# MASTERARBEIT | MASTER'S THESIS

Titel | Title

Geophysical Characterisation of an Intermittent Stream's Subsurface using Electrical Resistivity Tomography


verfasst von | submitted by

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angestrebter akademischer Grad | in partial fulfilment of the requirements for the degree of

Master of Science (MSc)

Wien | Vienna, 2024

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| Studienkennzahl lt. Studienblatt \| Degree programme code as it appears on the student record sheet: | UA 066 299 |
| Studienrichtung lt. Studienblatt \| Degree programme as it appears on the student record sheet: | Masterstudium Environmental Science |
| Betreut von \| Supervisor: | Ass.-Prof. Dr. Chi Zhang |

**Acknowledgments**

I extend my gratitude to my thesis advisor, Ass. -Prof. Dr. Chi Zhang, from the Faculty of Earth Sciences, Geography and Astronomy, University of Vienna, for her invaluable guidance, unwavering support, and patience throughout my master's thesis journey. I am profoundly grateful for her mentorship since the beginning of this endeavor, including her assistance in a mini research project reviewing the geophysics suite, which was a precursor to this master’s thesis. I have greatly benefited from her vast knowledge and expertise in environmental geophysics. I would also like to thank Sam Zipper, Ilinca Popescu, Kyle Compare, and Erin Seybold for generously allowing me to utilize their electrical resistivity tomography datasets. I am so grateful to my family for their unwavering support and encouragement throughout this academic pursuit, even from a distance (they are in South Africa). A heartfelt thank you to my parents, especially my mother, who is now retired but a teacher by profession. Thank you for instilling in me the value of education and prioritizing it throughout the years. My colleagues have also supported this journey, for which I will forever be grateful. Finally, I thank the Most High for seeing me through the past few years.

# Contents

# 1. Introduction

## i. Background

This work aims to contribute to existing hydrologic research, potentially enabling more effective management of groundwater resources in arid and semi-arid regions, through an enhanced understanding of groundwater recharge in intermittent streams. By exploring electrical resistivity tomography (ERT) as an investigative method in groundwater recharge studies, this thesis could help researchers obtain more useful information to inform water management strategies and policies. This research is topical, particularly for regions with intermittent streams, where infiltration through intermittent streambeds is considered a significant pathway of aquifer recharge (Goodrich et al., 2004; Quichimbo et al., 2020).

As stated by Messager et al. (2021), almost every river network on Earth has channels that periodically cease to flow. Streamflow cessation is naturally occurring globally (Messager et al., 2021). In addition, many formerly perennial streams (used interchangeably with rivers herein), in the past 50 years, have become intermittent due to water abstractions, climate change, and land use changes (Datry et al., 2014; Ficklin et al., 2018). A conservative estimate by Tooth (2000) suggests that intermittent rivers make up more than 30% of the total length and discharge of the global river network, which is expected to increase in future. While intermittent streams are ubiquitous, Messager et al. (2021), in the paper "Global prevalence of non-perennial rivers and streams," Messager et al. (2021) stated that intermittent streams are likely to be more prevalent in arid and semi-arid regions. The authors explain that for streamflow to occur, water from rainfall, snowmelt, or releases from existing storage, such as lakes, reservoirs, and groundwater, must surpass losses from infiltration and evapotranspiration. In regions where evaporation rates notably exceed precipitation for a significant portion of the year, as indicated by a low aridity index (the ratio of mean annual precipitation to mean annual potential evapotranspiration), intermittent rivers constitute substantial portions of the river networks (Messager et al., 2021). Water loss from the stream channel by evapotranspiration and infiltration is frequently associated with intermittent streams. This water loss is referred to as transmission loss and is a major hindrance to streamflow.

Due to a shortage of surface water resources, arid and semi-arid regions often rely heavily on groundwater, placing significant stress on groundwater resources. Consequently, aquifers in these regions are often at risk of groundwater depletion. With extensive groundwater withdrawal in these regions, it becomes imperative that hydrologists and resource managers have a robust understanding of the amount of water that actually recharges the aquifer after natural abstractions, to ensure a safe yield. The concept of safe yield is crucial in maintaining groundwater levels. The safe yield refers to the quantity of water that can be continuously withdrawn from an aquifer without causing undesirable effects (California Department of Water Resources., 2003). That undesirable effect is groundwater depletion. To prevent groundwater depletion, it is essential to ensure that groundwater is not abstracted at a rate higher than the rate at which it is recharged. This balance necessitates a clear understanding of the volume of water that recharges the aquifer, a major challenge in groundwater management. Safe yield estimation is especially critical in arid and semi-arid regions where groundwater is often the primary source of water. Hydrologists have attempted to estimate natural recharge rates to aquifers for decades to determine the long-term yield (Theis, 1937).

The difficulties faced by hydrologists in recharge estimation are primarily attributed to two factors. Firstly, intermittent streams have an unsaturated zone between the stream channel and the aquifer. Thus, water travels a distance before it reaches the aquifer and qualifies as recharge. Natural abstractions occur along the way, with only a portion recharging the aquifer. The complexity is in estimating how much of the infiltrated water actually reaches the aquifer. The second hindrance is that the way water infiltrates the unsaturated zone (the path it takes) is determined by the geologic characteristics of the of the sand and rock that is infiltrated. The earth’s subsurface is heterogeneous, changing in composition and structure from one point to the other. To truly understand the subsurface character and thus, the path water takes in the subsurface, it requires a thorough investigation of the subsurface, with a dense sampling. With more points in the subsurface sampled, researchers can be more confident in the geology between each point, as this reduces the space for which the researcher has to make inferences. The less points in the subsurface sampled, the more assumptive the deductions are that are drawn. Investigations on geological structure and composition are often conducted using drilling. Collecting core samples is the most frequently used method for determining the type of geological material present at a site (Hunkeler, 2017). Drilling for core samples provides granular data, but these are point measurements. The major shortcoming of this method is that it only provides information that particular point. Investigations covering a larger area become a challenge due to the number of core samples that would need to be taken. Given the cost and logistics of this sampling method, it is generally not feasible to increase the drill density to a level that would sufficiently satisfy the needs of recharge studies. Hydrologists' deductions and modelling of groundwater recharge have primarily been hindered by the shortcomings in the methods available for characterising the subsurface geologic framework.

Surface geoelectric measurements offer a modern approach to estimating specific aquifer properties (Ahmed & De Marsily, 1987; Khan et al., 2002), and properties of the unsaturated zone, as seen in Q. Y. Zhou et al. (2004), where ERT was used to characterise the unsaturated zone around a borehole. Surface geoelectric techniques are part of the geophysics suite, which has gained pull in recent decades. Though geophysics is used to achieve the same objective as drilling, based on historical applications, it is advisable not to see it as an alternative, but rather a supplement to enhance other approaches. It enables researchers to address the limitations of conventional methodologies or the limitations between geophysical methods if two of these are paired. A benefit of using geophysics is that it is a non-invasive method, meaning there is no need to physically penetrate the ground, as measurements can be taken at the ground surface. Other advantages of geophysics are that it provides a denser set of measurements and requires much less of a financial and time investment. While geophysics has several practical advantages, it does have some limitations which is why it is typically not used as a standalone method. Additionally, as in all research, data validation is important. Using more than one method helps ensure that deductions are made based on accurate data. This is critical considering geophysics' shortcomings. Data collection errors and modeling errors are frequently highlighted in geophysical investigations. Moreover, ERT specifically is prone to noise and ambiguity, making interpretation challenging. To overcome the ambiguity, ERT is often paired with another method – it could be an additional geophysical method. The purpose is served as long as the methods do not share the same limitations. The methods paired should be complimentary.

In this research, the utility of geophysics is explored, specifically ERT, in investigating groundwater recharge in intermittent streams, with recharge being a function of the subsurface heterogeneity and geologic framework. The sheer quantity of measurements required to capture information on subsurface heterogeneity precisely poses perhaps the most significant obstacle to groundwater recharge estimation. Providing more measurements, geophysics can support investigations and help “fill in the gaps” in measurement and in understanding. Enhanced measurements facilitated by geophysics can contribute to developing more effective water management strategies and formulating informed policies. This is paramount in arid and semi-arid regions, where groundwater depletion poses a significant threat and where intermittent streams prevail. To conduct this study, secondary ERT data will be used. The data was collected at Larned Research Site (LRS). The LRS is located on an intermittent reach of the Arkansas River near Larned, in Kansas, the United States. In this way, the researcher aims to showcase the potential of employing geophysics in similar investigations.

***Groundwater use in the United States***

The United States Geological Survey (USGS) has made significant contributions to hydrologic research in the United States. Based on their estimations, in 2015, of the total fresh groundwater withdrawals in the United States, 82,300 million gallons per day (~311,500 million liters per day), irrigation accounted for 70%, primarily in California, Arkansas, Nebraska, Idaho, and Texas (USGS, n.d.). In these five states, fresh groundwater irrigation withdrawals collectively comprised 46% of the nationwide total for all categories. Almost all groundwater extractions (97%) were from fresh sources, predominantly utilized for agricultural irrigation (USGS, n.d.). Saline groundwater withdrawals were chiefly allocated for mining activities (80%) and were concentrated in Texas, California, and Oklahoma (USGS, n.d.). Fresh groundwater consumption for irrigation surpassed that for public water supply by over threefold, with public supply being the next most significant consumer of fresh groundwater nationally (USGS, n.d.). A map of the United States showing water withdrawals per state is presented in Figure 1.

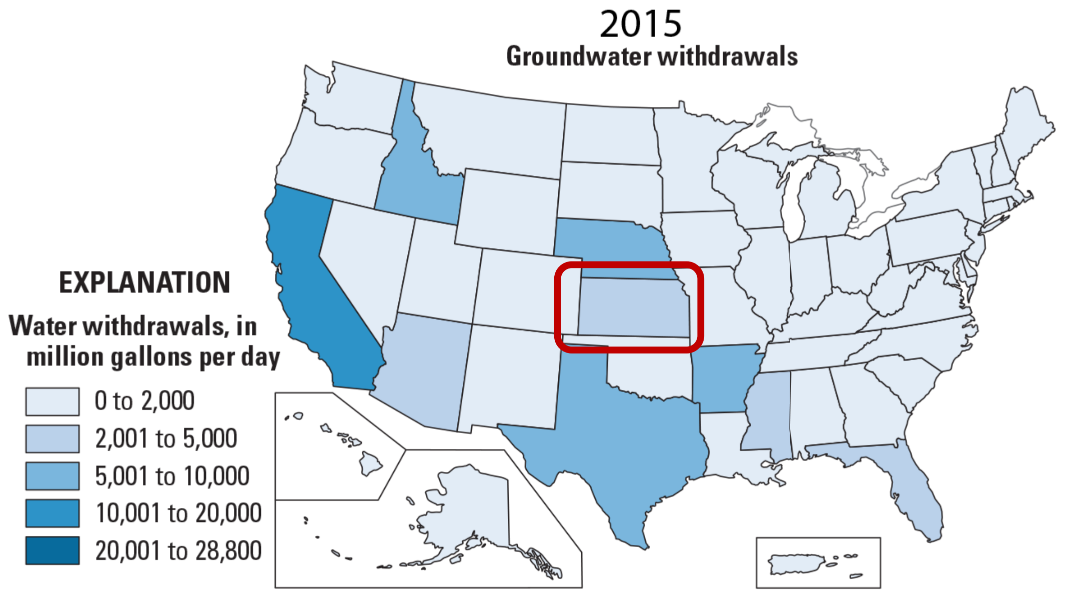



*Figure 1.* Map of the United States showing water withdrawals for the year 2015, per state, in million gallons per day. Kansas is circled in red (adapted from USGS, n.d.).

### *The High Plains Aquifer*

In the High Plains region, which constitutes several states in the United States, including parts of Kansas, extensive groundwater withdrawal has caused concern about the long-term sustainability of the High Plains aquifer (Buchanan et al., 2001). The concern today is that withdrawals exceed recharge, which leads to groundwater depletion as is observed for the High Plains aquifer, which underlies several states in the United States, all collectively referred to as the High Plains region. The High Plains region is divided into northern, central and southern High Plains regions, it underlies parts of Colorado, Kansas, Nebraska, South Dakota, and Wyoming in the northern part, parts of Colorado, Kansas, New Mexico, Oklahoma, and Texas in the central part, and eastern New Mexico and northwestern Texas in the southern part (USGS, 2021). The High Plains aquifer, which includes the renowned Ogallala aquifer, stands as a vital water source for a significant portion of western and central Kansas, providing 70% to

80% of the daily water consumption for residents of the state (Buchanan et al., 2001). This aquifer plays a pivotal role in sustaining the region's urban centers, industries, and a considerable portion of its agricultural activities (Buchanan et al., 2001). However, extensive pumping from this aquifer has resulted in continuous declines in water levels, particularly in the western sector of the region. This outcome has been described as the effect of large-volume pumping over decades (Buchanan et al., 2001).

It has been widely recognized for some time that groundwater withdrawals can lead to a reduction in streamflow, affecting both human uses and ecosystems (Barlow & Leake, 2012). The first comprehensive elucidation of the impact of groundwater extraction on surface water was provided by the renowned hydrologist Charles V. Theis of the USGS, who made valuable contributions to groundwater research during his long career. In his 1940 paper titled "The Source of Water Derived from Wells," Theis highlighted that the water withdrawn by pumping primarily originates from declines in aquifer storage. Also stating that with continued pumping, the repercussions of groundwater extraction can extend to interconnected streams, lakes, and wetlands through diminished discharge rates from the aquifer to these surface water systems (Theis, 1940). Groundwater is an essential component of streamflow, according to Barlow & Leake (2012), sometimes contributing up to 90% of the annual streamflow in certain parts of the United States. Consequently, to efficiently manage water resources, hydrologists and resource managers need to grasp the effects (including magnitude, timing, and locations) of groundwater pumping on rivers, streams, springs, wetlands, and groundwater-dependent vegetation (Barlow & Leake, 2012).

To determine the effect of groundwater pumping and the long-term sustainability of aquifers, researchers need to comprehend groundwater recharge. Winter (2001) proposed three main factors in the hydrologic landscape that govern recharge: climate, topography, and the geologic framework. The absence of sufficient data on the geologic framework prompts reliance on assumptions about mechanisms by which water moves through the unsaturated zone to the saturated zone (the aquifer), often resulting in an oversimplified representation of reality (Healy, 2010). Given that recharge preferential flow paths are determine by subsurface geology and the earth’s subsurface is highly heterogeneous, methods that can provide dense sets of measurements for the characterization of the subsurface, while still covering an extensive area are needed, for regional or catchment groundwater recharge studies.

### ii. Geophysics

As aforementioned, geophysics is gaining popularity in subsurface studies, not only to serve the purpose of aiding geologic characterisation, but also for the monitoring of fluids in the Earth's interior. Geophysics is defined as relating to the physics of the earth and its surroundings, and provides a suite of methods, with this basis, for examining the Earth and its surrounding environment (Telford et al., 1990). The geophysics suite is mainly used to investigate the Earth's internal structure. This is achieved by analyzing the physical properties observed at or above the Earth's surface and applying mathematical models to predict the conditions that could cause these attributes (Wheeler & Cheadle, 2014). The act of predicting the conditions from the attributes is called geophysical inversion – a necessary step in geophysical surveys to obtain meaningful information from the survey data. Geophysical inversion is part of processing the geophysical datasets – the collected measurements. The degree of processing required in this step, often relates to the signal-to-noise ratio of the collected data (Yilmaz, 2001).

There are numerous earth properties that the geophysics suite uses to provide insights on the subsurface. The Earth's internal composition and structure can be investigated using seismic, gravity, electrical, and magnetic methods (Telford et al., 1990). Variations in electrical conductivity, naturally occurring earth currents, the decay rate of introduced artificial potentials, and local changes in gravity, and magnetism, all provide valuable insights into subsurface features. Geophysicists have utilized these properties of the earth to identify promising areas for mining and locating metal deposits, since at least 1843, when magnetics was used (Telford et al., 1990).

#### *Hydrologic Applications*

Within geophysics, exists several subfields and Hydrogeophysics is one of them. The field of hydrogeophysics emerged in the late 1990s, partly driven by investigations into stochastic subsurface hydrology which supported the argument for better field-based investigative techniques (Binley et al., 2015). Stochastic hydrogeology employs physical principles and probability concepts to develop analytical tools for interpreting measurements across spatial regions (Rubin, 2003). These tools aim to extract information to evaluate and model physical processes within this domain. The development of practical and robust data inversion techniques greatly aided the advancement of new hydrogeophysical approaches (Binley et al., 2015). These techniques were often employed to quantify the heterogeneity in shallow subsurface layers and understand the dynamics of subsurface fluids associated with them (Binley et al., 2015). According to Binley et al. (2015), the demand for quantitative characterization led to numerous investigations into petrophysical relationships, establishing connections between hydrologically relevant properties and measurable geophysical parameters. Based on the observations of Binley et al. (2015) in "The emergence and evolution of hydrogeophysics," hydrogeophysical studies primarily focused on relatively small-scale experiments; however, in recent years, there has been a notable shift towards larger-scale characterization. The ongoing development of geophysical technologies is fueled, in part, by the growing necessity to comprehend and quantify the fundamental processes governing sustainable water resources and ecosystem services (Binley et al., 2015).

### iii. Secondary Analysis of Existing Data

To explore the utility of a method in a study, typically the researcher would use the method to make an assessment. This would require resources that are not at the current researcher's disposal. Consequently, existing (or secondary) data will be used for this thesis, making this work a secondary analysis of existing data. Any analyses of existing data collected for research studies or analyses of data collected for other purposes (such as registry data) are considered 'secondary analyses of existing data,' regardless of whether the individuals conducting the secondary analyses were involved in the initial data collection process (Cheng & Phillips, 2014). This methodology is becoming increasingly popular in research (Cheng & Phillips, 2014).

Cheng & Phillips (2014) described the utility of using existing data. To optimize the yield of data collection endeavors, researchers frequently evaluate a broader range of variables than is strictly necessary to address their original hypotheses. These additional data are often underutilized or underexplored by the original research team due to constraints such as limited time, resources, or focus (Cheng & Phillips, 2014). If the research team is willing to share their data with other researchers possessing the interest, skills, and resources to conduct supplementary analyses, it can significantly enhance the team's productivity that executed the original study (Cheng & Phillips, 2014). According to Cheng & Phillips (2014), researchers using secondary data employ the following two approaches for analyzing the datasets: a 'research question-driven' approach or a 'data-driven' approach. In the research question-driven approach, researchers start with a predefined hypothesis or question and then seek appropriate datasets to address the inquiry. According to the authors, in the data-driven approach, researchers examine variables within a specific dataset and determine what questions can be addressed based on the available data. In practice, these two approaches are often employed jointly and iteratively, with researchers using insights gained from one approach to inform and refine their approach using the other method (Cheng & Phillips, 2014).

The geophysical data utilized in this thesis was obtained from Compare et al. (2021). Compare et al. (2021) collected ERT data in June 2020 and another set of measurements was taken in November 2021 to characterize the subsurface heterogeneity at Larned Research Site (LRS). LRS is a Kansas Geological Survey (KGS) research site on a 7th-order intermittent reach of the Arkansas River, in the USA (Zipper et al., 2022). The region is heavily reliant on groundwater, leading to concerns about the sustainability of the underlying High Plains aquifer. The High Plains aquifer is the primary source of water in a major agricultural region of the United States (USGS, 2021). The ERT surveys were a part of one aspect of a more extensive study that aimed to explore the relationship between aquifer dynamics and surface water intermittency (Compare, et al., 2021). The researchers graciously granted permission for the current researcher to utilize the ERT survey datasets. The survey research article of the data collectors indicated that only limited deductions could be made from the datasets. In using these datasets, the current researcher will attempt to acquire additional insights that could enhance the understanding of recharge at the site and, in doing so, will explore the capabilities of ERT in groundwater-surface water research and the impact of data processing on the reliability of the inversions.

### iv. Preliminary Study

The initial study, conducted by Compare et al. (2021), aimed to characterize subsurface heterogeneity to explore the relationship between aquifer dynamics and surface water intermittency. Compare et al. (2021) identified lateral and vertical heterogeneity in the subsurface. This indicates the potential existence of preferential flow paths connecting hydrostratigraphic units beneath the river reach, along with potential exchange between the alluvial aquifer and the confined High Plains aquifer (Compare et al., 2021). The deductions made by Compare et al. (2021) were limited. Unfortunately, due to the coarse and dry conditions of the sandy substrate, the electrodes had limited contact with the ground, resulting in noisy ERT datasets that only provided insights to a depth of approximately 10 m. Only a few qualitative observations could be made (Compare et al., 2021).

Notwithstanding, the resulting paper of Compare et al. (2021) stated that the data revealed notable variations in resistivity both horizontally and vertically, which could be attributed to variations in sediment composition. Three subsurface conceptual models (Figure 2) were input into EarthImager by the researchers and run through forward modeling functions to create resistivity pseudosections, which were then inverted. Each model differed in vertical and horizontal heterogeneity (Figure 2) (Compare et al., 2021).

