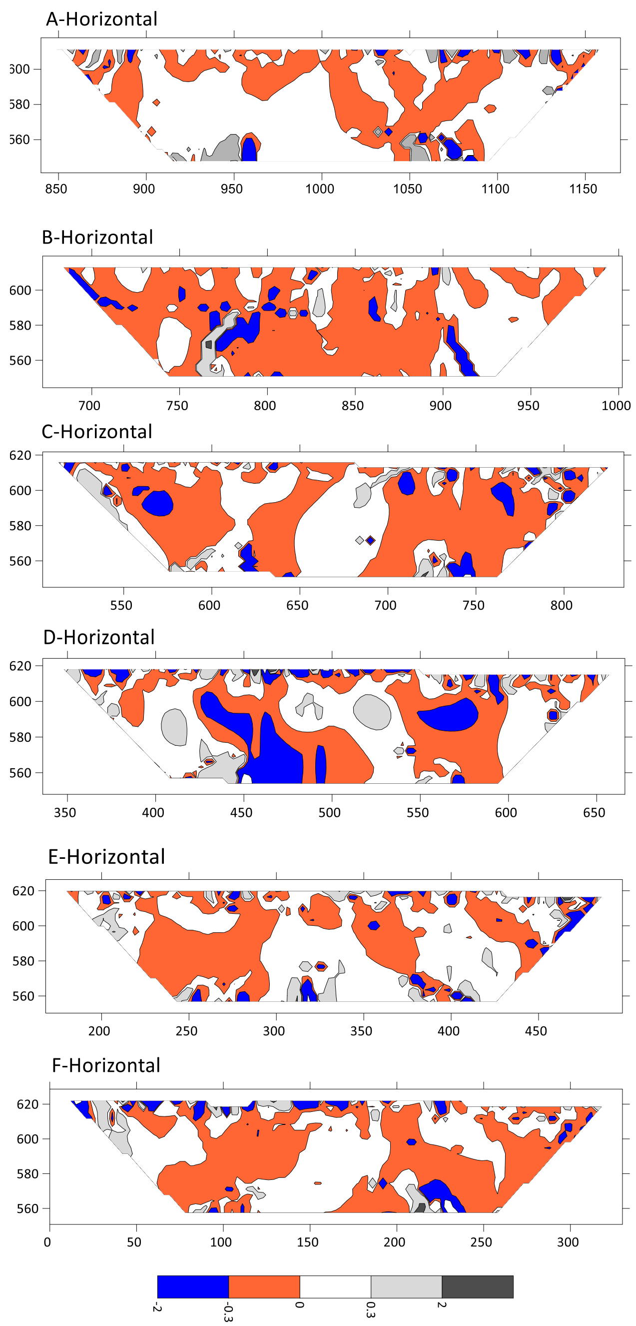
B-Horizontal



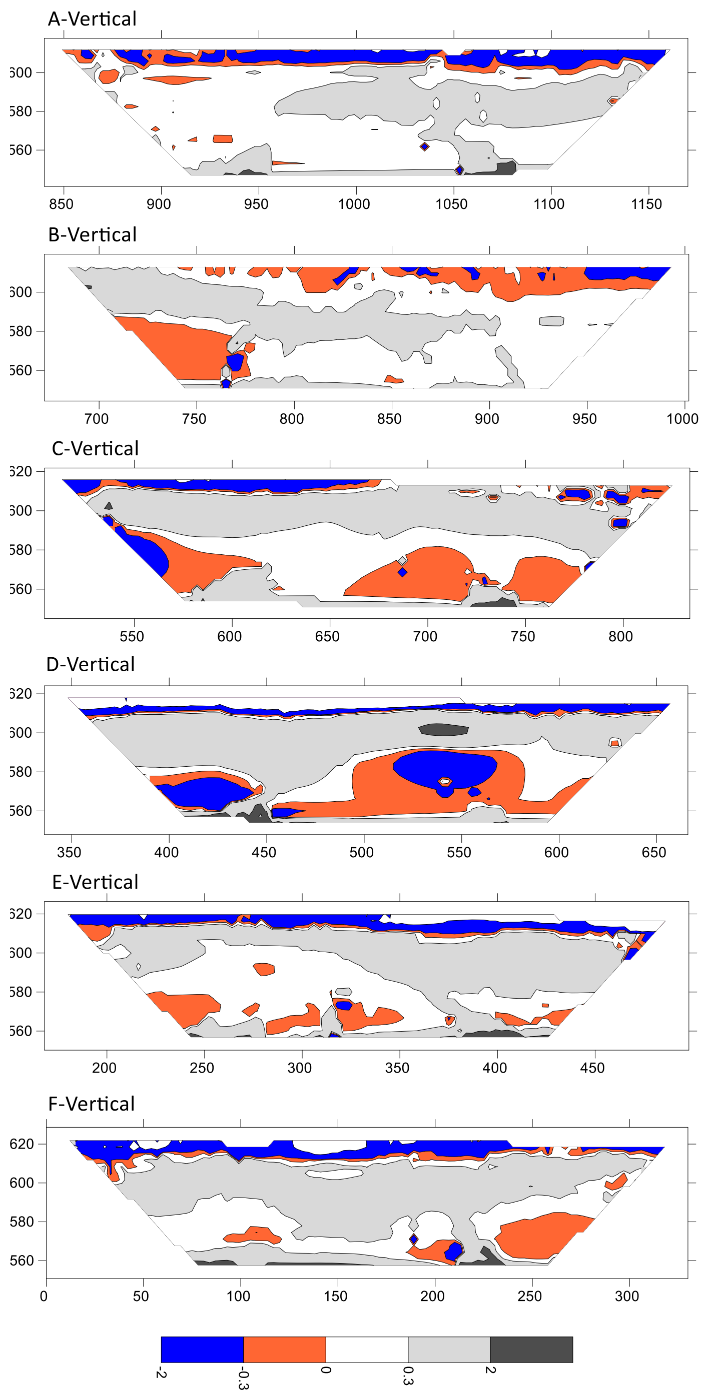
First derivative based image of WAT-01A and WAT-01B – vertical orientation



