Assessment of vulnerability and contamination potential of ozark plateau aquifer in Cherokee County, KS

by

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B.S., Enugu State University of Science and Technology, 2015

M.S., University of Nigeria, 2021

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Geology

College of Arts and Sciences

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2025

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Abstract

Access to clean drinking water is essential for public health. However, groundwater contamination by toxic metals like lead (Pb) and zinc (Zn) as well as nitrate poses a significant threat to drinking water supplies, particularly in areas with a history of mining. These metals can cause neurological disorders in children, heart disease, kidney problems, and more. This study investigates the vulnerability of aquifer systems in Cherokee County, Kansas, a former mining district within the Tri-State Mining District, designated as a Superfund site by the US Environmental Protection Agency (EPA) due to environmental degradation. Limited research exists regarding the vulnerability of Cherokee County's aquifers to heavy metal contamination. This study employs the DRASTIC model, a well-established method that considers seven hydrogeological parameters: depth to water table (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of the vadose zone (I), and hydraulic conductivity (C) to evaluate aquifer vulnerability. The DRASTIC analysis identified two vulnerability zones within Cherokee County: very low (risk index 31-80) and low vulnerability (risk index 80-120). The very low vulnerability index is primarily concentrated in the southwest and northeast parts of the study area, whereas the low vulnerability index dominates the study area.

The model’s model performance assessed using water quality data, which revealed a weak correlation between DRASTIC index and concentrations of lead (R^2=0.44) and nitrate (R^2=0.46) which suggests the model effectively identified areas where this contaminant is prone to aquifer contamination. The weak correlation for zinc (R^2=0.25) highlights the need for integration of additional geochemical and isotopic analysis to confirm contamination sources and enhance accuracy of prediction.

This study provides valuable insights into future research and resource management strategies in Cherokee County. By identifying vulnerable areas, these findings can inform land-use planning, pollution prevention measures, and potential remediation efforts, ultimately aiming to protect public health and ensure sustainable groundwater resources. The findings also highlight the broader applicability of the DRASTIC framework for assessing aquifer vulnerability regions facing similar contamination challenges.

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Acknowledgements

First and foremost, I would like to express my deepest gratitude to God Almighty for His guidance, strength, and wisdom throughout this journey. His grace has been my source of perseverance and inspiration in completing this thesis.

I am profoundly thankful to the Department of Geology at Kansas State University for providing the resources and support necessary for this research. Special thanks to the Department Head, Dr. Pamela Kempton, for fostering an environment of academic excellence and for her unwavering encouragement throughout my time at K-State.

To my academic advisor, Dr. Karin Goldberg, I owe an immeasurable debt of gratitude. Her mentorship, guidance, and unwavering support have been the cornerstone of this research. Dr. Goldberg's dedication, wisdom, and encouragement have not only shaped this work but have also profoundly influenced my growth as a researcher. She is truly remarkable, and I am incredibly fortunate to have her as my advisor.

I would also like to extend my heartfelt appreciation to my advisory committee members, Dr. Matthew Kirk, and Dr. Behzad Ghanbarian, for their invaluable insights, constructive feedback, and encouragement throughout this process. Their expertise and support have greatly enriched this research.

Special thanks to Shreya Chatterjee for her assistance with the NWIS data and to Fidelis Onwuagba for providing valuable resources that contributed to this work. Your help and collaboration have been deeply appreciated.

Finally, I am grateful to Kansas State University for the academic platform and opportunities it has provided. This institution has been instrumental in my growth, and I am honored to have been part of such a vibrant and supportive community.

This journey would not have been possible without the collective support of these individuals and institutions, and I am forever thankful for their contributions.

Dedication

This work is dedicated to the memory of my beloved father, Mr. Godwin Okolo, whose love, wisdom, and unwavering belief in the power of education continue to inspire me every day. Though he is no longer with us, his legacy lives on in the values he instilled in me and the dreams he encouraged me to pursue.

I also dedicate this thesis to my entire family, and friends whose unconditional love, support, and sacrifices have been my foundation throughout this journey. Your encouragement has been my strength, and this achievement is as much yours as it is mine.

Chapter 1 - Introduction

Groundwater is an important resource for various human activities, including drinking water supply, agricultural, and industrial use. Globally, groundwater provides approximately 30% of fresh water, highlighting the importance of protecting and managing these critical resources to reduce depletion and maintain quality. Ensuring the sustainability of groundwater is essential for meeting future needs. However, over the years, groundwater has been heavily contaminated due to mining, agricultural practices, and urbanization. This degradation has not only reduced water quality but also raised serious public health concerns.

The contamination of groundwater by heavy metals like lead (Pb), zinc (Zn), and cadmium (Cd) poses significant health challenges. Exposure of children to these metals has been linked to neurological disorders, cardiovascular and renal disorders (Bayer et al., 2005; Johnson et al., 2016). To address these challenges, it is important to assess and manage groundwater vulnerability in areas with historic contamination.

The Ozark Aquifer (Fig. 1.1), also known as the Springfield Plateau Aquifer, cuts across parts of Kansas, Oklahoma, Arkansas and Missouri and provides water to many communities and industries throughout the region. This aquifer is composed primarily of the Mississippian limestones which have undergone extensive karstification that created complex geologic conduits and fractures that increased rapid groundwater flow (Ford and Williams, 2007).

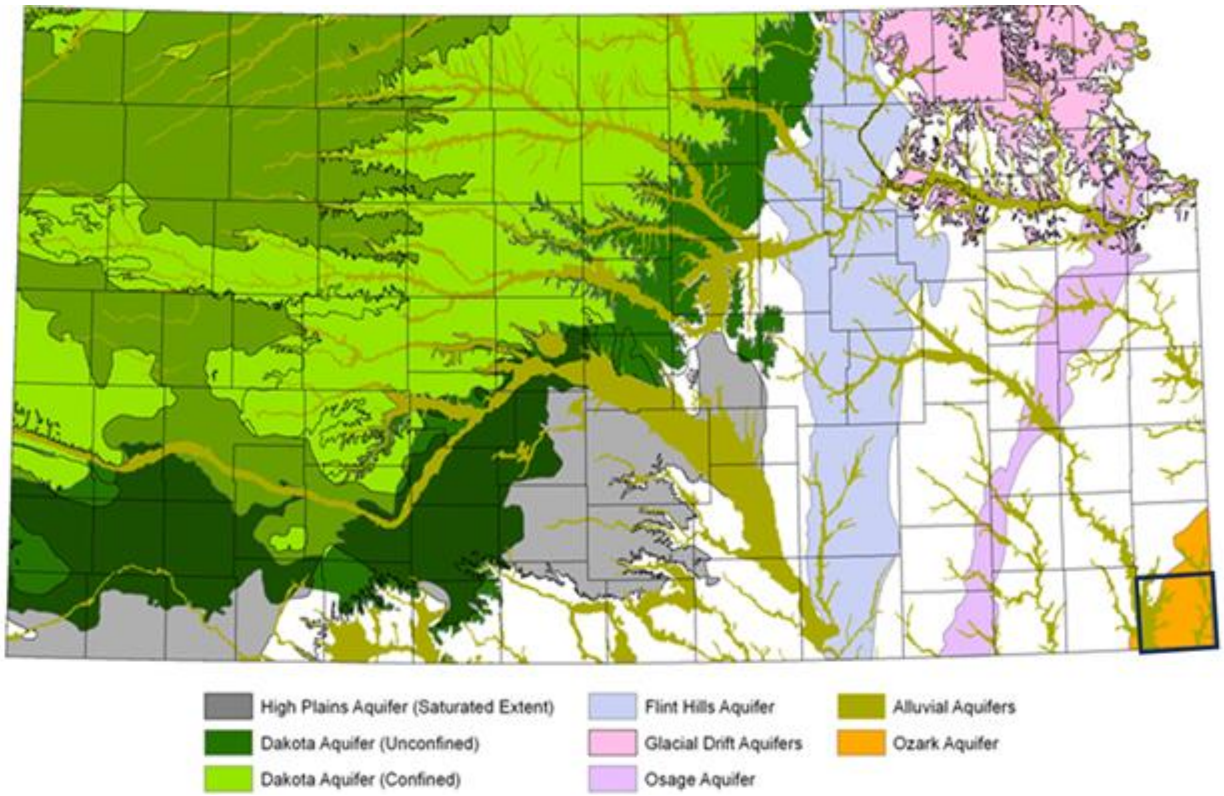

Figure 1.1:Aquifer systems in Kansas, including the Ozark Aquifer in southeastern Kansas (Kansas Geological Survey). The study area is highlighted in black.

Cherokee County in southeastern Kansas, is part of the Tri-State mining district, comprising Kansas, Oklahoma and Missouri. This region has a long history of mining activities that led to environmental degradation, including heavy metal contamination in soil, sediment and especially groundwater (Macfarlane et al., 2005; Pope, 2005). The U.S. Environmental Protection Agency (USEPA) designated some part of Cherokee County as a Superfund site in 1983 (Fig. 1.2), highlighting the significant contamination from historical lead and zinc mining operations. This contamination has had detrimental effects on both the environment and human health (Johnson et al., 2016).

Cherokee County depends heavily on the Ozark Aquifer to supply its water needs. Despite the reliance, there is a surprising lack of comprehensive studies evaluating the aquifer's susceptibility to contamination and the potential health risks for residents. This research sought to address this knowledge gap by conducting an in-depth assessment of groundwater vulnerability and contamination risk of the Ozark Plateau Aquifer in Cherokee County.

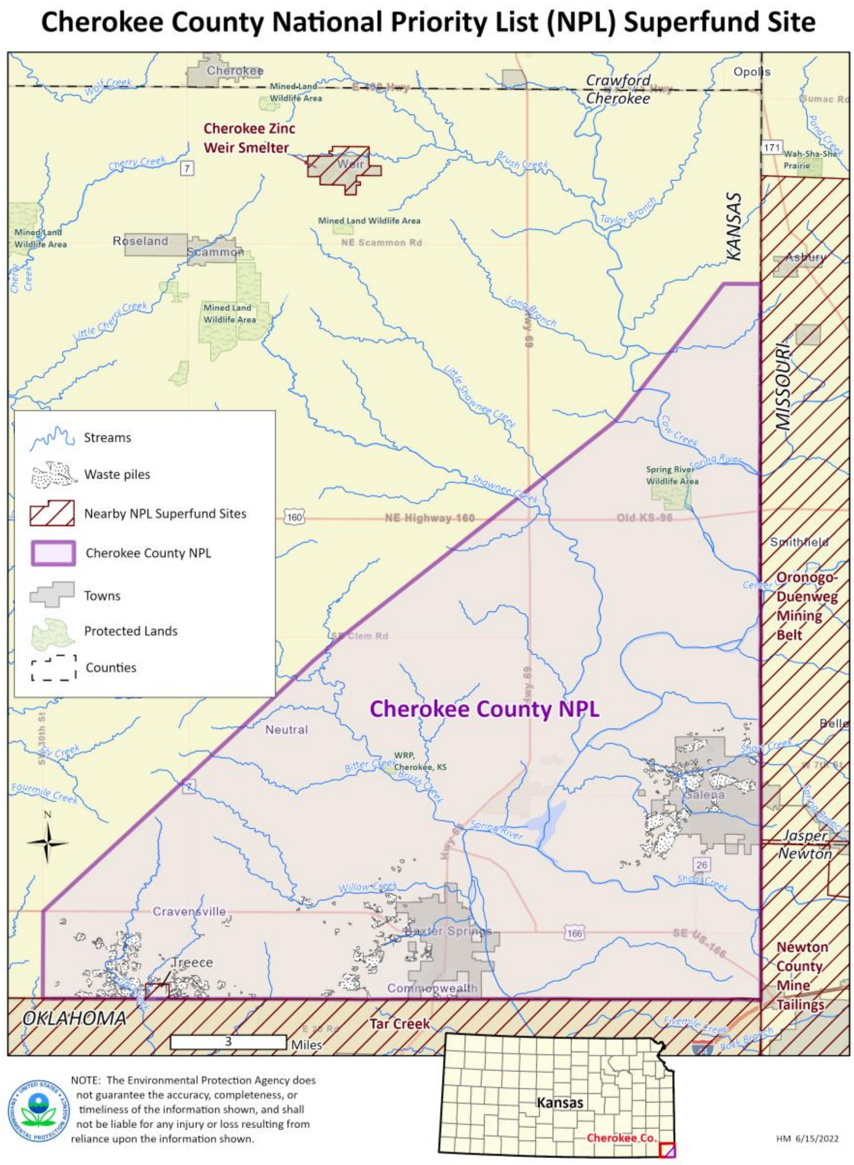

Figure 1.2:Cherokee County National Priority List (USEPA).

1.1 Statement of problem

The Ozark Aquifer is the main source of fresh water for communities and industries in southeastern Kansas, but it also plays an important role in the economic history of this region due to its extensive mining activities over the years. Lead mining in Cherokee County began in 1877 and stopped around 1970, the mines have been in operation within or near aquifer boundaries, which has resulted in substantial environmental degradation. These mining operations often involve excavation of the soil that alters the natural landscape (Fig. 1.3). Thereby exposing minerals to surface waters and facilitating dissolution into groundwater systems. Heavy metals, such as lead, zinc and cadmium, often leach into the groundwater from mine tailings and piles of waste rock (USEPA, 2023c) (Fig. 1.3). These contaminants pose significant health risks when consumed through drinking water, including neurological problems especially in children, kidney disease, and increased cancer risks (WHO, 2021; EPA, 2023).

Besides heavy metals, acid mine drainage (AMD) is another major concern for this region. AMD, which mostly occurs when sulfide minerals are exposed to water and air, results in the generation of sulfuric acid that further mobilizes harmful like aluminum, iron and manganese (Nordstrom et al., 2015). Due to the presence of karstic conduits in this region, acidic runoff can rapidly infiltrate into the aquifer, altering its geochemical balance and raising contamination levels.

Historic legacies persist, despite regulatory efforts aimed at mitigating these impacts. Remediation efforts often face several challenges due to the complexity of the karst system and challenges associated with monitoring non-point sources of pollution. The Ozark Aquifer's vulnerability is thus escalated by these legacy mining operations, prompting comprehensive assessment to understand the current contamination patterns and predict future trends.

The study aimed at assessing the vulnerability of the Ozark Plateau Aquifer to contamination in Cherokee County, focusing on areas affected by legacy mining. The assessment utilized hydrological modeling, GIS mapping, and geochemical data compilation for vulnerability analysis. We sought to provide insights into how mining related contaminants move through the aquifer to identify critical zones at risk and inform sustainable groundwater management strategies to ensure safe and reliable access to groundwater resources for future generations.

Figure 1.3: Abandoned lead and zine mines and chat piles in Galena, Cherokee County (Kansas Geological Survey, KGS).

1.2 Study Area

Cherokee County in southeastern Kansas covers an area of 1200 square miles (3100 km^2) (Fig. 1.4), where towns like Baxter Springs, Columbus, Galena, and West Mineral encompass activities that range from industrial to residential.