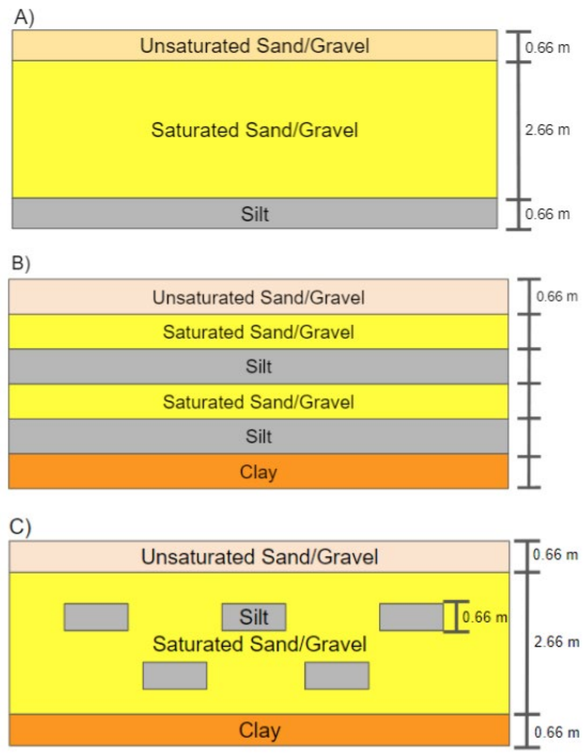



*Figure 2.* Three conceptual models were simulated using forward models. Each model has a thickness of 4 m and a length of 31 m: (a) the most basic model, (b) a model characterized by vertical heterogeneity, and (c) a model exhibiting both vertical and lateral heterogeneity (Compare et al., 2021).

In the study by Compare et al. (2021), the results from inverting the conceptual models were compared to the measured data inversion of the sandbar transect. The structure of the three conceptual models could still be recognized in the inversions, with some minor deviations, such as alternating layers in Model A. Of the three conceptual models, the third model (Model C), with silt lenses scattered throughout at a depth of between 1-3 m, is visually the closest match to the field data inversion shown in Figure 3d. Comparing these, they both have pockets of varied resistivities scattered throughout. However, the field data is more heterogeneous than any of the conceptual models. Several hindrances constrained the interpretation of the results. First, the field sandbar ERT transect inversion did not fully converge at a solution, as the final iteration had a root mean squared (RMS) data misfit of 29.21%. The researchers could not improve this value despite extensively exploring various parameter options inside the EarthImager software. As a result, this inversion is not a true inverted image of the subsurface, and primarily qualitative observations were made. Second, the range of resistivities in the field-data model is more significant than in any conceptual model. It looks as though a highly resistant material (seen as the red patch in Figure 3d) is skewing the scale and making comparison difficult. The value of this highly resistant patch (more than 20,000 Ωm) may indicate a transported boulder or an unexpected anthropogenic material present in the subsurface, below this reach, due to the Arkansas River's history of flooding and this site being known as a local recreational site. Compare et al. (2021) concluded that further research is necessary to delve into subsurface heterogeneity within the alluvial aquifer and the confining unit.

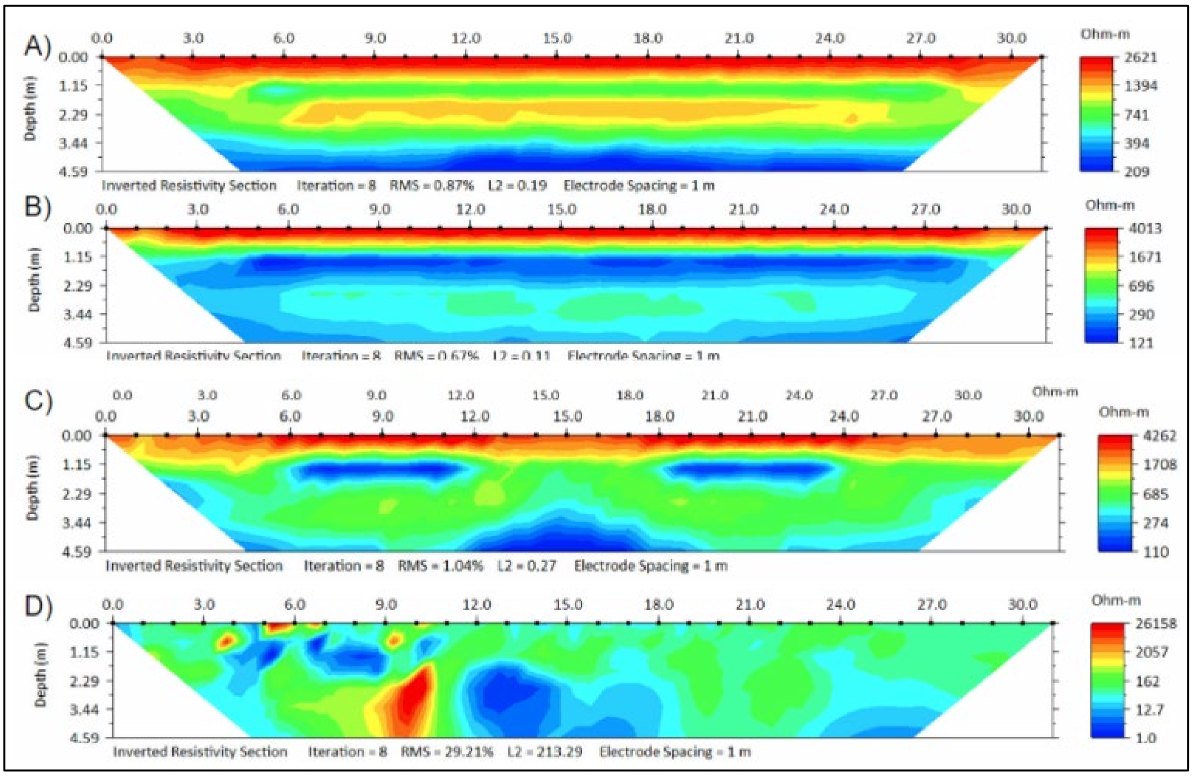



*Figure 3.* Forward model inversions were conducted, incorporating (a) the most basic model (see Figure. 2a), (b) a model with vertical heterogeneity (see Figure. 2b), (c) a model featuring both vertical and lateral heterogeneity, and (d) Arkansas River sandbar ERT transect inversion for comparative analysis. It is important to note that the color bar limits vary among the plots (Compare et al., 2021).

### v. Motivation for this Thesis

While the data collectors did select the study site, understanding groundwater recharge in intermittent streams is becoming increasingly important. Intermittent streams are ubiquitous but are more familiar to drylands – arid and semi-arid regions (Tooth, 2000). These parts of the world have limited surface water availability and are, therefore, highly dependent on groundwater. To ensure that the aquifers supporting these populations are not depleted, recharge processes must be understood and quantified. If water is extracted at a rate more significant than the replenishment rate of the aquifer, the aquifer runs the risk of depletion. The sustainability of aquifers, especially in regions heavily reliant on groundwater, is a pressing concern today, as is the case for the High Plains Aquifer, the confined aquifer underlying the intermittent reach at LRS. In these areas, understanding recharge is crucial for sustainable water use.

Unfortunately, recharge estimations are still impeded by a lack of data to capture spatial variability in the geologic framework sufficiently. Understanding seepage through intermittent streamsbeds requires elucidating preferential flow and denser measurements. ERT could help address this limitation. The LRS ERT datasets will be used to assess the capabilities of the ERT method in recharge studies. This study will examine recharge as a function of hydraulic conductivity, a geologic property that governs water flow, which can be determined using ERT and information from a previous study near the site. In a survey conducted by Healey et al. (2001), the electrical conductivity (the inverse of electrical resistivity) of the unconsolidated sediments was assumed to be primarily a function of grain size. Thus, low electrical conductivity values were supposed to indicate sand and gravel; intermediate values were taken to indicate silt, and high values were considered to indicate clay. This means the opposite for electrical resistivity: high values of electrical resistivity for sand and gravel, intermediate for silt, and low values for clay. No cores were taken at the site, but the viability of the assumed relationships can be confirmed by previous work, which characterizes the unconsolidated alluvial deposits at a separate KGS site (Butler et al., 1999).

Building upon previous research in the same study area, this study employs the same datasets with the overarching goal of extracting more meaningful and insightful information. The distinguishing factor lies in the approach to data processing, which lacks uniformity due to the absence of standardized methods. Instead, it involves meticulous data point removal, potential application of error filters, and exploration of various software packages. Additionally, forward modeling supports interpretation, requiring multiple iterations to align with the measured data. Through a systematic and iterative approach to data processing and interpretation, this thesis aims to overcome the challenges posed by the noisy datasets, ultimately advancing our understanding of groundwater-surface water interactions in the study area.

The initial researchers could only make a few qualitative deductions from the data. Given the topic's importance and the data's availability, this study is positioned to contribute to the field regarding appropriate methods, and it can enhance the initial study's findings. This collaboration could enhance the credibility and robustness of the research and enable the researchers to address critical gaps in current understanding. Ultimately, the findings have the potential to inform groundwater management strategies, contribute to sustainable water resource utilization, and pave the way for more effective environmental policies, all while showcasing the utility of ERT as a valuable tool in hydrogeological research. This research will be centered on the following question:

**“What additional insights can the electrical resistivity tomography datasets provide about the recharge mechanisms occurring at Larned Research Site?”**

By answering this question, the researcher aims to achieve the following research objectives:

1. **Enhance the understanding of groundwater recharge mechanisms at Larned Research Site.**
2. **Contribute to the literature on suitable methods for acquiring information relevant to groundwater recharge estimation.**

### vi. Research Limitations

Working with secondary data has inherent limitations. Limitations are deficiencies within the research design that could potentially impact the outcomes and conclusions of the research (Ross & Bibler Zaidi, 2019). One of the primary limitations is that secondary data may not provide all the information of interest, and this is not in the researcher's control. The current researcher is conducting this study from Austria, and the research site is in the United States, thus, due to the cost of travel, preventing the possibility of acquiring additional data from the site. The collection of supplementary data to support the existing datasets is therefore rendered impractical. The second limitation pertains to the method used to collect the data. While geophysics has many benefits, geophysical data tends to be inherently non-unique. The inverse problem is non-unique, meaning multiple models could explain the same dataset equally well (Pelton et al., 1978; Snieder, 1998). In addition, geophysical datasets, particularly ERT, can be contaminated by noise. Real data are invariably contaminated with noise, further complicating the inversion process (Olayinka & Yaramanci, 2000). It is, therefore, critical that models are validated before they are interpreted. The third limitation relates to data processing. Geophysical data can be processed using various software packages, and processing is essentially trial and error, requiring several iterations that include removing erroneous measurements and using an error filter. This means that different inversion results can be produced for the same dataset depending on how the data was processed.

## 2. Groundwater-Surface Water Interactions

In this chapter, the basic groundwater-surface water interaction mechanisms are explained. Surface water generally refers to all water that occurs on the surface of the Earth in features such as streams, lakes, wetlands, bays and oceans. Surface water also includes solid forms of water such as snow and ice (Winter, 1999). Beneath the Earth's surface water is found in pore spaces in soil and rock. Not all water in the subsurface is referred to as groundwater. Groundwater typically refers to water in the saturated zone in subsurface pore spaces, as well as defined channels in karst formations (Brands et al., 2016). Groundwater and surface water interact naturally as part of the hydrologic cycle.

Winter (1999) stated, "In arid and semi-arid regions, water seepage from streams can be the principal source of aquifer recharge. Despite its importance, recharge from losing streams remains a highly uncertain part of the water balance of aquifers in these regions." There is still much uncertainty today, and with increasing demand and climate change, the necessity to understand recharge has rapidly grown. The statement excerpted from Winter (1999) can be perceived as the basis of this thesis, directly addressing the research's core objectives: (1) enhance the understanding of groundwater recharge mechanisms at the Larned Research Site and (2) contribute to the literature on suitable methods for acquiring information relevant to groundwater recharge estimation.

Without informed groundwater management strategies, regions could face seawater intrusion, land subsidence, streamflow depletion, and dry wells (Jasechko et al., 2024). Studies such as this could facilitate better management of groundwater resources in the most vulnerable regions.

### i. Mechanisms of Exchange

Exchanges between surface water and groundwater occur through subsurface lateral flow within unsaturated soil layers and infiltration into or exfiltration from saturated zones below the water table. In karst or fractured terrains, exchanges mainly occur via flow within fractures or solution channels (Sophocleous, 2002). Groundwater-surface water exchanges exhibit significant spatial and temporal variations (Ellis et al., 2007; Krause et al., 2007), primarily influenced by the heterogeneous distribution of aquifer properties (Conant Jr, 2004; Malard et al., 2002; Storey et al., 2003; Wondzell & Swanson, 1996; Wroblicky et al., 1998) and streambed permeabilities (Conant Jr, 2004; Malard et al., 2002). It has been found that aquifer heterogeneity exerts a more pronounced influence on the spatial distribution of exchange than the streambed (Kalbus et al., 2009).

As aforementioned, Winter (2001) stated three main factors in the hydrologic landscape that govern water flow: climate, topography, and the geologic framework. The climate impact relates to rainfall, wind, and temperature – factors that determine how much water runs into streams and how much is evaporated. One could include vegetation, which affects transpiration, an additional water abstraction. Hydrologic exchanges – whether surface waters lose water to or gain water from groundwater through their bed – depend on the hydraulic gradient. Hydraulic gradient is the change in hydraulic head across a flow path, representing the mechanical energy that drives groundwater flow (Woessner & Poeter, 2020). Groundwater flows in the direction of decreasing head. If water is motionless, the hydraulic gradient is zero, and the head value is the same everywhere. (Woessner & Poeter, 2020).

Early studies on regional groundwater systems conducted by (Hubbert, 1940) and (Toth, 1963) proposed a conceptualization of the water table as a subdued reflection of the topography. In other words, the hydraulic head, which is the pressure exerted by groundwater, often (in unconfined aquifers) mirrors the elevation of the water table, which is influenced by topography. This means that in unconfined aquifers, topography influences the direction of flow. Toth (1963) identified three simultaneously occurring types of groundwater flow:

- Local Flow: This type involves recharge and discharge at adjacent local maxima and minima. Groundwater moves within relatively short distances between high and low points in the landscape (Toth, 1963).
- Intermediate Flow: Intermediate flow encompasses multiple topographic highs and lows between recharge and discharge areas. Groundwater traverses varying elevations within the terrain, exhibiting a more complex movement pattern (Toth, 1963).

- Regional Flow: Regional flow is characterized by recharge at the water divide, typically the highest point in the basin, and discharge at the basin's bottom. This type of flow entails movement over large distances, reflecting the overall drainage pattern of the basin (Toth, 1963).

A stream can lose water in one section and gain water in another. Which of these processes occurs is mainly determined by the location of the surface water in local and regional groundwater flow systems (Toth, 1963). At a regional scale, groundwater is recharged near topographic divides – elevated areas of land that separate adjacent drainage basins or watersheds – and discharged in valleys (Condon & Maxwell, 2015). Subsequent research has demonstrated that topography significantly affects groundwater movement across various spatial scales. Steeper topography tends to correlate with deeper water table depths, greater regional groundwater flow, and heightened groundwater exchanges with surface water bodies (Marklund & Wörman, 2007), supporting the idea of topographic dominance (Condon & Maxwell, 2015). However, it is recommended that caution is exercised as topography may not always be the dominant control on groundwater levels – several additional sources concur that interactions are predominantly influenced by three key factors: (1) topography, (2) geology, and (3) climate – these factors collectively shape the movement and distribution of groundwater within the subsurface (Freeze & Witherspoon, 1967; Haitjema & Mitchell-Bruker, 2005; Winter, 1999). On a smaller scale, the exchange can be influenced by geomorphological factors such as ripple and dune bedforms (Elliot & Brooks, 1997; Käser et al., 2009). When the current in a stream encounters obstacles such as bedforms, it accelerates over these features. This acceleration leads to changes in pressure, subsequently inducing water movement into and out of the bed. Käser et al. (2009) refer to this as current–objective interaction or pumping exchange.

### ii. Stream-aquifer Exchange

Streams interact with groundwater in three primary ways: gaining water from groundwater through the streambed, losing water to groundwater through the streambed, or existing as losing disconnected streams (Kalbus et al., 2006; Winter, 1999). These processes are illustrated in Figure 4. According to Kalbus (2006) and Winter (1999), gaining streams occur when the water table near the stream exceeds the elevation of the stream-water surface while losing streams experience the opposite scenario where the water table is below the stream-water surface. Disconnected streams occur when the water table lies below the streambed, creating an unsaturated zone between the stream and the aquifer (Kalbus et al., 2006; Winter, 1999). If an unsaturated zone develops and the water table is lowered further, the infiltration rate asymptotically approaches a constant value. When further reductions of the water table have no significant effect on the infiltration rate, the stream is said to be disconnected (Brunner et al., 2009). The state of connection between groundwater and surface water systems is a significant determinant of the degree to which a change in the water table level affects the infiltration rate of the overlying surface water body (Datry et al., 2016).

The interface between groundwater and surface water systems is a dynamic zone containing a mixture of surface and groundwater. The groundwater-surface water interface is primarily found in alluvial sediments adjacent to surface water bodies such as streambeds, lake beds, riparian zones, and flood plains (McLachlan et al., 2017). Although conceptually representing a boundary, the interface is commonly used to describe the intricate network of alluvial sediments near surface water bodies. Typically, it extends vertically for several meters and horizontally over hundreds of meters (McLachlan et al., 2017). In stream environments, these are termed hyporheic zones. These zones, which dominate the existing literature on exchange (Barthel & Banzhaf, 2016), constitute parts of alluvial aquifers directly adjacent to streams, both vertically and laterally, facilitating the mixing of stream water and groundwater (Gooseff, 2010). It is widely recognized that the interface governs water exchange and plays a crucial role in transporting nutrients and pollutants (Fleckenstein et al., 2010; Kalbus et al., 2009), influencing water bodies' overall health and integrity. Consequently, it emerges as a central focus for scientific investigation.

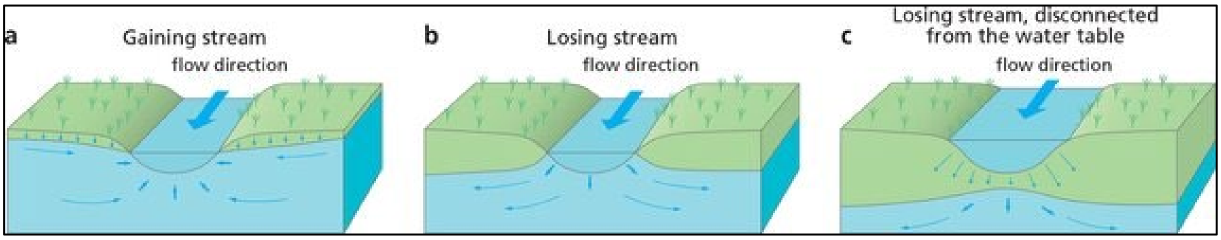



*Figure 4.* Groundwater-streamflow interactions (a) Gaining stream (b) Losing stream (c) Losing disconnected stream (Bierkens et al., 2021).

***Aquifer Recharge in Intermittent Streams***

Researchers studying groundwater-surface water interactions in intermittent streams typically seek to comprehend groundwater recharge. Most intermittent streams lose water for a large part of the year. Transmission losses, a distinctive trait of intermittent streams, are primarily responsible (Cataldo et al., 2010). Infiltration through intermittent streambeds is considered a significant pathway of aquifer recharge in drylands (Goodrich et al., 2004; Quichimbo et al., 2020). Thus, it plays a critical role in replenishing aquifers in water-stressed regions. As aforementioned, groundwater management strategies should be underpinned by a sound understanding of recharge to ensure the safe yield of groundwater. The difficulty in recharge estimation lies in the number of water abstractions in the stream channel and the unsaturated zone, making it difficult to determine the volume of water that reaches the aquifer to become groundwater. Runoff absorbed by stream alluvium is subjected to several abstractions. The first two extractions, which are relatively immediate, are transpiration by vegetation near the channel and evaporation from the wetted channel. On longer time scales (> five days), subsurface soil and geology may retain transmission losses near the surface, where vegetation absorbs and transpires it or diverted downslope to areas of discharge or more vegetation and subsequent transpiration. The proportion of infiltrated water that escapes near-channel evapotranspiration and wetted channel evaporation to become groundwater is difficult to determine (Goodrich et al., 2004).

### iii. Geophysics Applications

In groundwater-surface water research, geophysics can be employed for rock and soil mass characterization, void detection, and dynamic process monitoring. Rock and soil mass characterization involves analyzing properties like strength, fracture density, and homogeneity to gain insights into subsurface structures and their influence on groundwater flow. Void detection identifies zones of environmental importance or connectivity between surface water and groundwater. Dynamic process monitoring entails tracking changes in subsurface conditions, such as fluid flow, utilizing repeat surveys or continuous monitoring methods. McLachlan et al. (2017) categorize groundwater-surface water exchange into three domains: characterizing the subsurface structure, mapping connectivity zones, and monitoring hydrologic processes.

#### *Characterising Subsurface Structure*

The geology and heterogeneities of the subsurface can be characterized using geophysical techniques such as electrical resistivity, induced polarization, and ground-penetrating radar (Davis & Annan, 1986; Lowrie, 2007; Nyquist et al., 2009). While these methods are non-invasive, interpreting geophysical data often necessitates using invasive techniques like boreholes. Combining borehole data with electrical resistivity, induced polarization, ground-penetrating radar, or seismic methods enhances the resolution of deeper subsurface measurements. Geophysical approaches provide a level of resolution that would be unattainable with point measurements alone (McLachlan et al., 2017).

#### *Mapping Water Connectivity Zones*

Subsurface heterogeneity introduces variability in groundwater-surface water connectivity (McLachlan, 2019). Identifying zones of connectivity is essential for characterizing groundwater-surface water interactions and has significant implications for water management and environmental assessment (Binley et al., 2013). Contrasts in geophysical properties delineate these zones. Electromagnetic techniques have proven effective in mappinggroundwater-surface water interfaces, particularly in cases with substantial variations in either surface water or groundwater electrical conductivity, serving as natural tracers of subsurface flow (Lane Jr et al., 2020; Vogt et al., 2010). Vogt et al. (2010) demonstrate that electrical conductivity can be an alternative to other natural tracers, such as in bank filtration water tracing using electrical resistivity. However, intermittent streams pose challenges for tracer methods due to dry periods.