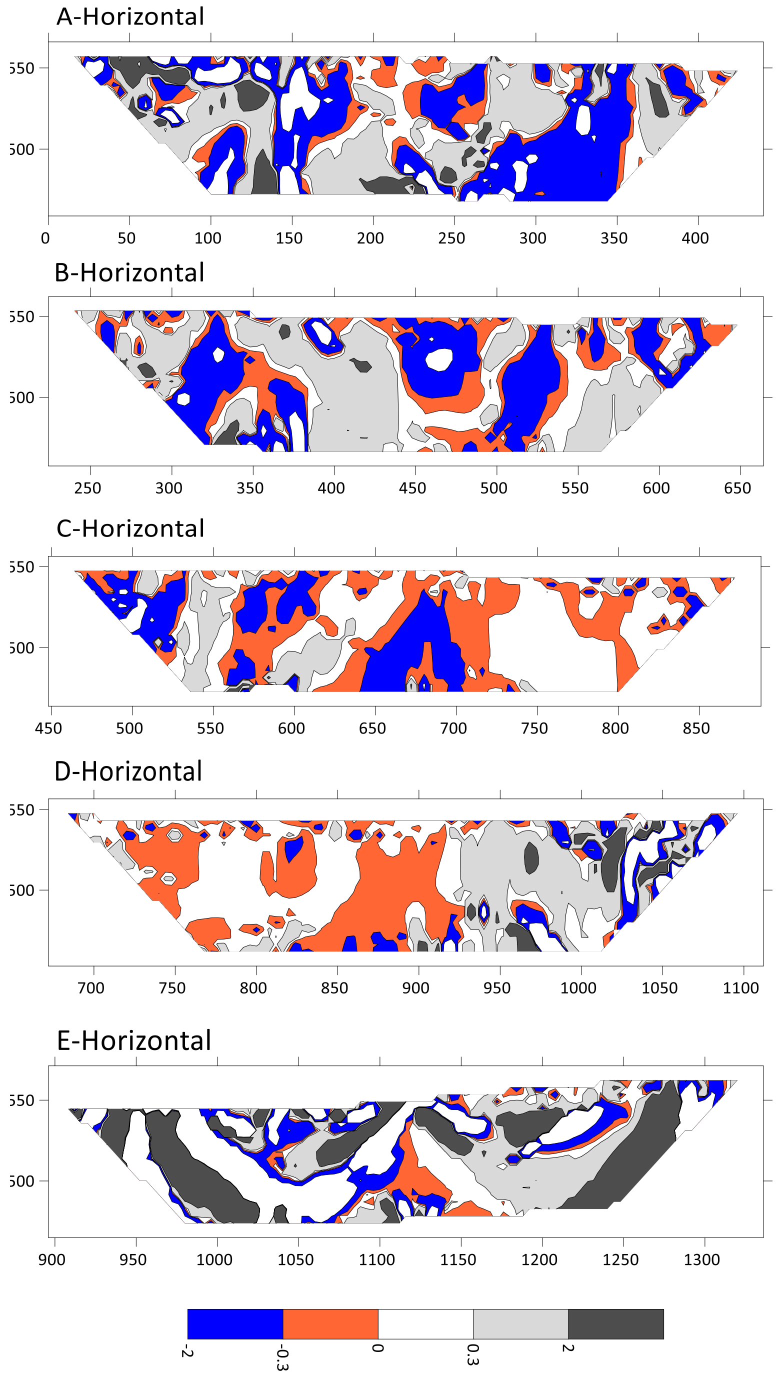
First derivative based image of WAT-02 (A-F) – horizontal orientation