The underlying karstic aquifer consists of Mississippian-age limestones that are part of the Boone Formation. They exhibit high permeability due to their fractured nature, leading to rapid recharge and flow of water through interconnected conduits and fractures. These characteristics make the aquifer particularly prone to contamination from surface activities like mining and agriculture. Historically, Cherokee County is known for its significant mining operations that have left a series of mine tailings and waste rock that pose significant risk to groundwater. Given these factors, Cherokee County is the ideal case study area to investigate Ozark Plateau Aquifer vulnerability to contamination.

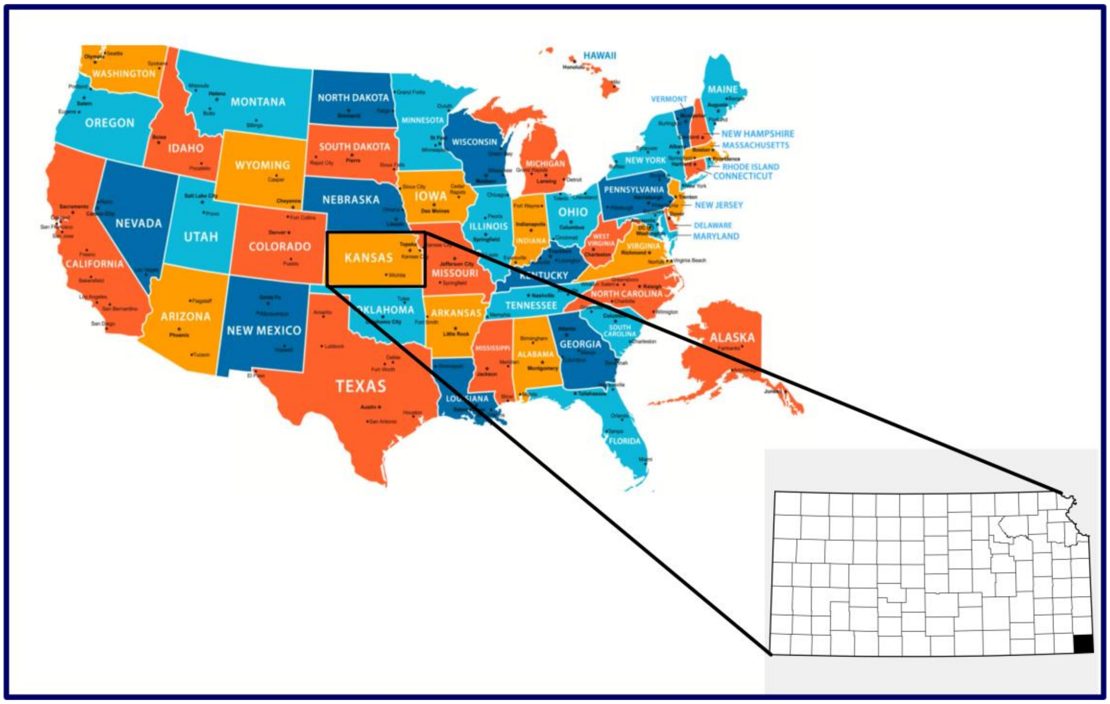

Figure 1.4: Location of the study area (highlighted in black) in southeastern Kansas (ontheworldmap.com, KGS).

1.3 Significance of research

Groundwater is a vital resource essential for human consumption, industrial processes, agricultural activities and health of the ecosystem. However, anthropogenic activities, such as industrialization, agriculture and mining, have increasingly jeopardized its quality and availability. The Ozark Plateau Aquifer, characterized its karstic formations, is particularly vulnerable to rapid contaminant transport due to its unique geological features.

The coincidence between the occurrence of karstic properties in the Ozark Plateau Aquifer and the long history of legacy mining operations in Cherokee County make this area highly vulnerable to contamination. The mining activities left behind mine tailings and waste dumps that continuously leach heavy metals into groundwater. In addition, agricultural runoff has introduced nutrients and other toxic elements that can infiltrate the aquifer through sinkholes and disappearing streams.

The significance of this study lies in several key areas:

Public Health and Environmental Protection: understanding the present condition of groundwater quality and highlighting areas at risk of contamination will enable local authorities to implement targeted remediation efforts and protective strategies to safeguard water resources from further degradation. Lead, zinc and nitrate contamination in groundwater poses significant health risks (Fig. 1.5), which includes neurological disorders especially in children, cardiovascular diseases, and methemoglobinemia (blue baby syndrome) (USEPA, 2002). By highlighting high risk zones, this study will help enhance efforts to safeguard public health. The findings may contribute to reducing health problems in areas affected by contaminated groundwater (Ghahremanzandeh et al., 2018).

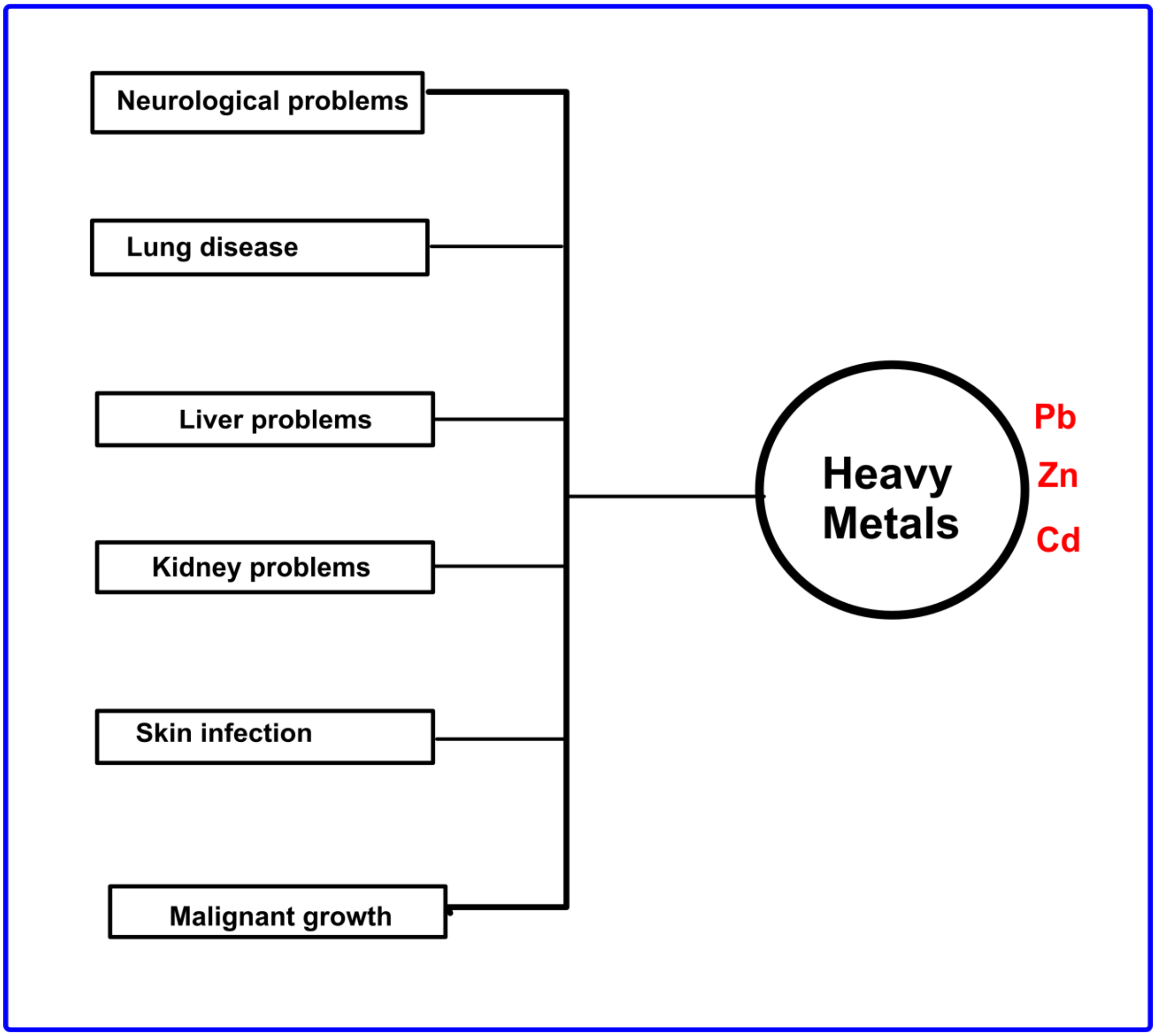

Figure 1.5: Health related problems caused by heavy metals (modified from Aziz et al., 2003).

Heavy metals and nitrate are not only a threat to humans but also to the ecosystem. The vulnerability and contamination maps highlight areas at risk to contamination and help protect the ecosystem by identifying critical areas for conservation, especially in areas where groundwater interacts with surface water, amplifying ecological impacts on contamination (Johnson et al., 2016).

Enhancement of groundwater management: The Ozark Plateau Aquifer is a vital source of water for domestic, agricultural and industrial activities in the Tri-State District. The legacy mining has left a cascading effect on the environment, which requires informed management strategies to balance water use with protection measures. This research delivers vulnerability and contamination maps that may speed up remediation efforts, while ensuring sustainable use of groundwater resources. These maps are crucial for stakeholders, policymakers and water resource managers to prioritize areas for intervention (Sener et al., 2009).

Advancement of Scientific Knowledge: This study enhances the understanding of the aquifer vulnerability in karst systems. Testing of the model's prediction with water quality data from National Water Information System (NWIS), a comprehensive database by the U.S. Geological Survey (USGS) that provides access to water resources data collected from several sites across the United States, enhances the reliability and applicability of the DRASTIC method. It also provides a framework that can be used in similar hydrologic settings globally (Aller et al., 1987).

In summary, this research holds significant implications for environmental protection, public health, sustainable development, policy making and scientific advancement. The overarching goal was to contribute to improving water resource management and community resilience posed by groundwater contamination.

1.4 Geologic setting

Cherokee County lies in the Cherokee lowlands and the Ozark Plateau regions. This area is characterized by a complex interplay of Mississippian Pennsylvanian sedimentary rocks (Fig. 1.6), karstic features and structural elements. The area is primarily composed of limestones, dolomites, sandstones and shales with significant karstification in the Mississippian units. The carbonate rocks are highly permeable due to their dissolution by groundwater over time, creating extensive network of conduits and sinkholes that facilitates rapid water movement (Ford and Williams, 2007; Macfarlane et al., 2005; Pope, 2005).

Overlying the Mississippian rocks are Pennsylvanian rocks which include the Cherokee Group, characterized by interbedded sandstones, shales and thin coal seams. These units are important aquitards that can impede groundwater movement. The interbedding of permeable and impermeable layers play a crucial role in groundwater flow and recharge dynamics (KGS, 2004).

Faults and fractures within the bedrock also play a crucial role in determining groundwater movement and recharge dynamics (Fig. 1.6). The faults increase permeability and enhance downward migration of fluids and contaminants. Surface interactions with the Cherokee shales and shallow aquifers further influence the geochemical composition of groundwater.

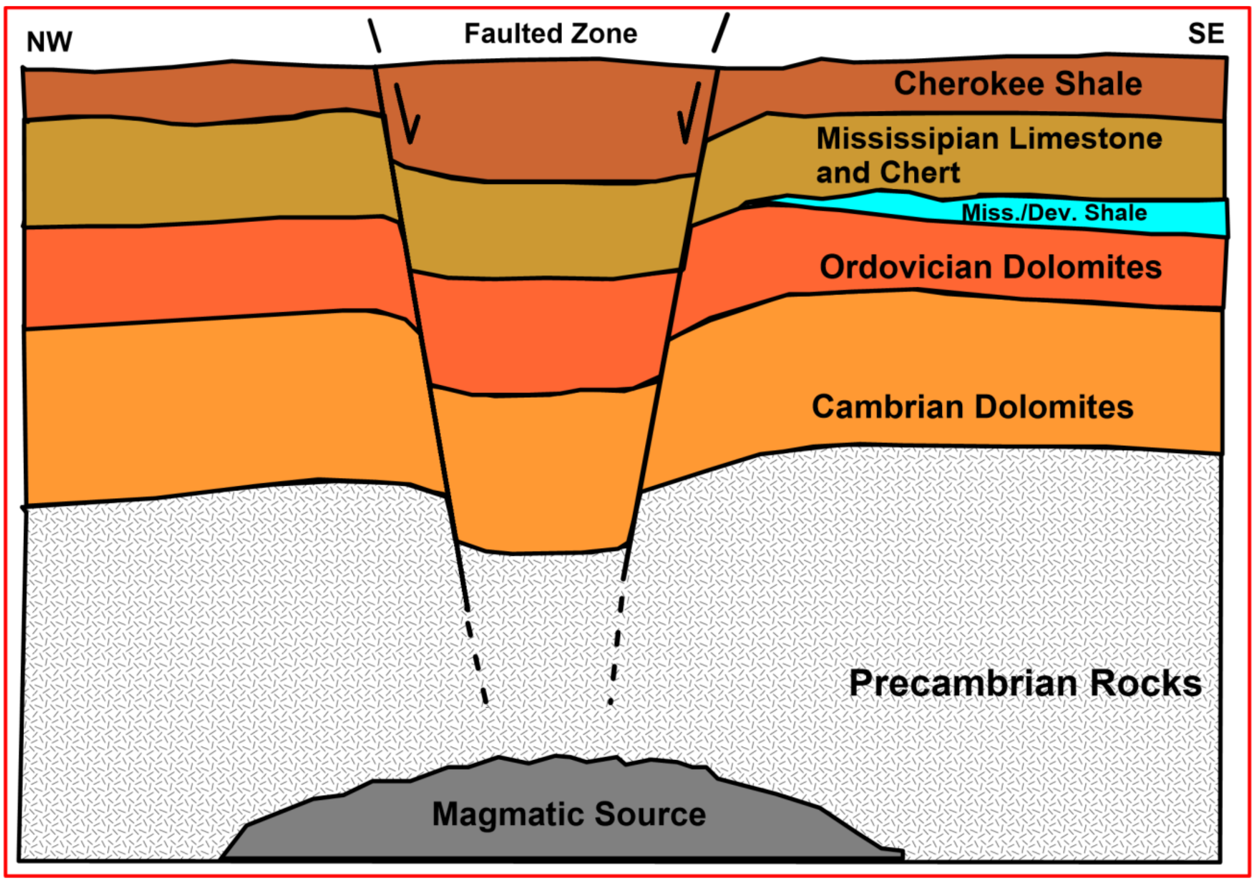

Figure 1.6: Geologic cross-section of Cherokee County showing the stratigraphy and fault zones (modified from KGS).

1.5 Hydrology

The Ozark Plateau Aquifer is characterized by high transmissivity and storativity because of the karstified limestone and dolomite units. Groundwater flows predominantly in this aquifer through fractures, bedding planes and conduits, resulting in rapid transport of water and potential contaminants. The aquifer is primarily recharged through precipitation, infiltration and losing streams owing to the absence of thick overlying clay and silt layers in many areas (Macfarlane et al., 2005).