### *Monitoring and Quantifying Exchange*

Contrasts in geophysical properties can also be leveraged to monitor and quantify groundwater-surface water interactions at local scales (McLachlan, 2019). The dynamic nature of groundwater-surface water exchanges necessitates temporally distributed measurements. Geophysics enables the acquisition of continuous measurements required to monitor changes in survey data over time (McLachlan et al., 2017). Temperature sensing is a valuable tool for monitoring studies (Briggs et al., 2012; Glaser et al., 2021; Mamer & Lowry, 2013). Besides heat tracing methods, geophysical monitoring studies predominantly utilize electrical resistivity imaging (ERI). For example, Watlet et al. (2018) employed long-term electrical resistivity tomography (ERT) to investigate the source of drip discharge spots in caves, supporting modeling approaches for karst hydrologic processes. Christiansen et al. (2011) demonstrated the utility of time-lapse gravity measurements for monitoring purposes.

### *Intermittent streambed studies*

There is a clear imperative for advancing our comprehension of stream network dynamics within catchments. This necessity is particularly pronounced in arid basins, where streambeds are believed to be pivotal as the primary conduits for groundwater recharge. In inter-channel areas, infiltration is generally less significant due to several factors. Most rainfall in these areas is either transpired by vegetation, evaporated directly from the soil surface, or directed into channels and depressions (Scanlon et al., 1999, 2003; Walvoord et al., 2002). Capturing infiltration and transmission loss at the basin scale presents considerable challenges, with point-and-reach scale measurements often failing to upscale accurately. Understanding which parts of the basin stream network contribute to groundwater recharge is essential for conservation efforts and recharge capability's strategic development (Shanafield et al., 2020). Although geophysical methods are not commonly utilized in streambeds, especially in intermittent streambeds, they offer a unique opportunity to explore potential infiltration areas and, thus, groundwater recharge on a larger spatial scale than many other field methods allow. Geophysical surveys of streambeds have been conducted for segments ranging from a few meters to several km in length. For instance, Clifford & Binley (2010) employed 9-meter electrical resistivity tomography transects to investigate streambed stratigraphy along the River Leith in the United Kingdom, a small groundwater-fed stream. They successfully identified the boundary between the alluvium and bedrock beneath the riverbed. In a rare dry streambed study, Callegary et al. (2007) examined recharge potential across 41 km of two dry, ephemeral streams in Arizona, United States, using discrete transects spaced 25 m apart. Their approach combined geophysical measurements, vegetation surveys, and stream geometry parameter assessment to develop a recharge potential metric applicable to other ephemeral streams.

## 3. Geophysical Methods

### i. Method overview

Geophysics encompasses a range of investigative techniques providing insights into the shallow subsurface environment. Together, these techniques can offer a comprehensive understanding of geologic frameworks and fluid dynamics. Table 1 provides an overview of the methods described, including the measured parameters, the geophysical properties, and the derived properties of each. This list of methods is not exhaustive and merely provides a brief overview of the most used geophysical techniques in groundwater-surface water research. It is important to be aware that geophysical methods are not universally applicable; their suitability depends on the specific information sought and the depth of investigation required. Consequently, a thorough understanding of the strengths and limitations of each method is essential to ensure the success of an investigation. Survey design plays a pivotal role in a geophysical inquiry, arguably being the most crucial aspect. In survey design, the study objectives are carefully reviewed to formulate a robust field program and data processing methodology. Effective survey design and meticulous data acquisition are imperative for acquiring useful information.

***Seismic Methods***

The seismic method is highly regarded as the most critical and prominent geophysical technique due to its high accuracy, resolution, and penetration capabilities. Widely utilized in petroleum exploration, it also finds applications in groundwater exploration and civil engineering, particularly for assessing bedrock depth. Seismic methods involve generating seismic waves and measuring travel times from sources to geophones. Structural information is derived from the paths of these waves. These methods provide insights into the geologic structure rather than directly locating resources. Thus, they are valuable for studies requiring precise subsurface structural knowledge, such as engineering surveys and groundwater resource mapping (Telford et al., 1990).

### *Natural Electrical Methods*

The self-potential method relies on the electrical properties of rocks and minerals, utilizing natural electric potentials, electrical conductivity, and the dielectric constant for electrical prospecting. Subsurface processes, such as groundwater flow and mineralization, generate these potentials. Equipment for this method is simple, requiring electrodes connected to a millivoltmeter, with nonpolarizing electrodes crucial for avoiding noise. These electrodes are immersed in a saturated solution of their respective salts and placed in contact with the ground to measure potentials accurately (Telford et al., 1990).

### *Electromagnetic Methods*

As Maxwell's equations describe, the relationship between electric and magnetic fields is fundamental to electromagnetic theory (Ma, 2016). Time-varying electric fields induce magnetic fields and vice versa (Guru & Hiziroglu, 2009), illustrating the interconnected nature of these phenomena. According to Telford et al. (1990), electromagnetic methods in geophysics utilize this principle, transmitting and spreading electromagnetic fields in the Earth's subsurface. The conductivity of the ground is measured, aiding in subsurface characterization. Electromagnetic measurements can use direct or alternating current fields, with energy transmitted into the ground through direct contact or inductive coupling (Telford et al., 1990). This method is effective for materials with high electrical conductivity and is commonly employed in mineral exploration due to its versatility. Interpretational challenges exist due to magnetic field variations, impacting interpretations' uniqueness (Mugiraneza & Hallas, 2022; Telford et al., 1990).

### *Induced polarization*

According to (Telford et al., 1990), induced polarization is commonly utilized in base-metal exploration and, to a lesser extent, in groundwater exploration. This method resembles the resistivity technique, employing a standard four-electrode DC resistivity setup; however, the current is abruptly halted. Unlike in resistivity, where the voltage across potential electrodes drops to zero instantaneously, induced polarization decreases slowly after an initial sharp decline from the original steady-state value. This decay occurs over a period ranging from seconds to minutes. When the current is reactivated, the voltage experiences a sudden initial increase and then gradually builds up over a similar time interval to the original DC amplitude. The decay voltage is measured over time (time-domain), and the build-up time, being finite, indicates that the apparent resistivity varies with frequency (the number of times the current changes direction per second), decreasing as the frequency increases. In induced polarization, it is customary to measure both the apparent resistivity (using similar, albeit more complex equipment) and the induced polarization effect at each station (Telford et al., 1990).

***Ground Penetrating Radar***

Ground penetrating radar is a comparatively young geophysical technique used to investigate underground structures and has extensive applications. Electromagnetic theory forms its basis. Ground penetrating radar detects structures and changes in material properties within lossy dielectric materials using electromagnetic fields (Annan, 2005). A lossy dielectric material is one in which the electric conductivity is not equal to zero, yet it is not a good conductor (Tang & Resurreccion Jr, 2009). As explained by Annan (2005), ground penetrating radar employs the "echo principle" used in reflection seismology. A high-frequency signal is sent into the subsurface via a transmitter antenna before traveling to the receiver antenna, e.g., by reflection from an interface with opposing electrical characteristics. The course of the radar signal through the ground can be traced as a beam that encounters refractions, reflections, and diffractions at points where the dielectric constant varies. Measurements of reflection and transmission are related to the material physical properties by constitutive relationships - the mathematical equations or formulas that describe how the measurements taken by ground penetrating radar relate to the physical properties of the materials in the subsurface (Annan, 2005).

*Table 1.* Commonly used geophysical methods in groundwater-surface water studies are the geophysical properties they measure and the physical properties that can be derived (Binley et al., 2015)

| **Geophysical Method** | **Measured parameter** | **Geophysical Properties** | **Derived Property and State Examples** |
|---|---|---|---|
| Induced polarization | Voltage decay | Electrical conductivity, chargeability | Water content, clay content, pore water conductivity, surface area, permeability |
| Self-potential | Naturally occurring electrical potential | Electrical sources, electrical conductivity | Water flux, permeability |
| Electromagnetic induction | Response to electromagnetic pulses | Electrical conductivity | Water content, clay content, salinity |
| Ground penetrating radar | Travel times and amplitude of electromagnetic waves | Permittivity, electrical conductivity | Water content, porosity, stratigraphy |
| Seismic methods | Travel time of reflected/refracted seismic wave. | Density and elastic moduli | Geological structure, groundwater detection |

### ii. Electrical Resistivity

This section details only the direct current (DC) resistivity method, as this method is the focus of this thesis. ERT, as the name suggests, is a resistivity technique that integrates the principles of electrical resistivity with tomographic imaging, elucidating the flow of current through various layers of materials with differing resistivities within the subsurface. Resistivity is the inverse of conductivity. The resistivity of a material indicates how effectively it impedes the flow of electrical current (Herman, 2001), and this is the geophysical property that is used in ERT survey to insights, as it differs from one material to another. These contrasts, referred to as anomalies in geophysics, are what geophysicists use for interpretation. Geophysics relies on contrasts in geophysical properties. For example, copper, a proficient conductor, exhibits a resistivity on the order of $10^{-8}$ Ω m, whereas wet topsoil, an intermediate conductor, registers at around 10 Ωm, and sandstone, a poor conductor, reaches approximately $10^{8}$ Ωm (Herman, 2001). Given this substantial range, determining the resistivity of an unidentified material holds promise for material identification, even with limited additional information available (Herman, 2001). It is important to note that while the resistivity method effectively delineates horizontal beds and vertical contacts, it is less suitable for irregularly shaped bodies and can lead to ambiguity in interpretation (Telford et al., 1990).

The electrical resistivity setup is described in Telford et al. (1990). This method typically employs an artificial current source, which is introduced into the ground using either point electrodes or long-line contacts. However, the latter is now rarely utilized. The standard procedure entails measuring potentials at nearby electrodes while the current flows. The current and voltage are recorded which is used to determine the effective or apparent resistivity of the subsurface (Telford et al., 1990). Three main electrode configurations are used for the placement of the electrodes. Advanced Geosciences Inc. (AGI), a leading developer and manufacturer of resistivity/IP/SP imaging systems, explains how apparent resistivity can be calculated for each configuration (Advanced Geosciences Inc., 2019). A description of each electrode configuration based on Advanced Geosciences Inc. (2019) is provided, including their advantages and limitations.

According to Advanced Geosciences Inc. (2019), the Wenner electrode array (Figure 5) is the most basic configuration, where four electrodes—labeled as A, M, N, and B—are arranged in a linearly with equidistant spacing. The outer electrodes, A and B, serve as current electrodes, while the inner electrodes, M and N, function as potential electrodes. Using the Wenner array, the resistivity of subsurface layers is determined by increasing the distance between the electrodes while keeping the center point of the array fixed. This technique is known as vertical electrical sounding (VES) or electrical drilling. Horizontal variations in resistivity are detected by moving the four electrodes across the surface while maintaining a constant distance between them. This approach is referred to as profiling or occasionally electrical trenching. The Wenner array is commonly utilized for profiling to horizontally examine the ground, such as in soil testing, and at times for VES to vertically explore the ground, particularly in defining horizontal layers. One logistical advantage of employing the Wenner array in profiling is that only four electrodes need to be moved for each new measurement along the line. A disadvantage of the Wenner array is that it is cumbersome for VES surveys, due to the need to move all four electrodes for each new measurement. This requires considerable walking, especially with larger electrode spacings (Advanced Geosciences Inc., 2019).

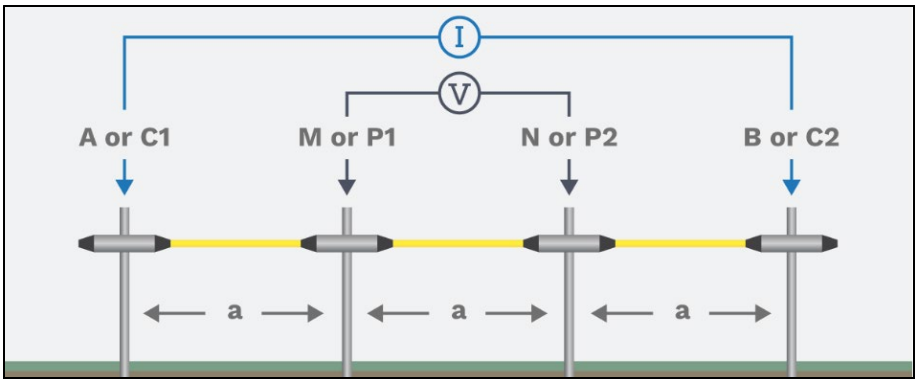



*Figure 5.* Wenner configuration (Advanced Geosciences Inc., 2019).

According to Advanced Geosciences Inc. (2019), the Schlumberger array (Figure 6) is a configuration where four electrodes are arranged linearly around a shared midpoint. The two outer electrodes, A and B, serve as current electrodes, while the two inner electrodes, M and N, function as potential electrodes positioned closely together. In the Schlumberger array setup, during each measurement, the current electrodes A and B are gradually moved outward to increase their separation throughout the survey. Meanwhile, the potential electrodes M and N remain stationary until the measured voltage diminishes to a level that is too small to be accurately recorded. At this point, the potential electrodes M and N are relocated outward to a new spacing. As a general guideline, the distance between M and N should ideally be equal to or less than one-fifth of the initial distance between A and B. This ratio may decrease to approximately one-tenth or even one-fifteenth depending on the strength of the signal. The Schlumberger array is a popular choice for conducting vertical electrical sounding

(VES) to explore groundwater and aggregate minerals. Compared to the Wenner array, VES with the Schlumberger array offers improved resolution and requires less time to set up and is considered the best array for VES. The Schlumberger array is additionally employed in mapping or profiling to detect lateral changes in resistivity. Typically, profiling involves employing larger fixed AB current electrode pairs and relocating MN potential electrode pairs between them. Alternatively, it can follow the Wenner profiling approach, maintaining a fixed spacing between the four electrodes ABMN. One limitation of profiling, regardless of the array used (Schlumberger or Wenner), is its reliance on the requirement of homogeneous horizontal layers, which are seldom found in nature (Advanced Geosciences Inc., 2019).

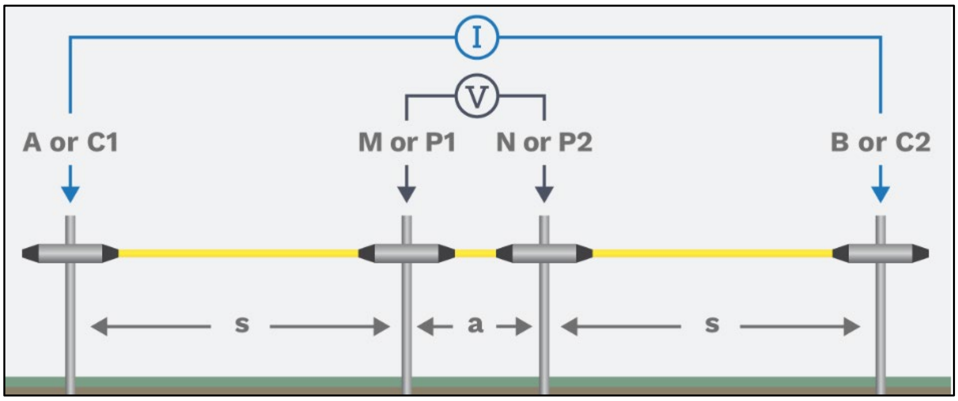



*Figure 6*. Schlumberger configuration (Advanced Geosciences Inc., 2019).

According to Advanced Geosciences Inc. (2019), the dipole-dipole array (Figure 7) comprises a current electrode pair A and B, along with a potential electrode pair M and N. This setup provides a means to visualize raw data for understanding the cross-section of the Earth. Practitioners of the dipole-dipole array analyze a measurement value known as apparent resistivity, which represents a weighted average of the resistivities beneath the four electrodes used during the measurement. Typically, modern instruments calculate apparent resistivity based on the geometry between the four electrodes, the injected current, and the measured potential. The outcome of a dipole-dipole survey is depicted in a pseudo-section. For each measurement, the apparent resistivity data is plotted at the midpoint between the two dipoles and at a depth corresponding to half the distance between the two dipoles. The data is eventually mapped out and colored, giving a basic (though sometimes quite distorted) depiction of what lies beneath the surface. Although this method doesn't give a direct image of the ground, the data points obtained from these measurements offer a representation of the cross section that can be analyzed. Nowadays, advanced inversion software can recompute all these apparent resistivity values to yield "true" resistivity values, enabling the creation of a more accurate ground image. The main benefit of the dipole-dipole array is its excellent resolution. It offers a highly detailed image rather than a broader overview, unlike the Wenner array. A disadvantage of this array is that if the dipoles are spaced too far apart, they may lose the signal, leading to a reduced ability to penetrate deeper into the earth (Advanced Geosciences Inc., 2019).

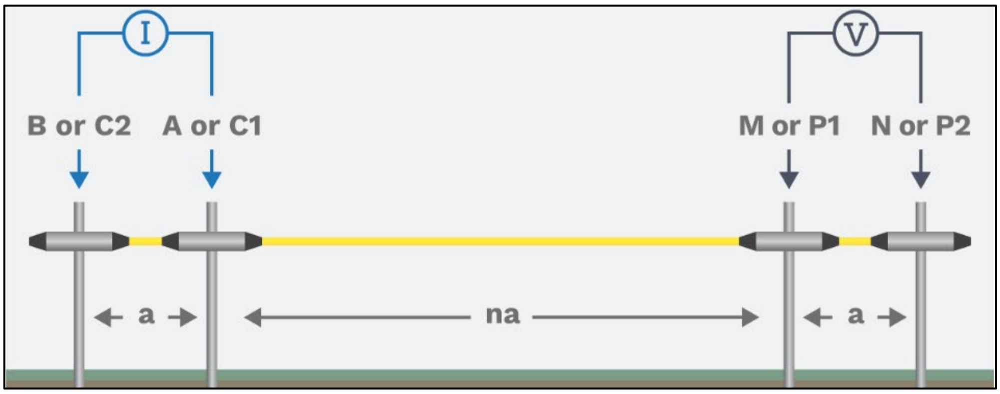



*Figure 7.* Dipole-Dipole configuration (Advanced Geosciences Inc., 2019).

Telford et al. (1990), explained that while the resistivity has limitations, it is still useful. In theory, the resistivity method offers advantages as it enables the acquisition of quantitative results using a controlled source with specific dimensions. However, practical constraints hinder resistivity methods from fully realizing their potential. Resistivity surveys assume a homogeneous medium, which is rarely the case in the field. Most rock masses showcase heterogeneity and anisotropy. Consequently, the apparent resistivity measured by these arrays may not accurately reflect the actual resistivity of the subsurface. To obtain the true resistivity, the data needs to be inverted. Resistivity methods are also susceptible to minor conductivity variations near the surface, resulting in elevated noise levels. This, coupled with the difficulty of maneuvering multiple electrodes and long wires through wooded terrain, has led to the electromagnetic method gaining popularity in specific applications. Nonetheless, resistivity methods will remain relevant due to the rapid advancement of induced polarization techniques, which incorporate resistivity data, ensuring continued use (Telford et al., 1990). Groundwater exploration frequently relies on resistivity methods for regional mapping and profiling, often complemented by seismic refraction, to help identify saturated zones and clarify any ambiguity in the resistivity data (Lee et al., 2021).

### iii. Resistivity Data Processing

Interpreting resistivity data often involves employing a two-dimensional model comprising numerous cells. This approach allows for a more detailed analysis and representation of the subsurface features and properties (M. Loke et al., 2013). There are two ways in which data processing can be approached: (1) using inverse modelling, and (2) using forward modelling. It is common for both to be applied, with forward modelling supporting interpretation of the models produced by inversion. Inversion is a tool applied in geophysics, which uses algorithms (computational techniques) to recover subsurface physical property distribution from field-collected data to produce an interpretable solution (Oldenburg & Li, 2005).

Geophysical inversion can be understood as an effort to match the behavior of an idealized subsurface model to a finite set of real-world observations. Inversion derives estimates for the model parameters by attempting to align the model response with the observed data. (Lines & Treitel, 1984). Lines & Treitel (1984) emphasized that if the model lacks physical relevance, its parameter estimates will be meaningless. A challenge in geophysics is that there will always be more than one possible solution that adequately fits the observations.

Forward modelling can also be used, to aid interpretation of the inversions. In forward modelling, the researcher attempts to determine the true subsurface model based on the collected measurements through an iterative process. Since the fundamental principles of geophysical methods are well understood, synthesizing data sets from a model of geophysical properties is simple (Binley, 2015).

According to McLachlan et al. (2017), forward modelling serves two primary purposes: (1) supporting survey design (2) supporting inversion and interpretation of the measured data.

# 4. Geologic Setting

## i. Larned Research Site

The study relies on Electrical Resistivity Tomography (ERT) data obtained from the Larned Research site (LRS). The LRS is a Kansas Geological Survey (KGS) research site located on a 7th-order intermittent reach of the middle Arkansas River (Zipper et al., 2022). The LRS is located about 10 km northeast of Larned, in South Central Kansas, at a latitude of 38°12'13" N and longitude of 99°00'07" W (Zipper et al., 2022). The U.S. Geological Survey stream-gauging station (USGS 07141220) is just downstream of the KGS LRS and has been collecting data since 1998 (Zipper et al., 2022). The area within which the study site is located relies heavily on groundwater for agricultural use. Between 1990 – 2019, over 1 million cubic meters of groundwater was pumped annually within 2 km of the study site (Zipper et al., 2022). The underlying High Plains aquifer is a critical resource in the region and faces groundwater depletion as a result of decades of large-volume pumping (Buchanan et al., 2001).