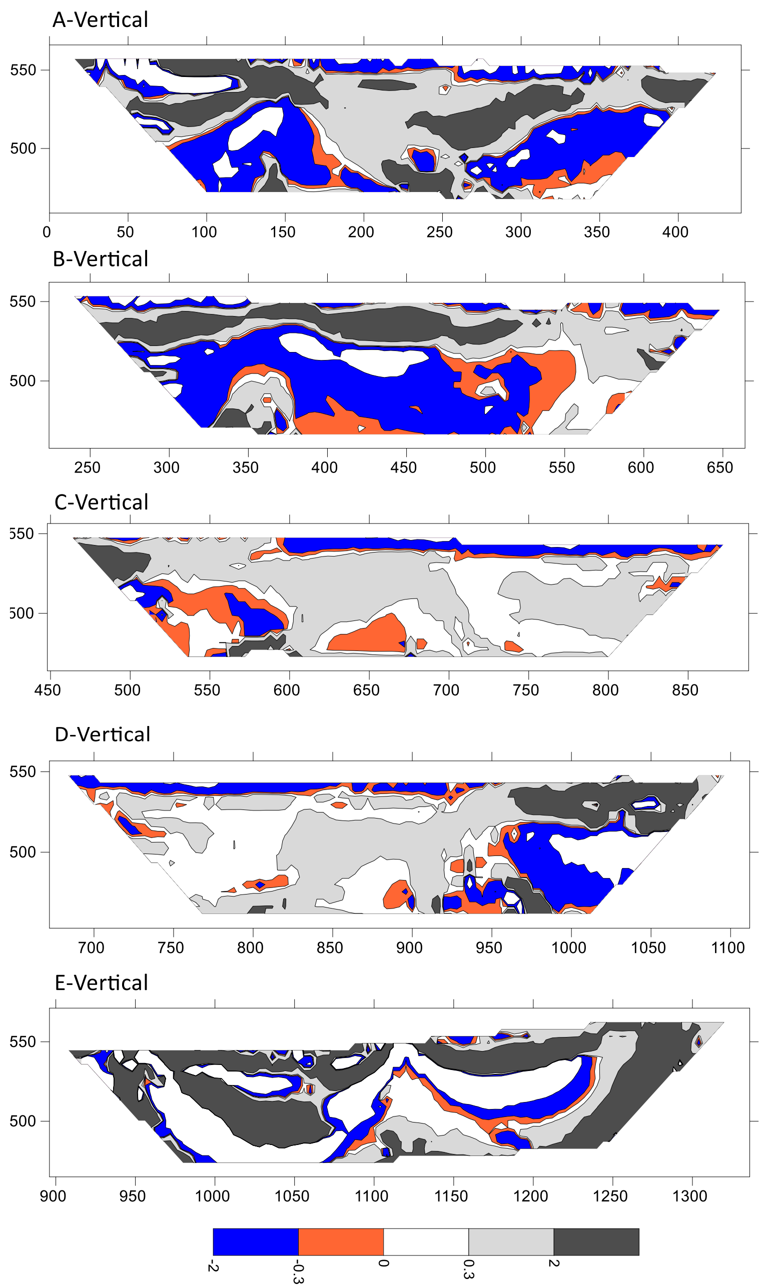
First derivative based image of WAT-02 (A-F) – vertical orientation