The Pennsylvanian Cherokee Group acts as a confining layer in some areas, limiting groundwater flow. However, its heterogenous composition (interbedded shales and sandstone) and contributing may allow localized slow water movement through more permeable zones.. However, in areas where the overlying layers are thin or absent, the aquifer is highly vulnerable to contamination from the surface. To effectively manage and protect the Ozark Plateau Aquifer, it is important to understand its hydrological characteristics and identify areas that are particularly susceptible to contamination (USEPA, 2002).

Chapter 2 - Methodology

This research integrated GIS-based DRASTIC model, geochemical analyses, and spatial mapping tools to assess groundwater vulnerability and contamination potential in Cherokee County, Kansas. The DRASTIC model, developed by the U.S. Environmental Protection Agency (Aller et al., 1987), evaluates groundwater vulnerability based on seven parameters: depth to groundwater, net recharge, aquifer media, soil media, topography, vadose zone impact, and hydraulic conductivity (Fig. 2.1). These parameters are spatially mapped using geographic information system (GIS) to generate input layers, each weighted and rated based on their contribution to aquifer vulnerability (Table 2.1). Data for these layers were obtained from the Kansas Geological Survey, soil maps, remote sensing imagery, the United States Geological Survey (USGS) and the NWIS database (USEPA, 2002).

2.1 DRASTIC Model Parameters

The DRASTIC model assesses groundwater vulnerability through seven hydrogeological parameters, each representing distinct factors influencing contaminant transport and attenuation. These parameters were selected based on their demonstrated significance in controlling pollutant movement through the vadose zone and into aquifers (Aller et al., 1987).

Depth to Water Table (D) represents the vertical distance from the ground surface to the water table. This parameter critically determines the time available for contaminant attenuation processes such as adsorption, biodegradation, and chemical transformation.

Net Recharge (R) quantifies the annual amount of water that infiltrates through the vadose zone and reaches the water table. The recharge parameter was derived from local precipitation data and soil infiltration characteristics.

Aquifer Media (A) describes the lithological composition of the saturated zone, which controls groundwater flow velocity and contaminant dispersion. The study area exhibits varied aquifer media, ranging from low-permeability shale to highly permeable gravel deposits. Gravel-dominated aquifers showed significantly higher vulnerability due to their enhanced transport potential.

Soil Media (S) characterizes the upper unsaturated zone immediately below the land surface. Soil properties such as texture, organic matter content, and permeability influence initial contaminant retention and transformation. Sandy soils have limited contaminant retention capacity, contributing to higher vulnerability scores.

Topography (T) accounts for land surface slope, which affects runoff potential and contaminant residence time on the surface. Flatter terrain (<5% slope) promote greater infiltration of surface-applied contaminants compared to steeper regions.

Impact of the Vadose Zone (I) represents the lithology and thickness of the unsaturated zone between the soil layer and water table. This parameter is particularly significant in areas where the aquifer is overlain by permeable materials that provide minimal contaminant attenuation.

Hydraulic Conductivity (C) of the aquifer governs the rate of groundwater flow and consequent contaminant plume development. High conductivity values have greater potential for contaminant migration over larger distances.

Each parameter was assigned both a rating (1-10) based on local hydrogeological conditions and a predetermined weight (1-5) reflecting its relative importance in vulnerability assessment. The composite DRASTIC Index, calculated as the weighted sum of all parameters, effectively identified highly vulnerable zones.

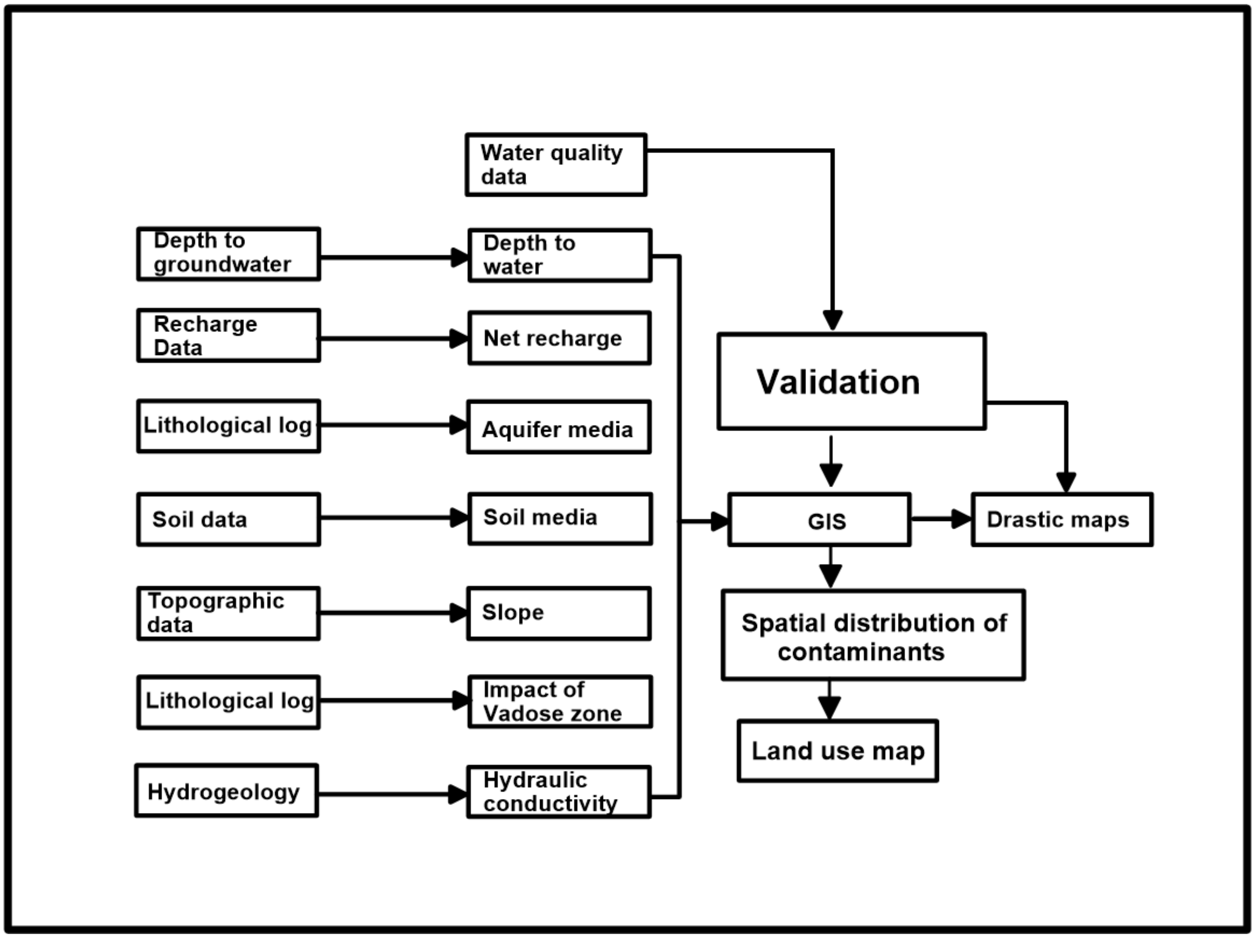

Figure 2.1: Workflow adopted in this research (modified from Aller et al., 1987).

Water concentrations of lead (Pb), zinc (Zn), and nitrate (NO_3^-) were extracted from the NWIS database, and used to explore a correlation between the DRASTIC model and concentration of this contaminants. This data represents a time-series data collected annually and are key indicators of contamination from historical mining activities and agricultural practices. The use of historic water quality data is a caveat in the relationship assessment process, as these data do not fully represent current contamination levels. Using GIS, the spatial distribution of Pb, Zn, and NO_3^- concentrations were overlain on the DRASTIC vulnerability map. A comparative analysis then evaluated how well the model predicted high-risk zones. By linking these contamination indicators with DRASTIC outputs (Table 2.2), the study ensured a robust relationship assessment process, confirming the model's ability to accurately identify vulnerable areas (Ghahremanzadeh et al., 2018).

Table 2.1: Parameters with assigned weights for DRASTIC model (Aller et al., 1987).

Factor	Weight
D Depth to water	5
R Net recharge	4
A Aquifer media	3
S Soil media	2
T Topography	1
I Impact of the vadose zone	5
C Hydraulic conductivity of the aquifer	3

Table 2.2: Criteria for the vulnerability assessment in the DRASTIC model (Aller et al., 1987)

Degree of Vulnerability	Vulnerability Index
Very Low	< 80
Low	80 - 120
Average	121 - 160
High	161 - 200
Very high	>200

2.2 Data sources

Data for the DRASTIC parameters were obtained from the following sources, with full metadata and resolution details provided (Table 2.3). All datasets were processed in ArcGIS Pro (v3.1) using a consistent 30-meter spatial resolution grid for analysis.

Table 2.3: Data sources and GIS input parameters for the DRASTIC model

Input parameter	**Data sources**	**Data form in GIS**
Depth to water **(D)**	KGS database/WWC5 https://www.kgs.ku.edu/Magellan/WaterWell/index.html	Vector (point data)
Net recharge **(R)**	KGS database/WWC5 https://www.kgs.ku.edu/Magellan/WaterWell/index.html	Vector (point data)
Aquifer media **(A)**	KGS database/WWC5 https://www.kgs.ku.edu/Magellan/WaterWell/index.html	Vector (point data)
Soil media **(S)**	Food and Agricultural Organization (FAO/UNESCO) Database, 0-10km depth, resolution 1: 5,000,000 scale https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/	Vector (polygon)
Topography **(T)**	Google Earth / Arc GIS, NASA SRTM (Shuttle Radar Topography Mission) v3 Global 30m resolution DEM, 30m resolution	Raster data
Impact of vadose zone **(I)**	KGS database/WWC5 https://www.kgs.ku.edu/Magellan/WaterWell/index.html	Vector (point data)

Hydraulic conductivity **(C)**	USGS Groundwater availability in the Ozark Plateau Aquifer system	Point data

2.3 Calculation of DRASTIC index values

The DRASTIC vulnerability index, a dimensionless score was calculated by summing each parameter rating and corresponding weights (Table 2.4).

Drastic index = (Dr×Dw) + (Rr×Rw) + (Ar×Aw) + (Sr×Sw) + (Tr×Tw) + (Ir×Iw) + (Cr×Cw)

where **D, R, A, S, T, I**, and **C** are the seven DRASTIC parameters, **r** is the parameter rating (unitless, based on ranges in Table 2.4) and **w** is the fixed weight reflecting each parameter's relative importance to vulnerability (Table 2.4).

The values obtained are classified according to (Aller et al., 1987) and represent a degree of vulnerability where low index scores indicate low vulnerability and high index scores represent high vulnerability to contamination (Table 2.2).

Table 0.1: Rating and weighting of DRASTIC model indicators.

Indicator	Range	Rating	Weight
Depth (m)	0 - 20 20 – 40 40 – 60 60 – 80 >80	10 7 5 3 1	5
Net recharge (gpm)	2 – 161 161 – 360 >360	3 7 10	4
Aquifer media	Shale Limestone Sandstone	3 5 6	3

	Gravel	8	
Soil media	Clay loam Sandy clay Sandy loam	2 3 5	2
Topography (m)	200-250 250-300 >300	3 4 6	1
Vadose zone	Shale Limestone Sandstone	3 5 7	5
Hydraulic conductivity (ft/day)	<3 3-6 6-9 >9	2 3 5 6	3

2.4 Relationship assessment through correlation/statistics analysis

To understand the relationship between the DRASTIC index and contaminants, linear regression analysis was performed using the R software. A linear approach was selected based on prior studies demonstrating quasi-linear trends between DRASTIC indices and point-source contaminants (e.g., nitrate in Babiker et al., 2005). The coefficient of determination (R^2) was calculated to determine the proportion of variance in contamination concentration explained by the DRASTIC index. This analysis was done for each contaminant, with the DRASTIC index as the independent variable and contaminant concentration as the dependent variable.

The linear relationship approach aligns with established practices in groundwater vulnerability assessment (Nobre et al., 2007; Almasri, 2008), where DRASTIC scores often show proportional relationships with contaminants like lead, zinc and nitrate. However, because of the complexity of the hydrological system, further investigation could explore multiple linear regression or non-linear models for a robust assessment.

The range of R^2 values is between 0 and 1 and is interpreted according to Hauke and Kossowski (2011):

$R^2 > 0.7$ strong relationship

$R^2 \leq 0.5$ moderate relationship

$R^2 < 0.5$ weak relationship

Scotter plots with fitted regression lines were used to visualize the relationship between DRASTIC index and contaminant concentration.

Chapter 3 - Results

The results of the groundwater vulnerability and contamination evaluation of the Ozark Plateau Aquifer in Cherokee County, Kansas combine the output from a GIS-based model with water quality data for lead (Pb), zinc (Zn), and nitrate (NO_3^-) to assess the relationship between aquifer vulnerability and contamination concentrations.

The findings are presented in three categories. First, the results from the DRASTIC model are detailed, followed by maps of the distribution of lead, zinc and nitrate concentrations across the study area and finally, the relationship between the DRASTIC index and contaminant concentration computed using statistical methods.

The spatial analysis utilizes kriging, a geostatistical interpolation method, to generate maps of DRASTIC parameters and contaminant distribution based on the data recorded at the completion of wells from KGS/WWC5 database.

3.1 DRASTIC parameters

3.1.1 Depth to groundwater (D)

The depth to groundwater values used in this study were derived from well completion records (KGS, 2023), representing static measurements taken during initial well construction. Shallow groundwater tables are more susceptible to contamination due to shorter travel distances and reduced attenuation processes like biodegradation or adsorption. The depth to groundwater map (Fig. 3.1) shows the spatial variation in groundwater depth across the county.