Phreatophytic cottonwood trees dominate the riparian floodplain at the site. When the water table is within the root zone, these trees can cause water level changes due to groundwater uptake (Butler et al. et al., 2007; Loheide et al., 2005). Since 2001, the KGS has been conducting research at the site. LRS was first established to investigate riparian zone processes within an ecohydrological context resembling the narrow riparian corridors commonly found in the United States High Plains region. (Butler Jr et al., 2007). Natural riparian corridors are the most diverse, dynamic, and complicated biophysical environments on the terrestrial portion of the earth (Naiman & Decamps, 1997).

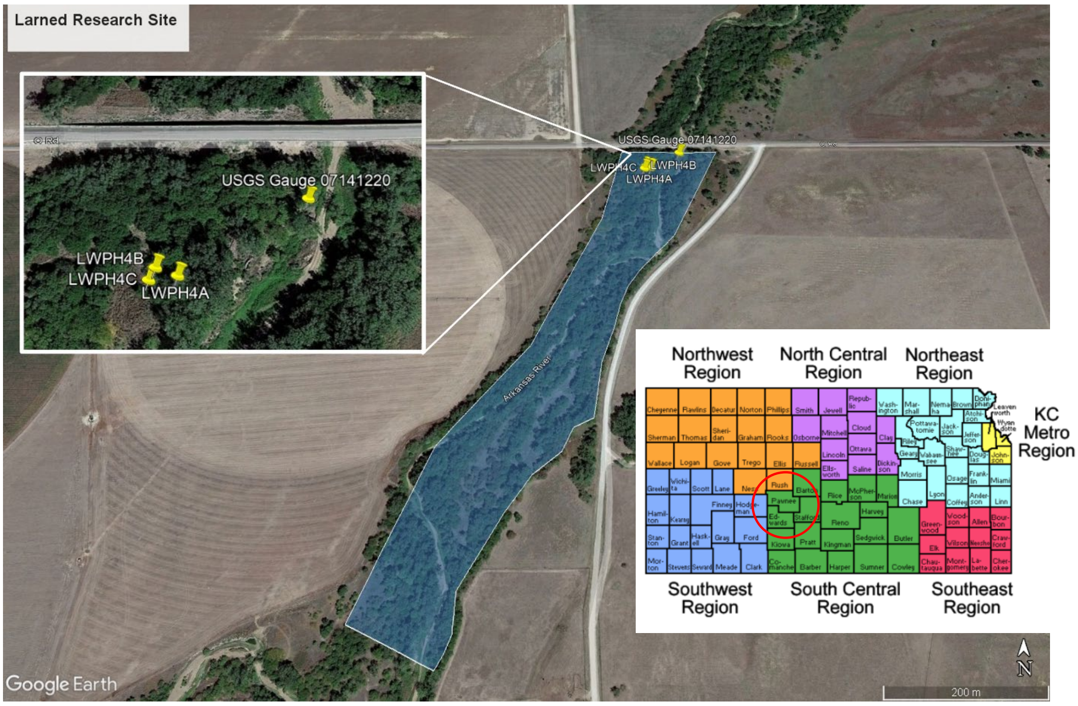



*Figure 8.* Map of the study site. The blue polygon on represents the LRS study area. The map showing the states was adapted from Kansas Adjutant General's Department, (n.d.).

Past research conducted at the site has focused on hydrostratigraphic characterization as seen in Healey et al. (2001). Furthermore, the research at LRS has focused on understanding hydraulic head responses to natural stimuli, including plant water uptake and barometric pressure (Butler Jr et al., 2007). Electrical conductivity profiles of the area are provided in Figure 9, taken from (Healey et al., 2001), and a conceptual model of the subsurface at LRS, based on these profiles is provided in Figure 10.

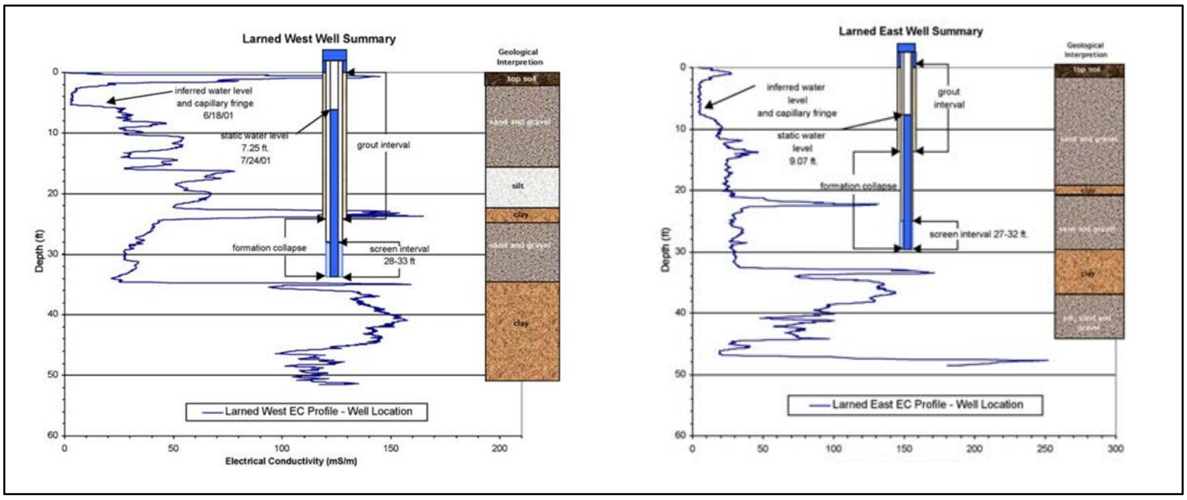



*Figure 9.* Electrical conductivity profiles were used for a conceptual model of LRS (Healey et al., 2001).

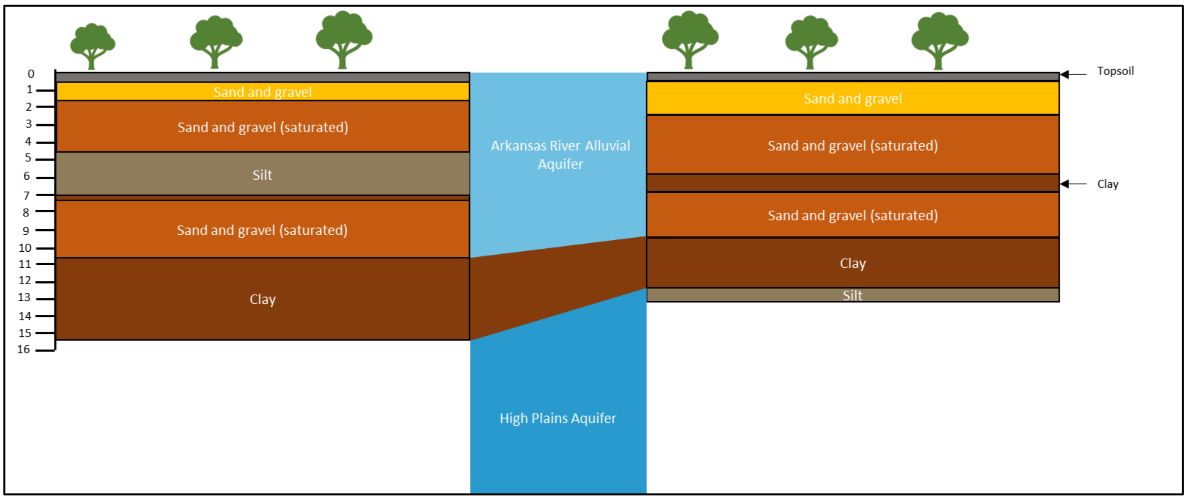



*Figure 10.* Conceptual model of LRS subsurface with the Y-axis indicating depth in meters. The conceptual model is based on electrical conductivity profiles from a previous study in the study area conducted by Healey et al. (2001).

From top to bottom, the central stratigraphic units at LRS are a surficial (Arkansas) alluvial aquifer, a leaky confining unit, and the highly pumped High Plains aquifer (Healey et al., 2001). The alluvial aquifer comprises unconsolidated sediments deposited by rivers in stream valleys – gravels and sands with a few clay layers extending around 10 meters below the surface. Below this is a leaky confining unit composed of clay several meters thick, but the thickness varies depending on the location (Healey et al., 2001). The leaky confining unit separates the local alluvial aquifer from the confined regional High Plains aquifer (Healey et al., 2001). The High Plains aquifer mainly comprises silt, sand, gravel, and clay—rock debris that washed off the Rocky Mountains and other more local sources over the past several million years (Buchanan et al., 2001). It is estimated to be 30 meters thick at LRS (Healey et al., 2001).

***The High Plains Aquifer***

According to (Buchanan et al., 2001), the High Plains aquifer constitutes a regional aquifer system comprising numerous smaller units that share geological similarities and are hydrologically connected – meaning water can migrate between them. The aquifer lies beneath parts of eight states within the Great Plains region, encompassing approximately 30,800 square miles in western and central Kansas (Buchanan et al., 2001).

The High Plains aquifer contains usable water in the tiny pore spaces between its sediment particles, and is western and central Kansas's most crucial water source, supplying 70% to 80% of Kansans' daily water needs, providing water to the region's cities, industries, and farmland (Buchanan et al., 2001). Arguably, the most prevalent and critical inquiry regarding the High Plains aquifer pertains to its sustainability for continued large-scale pumping. Withdrawals from the High Plains aquifer in Kansas have caused significant declines in water levels, prompting doubts about the aquifer's long-term viability as a sustainable resource for irrigated agriculture (Buchanan et al., 2001).

***The High Plains Region***

Figure 11 is a map showing the High Plains region – the area below which the aquifer lies. The High Plains region is categorized into three distinct parts based on its hydrogeological boundaries: the northern, central, and southern regions (Ajaz et al., 2020). The region includes parts of Colorado, Kansas, Nebraska, South Dakota, and Wyoming in the northern part, parts of Colorado, Kansas, New

Mexico, Oklahoma, and Texas in the central part, and eastern New Mexico and northwestern Texas in the southern part (USGS, 2021). The High Plains region has a continental climate with solid seasonality of temperature extremes (Stanton et al., 2011). Natural recharge from precipitation to the High Plains aquifer is minimal, partly because much rain falls during the growing season when plant roots intercept soil moisture (Buchanan et al., 2001). Most of the creeks and rivers that flow out of the High Plains region have been modified with control structures and channelization to make the water available for residential and agricultural purposes (Ajaz et al., 2020). Due to wells extracting significant amounts of water, some reaches that were once perennial have become completely dry in recent decades (for example, that between Dodge City and Garden City in Kansas) (Whittemore, 2002).

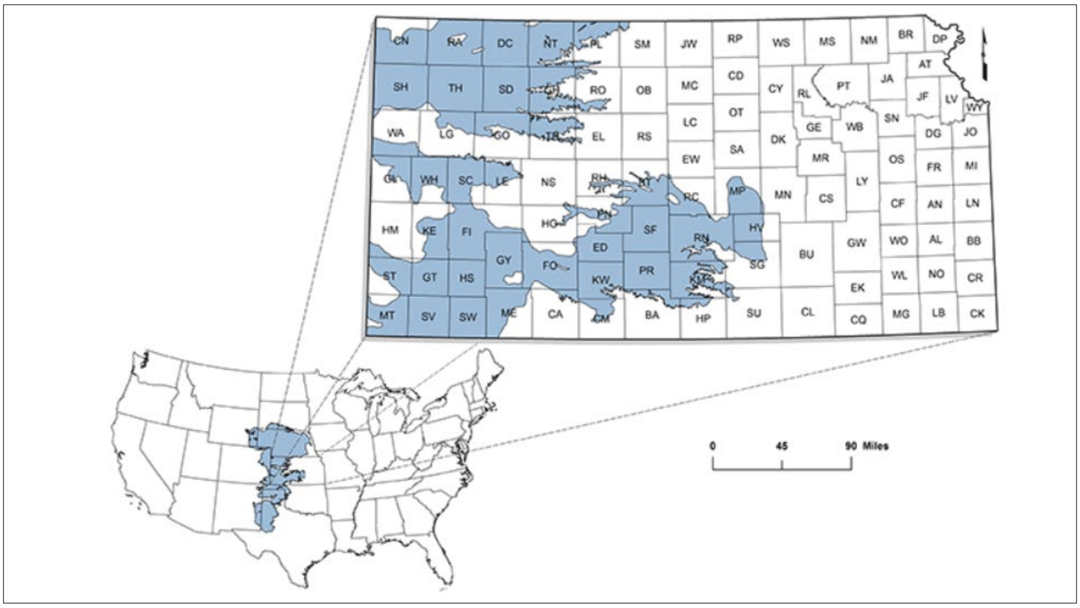



*Figure 11.* High Plains aquifer in Kansas (Buchanan et al., 2001).

### ii. ERT Survey at Larned Research Site

Two ERT surveys were performed by Compare et al. (2021) to investigate the subsurface at LRS, referred to hereafter as survey 1 and survey 2. Survey 1 (June 4, 2020) involved the collection of two transects, one along the riverbank and the other along a sandbar within the river. Both lines were approximately in a northeast-southwest direction. The *ARES-II* system was used to conduct the transects with stainless steel electrodes spaced one meter apart. Each profile was measured using both Wenner and Dipole-dipole configurations. The survey 1 transects are marked in red in Figure 12**Error! Reference source not found.** In Survey 2 (November 12, 2021), three transects were obtained along the Arkansas River floodplain. Line 1 in survey 2 was in a north-to-south direction, Line 2 was in a north-west to south-east orientation, and Line 3 was in a south-west northeast direction. The transects were acquired using the ABEM Terrameter LS 2 with an electrode spacing of three meters. The transects are marked in blue in Figure 12.

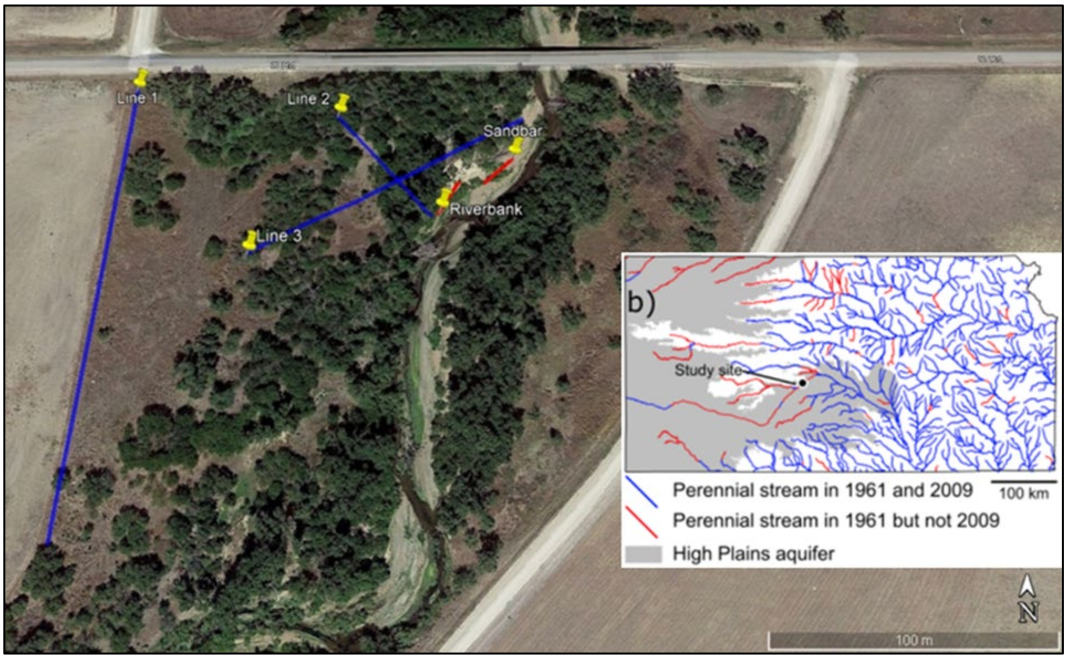



*Figure 12.* (a) Map of the study site showing transects of both surveys. Survey 1 transects are marked in red, and Survey 2 transects are marked in blue (b) Map depicting the loss of perennial streams in western Kansas adapted from Compare et al. (2021).

### iii. Processing the Survey Datasets

During an ERT survey, the measured data is converted into apparent resistivity using measured voltage and current. The apparent resistivity data is then inverted to extract meaningful information – the true resistivity distribution (M. H. Loke et al., 2020). Apparent resistivity measurements obtained from surveys are often visualized through pseudosections (M. Loke et al., 2013). While pseudosections offer a valuable graphical representation of the data, it is essential to note that they can present a distorted view of the subsurface. This distortion arises because the contour shapes are influenced by the array type and the actual subsurface resistivity (M. Loke et al., 2013). Pseudosections of the riverbank transect are presented in Figure 13, showing the notable difference in resistivity distributions for the same transect but different configurations. Evidently, when calculating the true resistivity, the geometry of the electrodes (the geometric factor) is considered in the formula.

Blanchy et al. (2020) provided insight into ResIPy capabilities in a paper about the software package. The data processing step began with the importation of the data into ResIPy, a relatively new open-source software package designed to streamline geoelectrical data inversion. ResIPy combines an open-source graphical user interface with a Python application programming interface, offering a more intuitive and user-friendly solution. Utilizing established R2/cR2 inversion codes for ERT and induced polarization, ResIPy simplifies data importation, filtering, error modeling, mesh generation, inversion, and visualization of inverse models. (Blanchy et al., 2020). Many non-commercial tools are developed using command-line software, making them challenging for new users to navigate and limiting their use in educational settings. There is a rising interest in open-source codes within the scientific community (Blanchy et al., 2020). These codes allow users and developers to access, comment, and enhance the software. This collaborative approach encourages contributions from multiple developers, fostering innovation and improvement within the scientific software landscape (Blanchy et al., 2020). Adopting an open-source approach enables users to customize codes to meet their specific requirements. Notable examples of successful open-source codes in geophysics include pyGIMLI (Rücker et al., 2017) and SIMPEG (Cockett et al., 2015), both offering a Python application programming interface (API) (Blanchy et al., 2020). These tools empower users to access and modify code, facilitating collaboration and innovation within the geophysics community. For more details on the inner workings of ResIPy, refer to Blanchy et al. (2020).

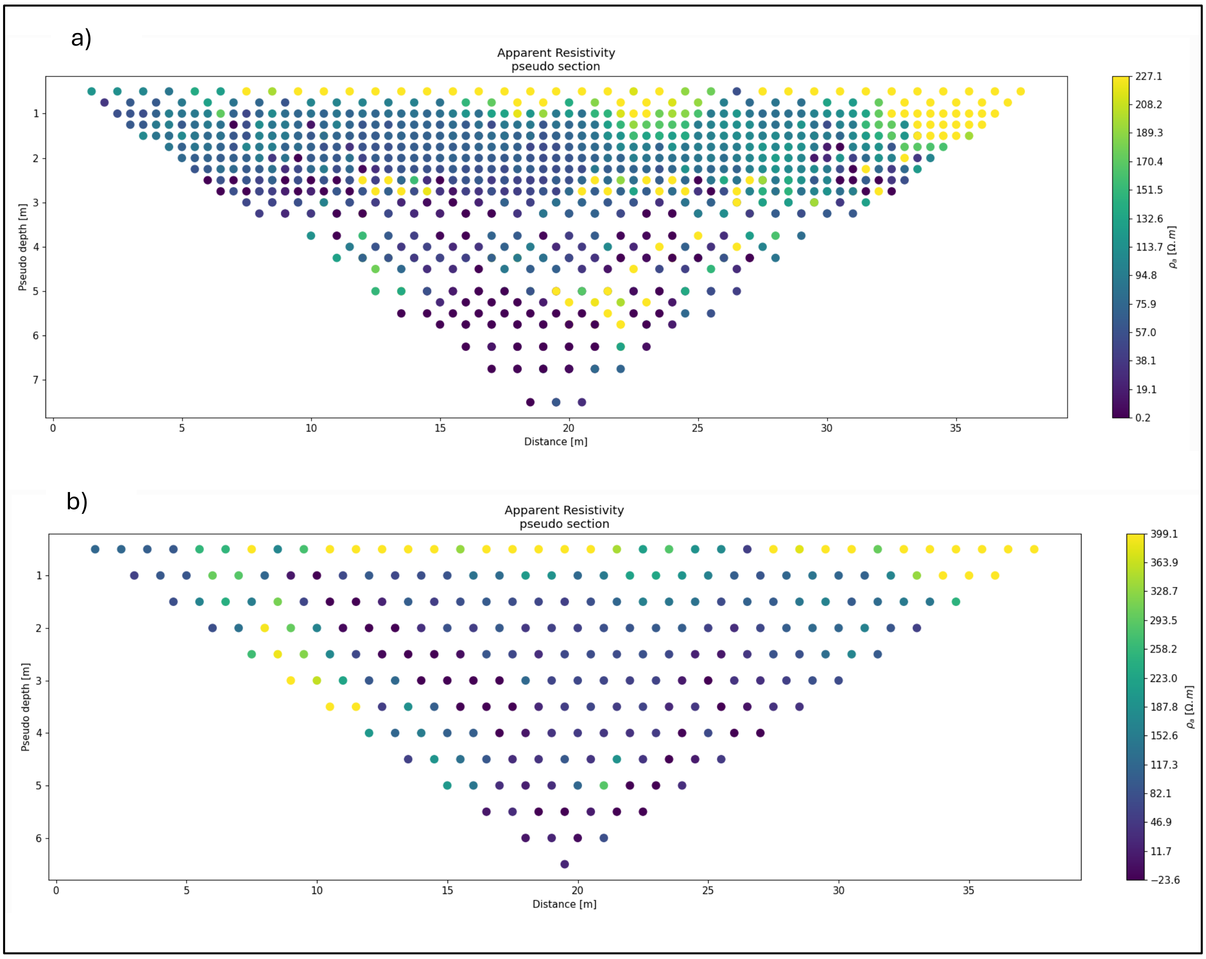



*Figure 13.* Pseudosections for the same transect (a) Dipole-Dipole configuration and (b) Wenner configuration.