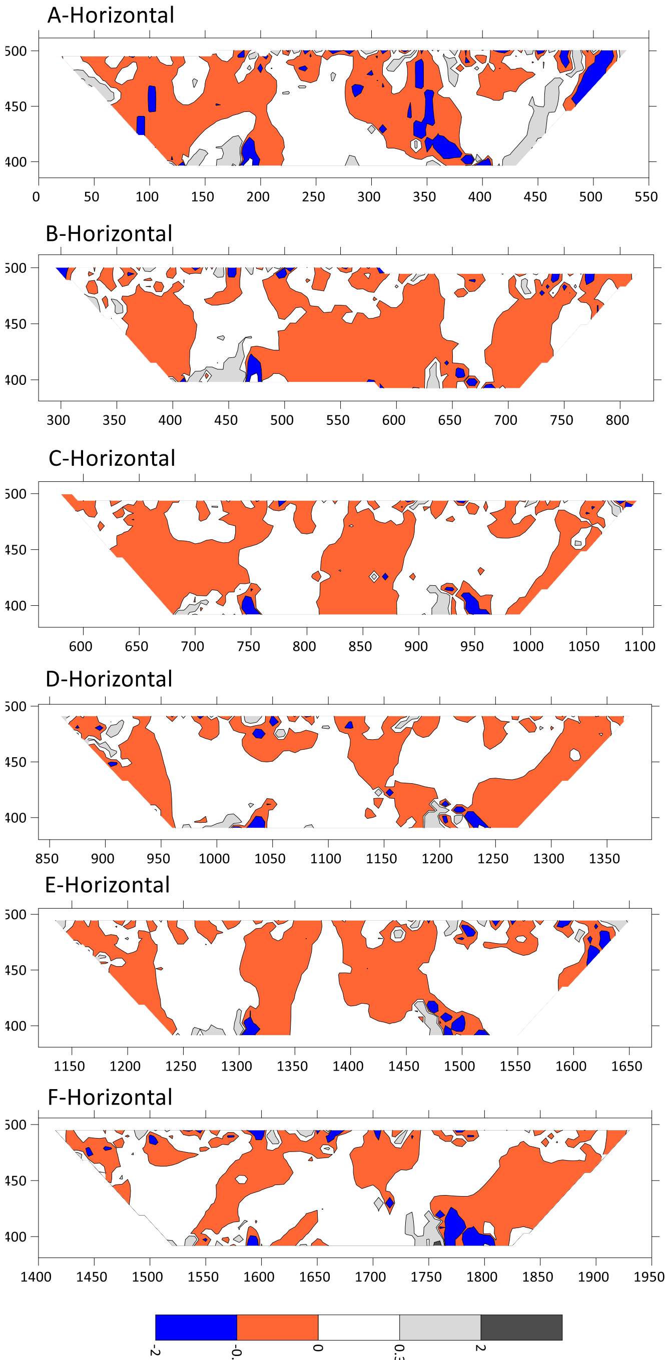
First derivative based image of WAT-03 (A-E) – horizontal orientation