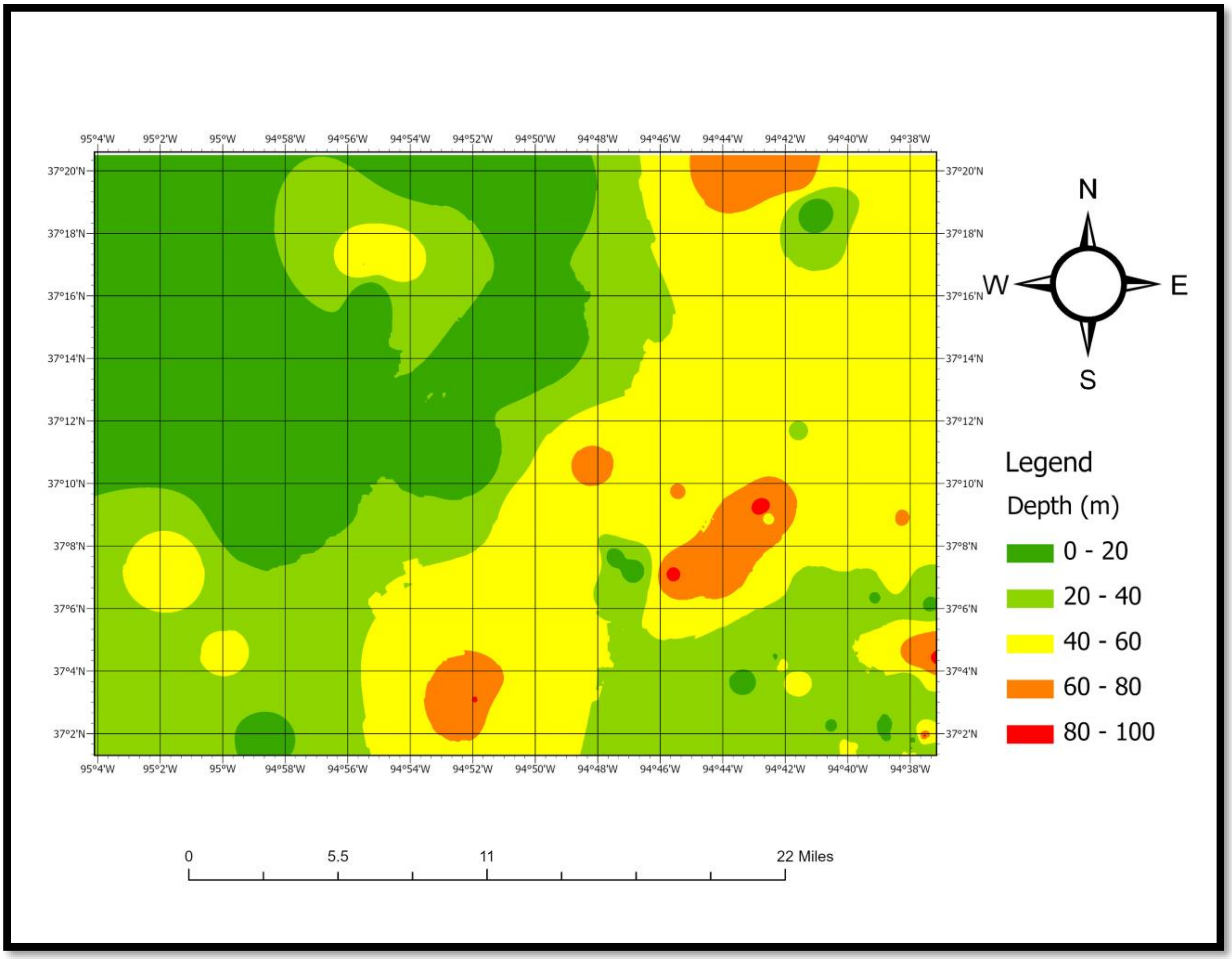

Figure 3.1: Spatial distribution of depth to groundwater in Cherokee County, Kansas.

The depth to groundwater in Cherokee County exhibits distinct spatial patterns (Fig. 3.1). Shallow depths (<20 m) dominate the northwest quadrant, while moderate depths (20–60 m) form a NE-SW trending band through the central region. Depths exceeding 60 m occur in isolated areas of the northeast, central east, and south-central county.

3.1.2 Net recharge (R)

Recharge is the amount of water that is added to the aquifer through precipitation, infiltration, irrigation return flow or other sources. High recharge rates enhance the infiltration of pollutants into the subsurface. In Cherokee County, sandy soils and karstic bedrock significantly contribute to high recharge rates in some areas. The recharge map (Fig. 3.2) illustrates the spatial variation of groundwater recharge across Cherokee County.

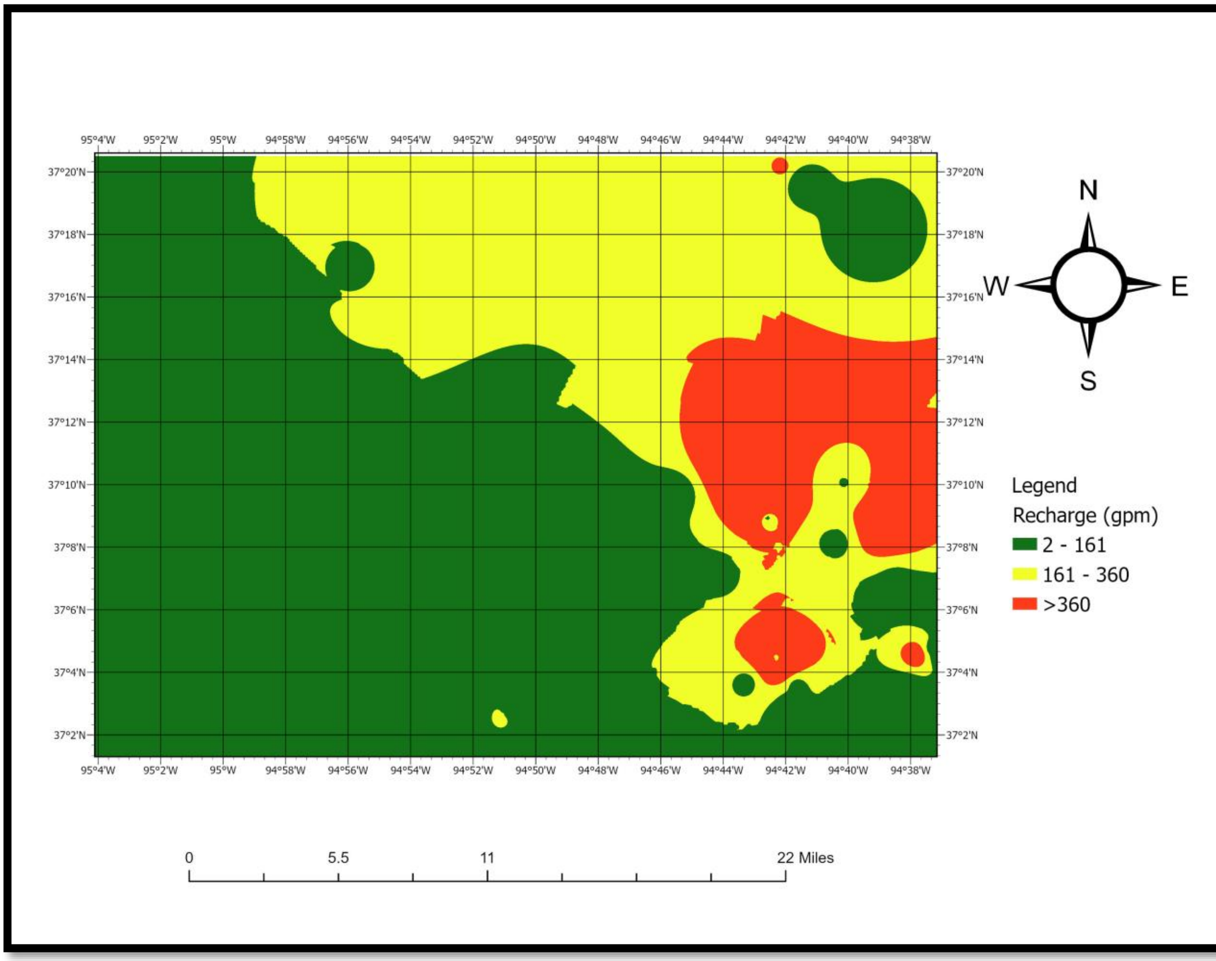

Figure 3.2: Spatial distribution of recharge rates in Cherokee County, Kansas.

Areas with high recharge rates (360 gpm) are primarily located in eastern Cherokee County and characterized by karstified limestone formations. These locations demonstrate high infiltration rates, which increase their vulnerability to contamination. Agricultural activities and legacy mining operations further elevate the risk of pollution, as fertilizers, pesticides, and heavy metals can easily infiltrate the groundwater system.

Moderate recharge areas (161-360 gpm) occur in the northwestern part of the study area, featuring intermediate infiltration rates due to the presence of mixed lithologies such as sandstone and shale, which have lower permeabilities. While these areas offer some filtration potential, localized vulnerabilities may arise in regions with fractures or faults that can accelerate water flow. Therefore, these moderate recharge zones require careful monitoring and protective measures to mitigate potential risks from agricultural runoff or industrial activities.

Low recharge areas (2-161 gpm) are predominantly located in the southwest and along the southern border of the county. These regions are characterized by thick layers of clay and shale, which significantly reduce water infiltration. As a result, these zones provide substantial natural protection against pollutants due to the low permeability of the overlying sediments.

3.1.3 Aquifer media (A)

The aquifer media in the study area consists of four primary lithologic types, shale, limestone, sandstone, and gravel. These materials exhibit distinct hydrogeologic properties that influence groundwater flow and contaminant transport. The spatial distribution of dominant lithologies is presented in the accompanying map (Fig. 3.3).

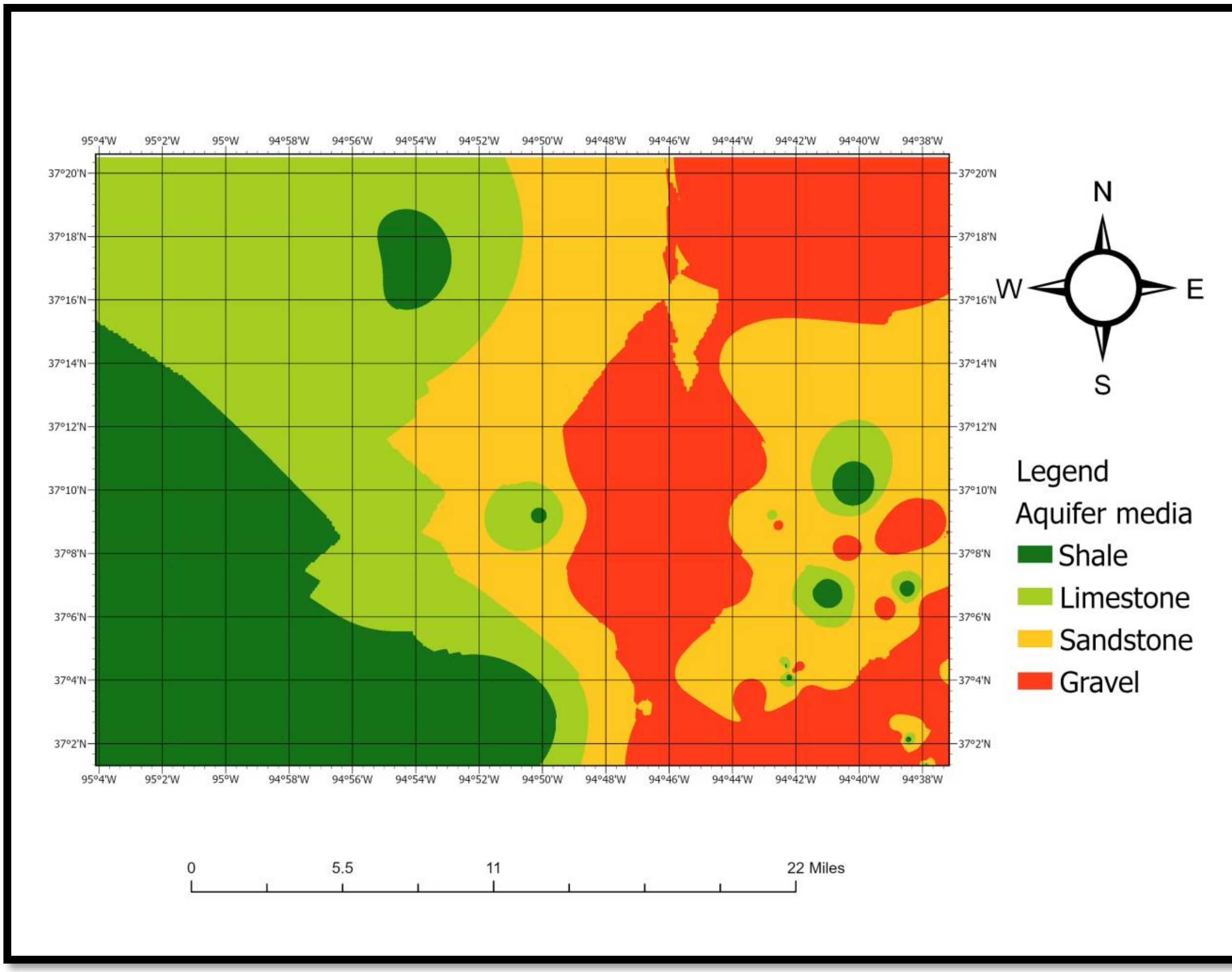

Figure 3.3: Spatial distribution of Aquifer Media in Cherokee County, Kansas.

Understanding the distribution of aquifer media is critical for evaluating groundwater vulnerability as different materials exhibit varying capacities for contaminant attenuation and transport.

Shales exhibit low permeability which significantly limits water and contamination. The shales occur predominantly in the southwest region and correspond to a low recharge zone, as seen in (Fig. 3.2). They act as a natural contaminant attenuation by limiting infiltration and restricting transport within the aquifer.

Limestones is the dominant aquifer media in the northwest area of the county and other scattered, restricted zones. Many limestone layers are karstified and characterized by dissolution-induced voids, conduits and sinkholes. The karst feature significantly increases vulnerability, facilitating rapid contaminant transport. The combination of karst and shallow water tables (Fig. 10) in northwest Cherokee County makes this region critical for implementing contamination control measures (Goldscheider et al., 2020)

Sandstones, found mainly in the central and central-eastern part of the study area, exhibit moderate permeability that enables groundwater flow through filtration. Sandstone layers are commonly interbedded with shale, creating a stratified system that influences contaminant transport. Despite offering better protection than limestones, these zones still require monitoring to prevent localized contamination, particularly in areas with significant agricultural or urban influence**.**

Gravel layers are less extensive than other lithological units and play a crucial role in aquifer recharge and contaminant transport. Dominant in the extreme northeast, central-east and southeast, they are found along active or historic river channels. Their high porosity and permeability facilitate rapid groundwater flow and contaminant transport. They often act as a direct pathway, particularly in regions with high recharge (Fig. 3.2).

3.1.4 Soil media (S)

The soil media map (Fig. 3.4) illustrates the spatial distribution and characteristics of soil types across Cherokee County, which plays a critical role in groundwater vulnerability. Soil acts as natural filters that attenuate contaminants before they reach the aquifer. Coarse grained materials like sand allow faster infiltration compared to fine grained clays that reduce infiltration capacity.