Figure 14 illustrates the functionalities of ResIPy and the workflow the user follows for both inversion and forward modeling. As mentioned, the process starts with importing the data which can include topography information if available. If the provided files lack Z coordinates, topography is excluded from the inversion, as was the case here. ResIPy allows the user to import reciprocal measurements which are often used to help filter the data, as it helps with error modeling and the assigning of weights to measurements to prevent erroneous measurements from skewing the results. Unfortunately, the researcher did not have reciprocal measurements to work with as they were not collected in the initial study. However, the user can remove “bad” data points in the pre-processing tab. The final pre-inversion step involves creating a finite element mesh, which ResIPy provides in 2D space, though a custom mesh can be imported for more complex models. The data was then inverted. Once the data converged at a solution, the researcher used the post-processing tab to address any error. The researcher opted to invert without making adjustments and opted to rather use an error filter in the post-processing tab for most datasets. An error filter of -3 and 3 was applied as the normalized error should ideally fall within this range. The filter removes outliers – points that are not within this range. The filter seemed to be an easier, more organized, and replicable approach to bad data. When inverting the data, ideally, running the inversion should reduce the RMS value with each iteration. If not, revisiting the inversion settings, such as the default error value, is necessary.

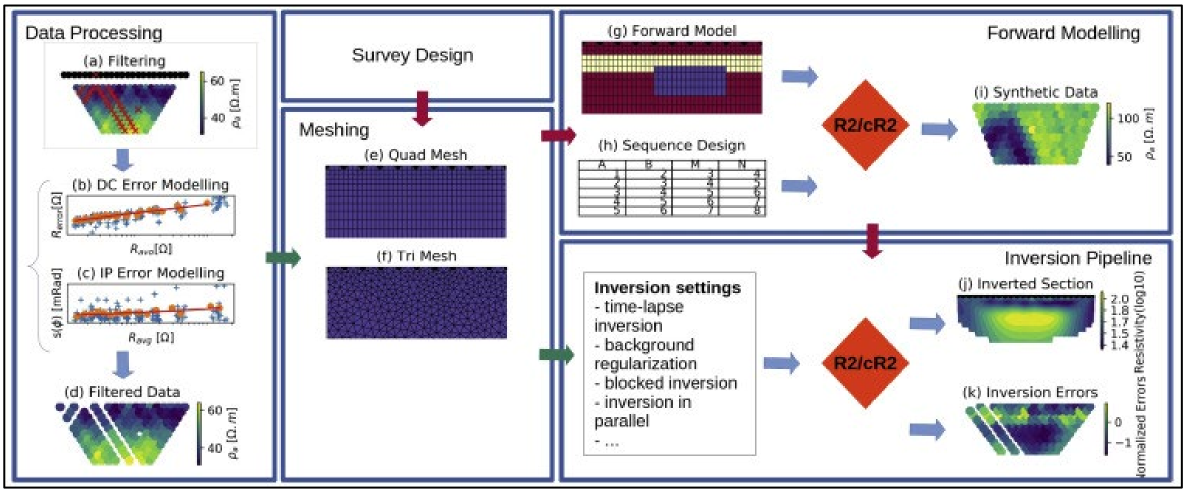



*Figure 14.* The inversion workflow (highlighted by green arrows) begins with data import and filtering to eliminate faulty measurements or electrodes (a). If reciprocal measurements are available, error models can be fitted for both DC resistivity (b) and IP (c). Subsequently, a quadrilateral (e) or triangular mesh (f) is generated, (d) and both the mesh and filtered data are sent to the inversion pipeline. Various inversion settings can be defined, such as blocking regions of the mesh or implementing time-lapse settings. The resulting inverted section is then produced with R2/cR2 (j), along with a diagnostic pseudosection depicting the normalized error of the inversion (k) (Blanchy et al., 2020).

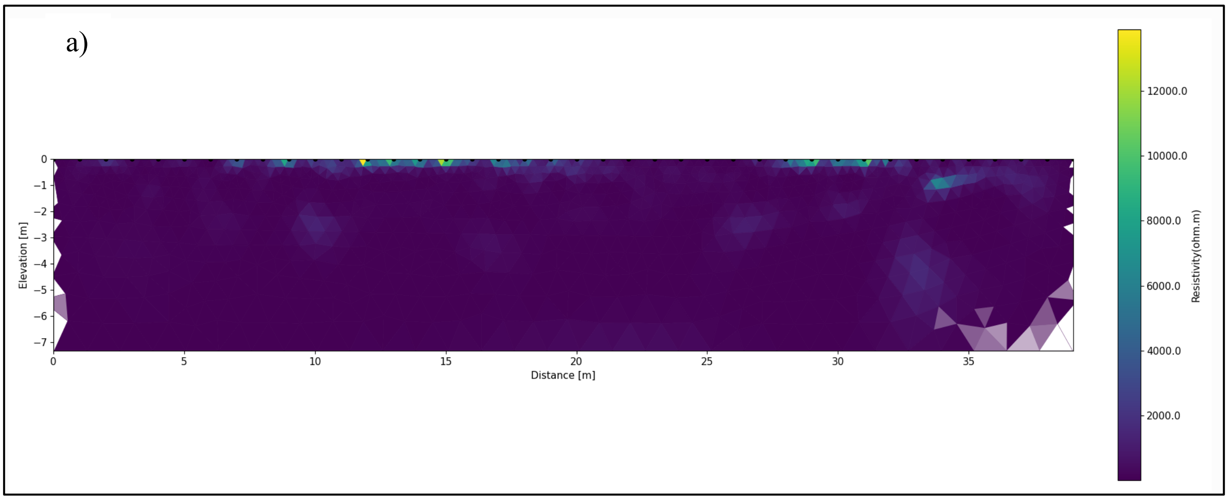
## 5. ERT Survey Results

Geophysics faces the inverse problem, seeking to deduce hidden structures from observable data. The inversion software – in this case, ResIPy – uses mathematical algorithms to reconstruct subsurface properties from surface measurements. This facilitates the construction of models depicting the earth's internal structure and composition. This chapter presents the reconstructed subsurface models and describes the findings obtained through the inversion of the ERT datasets using the workflow described in Chapter 4. Nine of the ten transects are described in this chapter, as well as the forward modeling outcome. Both Dipole-Dipole and Wenner inversion are defined for each transect. Additionally, each inversion is presented using two different scales. The first is the regular scale in ohmmeters, and the second is the log10 scale. The log tomogram better accommodates the wide dynamic range of resistivity values encountered in ERT surveys, enhancing contrast and allowing both low and high-resistivity anomalies to be visualized effectively. It is important to note that these profiles have not yet been validated in any manner. Thus, whether the profiles are reliable representations of the subsurface is uncertain.

### *Survey 1: Riverbank – Dipole-Dipole and Wenner Configurations*

The Dipole-Dipole and Wenner riverbank profiles are presented in Figure 15 and Figure 16, respectively. The top range for the Dipole-Dipole tomogram is ~ 3-14,000 Ωm, and 2-33,000 for Wenner. The tomograms show high resistivity near the electrodes. However, this could be noise due to poor contact between the electrodes and the ground. There is a highly resistant lens at about -1 m, with a resistivity of ~ 6,000., and another at a depth of 4 m with a resistivity of ~ 1,500 (Dipole-Dipole). Outside of these, it is visibly evident (see regular scale) that there is a more minor contrast in resistivity. There is still variability, but it is not highly contrasting. It is also challenging to determine if there are uniform strata. It does not seem like there is. Resistivities seem random both vertically and laterally. The log tomogram does not represent the degree of contrast but shows the "randomness" in resistivity values mentioned. These lenses in the log tomogram could be artifacts.

## Survey 1: Riverbank, Dipole-Dipole



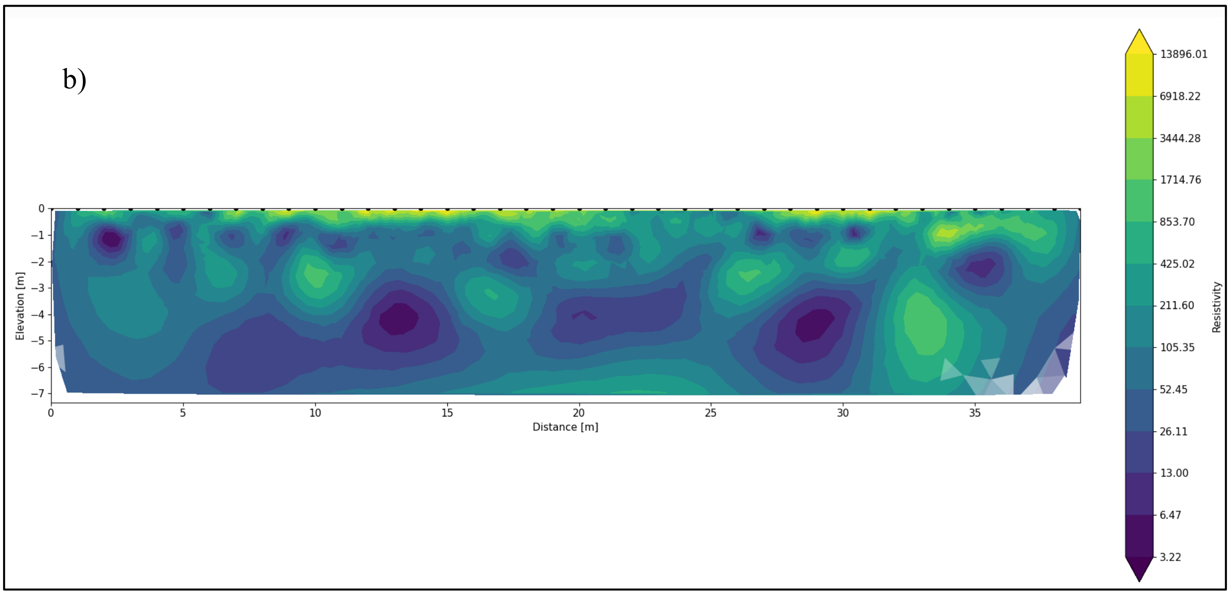




*Figure 15.* Riverbank profile using Dipole-Dipole electrode configuration. (a) Ohm.m (b) log10

**Survey 1: Riverbank, Wenner**

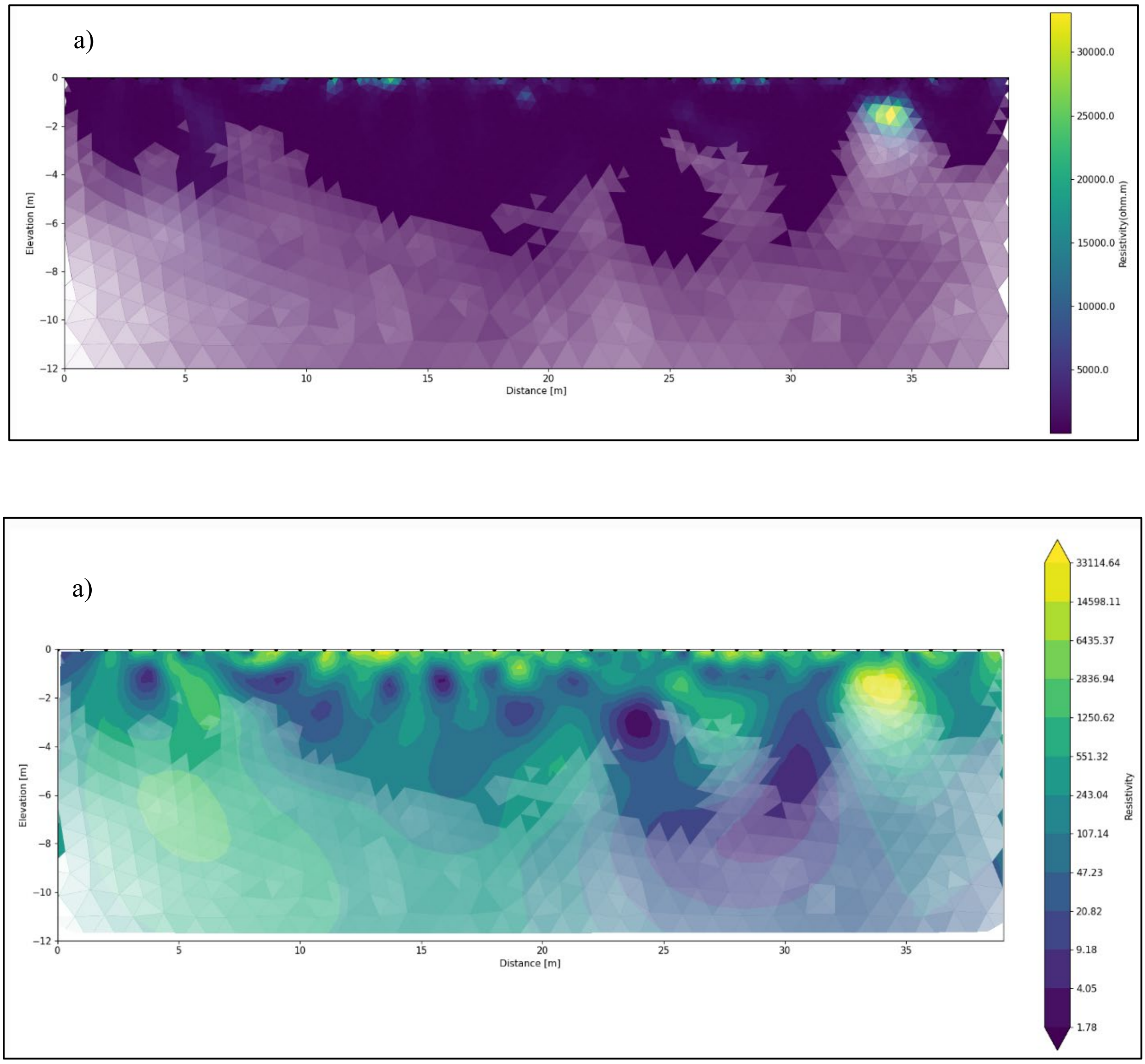
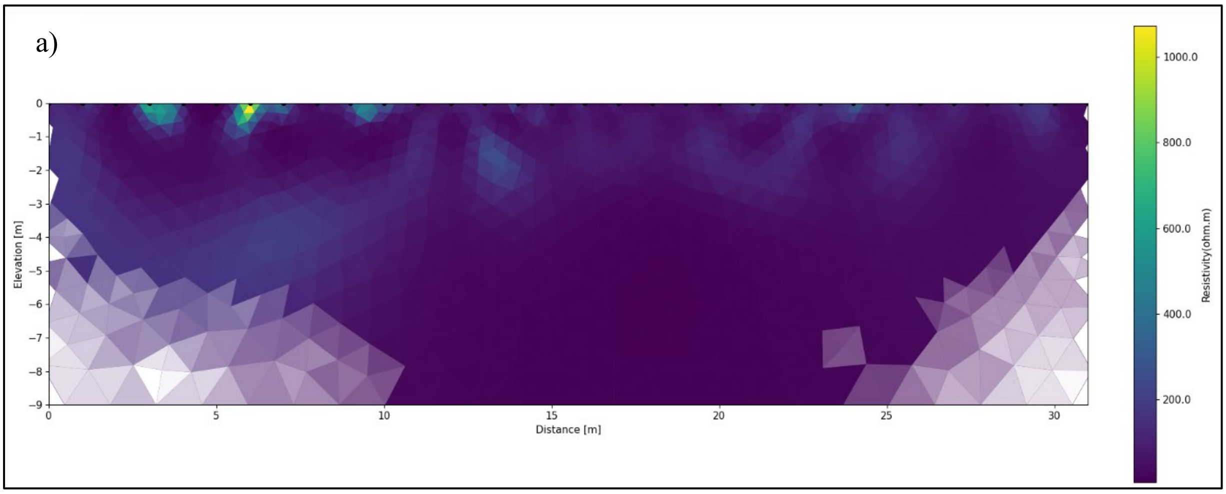



*Figure 16.* Riverbank profile using Wenner configuration. (a) Ohm.m (b) log10.

***Survey 1: Sandbar – Wenner Configurations***

Here, only the Wenner sandbar profile is presented in Figure 17. Unfortunately, an error message was displayed when opening the Dipole-Dipole sandbar dataset in ResIPy. Upon inspection of the file, it became apparent that there was an issue, as the measured parameters (current and voltage) were all zero. This resulted in the exclusion of the sandbar Dipole-Dipole transect from the analysis. The Wenner sandbar profile reveals similarities with the riverbank profiles. However, there seem to be more and more noticeable lenses than seen in the Riverbank, even though these have a lower resistivity than seen in the riverbank profile. These lenses exhibit resistivities ranging between 100-250 Ωm. Once again, there is what seems to be noise near the electrodes. The resistivity scale goes from about 10-1,000 Ωm.

**Survey 1: Sandbar, Wenner.**



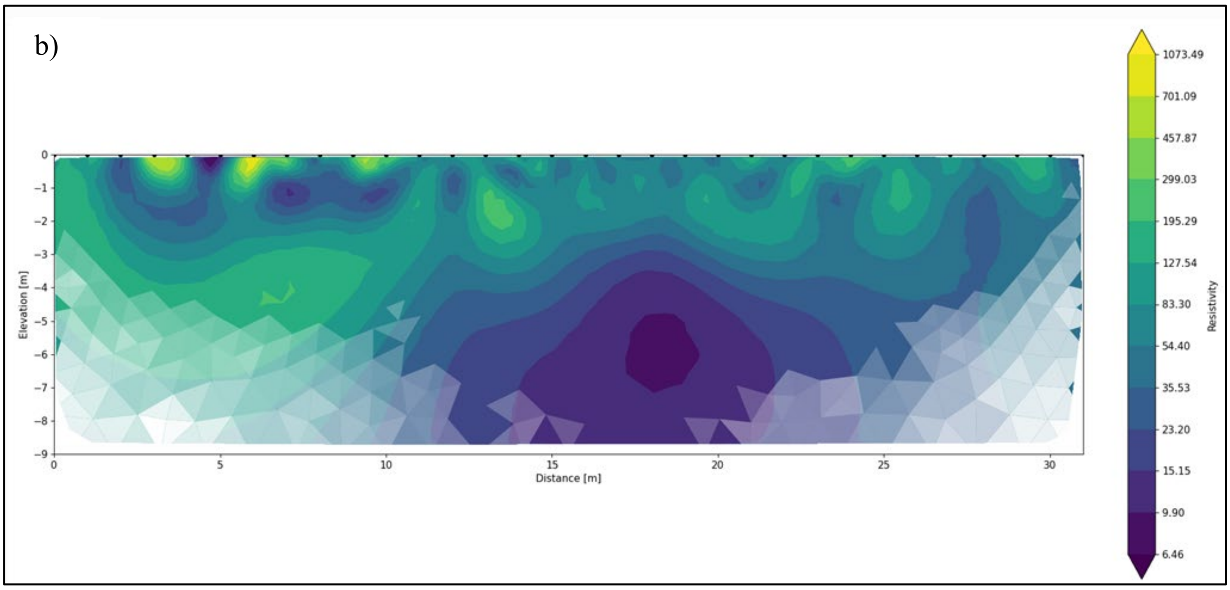




*Figure 17.* Sandbar profile using Wenner configuration. (a) Ohm.m (b) log10.

*Survey 2: Line 1 – Dipole-Dipole and Wenner Configurations*

The Dipole-Dipole and Wenner configurations are presented in Figure 18 and Figure 19, respectively. For line 1 of the second survey, using the Dipole-Dipole configuration, the resulting tomogram displays resistivities ranging from 10-6,000 Ωm and ~ 2,000-20,000 Ωm for Wenner. These tomograms do not exhibit areas of high resistance near the electrodes, as seen in survey 1 for both the riverbank and sandbar. Lenses can be seen almost uniformly distributed laterally at a depth of about 3 m for both configurations with a resistivity of between 1,000-2,000 Ωm for Dipole-Dipole and 1,000-4,000 Ωm for Wenner. There are two highly resistant bodies seen in both configurations. At around 10 m depth with a value of ~ 2,000 for Dipole-Dipole and 20,000 for Wenner. The other is at -13 m with a value of ~ 6,000 Ωm for both configurations.