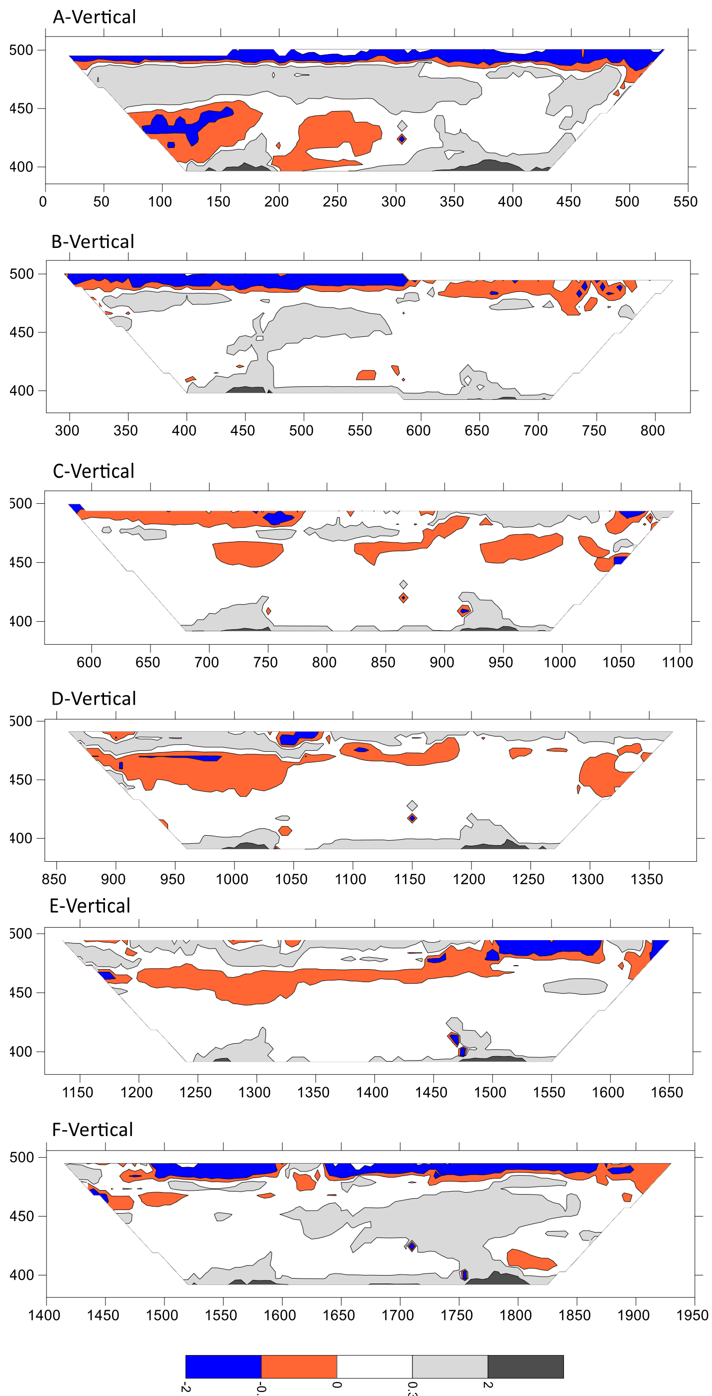
First derivative based image of WAT-03 (A-E) – vertical orientation