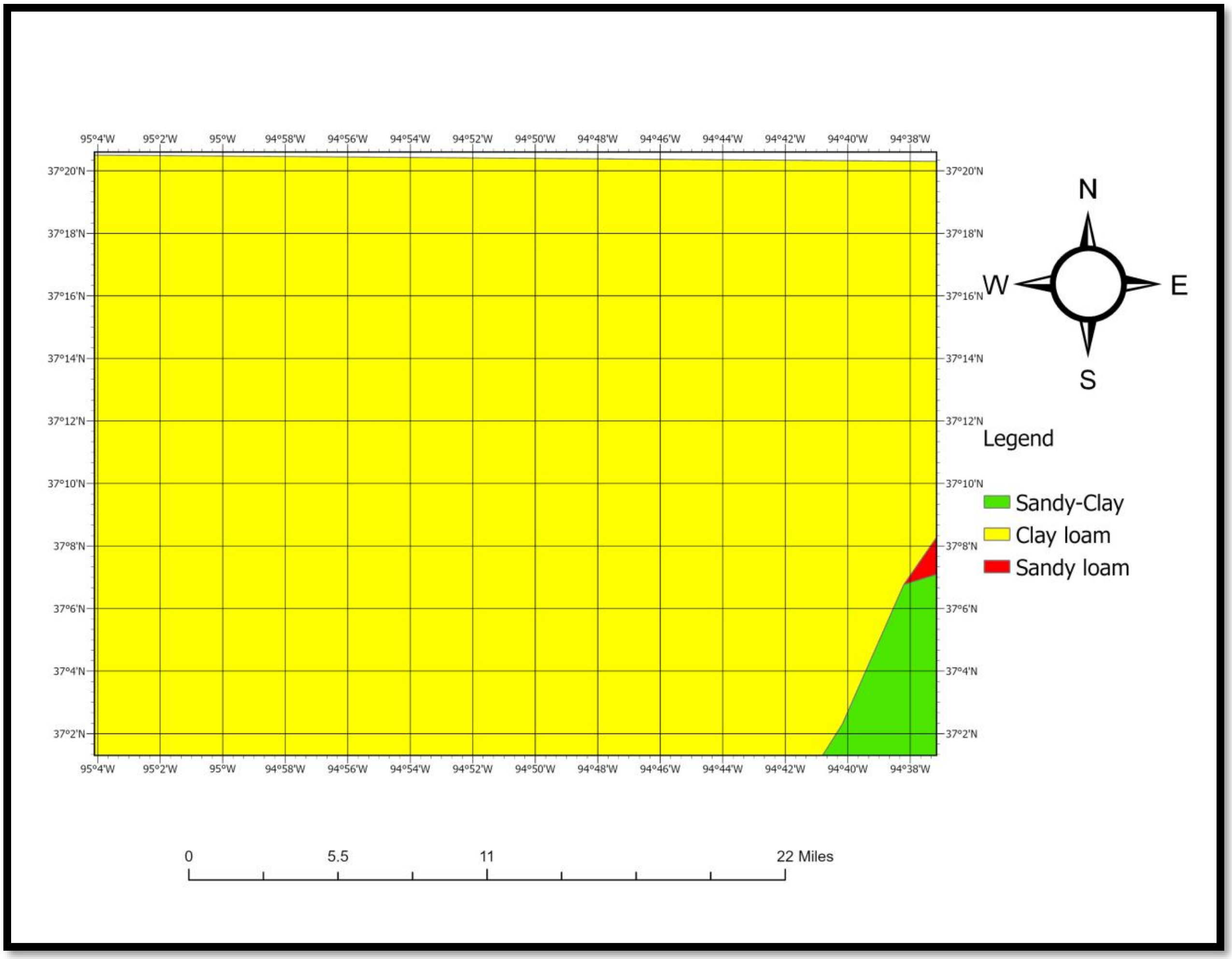

Figure 3.4: Spatial distribution of soil media in Cherokee County, Kansas (FAO soil map).

Cherokee County is dominated by clay loam soils, forming thick, fine texture layers with low permeability. These soils are highly effective in reducing infiltration rates and providing a natural barrier against contaminant transport. Their high adsorption capacity enables them to trap and retain pollutants, making them the most protective soil type in the region. However, localized vulnerability can arise from fractures, faults or disturbances caused by agricultural or industrial activities. These areas are critical for groundwater management and protection due to their natural filtration capacity.

Sandy clay soil is found only in the southeastern corner of Cherokee County. These soils exhibit a mix of properties, with moderate permeability and relatively high water-holding capacity. While they allow some infiltration of water and contaminants, their clay content enhances their ability to attenuate contaminants, offering partial protection to the underlying aquifer. Despite the potential groundwater protection, areas with sandy clay soil, especially in high recharge zones or agricultural areas, remain vulnerable to surface contamination due to the ease of nitrate leaching and limited infiltration capacity.

Sandy loam soils are found in a very restricted area in eastern Cherokee County and coincides with high recharge areas (Fig. 3.2). These soil types are highly permeable, enhancing rapid water infiltration and facilitating the movement of contaminants into the groundwater system. Their low adsorption capacity and high permeability make them particularly susceptible to contamination from fertilizers, pesticides and heavy metals. Hence, despite being very localized, they might pose substantial risk to groundwater resources.

3.1.5 Topography (T)

The topographic map (Fig. 3.5) highlights elevation variations and slope gradients, both of which significantly influence surface runoff, infiltration, and subsequent groundwater recharge. Among the seven DRASTIC parameters, topography is assigned the least weight, reflecting its relatively lower importance in determining the overall groundwater vulnerability compared to parameters like depth to groundwater or recharge. High-elevation (>290 m) areas are predominant in the -north-central and extreme southeastern Cherokee County. The steep slopes promote surface runoff, reducing infiltration and the potential for contaminants reaching the aquifer.

The low-elevation (230 - 260 m) areas are found in the southwest and southeastern parts of the county. The gentle slopes and flatter terrain enhance water pooling and infiltration, making them more susceptible to groundwater contamination.

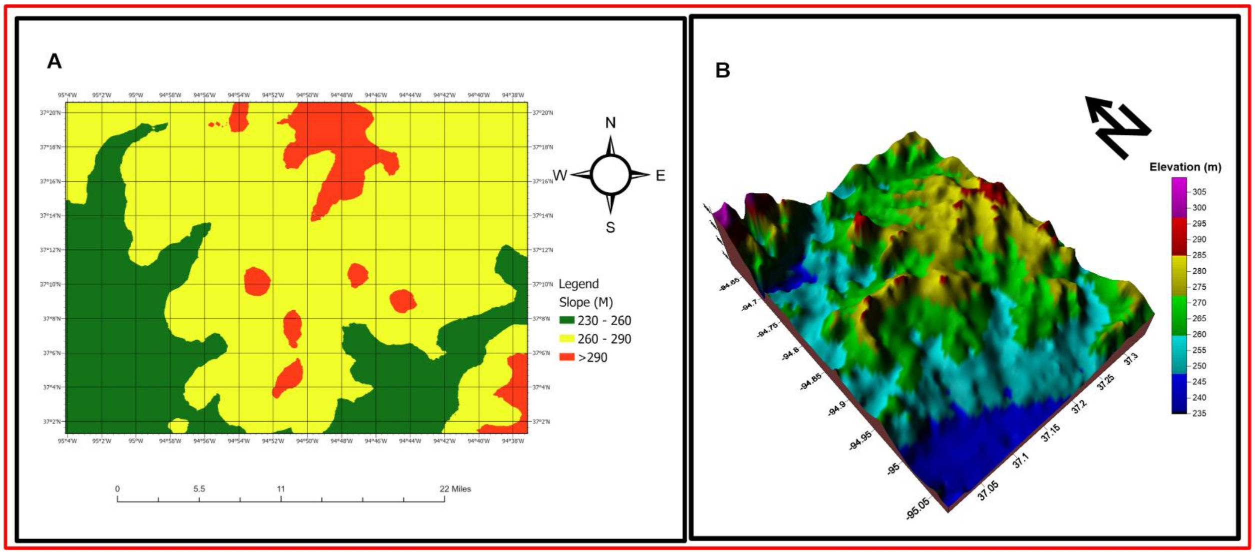

Figure 3.5: (A) 2D Topographic map of Cherokee County, showing elevation and slope variations, (B) 3D elevation map of Cherokee County.

3.1.6 Impact of vadose zone (I)

The vadose zone, between the surface and the water table, protects against the downward movement of contaminants. Thicker unsaturated zone offers greater buffering capacity but may still be vulnerable due to fractures or conduits.

The vadose zone map (Fig. 3.6) shows spatial variation in its composition and permeability. Limestone-dominated vadose zone is found across the county, mainly in the western and central eastern parts of Cherokee County. It exhibits high permeability due to karstification. Karst features such as sinkholes and conduits enhance rapid water contaminant transport through the vadose zone with minimal attenuation. Agricultural runoff and heavy metals from legacy mining pose significant risks in these zones due to their high permeability.

Sand-dominated vadose zones occur in patches primarily in the southeast and offer moderate permeability and protection. These areas allow for groundwater infiltration while providing some natural filtration and attenuation to contaminants. The efficiency of these zones in reducing contaminant transport depends on their thickness and the presence of interbedded materials, such as shale, that can enhance their attenuation ability. The spatial distribution of these geological materials highlights the need for tailored groundwater management strategies based on the varying protective ability of the vadose zone.

Shale-dominated vadose zones, characterized by low permeability, occur in the northeastern, central and southern parts of the study area. The fine-grained texture of the shale slows infiltration and provides great filtration and adsorption of pollutants, making these areas less vulnerable to contamination.

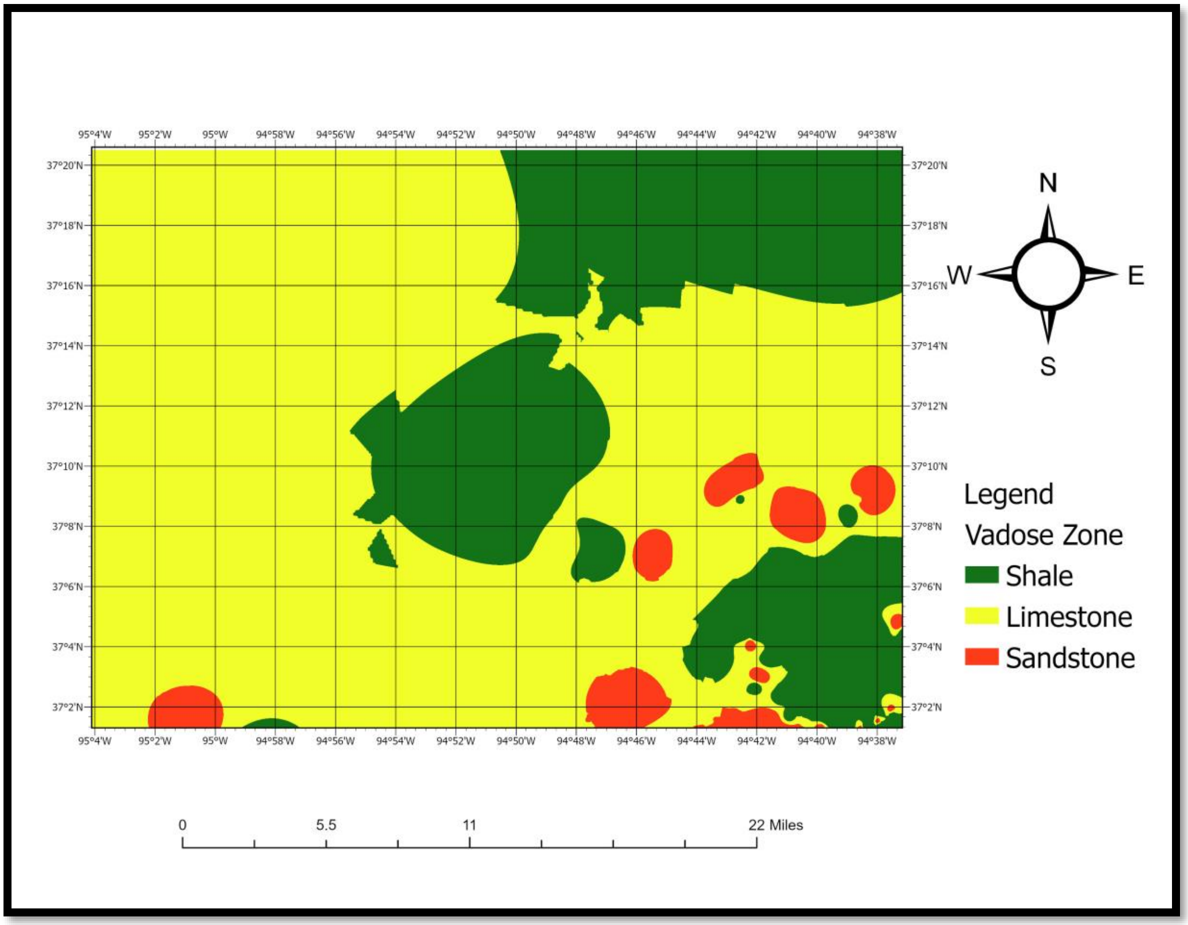

Figure 3.6: Impact of vadose zone composition, shale, limestone and sandstone in Cherokee County, Kansas

3.1.7 Hydraulic conductivity (C)

The hydraulic conductivity map of Cherokee County (Fig. 3.7) illustrates the spatial distribution of the aquifer's ability to transmit water through its pore spaces and fractures. Hydraulic conductivity is a critical groundwater vulnerability assessment parameter, as it controls the movement of water and contaminants within the aquifer. These variations are influenced by the type of geologic material in the aquifer.

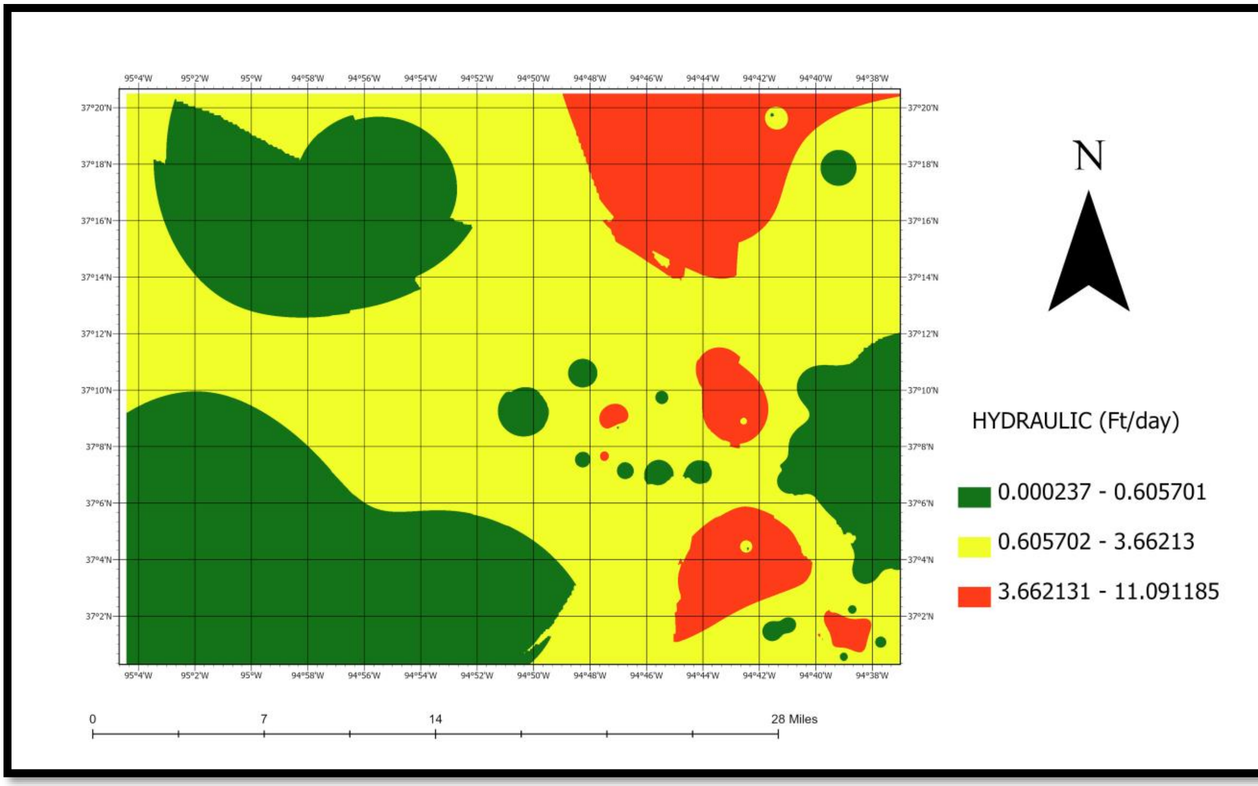

Figure 3.7: Spatial variability of hydraulic conductivity in Cherokee County, Kansas

Cherokee County is characterized mainly by low to moderate hydraulic conductivity (0.000237-19.091185 ft/d), reflecting the geological composition of the region. The dominant, low conductivity zones consist mainly of shale and clay-rich sediments. These materials significantly limit water movement and provide adequate natural protection against contamination. The moderate conductivity zones that form a north-south band across the eastern half of the county are characterized by sandstone and mixed lithologies. These zones facilitate steady groundwater flow while providing some natural filtration, thus offering partial protection against contamination.