## Survey 2: Line 1, Dipole-Dipole

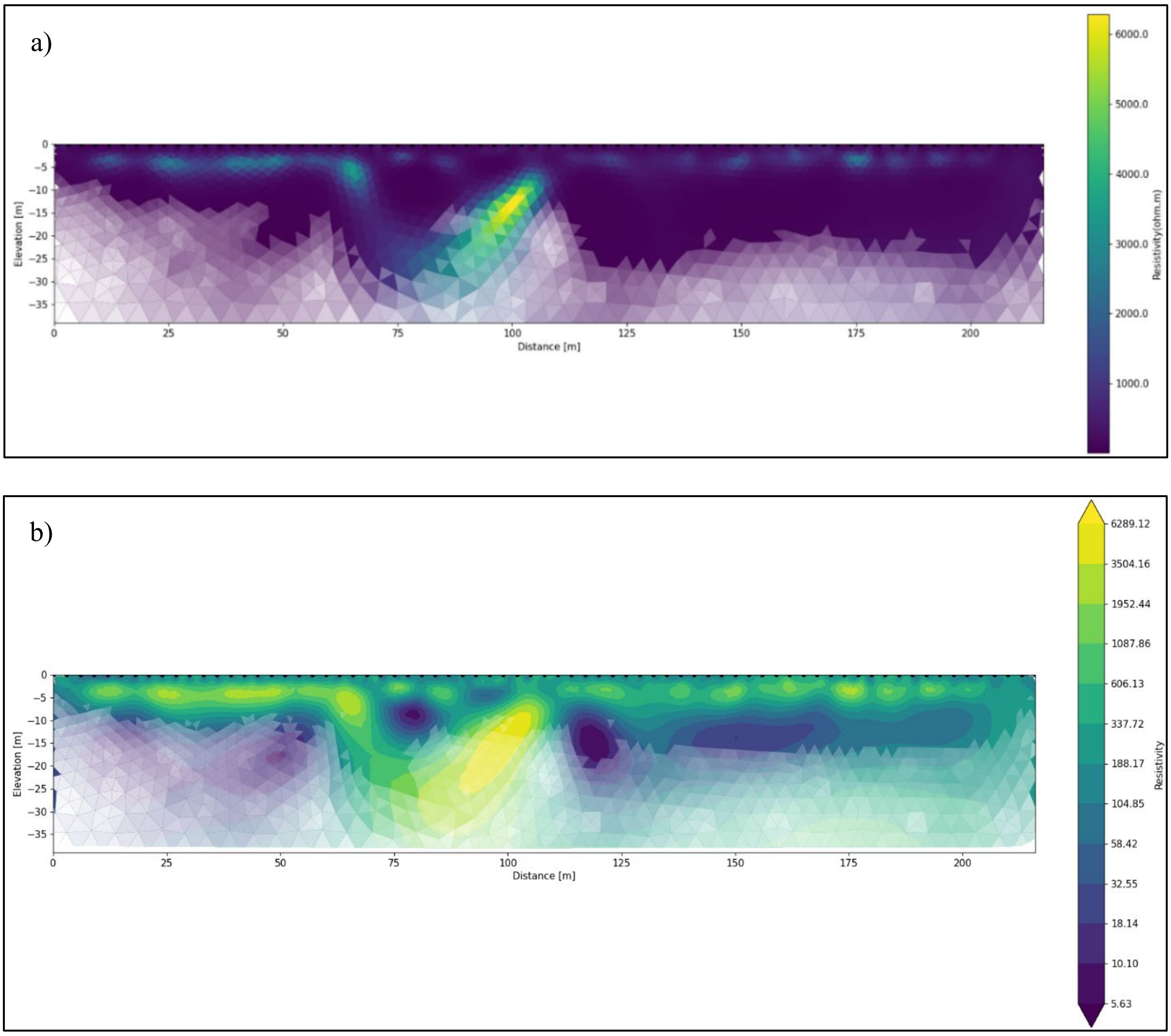



*Figure 18.* Line 1 profile using Dipole-Dipole configuration. (a) Ohm.m (b) log10.

**Survey 2: Line 1, Wenner**

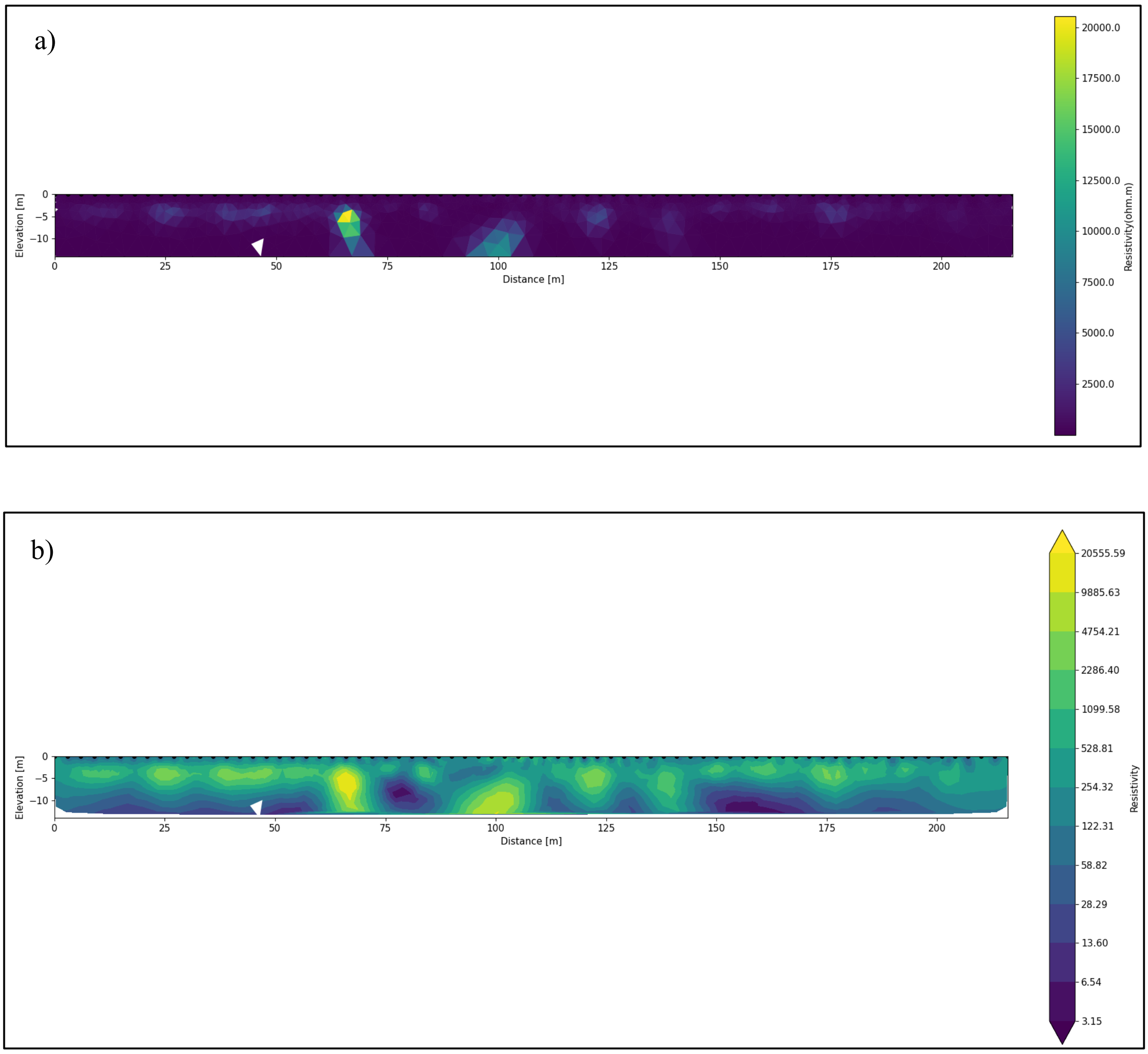



*Figure 19.* Line 1 profile using Wenner configuration. (a) Ohm.m (b) log10.

***Survey 2: Line 2 – Dipole-Dipole and Wenner Configurations***

The Dipole-Dipole and Wenner configurations are presented in Figure 20 and Figure 21, respectively. There are areas of high resistance near the electrodes for both configurations. The resistivity ranges from ~ 10-700 Ωm for the Dipole-Dipole configuration and ~ 20-1,000 Ωm for the Wenner configuration. There is little change in resistivity with depth, ranging between ~ 10-70 Ωm for both. For Dipole-Dipole, at depths of between 5-10 m, resistivity ranges from 15-20 Ωm. Above 5m, there is an increase in resistance. The resistivity ranges between 0-5 m from 30-70 Ωm. A small area of high resistance (900 Ωm) is near an electrode. In the Wenner profile, at depths of 2-6 m, the resistivity ranges from 20-40 Ωm. Above this (0-2 m), it increases to 60-70 Ωm. The highly resistant bodies observed in the previous profiles do not appear for both configurations. In both profiles, large lenses cover a larger area laterally than the lenses that appear in already described tomograms. There also seem to be only two of them. Like in the other profiles, these occur at a depth of about 3 m.

**Survey 2: Line 2, Dipole-Dipole**

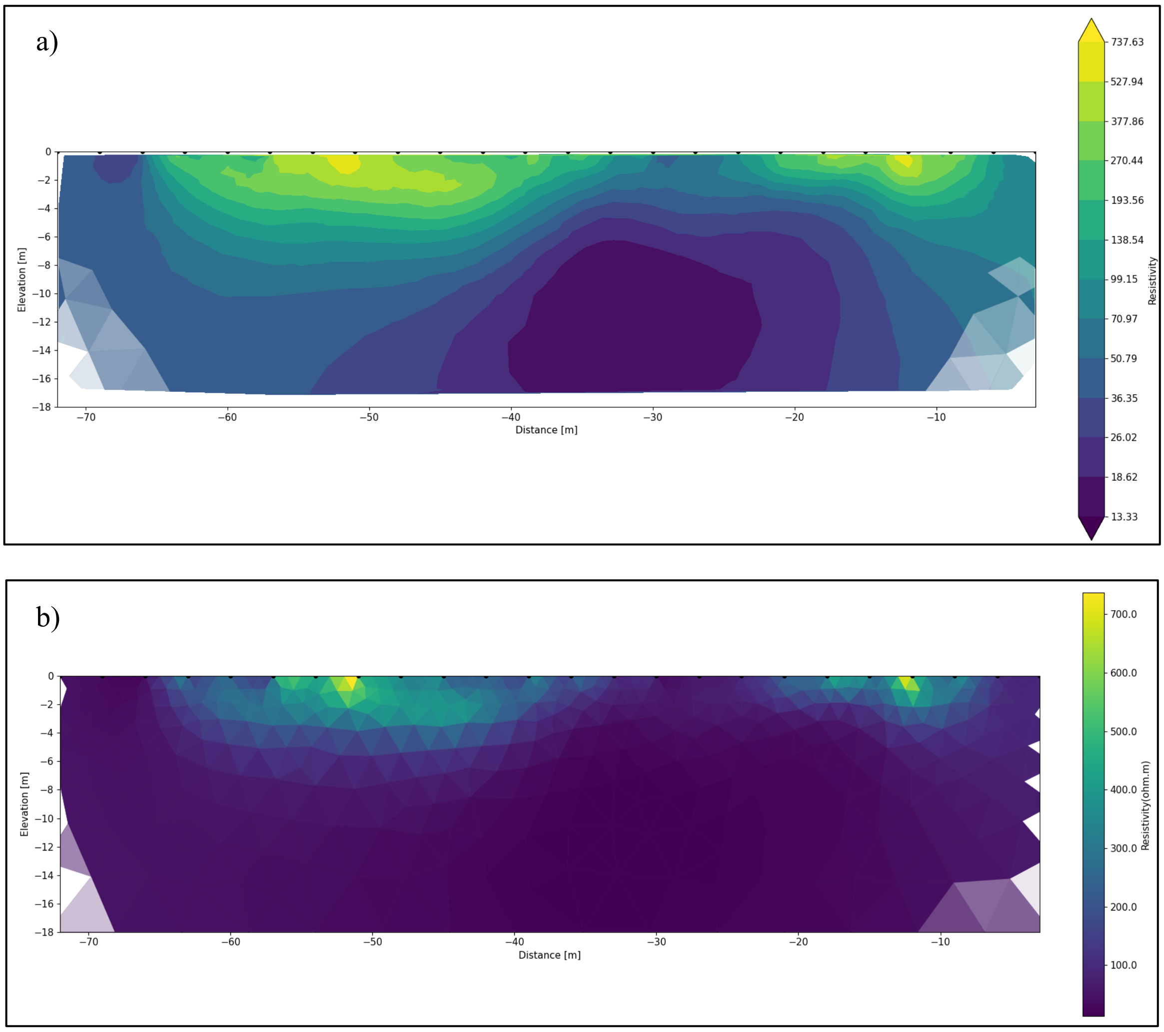



*Figure 20.* Line 2 profile using Dipole-Dipole configuration. (a) Ohm.m (b) log10.

## Survey 2: Line 2, Wenner

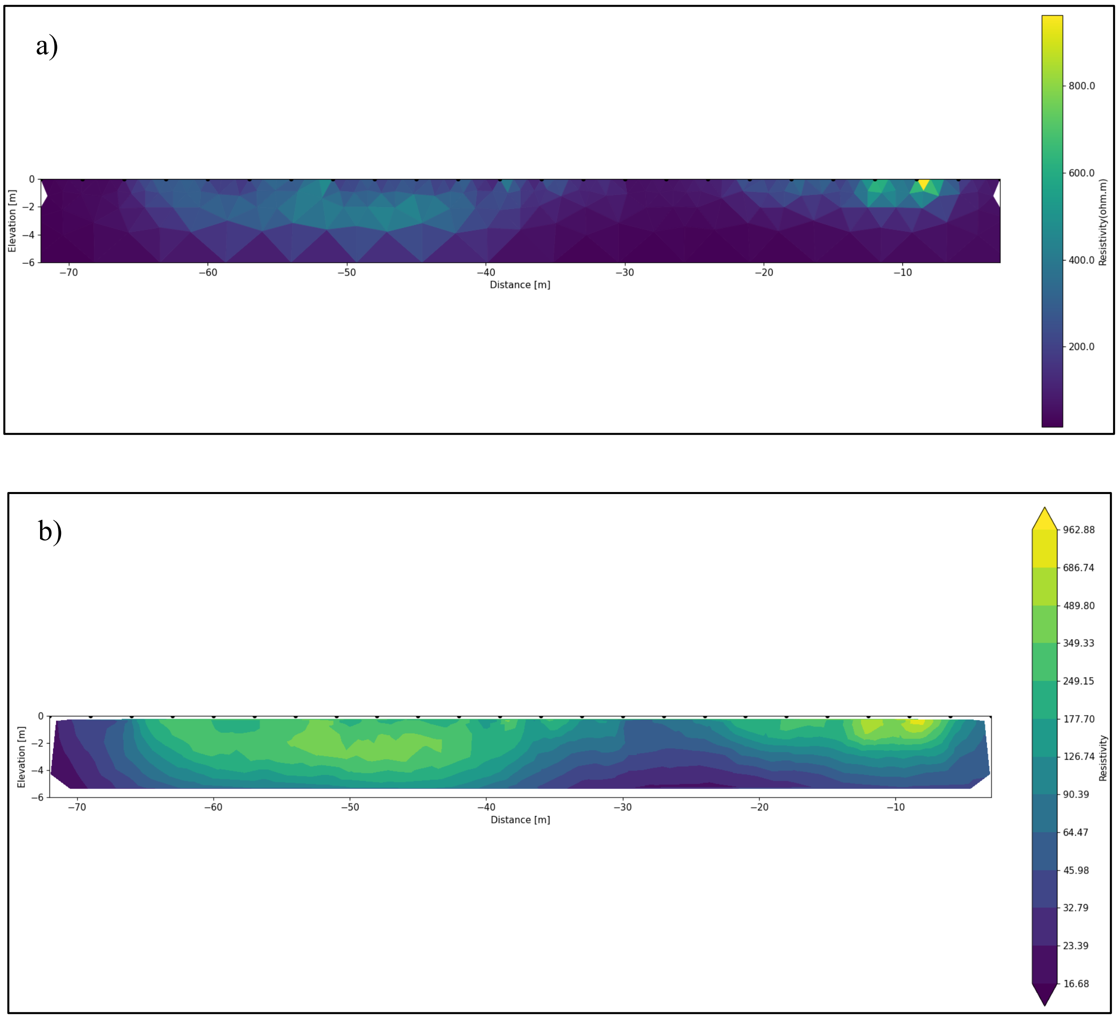
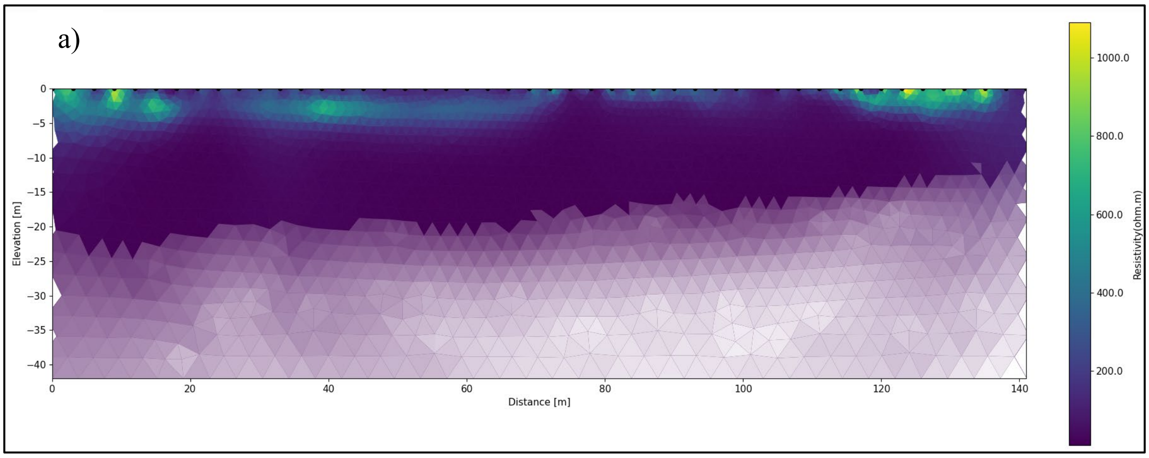



*Figure 21.* Line 2 profile using Wenner configuration. (a) Ohm.m (b) log10.

### ***Survey 2: Line 3 Dipole-Dipole and Wenner Configurations***

The Dipole-Dipole and Wenner configurations are presented in Figure 22 and Figure 23, respectively. The resistivity range for these profiles is ~ 10-1,100 Ωm for the Diple-Dipole configuration and ~ 10-1,600 Ωm for the Wenner configuration. There are areas of high resistivity near the electrodes for both configurations. The lateral variability in line 3 is also similar to what is seen in line 2, with fewer and larger lenses at a depth of ~ 3 m for both configurations. These lenses have a resistivity of ~ 700 Ωm for Dipole-Dipole and 500-600 Ωm for Wenner. The Wenner and Dipole-Dipole profiles display strong similarities, with slight resistivity differences. The highly resistant bodies observed in other profiles were also not observed in Line 3. Between a depth of 5-3 m, resistivity is 20-40 Ωm. Above this (0-3 m), resistivity ranges from 40-90 Ωm.

**<u>Survey 2: Line 3, Dipole-Dipole</u>**



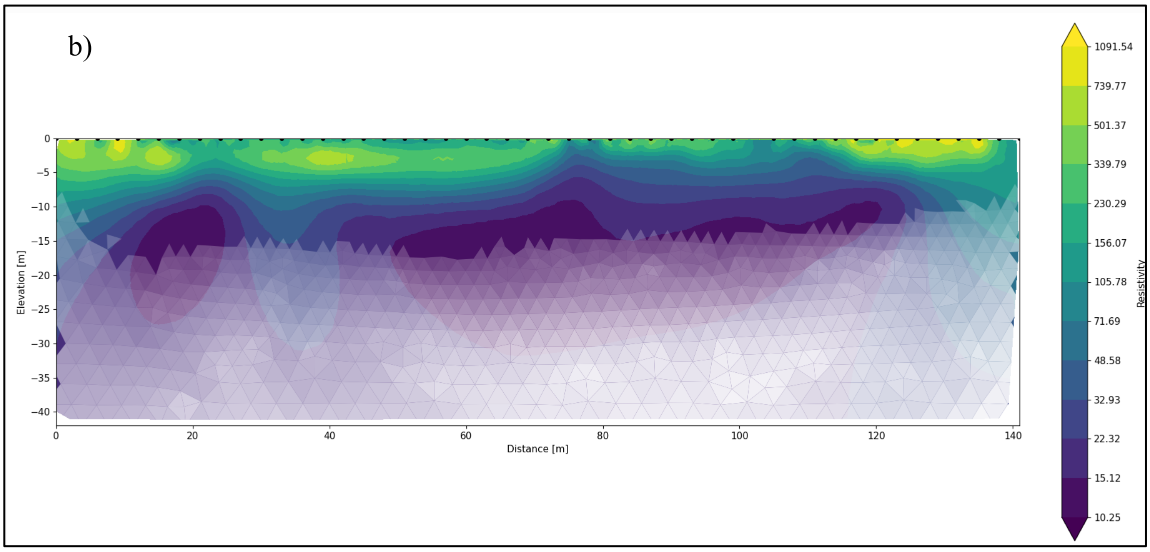




*Figure 22.* Line 3 profile using Dipole-Dipole configuration. (a) Ohm.m (b) log10.