First derivative based image of WAT-04 (A-F) – horizontal orientation

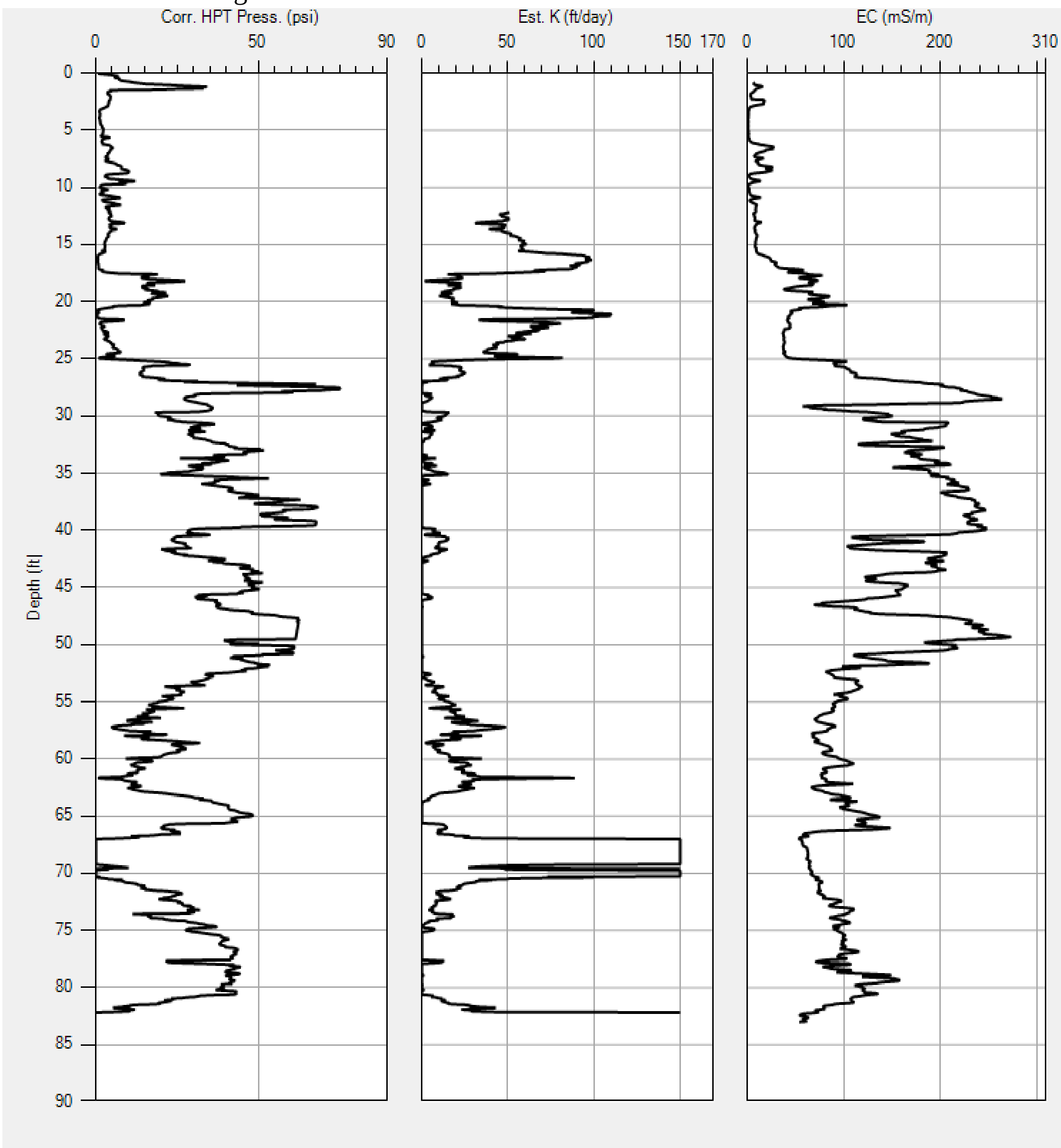


First derivative based image of WAT-04 (A-F) – vertical orientation



Appendix 2: Hydraulic Testing

USGS HPT/EC/K logs



VITA

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