3.2 DRASTIC map

The integration of the key hydrological parameters presented above allowed the calculation of the vulnerability index, displayed in the DRASTIC map of Cherokee County (Fig. 3.8). This map provides a comprehensive evaluation of groundwater vulnerability, highlighting areas at risk from surface contamination. The DRASTIC map displays two vulnerable zones: a very low (<80) and a low (80-106) vulnerability zones, showing the attenuation capacity of the geological and hydrological materials.

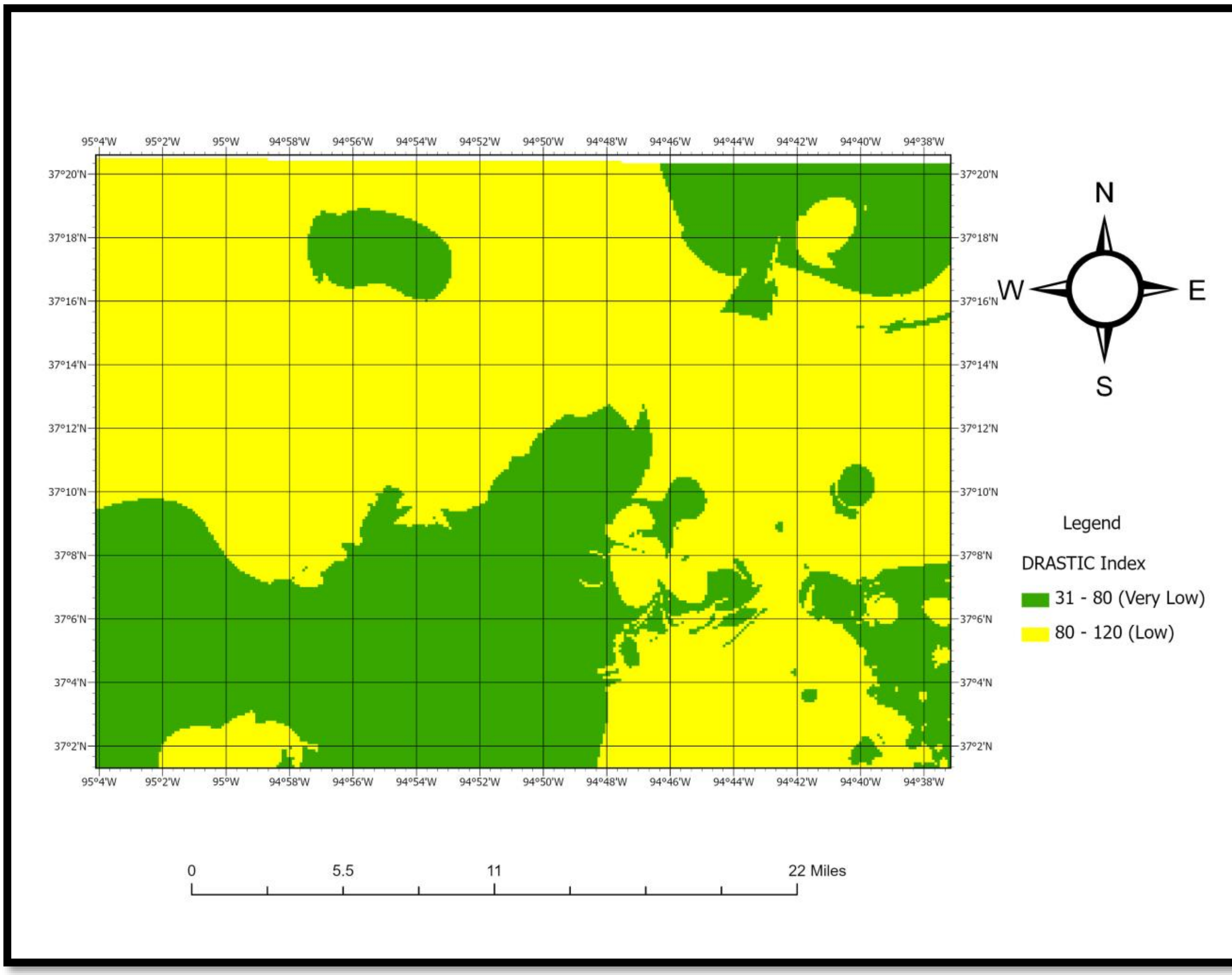

Figure 3.8: DRASTIC map indicating the vulnerability index of groundwater in Cherokee County.

The very low vulnerability zones (<80) dominate much of the southwest and northeast areas of Cherokee County, subordinately on the southeast and scattered areas. These areas are characterized by thick vadose zones composed of low permeability materials such as shale and clay, which act as effective barriers to contaminant transport. The depth to groundwater is generally greater in these zones and a low recharge rate further limits the potential for contaminants to infiltrate. Furthermore, moderate to steep slopes promote surface runoff, minimizing the risk of pollutants accumulating and infiltrating the aquifer. These factors contribute to the high level of natural attenuation observed in this zone.

Low vulnerability zones (80-120) are dominant in the study area. These regions feature moderate recharge rates, shallower groundwater levels, and more permeable soils, such as sandy or sandy clay textures (Fig. 3.2). Although the vadose zone in these regions offers some degree of attenuation, the presence of more permeable aquifer materials, including sandstone and karstified limestone, enhances the potential for contaminant transport when compared to very low vulnerability zones. Additionally, agricultural activities and historical mining operations in these areas require ongoing monitoring to address and mitigate localized contamination risks.

3.3 Relationship assessment

The relationship assessment of the DRASTIC model involved the analysis of the relationship between the concentrations of contaminants, specifically lead (Pb), zinc (Zn), and nitrate (NO_3), in Cherokee County. To assess the model's ability to predict the spatial distribution of groundwater contamination. It is important to note that these findings are based on historical water quality data, which poses a limitation in the assessment process, as this data may not accurately reflect current contamination levels.

Lead (Pb)

The result of the regression analysis for lead concentration and DRASTIC vulnerability index has an R^2 value of 0.44 (Fig. 3.9). The weak positive relationship shows that areas with high DRASTIC index values (more vulnerable) tend to have elevated lead concentration. However, the presence of a second population with Pb concentration approximately zero, irrespective of the vulnerability index, suggests that other factors beyond aquifer vulnerability may also influence lead distribution in the study area.

EPA's maximum contamination level for Pb is 0.015 mg/L and mining samples exceeded this threshold, especially in areas with legacy mining activities. This finding highlights the ongoing issue of lead contamination in vulnerable areas, which is enhanced by high recharge rates and shallow depths of the water table that facilitate rapid contamination transport. The moderate correlation suggests that while the DRASTIC index is a valuable indicator, lead levels are also influenced by factors beyond aquifer vulnerability, such as localized contamination sources.

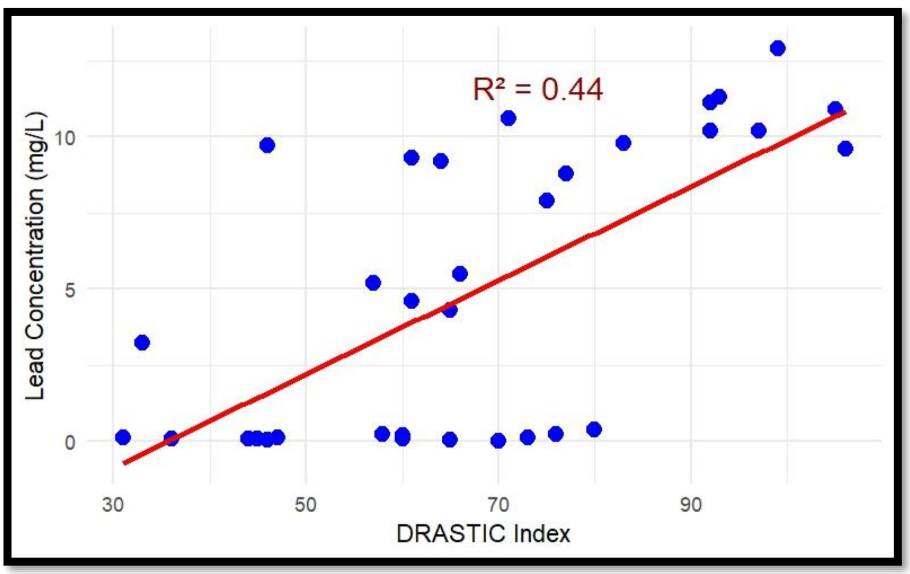

Figure 3.9: Positive correlation between DRASTIC vulnerability index and lead concentration (R^2 = 0.44).

Zinc (Zn)

Zinc exhibits the weakest correlation with the DRASTIC vulnerability index, with an R^2 value of 0.25 (Fig. 3.10), which suggests that localized geochemical and anthropogenic factors have a more significant influence on zinc distribution compared to the aquifer vulnerability. For instance, geochemical factors like pH, redox reactions and presence of minerals like carbonates or sulfides can affect zinc solubility and mobility in groundwater. On the other hand, anthropogenic factors, like historic mining, industrial discharge, agricultural activities and urban runoff can introduce zinc into groundwater and contribute to zinc variability. The EPA's secondary maximum contamination level (SMCL) for zinc is 5 mg/L, and while none of the observed concentrations exceeded the limit, the result suggests zinc levels are more spatially variable and less tied to DRASTIC parameters.

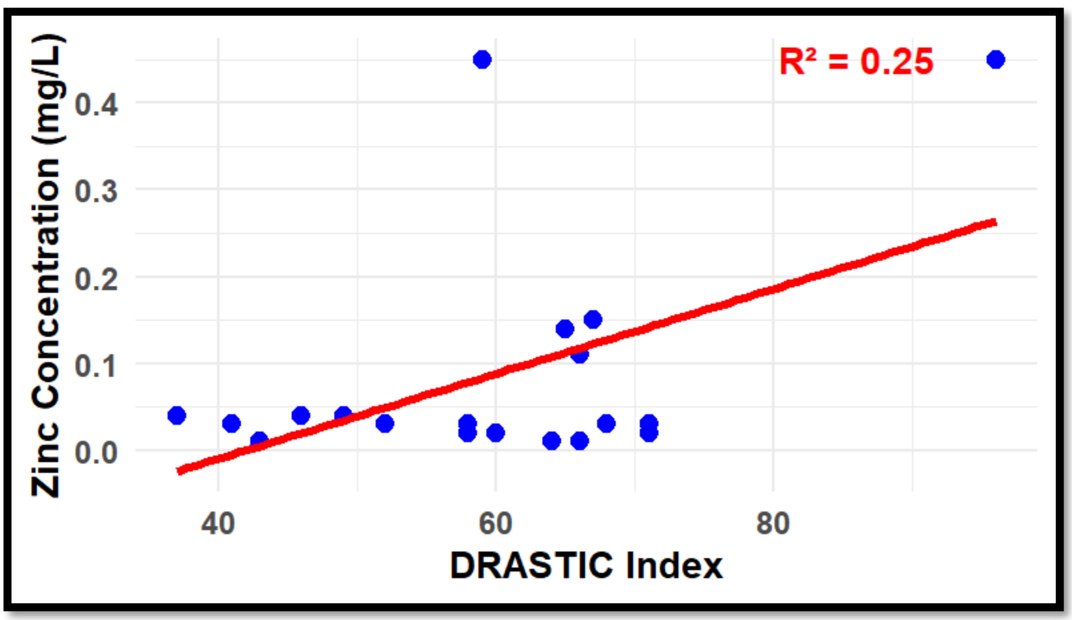

Figure 3.10: Weak positive correlation between DRASTIC vulnerability index and zinc concentration (R^2 = 0.25).

Nitrate (NO_3^-)

The regression analysis for nitrate concentration and DRASTIC vulnerability index showed an R^2 value of 0.46 (Fig. 3.11). This moderate positive correlation shows the mobility of nitrate in groundwater depends strongly on aquifer vulnerability parameters such as recharge, soil media and depth to water. The EPA's maximum contamination level (MCL) for nitrate as nitrogen is 10 mg/L as N. While none of the observed samples exceeded this limit, elevated nitrate levels were recorded in areas with intensive agricultural activities. These results are consistent with the model's prediction of increased vulnerability in agricultural regions with intensive fertilizer use.

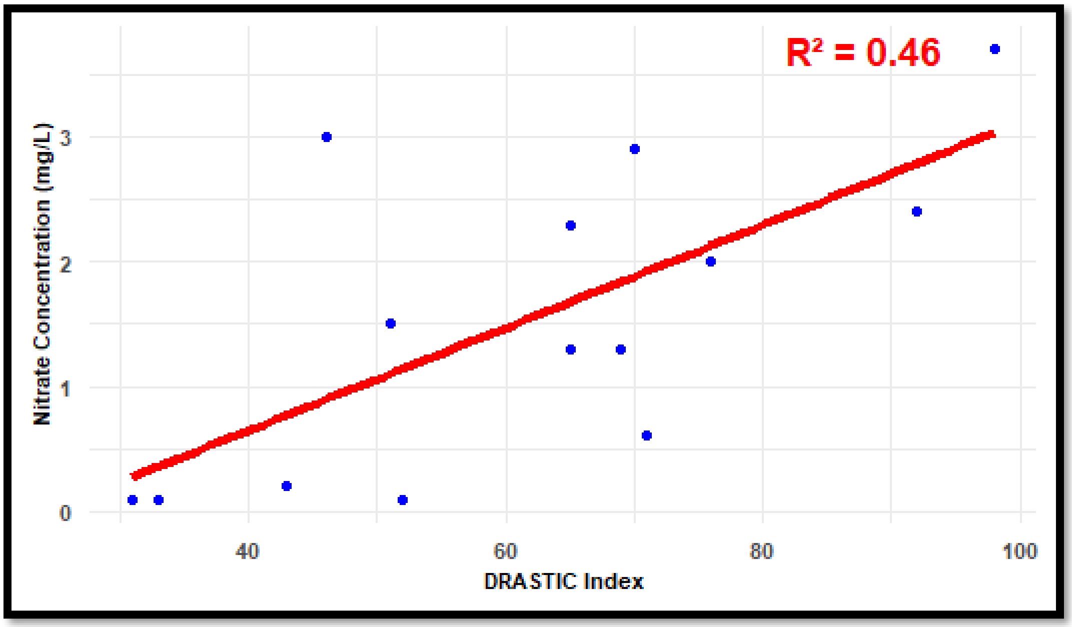

Figure 3.11: Relationship between DRASTIC index and nitrate concentration (R^2 0.46).