**Survey 2: Line 3, Wenner**

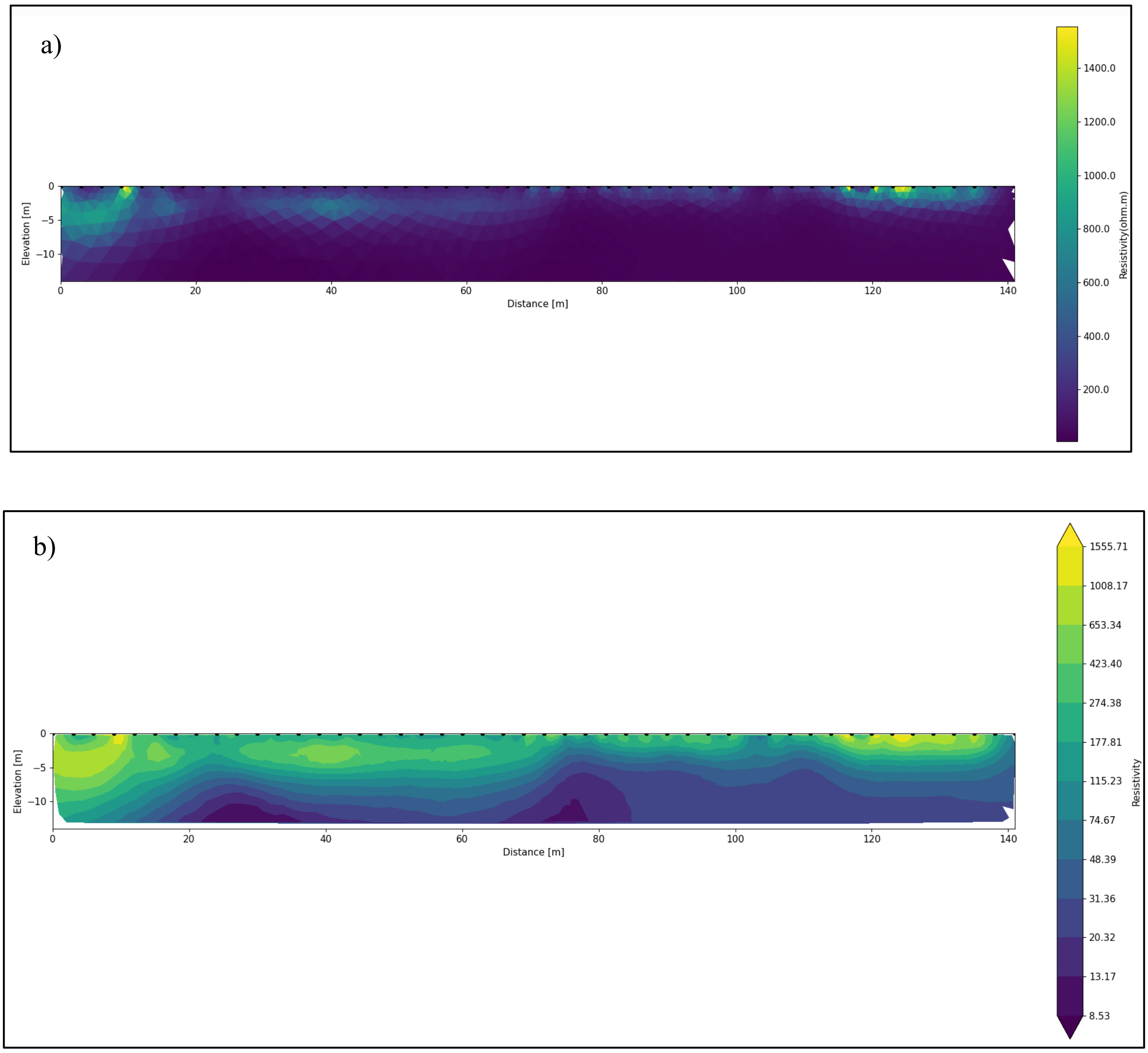



*Figure 23.* Line 3 profile using Wenner configuration. (a) Ohm.m (b) log10.

As mentioned, ResIPy can also be used for forward modeling which would entail producing a model to match the inversion results which can support interpretation of complex structures. The conceptual model in Figure 10 was used as the basis for the forward model development. The following values were assigned to each zone in the model: 3,000 Ωm for unsaturated sands and gravel, 1,000 Ωm for saturated sands and gravel, 200 Ωm for silt, and 10 Ωm for clay. These are the same values used by Compare et al. (2021).

After multiple attempts, the closest model aligns with lines 2 and 3 and is presented in Figure 24. A description of the zones in the model is included in the caption. Several models were created and inverted. The model and inversion included in Figure 25 has the most resemblance to the measured data, line 3 in Survey 2. The conceptual model in Figure 25 includes, from top to bottom, sand and gravel, saturated sand and gravel with silt lenses, silt, clay, saturated sand and gravel, and clay, as well as silt lenses at a depth of about 2 m. This is quite similar to the conceptual model selected by Compare et al., (2021). At a depth of 2-3 m (where the lenses occur in the real inversions), the conceptual model inversion reveals resistivity in the range of 400-500 Ωm, confirming what is observed in lines 2 and 3. There is, however, a slight difference outside the lenses. The resistivity does decrease with depth, as seen in lines 2 and 2. However, the resistivity is about 100 Ωm higher in the conceptual model inversion. While there are similarities between the conceptual model inversion and the measured data inversion, there are also some minor discrepancies. Another example is that the silt lenses in the conceptual model appear closer to the surface.

**Conceptual model with triangular mesh**

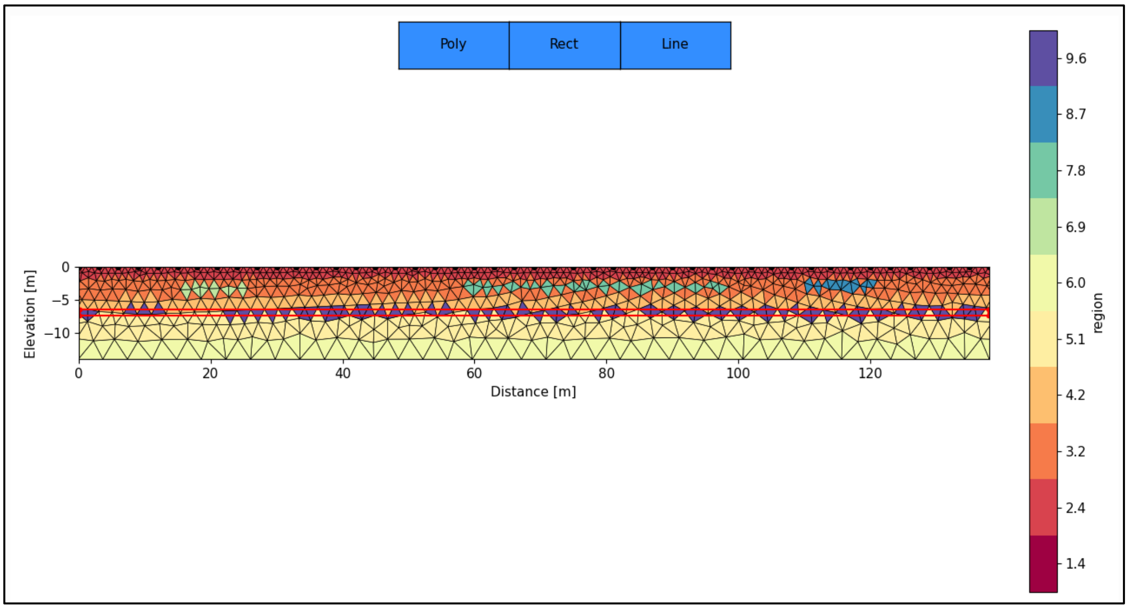



*Figure 24.* Screenshot from ResIPy: Synthetic forward model. (9.6) Clay. Regions 8.7, 7.8, and 6.9 are silt lenses. (6.0) Clay (5.1) Saturated sand and gravel (4.2) Silt (3.2) Saturated sand and gravel (2.4) Sand and gravel (1.4) Sand and gravel.

## Conceptual model versus line 3

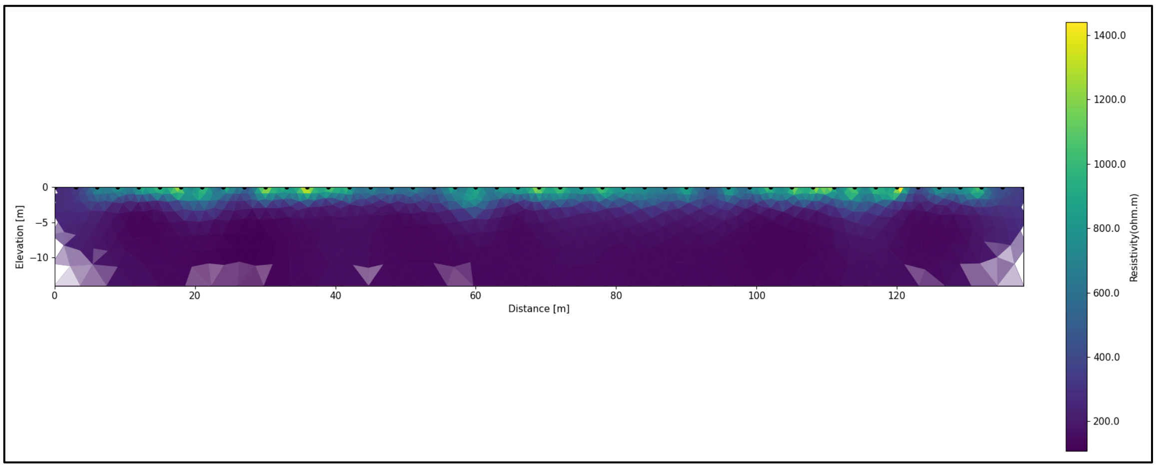



*Figure 25.* Inverted conceptual model.

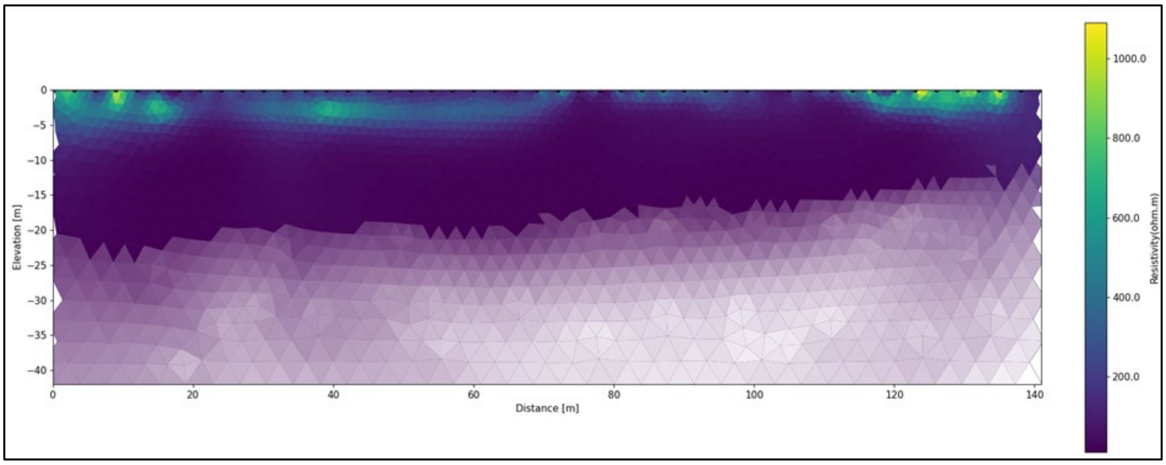



*Figure 26.* Line 3 (Dipole-Dipole) for comparison with conceptual model inversion.

## 6. Interpretation and Discussion

Concerns regarding the sustainability of aquifers, particularly in regions heavily reliant on groundwater, underscore the need for a comprehensive understanding of recharge processes. Water infiltration in intermittent streambeds is a critical pathway for aquifer replenishment in arid and semi-arid environments. Researchers have faced difficulties estimating this recharge due to several natural abstractions and abstractions for human use. Estimation of recharge requires an understanding of both disturbed and undisturbed recharge. Without recharge estimations, groundwater management strategies could be futile. Surface geoelectric measurements offer a promising alternative for estimating specific aquifer properties, potentially reducing the need for extensive test drilling and filling in the gaps in understanding. This study explored the utility of ERT in elucidating geologic properties necessary to comprehend recharge at the site. Particularly, hydraulic conductivity as variability leads to preferential flow paths.

The initial examination of the datasets by Compare et al. (2021) encountered several challenges, hindering quantitative interpretation. Initially, the sandbar ERT transect inversion failed to converge fully towards a solution, with the final iteration yielding an RMS data misfit of 29.21%. Despite exhaustive exploration of various parameter options within the software, researchers could not enhance this value. Consequently, the inversion did not accurately depict the subsurface, leading to predominantly qualitative observations. Additionally, the range of resistivities observed in the actual transect exceeded that of any conceptual models the researchers created to support the interpretation of the inversion by an order of magnitude. Notably, a highly resistant material seemed to skew the scale, complicating comparisons. This patch's exceptionally high resistivity values (exceeding 20,000 Ωm) suggested the potential presence of a transported boulder (McNeil 1980, as cited in Compare et al., 2021) or unexpected anthropogenic material in the subsurface, possibly linked to the Arkansas River's history of flooding and the site's reputation as a local recreational area (Compare et al., 2021). Compare et al. (2021) concluded that further investigation is warranted to explore subsurface heterogeneity within the alluvial aquifer and the confining unit.

The data collected by Compare et al. served as a preliminary study for a study conducted by Zipper et al. (2022) aimed at investigating whether flow and no-flow conditions represent distinct and stable hydrologic states. The study also utilized other data, such as discharge and meteorological data. The study sought to identify the feedback mechanisms that maintain stability in both flow and no-flow states and the factors that trigger shifts between these states. The findings from this study could support the interpretation of the ERT profiles. According to Zipper et al. (2022), regime shifts in streamflow dynamics at the Larned Research Site (LRS) were attributed to two primary factors. According to Zipper et al. (2022), upstream surface water and groundwater usage resulted in the disconnection of the LRS from the water supply originating from the headwaters in Colorado. Secondly, the flow regime at the LRS was influenced by the interplay between changing upstream inflows and local scale ecohydrological processes. During dry periods, the groundwater levels were lower in the semi-confined High Plains aquifer compared to the unconfined alluvial aquifer. Although streamflow was infrequent, when it did occur, the river's water levels were typically higher than those in the alluvial aquifer, indicating water movement from the stream into the aquifer. This could occur due to the pressure gradient created by the higher water levels in the river compared to the aquifer, causing water to seep into the groundwater system (Zipper et al., 2022).

Seasonal pumping in the High Plains aquifer exhibited a consistent pattern, with water levels declining during summer and recovering during winter. This pumping induced downward flow (due to a downward hydraulic gradient) through the leaky confining layer, resulting in delayed and moderated declines in water levels in the alluvial aquifer, consistent with previous research findings.

Zipper et al. (2022) proposed that interactions across different scales, encompassing regional processes like surface water inflows, groundwater pumping, and local ecohydrological feedback mechanisms, control streamflow dynamics and potentially induce significant regime changes. The primary ecohydrological feedback mechanisms identified included the balance between precipitation and plant water usage in the riparian corridor, influencing diffuse recharge through the soil column, and groundwater extraction for agricultural purposes, influenced by regional precipitation patterns and impacting streamflow dynamics by reducing local groundwater levels and limiting upstream inflows.

These findings suggest that the observed alternative stable states reflect stressors from human activities and climatic factors across much of the Arkansas River basin (Zipper et al., 2022).

### i. Model Selection and Validation

The first step in making any interpretations should be to determine if any inversions presented are considered “bad” inversions. In other words, it is necessary to check if the subsurface models that the inversion software produced are reliable. Reliability in this context refers to how close the inversions are to the true subsurface model the researcher is attempting to comprehend. This can be assessed using the RMS misfit and the number of iterations to converge at a solution. In Blanchy et al. (2020), a practical paper demonstrating ResIPy’s capabilities using examples, the authors state that without data cleaning of their dataset, the inversion phase angle did not converge within ten iterations, and this was evident in the consistent unrealistic and very high RMS misfit values per iteration. The authors stated that the inversion results did not show meaningful subsurface structures (Blanchy et al., 2020). Based on this, it is evident that the reliability of the inversion generally decreases as the number of iterations required increases. 10 is the maximum number of iterations allowed under the default setting in the software. The number of iterations can be increased; however, if more iterations are required, it is probably not advisable to use that inversion for interpretation. The remark by Blanchy et al. (2020) also indicates that very high RMS misfit values indicate unreliable models. The authors stated that the data was successfully inverted with an RMS misfit of 1.11 in 3 iterations. This can be used as a guide.

Looking at the inversion in this work, the RMS misfit decreased with each iteration for the LRS datasets. ResIPy does not provide the models for each iteration, so it is difficult to say whether there were significant changes with each iteration, as this could also indicate issues with the inversion. ResIPy does however provide information on the total number of iterations taken to converge at a solution (see Table 2). Shows the number of iterations each dataset required to converge. Based on this, lines 2 and 3 seem to be the most reliable representations of the subsurface at the LRS. According to the authors, three iterations should be the cut-off point for reliability. During the data processing, adjustments were made to the inversion parameters to reduce the number of iterations; however, most were failed attempts. The final RMS misfit values are provided in the table below.

*Table 2.* Showing details from the inversion log in ResIPy, including the number of iterations it took to converge and the final root mean square (RMS) misfit.

| **Profile** | **Iterations to converge** | **Final RMS misfit** |
|---|---|---|
| Riverbank: Dipole-Dipole | 13 | 1.05 |
| Riverbank: Wenner | 12 | 1.07 |
| Sandbar: Wenner | 6 | 1.10 |
| Line 1: Dipole-Dipole | 6 | 1.00 |
| Line 1: Wenner | 8 | 1.14 |
| Line 2: Dipole-Dipole | 2 | 1.04 |
| Line 2: Wenner | 3 | 1.00 |
| Line 3: Dipole-Dipole | 2 | 1.89 |
| Line 3: Wenner | 3 | 1.00 |

Forward modeling is crucial in selecting and validating subsurface models derived from real data inversions. In Chapter 5, the outcomes of forward modeling provide valuable insights into the accuracy of interpretations, particularly regarding lines 2 and 3. Through a meticulous comparison between simulated responses and actual data, the researcher gains confidence in the reliability of the interpretations made for these lines. This process reaffirms the fidelity of the selected subsurface models and underscores the significance of incorporating forward modeling techniques in the interpretation workflow. By offering a complementary approach to verifying and refining subsurface models, forward modeling enhances the robustness and credibility of geophysical investigations.

*Measurement Errors*

Using secondary data brings attention to the need to address measurement errors. While this is not the only source of error – there could also be modeling errors – it is an aspect that the researcher has limited control over, as the data was already collected, and collecting additional data is not feasible, as addressed under the limitations of this study. The objective of inverting direct current apparent resistivity data is to reconstruct the true resistivity distribution in the subsurface. However, this process faces several challenges that limit its accuracy. Measurement errors are one, and these are often unavoidable in scientific observations.

Reducing the adverse impacts of error on a study requires accurately describing inaccuracies. In ERT inversions, the overall error in the inversion log is determined by the square root of the sum of squares of measurement and modeling errors. Methods used to assess measurement errors include stacking (repeated measurement of transfer resistance through several cycles of current injection) and reciprocity checks (swapping the current and potential electrodes, which should yield the same response) (Tso et al., 2017). According to  LaBrecque et al. (1996) repeat and reciprocal measurements are measures of precision, not accuracy, and – sources of systematic error (equipment failure) are not accounted for. According to Tso et al. (2017), stacking errors are the most common type of error used in ERT. Modern ERT instruments have stacking functionality and immediately report stacking faults. In other words, stacking errors can be retrieved without having to re-run the measurement technique, which is particularly appealing in time-sensitive or time-consuming surveys (Tso et al., 2017). Reciprocity is also a commonly used measure. A small percentage of experimental studies do not report the treatment of error at all (Tso et al., 2017).

As per Tso et al., (2017), within ERT, inaccuracies in measurements influence the extent of data smoothing and the stage at which convergence occurs. These aspects are integrated into inversion through the adjustment of data importance in the objective function, thus, the estimation of measurement errors determines whether data will be excessively or insufficiently adjusted during inversion.. This principle is demonstrated here by comparing several inverted tomograms—the pictures in Figure 27 result from inverting ERT data corrupted by 5% noise. In the synthetic domain, a resistive target was inserted between x = 15 m and x = 20 m, and the topsoil was relatively conductive (Figure 27a). In Figure 27b, the data is inverted with 5% Gaussian noise. In Figure 27c, the data is inverted with 10% noise, which causes underfitting and a smooth image. In Figure 27d, 2% noise is assumed, with over-fitting and several artifacts being the result. Artifacts are misleading observations due to shortcomings in the method or equipment used (Tso et al., 2017).

After obtaining errors, an error model (often a linear relationship relating error to transfer resistance) is constructed (Binley et al., 1995). According to (Tso et al., 2017), once received, such a relationship can anticipate individual measurement errors and contribute to the data weight in inverse modeling. Some publications, however, assign observed errors directly in the inverse modeling, possibly erroneous unless the statistical robustness of the quantified error is proven. This method also makes detecting misleading data impossible (Beven & Westerberg, 2011). As a result of the recognized proportionality effects (Aster et al., 2018) in direct current resistivity measurement errors (Binley, 2015; Binley et al., 1995), error models typically depend on the average measured transfer resistance (Tso et al., 2017). This is because the error in transfer resistance increases as the magnitude of the transfer resistance itself increases (Tso et al., 2017). Measurement inaccuracies frequently arise from difficult electrode contact conditions. Zhou and Dahlin (2003) confirm from the observation that ERT error outliers usually correlate with high contact resistances for some of the electrodes used in a measurement. Outliers are measurements that are removed/ excluded from inversion. Not much can be done about measurement errors after collecting the data. These measures address the data collection challenges; however, errors can also stem from data processing. Processing geophysical data is essentially trial and error and requires several iterations; this leaves the potential to find more information from the existing datasets.