The results from the relationship assessment demonstrate the effectiveness of the DRASTIC model in predicting groundwater vulnerability, especially for surface-derived contaminants like nitrate. The scatter in the data points occurs because, while the DRASTIC model effectively captures major hydrogeological factors affecting nitrate vulnerability, nitrate contamination is influenced by additional factors, such as localized, farm-specific fertilizer practices, seasonal weather variations, small-scale soil differences, non-farm nitrate sources, and short-term water flow changes.

Chapter 4 - Discussion

4.1 Spatial distribution of groundwater vulnerability

The DRASTIC model results show that Cherokee County is predominantly very low to low vulnerability. Most of the county exhibits natural protection of groundwater due to low recharge rates, thick vadose zones, and the prevalence of low-permeability media such as the shale, particularly in the southwestern parts of the region. This is consistent with other regional studies on aquifer systems characterized by confining layers and low recharge rates, which act as natural protective barriers (Aller et al., 1987; Sener et al., 2009; Aboulouafa et al., 2017; Patel et al., 2022). In contrast, areas with higher DRASTIC index predominantly located in the southeastern and northwestern parts of the county are characterized by karstified limestone, sandy soils, and higher recharge rates, which contribute to increased vulnerability. The spatial patterns observed are consistent with those reported in other regional studies of karst aquifers, highlighting increased vulnerability due to minimal natural attenuation in karstified zones, where contaminants flow rapidly through fractures and conduits, thus emphasizing the need for protective measures (Ghahremanzadeh et al., 2018; Barbulescu, 2020).

4.2 Hydrological parameters influencing vulnerability

The weighting of the DRASTIC parameters played an important role in the vulnerability assessment. Parameters such as Depth to water (D) and vadose zone impact (I) are both weighed at 5, making them the main contributors to aquifer vulnerability. Depth to water (D) has a very strong effect on vulnerability particularly in areas with shallow groundwater levels in the southwest area of the county. Shallow depth coincides with high vulnerability score due to faster contaminant travel time, increasing the risk of aquifer contamination (Ghahremanzadeh et al.

2018). Similarly, net recharge (R) was a key factor in high vulnerability zones with a weight of 4. High recharge rates in the southeastern area, where permeable rocks dominate, facilitate the movement of surface pollutants into the aquifer. In contrast, areas with low recharger rates such as shale-dominated areas exhibit reduced vulnerability. This observation aligns with the findings of Aller et al., (1987), which identifies recharge as a significant determinant of groundwater vulnerability.

The vadose zone impact (I) was another important parameter in groundwater vulnerability. Vadose zones dominated by limestones are characterized by high permeability and increase contamination risk, while the shale-dominated vadose zone provides substantial protection against contaminant transport. This result highlights the buffering capacity of vadose zone in mitigating contamination transport and aligns very well with previous studies (Sener et al., 2009).

Topography was assigned to have the lowest rating and thus had the least impact on vulnerability studies. Flat areas in the southeast were associated with higher infiltration but their influence was reduced due to the dominance of other parameters.

4.3 Land use data in Cherokee County

The USDA Cropland Data Layer (CDL) land use map of Cherokee County provides a nuanced understanding of groundwater vulnerability. By integrating this data, we identified specific areas where land use practices may increase groundwater vulnerability. The county is characterized by a landscape dominated by agricultural activities, which accounts for majority of its land use (Fig. 4.1).

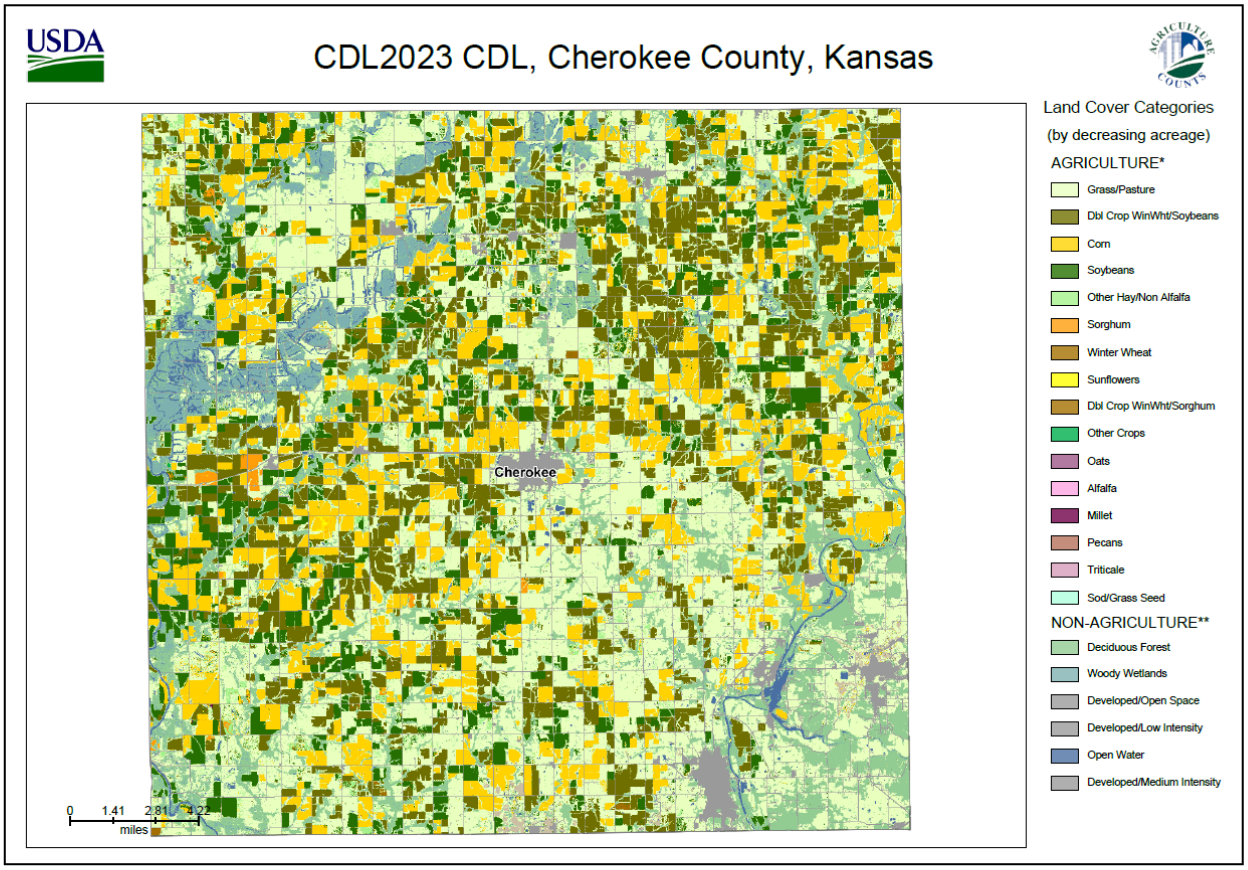

Figure 4.1: Land use map of Cherokee County (USDA).

According to Crop Data Layer (CDL) 2023, row crops like corn and soybeans cover approximately 38% of the county, concentrated in the eastern and central areas. These crops are supported by widespread fertilizer and pesticide use, which increase groundwater contamination risks, especially nitrate leaching. Although grasslands and pastures have declined by 15% since 2019, they remain significant for livestock grazing, while rotational crops like wheat and sorghum further support the region's agroeconomic framework. The dominance of agriculture and reliance on groundwater for irrigation makes the county's aquifers particularly vulnerable to contamination. This highlights the critical link between land use and aquifers vulnerability (USDA-NASS, 2023; Kansas Geological survey, 2020).

Non-agricultural land use includes woody wetlands, deciduous forests and developed areas which collectively cover around 32% of the county. Forested areas, primarily in the southwest, act as natural buffers, mitigating contamination through biofiltration and reducing surface runoff. Woody wetlands, though limited in extent, are crucial for nutrient retention and groundwater recharge. Urbanized areas increase stormwater runoff due to impervious surfaces, leaching heavy metals and other contaminants into the aquifer. These developed zones align with a moderate groundwater vulnerability score in the DRASTIC model, highlighting the interplay between urbanization and hydrological risks (Arnold and Gibbson, 1996; Tinier, 1999).

Although the county's overall DRASTIC index score indicates very low to low risk, localized agricultural and urban hotspots exhibit elevated contamination potential. For example, nitrate concentration exceeds 10 mg/L as N in groundwater around corn/soybean fields, which supporting the model's high-risk designation for these areas.

4.4 Contamination analysis and model relationship assessment

The DRASTIC model, performance was assessed using lead (Pb), zinc (Zn) and nitrate (NO_3^-) concentrations from the National Water Information System (NWIS), yielded a varying degree of correlation. The correlation between the DRASTIC index and contaminant concentration allowed the evaluation of the model's predictive power.

Lead (Pb)

The spatial distribution of lead concentration (Fig. 4.2) highlights localized contamination tied to legacy mining, industrial activities and complex hydrological dynamics. Many parts of the county exhibit elevated lead levels which exceeds the U.S. EPA maximum contamination levels of 0.015

mg/L. However, an anomaly in the distribution of lead concentration was observed with highest concentration in the northeast-southwest (NE-SW) band across the county, rather than aligning with the southeastern mining district the primary historic source of contamination. This distribution underscores the interplay of contaminant transport mechanism and anthropogenic influences. These areas are generally characterized by legacy infrastructure such as ageing pipes, abandoned mining sites and industrial zones.

High lead exposure poses a significant threat to human health. Children are particularly vulnerable with lead exposure linked to learning disabilities and behavioral problems (WHO, 2021). In addition, adults exposed to lead can lead to cardiovascular disease, decreased kidney functions and reproductive problems (CDC, 2023). Contaminated groundwater discharging into surface waters increases these risks, especially in areas close to mining sites, mine tailings and runoff pathways, necessitating urgent intervention to protect vulnerable population and biodiversity (Triantafyllidou et al., 2021).

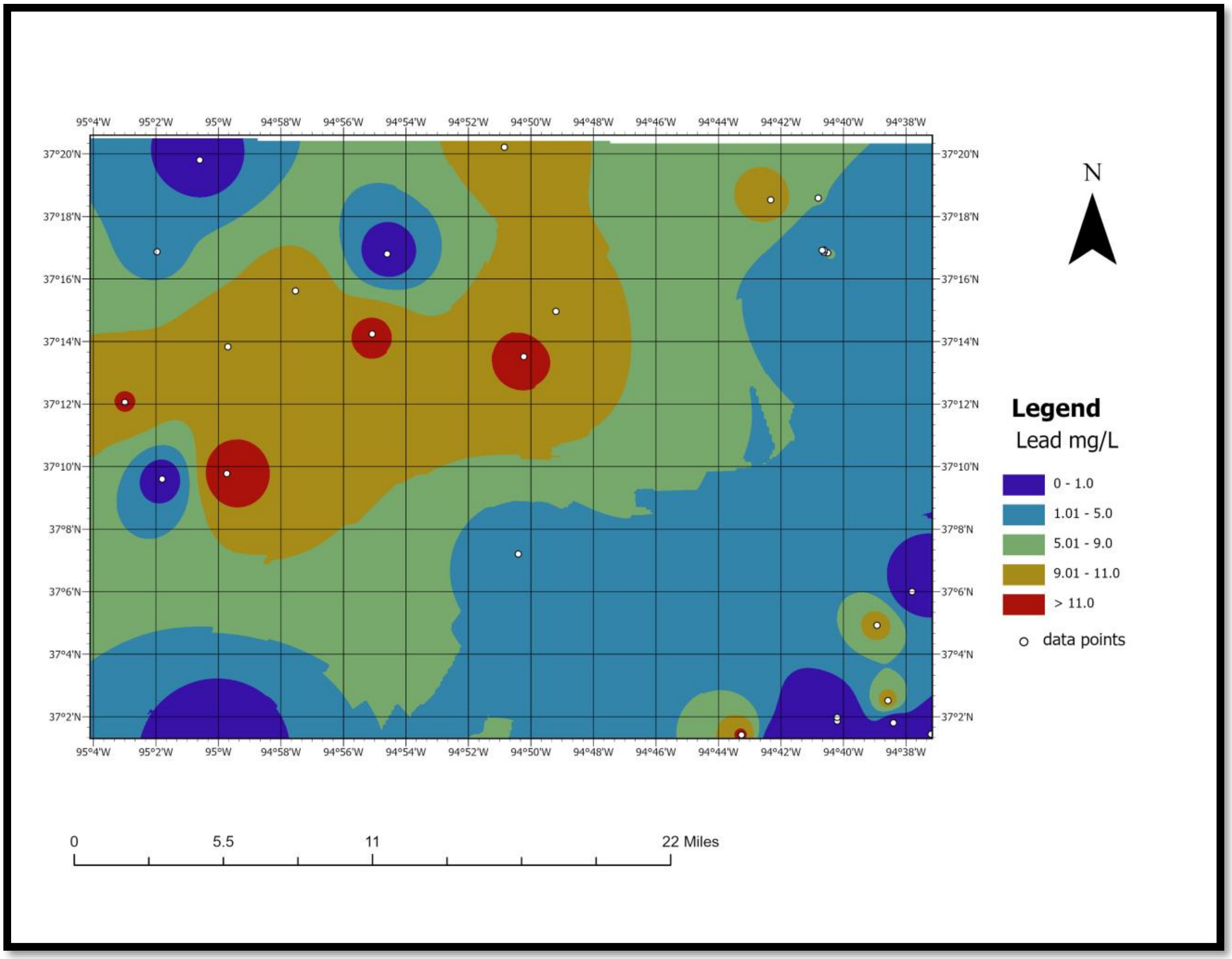

Figure 4.2: Spatial distribution of lead (Pb) in Cherokee County.

The weak correlation (R^2 = 0.44) highlights partial influence of historic mining activities on lead distribution, while also highlighting the role of additional localized factors such as anthropogenic and geochemical factors significantly affected lead migration. Additionally, abandoned industrial sites and corroded water infrastructure may act as secondary contamination sources, further reducing the predictive power of the DRASTIC model in this context. Studies have shown similar persistent influence of legacy mining on groundwater quality years after mining operation ended (Johnson et al., 2016).

Zinc (Zn)

Zinc showed the weakest correlation ($R^2 = 0.25$), which suggest limited dependence on aquifer vulnerability parameters. While zinc concentrations were below the EPA's secondary maximum contaminant level (5mg/L), the spatial variability (Fig. 4.3) of contaminant concentration suggests the influence of factors beyond hydrological parameters (Pope, 2005). The zinc distribution is likely governed by localized geochemical processes and anthropogenic activities. Elevated levels are often linked to historic mining sites (Fig. 1.2), manufacturing facilities and improper industrial waste disposal.