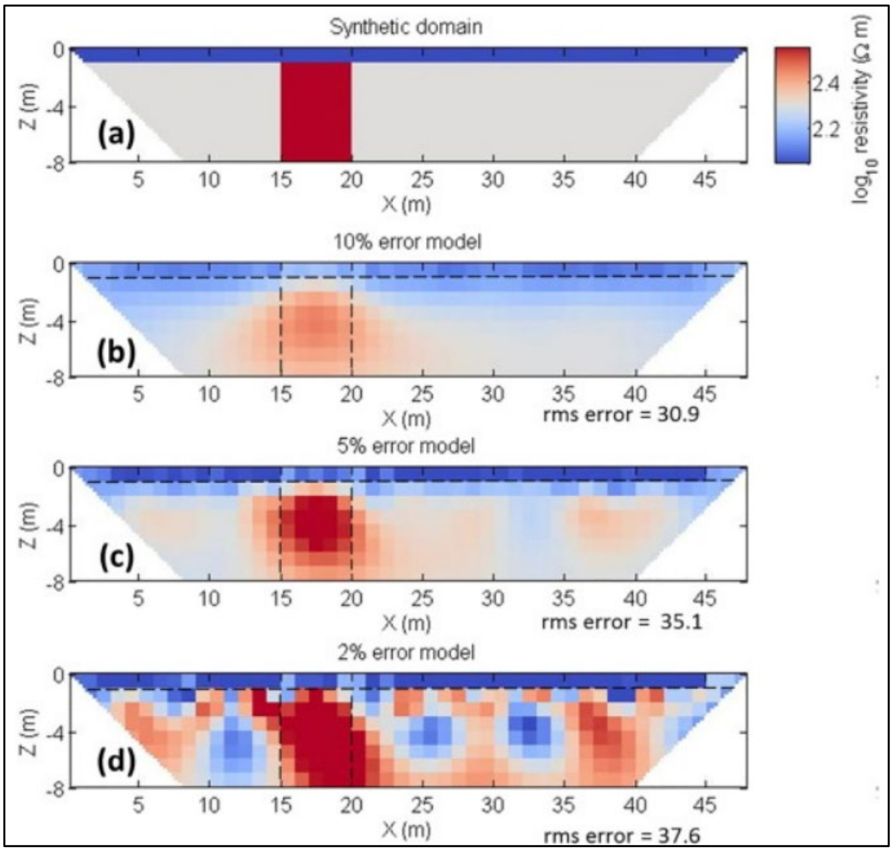



*Figure 27.* Synthetic problem to demonstrate the effect of measurement error estimation in inversion: (a) synthetic domain with a more conductive layer near the surface and a resistive area between x = 15 m and x = 20 m. This data is perturbed with 5% Gaussian noise, assuming (b) a 10% linear error model leading to under-fitting, (c) a 5% linear error model, and (d) a 2% linear error model leading to overfitting and artifacts (Tso et al., 2017).

### ii. Comparisons with the Preliminary Study

Before exploring the new findings resulting from the inversions conducted for this thesis, it is essential to address any similarities between the conclusions drawn by Compare et al. (2021) and this research. The initial comparison contextualizes this study within the existing literature, shedding light on areas of agreement or discrepancy. Such an analysis lays the groundwork for understanding the significance of our contributions and provides a framework for identifying novel insights derived from the current researcher's investigations. First, the current researcher will address the challenges that hindered the researchers who initially collected the data. This step is crucial to understanding the context within which this research was conducted and the potential limitations in the dataset.

During data processing, Compare et al. (2021) found that the true sandbar transect inversion did not fully converge at a solution, as the final iteration had a root mean squared (RMS) data misfit of 29.21%. The researchers could not improve this value despite extensively exploring various parameter options inside the software. As a result, this inversion is not a true inverted image of the subsurface, and primarily qualitative observations were made (Compare et al., 2021). The processing of the sandbar dataset also posed a challenge in this work. The Dipole-Dipole file could not be imported into the ResIPy inversion software. ResIPy gave an error message. To find the problem, the file was scrutinized in Microsoft Excel and Word. There was a problem as all parameters, including voltage and current, were displayed as zero. This suggests an issue with the file and not the inversion software. The cause could be a corrupt file or equipment malfunction. It is possible that there were errors during file transfer or storage, leading to unexpected readings. Additionally, there could have been issues with the electrodes, cables, or the instrument itself. However, the Wenner dataset converged and produced an inversion with a final RMS misfit of 1.10 (see Table 2). The inversion is presented in Figure 28 and Figure 29, using two different scales and contouring, thus displaying various degrees of contrast. Figure 28 shows more detail using a logarithmically spaced scale, but the actual y-axis values are still the same as the original in Figure 29.

**Sandbar Inversion**

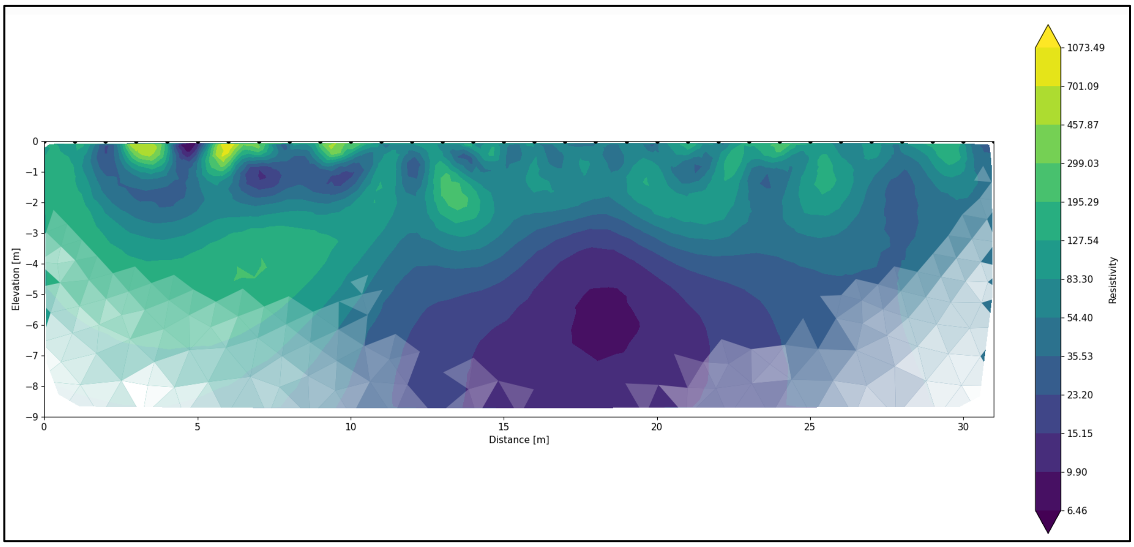



*Figure 28*. Sandbar Wenner inversion with an RMS misfit of 1.10, with resistivity displayed using a log10 scale on the y-axis and contours.

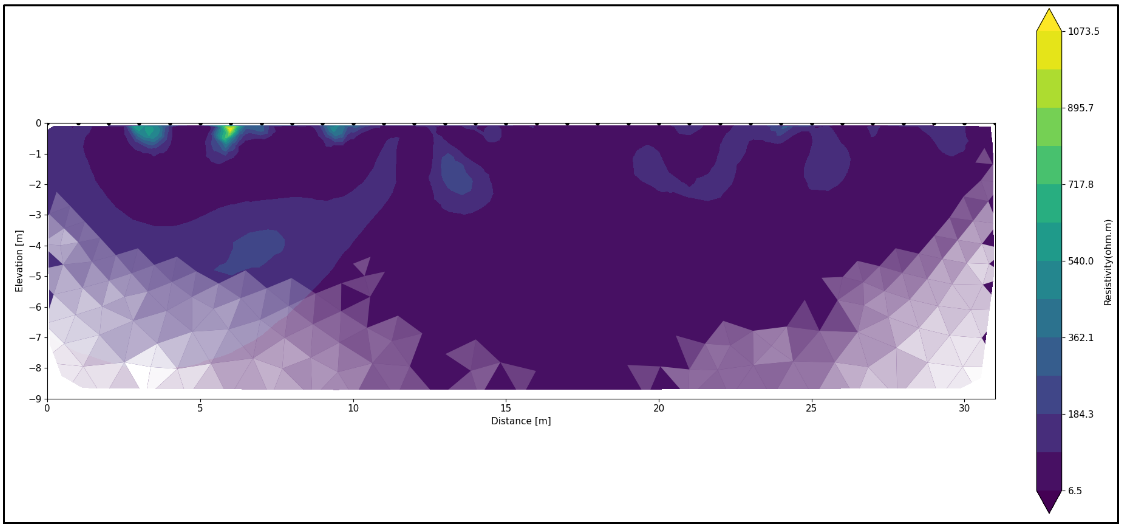



*Figure 29.* Sandbar Wenner inversion with RMS misfit of 1.10 with resistivity displayed in ohmmeters and using contours.

Another observation that Compares et al. (2021) hindered interpretation was that the synthetic model inversions (forward modeling) revealed that the real transect is an order of magnitude greater than in any of the conceptual models the researchers created (Compare et al., 2021). The researchers observed what was potentially a highly resistant material (the red patch in Figure 3d) that was possibly skewing the scale and making comparison difficult. The values of this highly resistive patch (more than 20,000 Ωm) could suggest the presence of a transported boulder or an unknown anthropogenic material beneath this area of the subsurface, likely to be from the Arkansas River's historical flooding and the site's reputation as a local recreational area (Compare et al., 2021). A more resistant material can be seen in the inversion around 5 m below the surface, at the exact location in the original study's inversion. However, it has a resistivity of approximately 200 Ωm compared to 20,000 Ωm observed by Compare et al. (2021). In this case, it could be a silt lens, not a boulder, as previously proposed. The range of resistivity seen in the scale also differs. The original study's range for the sandbank is 1-26,000 Ωm. Here, the range is 10-1,100 Ωm. Therefore, the highly resistant area visible in the preliminary study's tomogram could be an artifact. The sandbar Wenner inversion has an RMS misfit value of 1.10, far lower than what Compare et al. (2021) observed; however, the data required six iterations to converge at a solution. This reduces the viability of making any definitive deductions from this profile.

### iii. Interpretation of Selected Models

Based on the RMS misfit values of each inversion presented in Table 2, the researcher has deemed lines 2 and 3 the most reliable for interpretation. Lines 2 and 3 transect each other, as shown on the study site map in Chapter 4. These lines also show similarities. The resistivity range between the two lines is not much different. If referring specifically to the Wenner inversion, the top end of the scale is about 1,000 Ωm for line 2 and 1,600 Ωm for line 3. This slight difference between the two increases confidence in the inversions. Both lines display large lenses of a material with a higher resistivity at a depth of about 2-3 meters. The center of the lenses has a resistivity of ~400 Ωm in line 2 and 600 Ωm in line 3. Outside of these lenses, the resistivity decreases with depth ranging from 70-30 Ωm for line 2 and 90-20 Ωm for line 3. The depth of investigation differs, with line 2 only providing information until -5 m; for line 3, it is -13 m.

A notable difference between these tomograms and the riverbank, sandbar, and line 1 is that instead of several smaller lenses spaced out laterally (at a depth of ~3 m), there are fewer but larger lenses – larger in their lateral extent. The contrast in resistivity is also much smaller. Whereas, if you look at the Riverbank, which took 13 iterations to converge, the maximum resistivity appearing in the tomogram is 14,000 Ωm compared to 1,500 Ωm in line 3.

No universal relationship exists between lithology and resistivity. Moisture content and soil and moisture content chemistry are some of the factors that influence electrical resistivity values (Dafalla & AlFouzan, 2012). Thus, resistivity values will not be the same for all soils or gravels, for example, as they are determined by grain size and composition. Diverse sources in the literature offer approximate ranges of electrical resistivity values for different soil types and materials. When making a deduction on the kind of material responsible for the resistivities in the inversions, it is essential to consider that in the study conducted (Healey et al., 2001), the electrical conductivity of the unconsolidated sediments was assumed to be primarily a function of grain size. Thus, low electrical conductivity values were supposed to indicate sand and gravel; intermediate values were taken to indicate silt, and high values were considered to indicate clay. This means the opposite for electrical resistivity: high values of electrical resistivity for sand and gravel, intermediate for silt, and low values for clay. No cores were taken, but the viability of the assumed relationships can be confirmed by previous work, which characterizes the unconsolidated alluvial deposits at a separate KGS site (Butler et al., 1999).

The researcher concurs with previous findings based on the work of Healey et al. (2001) and Butler et al. (1999), combined with the forward modeling and inversion results for lines 2 and 3. Healey et al. (2001) were used for the model layers (the hydrostratigraphy), and the deduction made by Compare et al. (2021) on the lateral heterogeneity – the presence of silt lenses – was also factored into the model. The very highly resistant material in the inversion produced by Compare et al. (2021) could be an artifact that skewed the resistivity scale of the sandbar inversion, as the current researcher was able to make an inversion that converged at a solution in 6 iterations, and with a far lower RMS and that did not include the highly resistive material. Furthermore, line 2 and 3 inversions have proven to be reliable representations of the subsurface, based on an assessment made using the number of iterations, RMS, and unity of the inversions with the forward model based on previous work.

The vertical and lateral heterogeneity does indicate the potential existence of preferential flow paths connecting hydrostratigraphic units beneath the river reach, along with potential exchange between the alluvial aquifer and the confined High Plains aquifer as was suggested by Compare et al. (2021). However, the deductions attainable within this thesis were constrained, merely confirming qualitative observations made in prior studies. To thoroughly investigate the water flow between the unconfined and confined aquifers, a method with enhanced depth penetration, such as vertical electrical sounding, is necessary. Drilling would be beneficial for more granular data and for validating geophysical inversions. This would merely be to support the geophysical datasets. Geophysics is generally not used as an alternative to drilling but rather as a tool to increase the density of measurements and spatial coverage. The observations discussed until this point pertain to the alluvial aquifer. Unfortunately, the depth of investigation for all inversions produced in this work is not deeper than about 10 m below the surface and is even shallower in select transects. This means that deductions about water movement beyond this depth cannot be made, which includes the flow of water between the alluvial aquifer and the High Plains aquifer through the leaky confining layer.

# 7. Conclusions and Future Work

This thesis focused on exploring the additional insights that the ERT datasets can offer regarding the recharge mechanisms at the LRS. It aimed to enhance the findings of the original study conducted by Compare et al. (2021), thereby showcasing the potential of the ERT method in supporting groundwater recharge studies and ultimately water resource management by enabling resource managers and policy makers to make informed decisions based on accurate and reliable data on the geologic framework of the subsurface, which has been identified as a key factor influencing recharge, in addition to climate and topography (Winter, 1999). By addressing the research question:" What additional insights can the electrical resistivity tomography datasets provide about the recharge mechanisms occurring at Larned Research Site?", the researcher aimed to achieve two main objectives: (1) enhance the understanding of groundwater recharge mechanisms at the site and (2) contribute to the literature on effective methods for acquiring relevant information for groundwater recharge estimation. The findings of the current study serve to affirm and strengthen the conclusions drawn from prior research endeavors. By aligning with and substantiating the results of previous work, this study adds valuable weight to the existing body of knowledge in the field. This contribution is particularly significant as it provides a level of validation, reassuring the reliability and robustness of the findings. Such validation not only enhances the credibility of the current study but also fosters confidence in the established understanding of the subject matter.

A necessary step in research is data validation which is the process of assessing the reliability of data to prevent the drawing of conclusions from results that are not representative of reality. The ERT method is prone to noise, as well as error stemming from the data collection stage, but there could also be errors stemming from the processing of the collected data. To assess the reliability of the inverted models, the researcher considered the final RMS misfit, as well as the number of iterations taken to converge at a solution. These are both indicative of the reliability of the inversion result. Based on this, the researcher concluded that lines 2 and 3 were the most reliable and that these should be used for interpretation. Lines 2 and 3, as seen in Figure 12 in chapter 2 are perpendicular and intersect each other. These two lines show substantial similarity in the inversions. The resistivity scale does not differ significantly, with the lower end of the scale starting at about 10 Ωm for both and the top end of the scale differing only by about 500 Ωm. Line 3 reaches about 1,500 Ωm and line 2 reaches a maximum of roughly 1,000 Ωm. Secondly, the tomograms are visibly similar with fewer but larger (in lateral extent) lenses at a depth of around 2-3 m. These lenses are more resistant than the surrounding medium. In the surrounding medium the resistivity decreases progressively with depth. These interpretations align with Compare et al. (2021) who suggested the presence of silt lenses at a similar depth (between ~ 1-3 m depth).

In the original study, the researchers were challenged by the resistivity scale in the sandbar inversion with the top end of the scale reaching ~20,000 Ωm – it was known that this inversion was not reliable as the data did not converge at a solution and the inversion had a very high RMS misfit of 29.21%. The inversion did not align with their forward model which had a maximum resistivity of ~ 4,000 Ωm. The researchers suggested that the scale in the inversion of the measured data was skewed by the large highly resistant body visible in the tomogram. The current researcher produced an inversion of the sandbar with a lower RMS misfit (1.1) and the highly resistive material is not present in the tomogram and top end of the resistivity scale is ~ 1,000 Ωm. This affirms the skewing of the resistivity scale in the sandbar inversion in the original study. Even with this improved result, the sandbar inversion is not deemed the most reliable based on the number of iterations it required to converge.

Based on the conceptual model of the site in Figure 10, the researcher developed several models to match the inversions. The closest model was similar to the original researchers' model that had the closest resemblance, with clay lenses at 2-3 m depth. This confirms that there is lateral heterogeneity and suggests the presence of preferential flow paths connecting hydrostratigraphic units beneath the river reach, possibly facilitating exchange between the alluvial and confined High Plains aquifers as the initial researchers suggested. The forward modeling exercise utilized the electrical conductivity profile from Healey et al. (2001) and incorporated the lateral heterogeneity deductions by Compare et al. (2021). It produced an inversion that relatively closely resembled real inversions for lines 2 and 3 which seem to be reliable inversions.  This further validates the findings of both studies – the initial study and the current one.

As was the case in the initial research, the researcher's ability to make interpretations about the High Plains aquifer was impeded by the depth of investigation. Line 2 provided information up to a depth of 5 m, and line 3 offered insights down to -13 m. To investigate water flow between the unconfined and confined aquifers, a method with deeper penetration is necessary. Cross-hole ERT offers enhanced resolution and depth penetration, providing valuable insights into deeper geological structures and hydrologic properties (Bing & Greenhalgh, 2000; Chambers et al., 2007; Daily & Owen, 1991). Due to the cost of drilling boreholes and the time it requires, it could be used just to supplement the surface measurements. To address the ambiguity in ERT, seismic refraction could be used. Groundwater exploration which often relies on resistivity methods for regional mapping and profiling, often uses seismic refraction, to help identify saturated zones and clarify any ambiguity in the resistivity data (Lee et al., 2021).

In conclusion, while this study primarily validated qualitative observations from previous research, its significance lies in its ability to provide assurance amidst the inherent uncertainties associated with ERT findings, particularly when it is not supported by an additional method. By affirming and reinforcing earlier findings, this study strengthens existing knowledge on the geologic framework at the site which is necessary to comprehend recharge. This validation not only increases the credibility of the present study but also builds confidence in the capabilities of ERT in similar studies. While ERT does have limitations which can affect the reliability of the results, there are strategies that can be employed to, for example, reduce ambiguity, increase confidence in the data and increase the depth of investigation. Future studies at the LRS could explore integrating complementary methods such as seismic refraction surveys and cross-borehole ERT to overcome the constraints of ambiguity and shallow penetration observed in ERT. These approaches could provide deeper insights into subsurface structures and composition, and improve the accuracy of hydrogeological interpretations, particularly where deeper aquifers are of interest.

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## Abstract

Diese Arbeit widmete sich der Anwendung der Elektrischen Widerstandstomographie (ERT) zur Untersuchung der komplexen Dynamik von Aufladeprozessen im Kontext eines intermittierenden Flusses. Speziell konzentrierte sich die Studie auf den Arkansas River in der Nähe von Larned im Pawnee County, USA, mit dem Ziel, frühere Forschungsbemühungen durch die Nutzung vorhandener ERT-Datensätze zu ergänzen, die vom Kansas Geological Survey (KGS) Forschungsstandort erhalten wurden. Dieser Standort ist für seine Bedeutung in hydrogeologischen Studien bekannt. Durch die Nutzung vorhandener Daten und die Integration von Erkenntnissen aus früheren Studien sollte die Arbeit die komplexen unterirdischen Strukturen und die Verteilung der hydraulischen Leitfähigkeit, die die Aufladeprozesse entlang des Flusses beeinflussen, aufklären. Mit sorgfältiger Verarbeitung und Interpretation der ERT-Datensätze konnten nur begrenzte Schlussfolgerungen gezogen werden. Der Forscher reduzierte den RMS-Fehler, der im Profil der Sandbank in der ersten Studie beobachtet wurde, und validierte damit frühere Schlussfolgerungen zur horizontalen und vertikalen Heterogenität am Standort und deutete auf das Vorhandensein bevorzugter Fließwege zwischen hydrostratigraphischen Einheiten hin.

**Abstract**

This thesis delved into the application of Electrical Resistivity Tomography (ERT) to investigate the complex dynamics of recharge processes in an intermittent stream. Specifically centered on the Arkansas River near Larned in Pawnee County, USA, the study aimed to augment prior research efforts by utilizing existing ERT datasets obtained from the Kansas Geological Survey (KGS) research site. This site is known for its significance in hydrogeological studies. By leveraging existing data and integrating insights from previous studies, the thesis aimed to elucidate the intricate subsurface structures and hydraulic conductivity distributions influencing recharge processes along the river. With meticulous processing and interpretation of the ERT datasets, only limited conclusions could be drawn. The researcher reduced the RMS misfit observed for the sandbank profile in the initial study, thus validating previous deductions on the horizontal and vertical heterogeneity at the site and indicating the presence of preferential flow paths between hydrostratigraphic units.