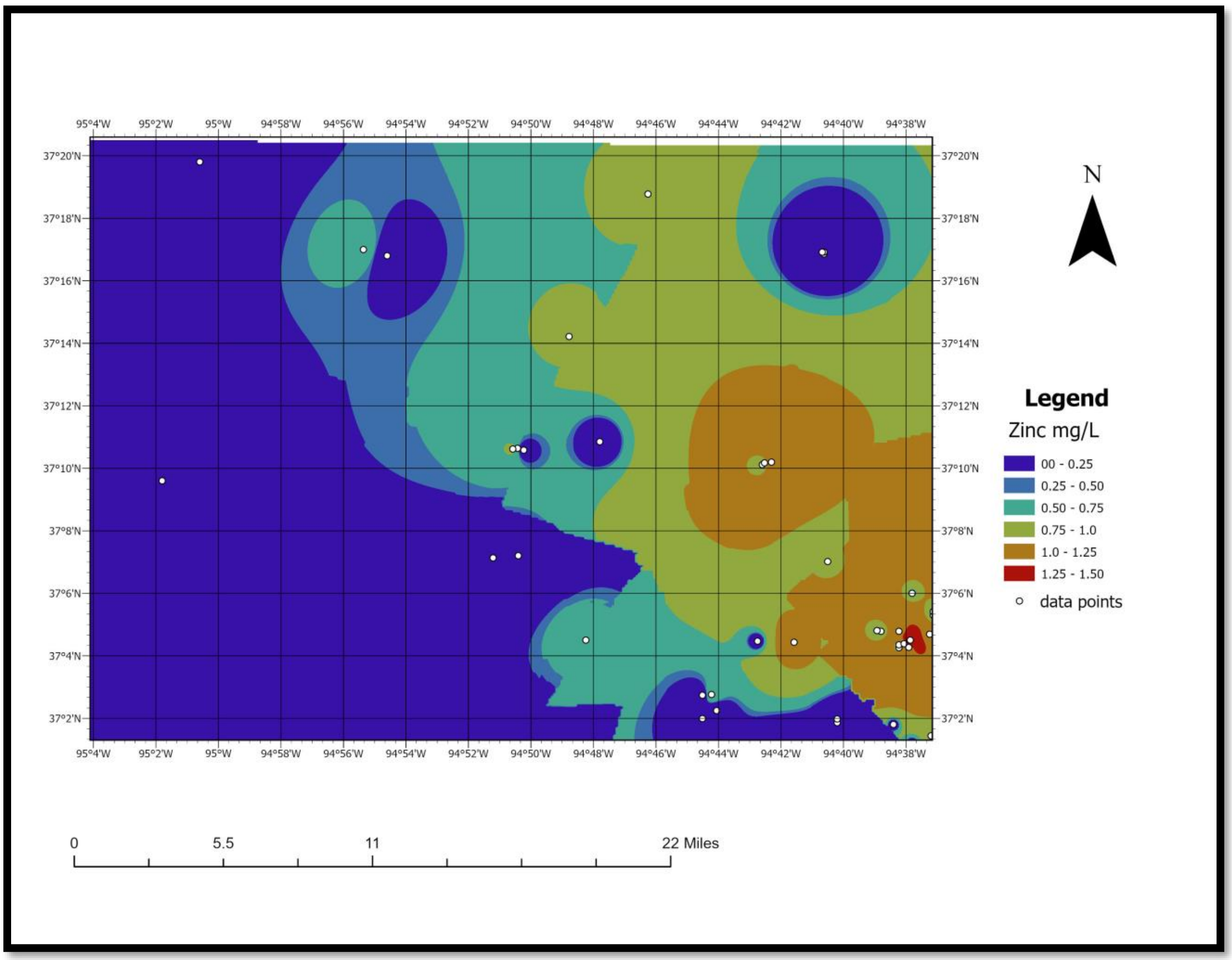

Figure 4.3: Spatial distribution of zinc (Zn) in Cherokee County.

The spatial distribution of zinc (Fig. 4.3) is heterogenous due to its adsorption to clay minerals and organic matter in aquifers. The limited mobility reduces its correlation with aquifer vulnerability while making the risk assessment complicated. Despite zinc concentration remaining below EPA's secondary maximum contamination level of 5 mg/L, the presence detectable zinc levels can still pose significant ecological risks, particularly to aquatic ecosystem where it bioaccumulates and to human exposure through consumption of affected organisms or contaminated water (Eisler, 1993). It is crucial to implement a combination of advanced groundwater monitoring, very strict policies on industrial discharge and public education on the environmental impact of zinc to ensure sustainable water resource management for the region.

Nitrate (NO_3^-)

The spatial distribution of nitrate in Cherokee County (Fig. 4.4) shows significant variation across the county. Like (Pb), nitrates showed a moderate correlation with (R^2 = 0.46), with elevated concentrations clustered around areas of intensive agricultural activities, the prediction of surface-derived risk, especially in agricultural areas (Fig. 4.1). The high mobility of nitrate compared to other metals highlights its tendency to quickly leach into the groundwater system after precipitation.

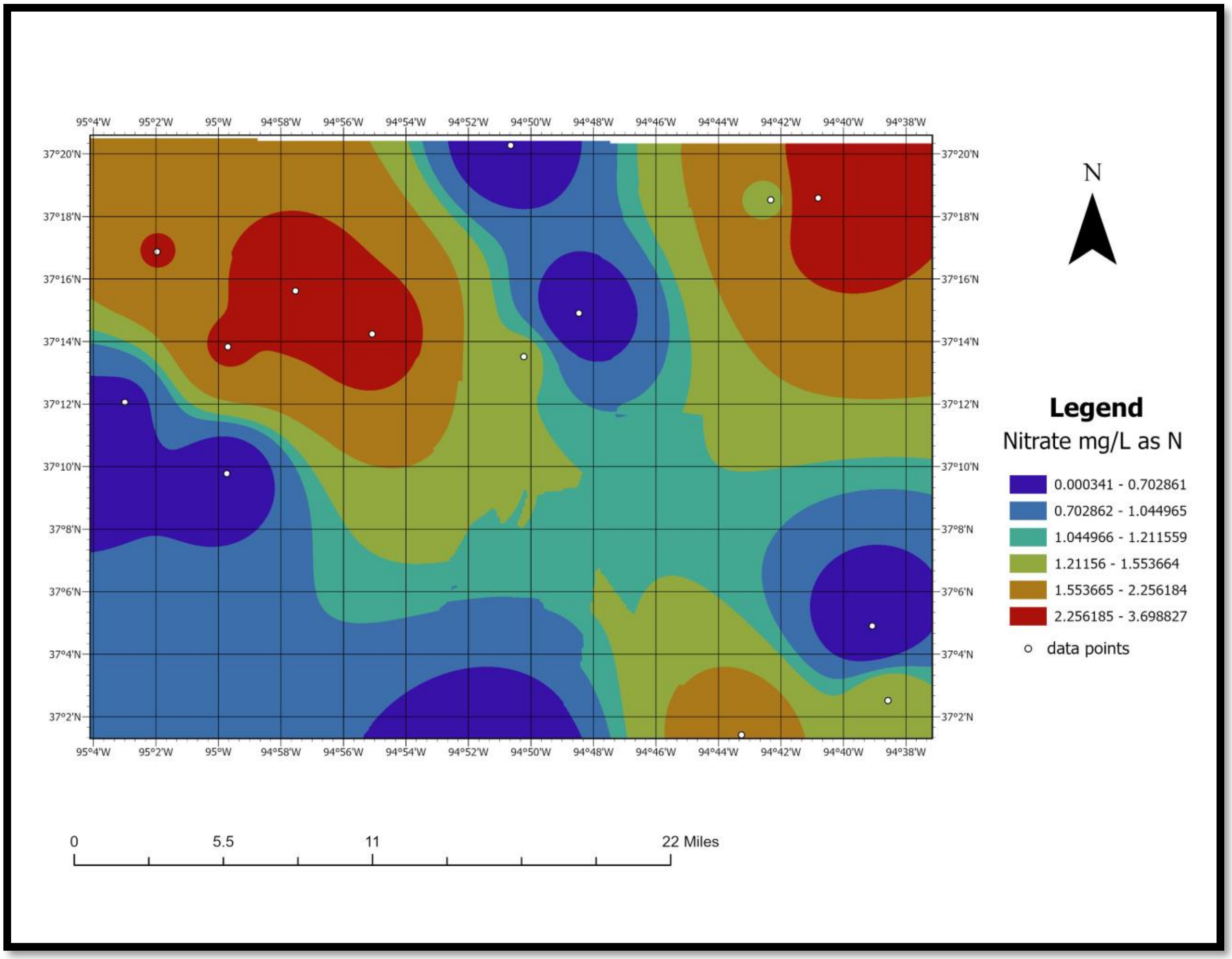

Figure 4.4: Spatial variability of nitrate concentration in Cherokee County, KS.

The prevalence of agricultural practices such as excessive application of nitrogen-rich fertilizers and suboptimal manure management exacerbates the potential for nitrate contamination (McFarlane et al 2005). While the nitrate levels remain below the US EPA maximum contaminant level (10 mg/L as nitrogen), their relative elevated levels highlight persistent challenges of managing nonpoint source pollution in these areas (Focazio et al., 2002).

4.5 Comparison with regional and global studies

Findings from this study align with global assessment of groundwater vulnerability using DRASTIC and similar models. A study in Morocco's Berrechid Plain shows that areas with shallow water tables and sandy soils exhibited high vulnerability to contamination, particularly to nitrate due to agricultural activities (Abouloufa et al.,2017). Similarly, Barbulesca (2020) highlighted the critical need for tailored modifications to DRASTIC models to account for specific pollutants and influence of land-use dynamics, which is consistent with the modifications applied to this study.

However, the moderate correlation observed in this study highlights the significant limitations of relying solely on traditional DRASTIC models when assessing vulnerability in historic contamination context (lead and zinc from legacy mining). While the DRASTIC model provides a preliminary assessment, the linear relationship with contaminant concentration may not fully capture the complexities of point source pollution or localized hydrological factors. Modified DRASTIC approaches can help refine vulnerability predictions. For instance, Aquifer Vulnerability Index (AVI) and Concentration of flow Overlying layers Precipitation (COP) offer complementary insight into aquifer vulnerability. The AVI evaluates vulnerability based on resistance of the overlying layers (Van Stempvoort et al., 1993) and could be applied to the karstic topography of the county, where there is high infiltration through fractured bedrocks. The COP model was designed to address surface water interaction and precipitation-driven recharge (Zwahlen, 2004), which may be more suitable for agricultural areas with high use of fertilizers, such as Cherokee's corn and soybean fields.

Additionally, isotopes studies can play a crucial role in differentiating pollutant sources and supporting vulnerability assessment. The stable isotopes of nitrogen ($\delta^{15}N$) and oxygen ($\delta^{18}O$) in nitrate can help identify different sources of nitrate like agriculture, septic system, and atmospheric input (Kendall et., 2007). Similarly lead isotopes ratio ($^{207}Pb/^{206}Pb$) can be applied to trace contamination to specific mining or industrial source (Komarek et al., 2008). The integration of isotopic analysis and vulnerability assessment would enhance the accuracy of the model and inform the development of targeted remediation strategies within Cherokee County.

4.6 Implications for water resource management

This study highlights the need for targeted interventions in highly vulnerable zones as identified by the DRASTIC model and confirmed through contamination data (lead, zinc and nitrate). Key recommendations in accord with global best practices and tailored to Cherokee County's unique situation include to:

- Restrict activities that increase contamination risks, like intensive agriculture and industrial operations in areas with high DRASTIC indexes.
- Deploy real-time groundwater monitoring devices in high-risk industrial and agricultural areas to capture current contamination levels and implement remediation strategies in historically impacted areas (Pope, 2005).
- Incorporate isotope studies to identify different contamination sources (Kendall et al., 2008).
- Apply phytoremediation in agricultural hotspots to absorb excess nitrate as demonstrated in India's Birbhum district (Thapa et al., 2023).
- Engage stakeholders in sustainable groundwater use practices and advocating for policies that address both point and nonpoint pollutions sources.

4.7 Limitations and future directions

A significant caveat in this study is the reliance on historic water quality data between 1972 and 2009, which may not accurately reflect current contamination levels. Contamination dynamics can be significantly altered by changes in agriculture fertilizer use patterns or industrial discharge regulations over time. This limitation means the model may not fully capture the complex interactions of contaminant transport, which often involves nonlinear processes. Additionally, the model does not account for seasonal variability in recharge rates or contaminant loading, which are critical in vulnerability assessment and contaminant transport.

A second significant limitation is the model's assumption that contamination occurs exclusively through vertical transport from surface. This fails to account for potential lateral contamination pathways, which may be important in areas with complex geology and legacy contamination. Similarly, the model does not distinguish between point and non-point sources of contamination, potentially underestimating risks with concentrated pollution sources.

The model also provides limited insight into groundwater recharge sources. While DRASTIC assumes precipitation as the primary source of recharge, the Ozark Plateau Aquifer may receive significant input from losing streams or inter-aquifer transfers. This uncertainty complicates efforts to trace contamination origins and predict contamination patterns. Additionally, the DRASTIC model's vulnerability assessment does not explicitly account for hydraulic conductivity variations within the vadose zone, representing a significant limitation in its predictive capability. While the model incorporates saturated zone hydraulic conductivity (parameter C) and general vadose zone media (parameter I), it overlooks how moisture-dependent permeability changes in unsaturated soils could affect contaminant transport rates. While the study currently relies on coarser FAO soil maps, incorporation of higher-resolution soil data from sources like the NRCS (Natural Resources

Conservation Service) soil surveys with resolution 1:24,000 scale offers significantly more detailed characterization of soil properties relevant to contaminant transport.

Future research should explore hybrid models that incorporate machine learning, such as Random Forest, to predict contaminant risk dynamically. Additionally, geochemical and biological transport processes would provide a comprehensive understanding of contamination pathways. The impact of climate variability on groundwater vulnerability is another critical area for the future. It is crucial to understand how extreme weather events, such as drought or intensive rainfall, can influence rates and contaminant leaching. Tools like the COP model, which focuses on precipitation-driven risks, could be valuable for Cherokee's climate conditions.

Finally, expanding high-resolution and real-time water quality monitoring networks is crucial for adaptive management. Deploying loT sensors in vulnerable areas to collect real-time data on water table fluctuation and contamination levels would enable more responsive decision making. In addition, the DRASTIC model should be periodically reviewed and refined to integrate real-time hydrological data, climate change and land use changes to improve groundwater vulnerability assessment. By addressing these limitations, Cherokee County can refine its groundwater vulnerability assessment while ensuring safety in the face of climate changes and evolving land-use practices.

Chapter 5 - Conclusions

The integrated GIS-based DRASTIC model to evaluate groundwater vulnerability of the Ozark Plateau Aquifer in Cherokee County showed that the county is predominantly very low to low vulnerability, with index values ranging from 31 to 120. The soil media (presence of impermeable shale layers) and vadose zone characteristics (thickness and composition) played a significant role in reducing contaminant mobility and groundwater vulnerability.

The model’s relationship assessment showed a moderate positive correlation between the DRASTIC index and lead (R^2 = 0.44) and nitrate (R^2 = 0.46) concentrations, while zinc concentration showed a weak correlation (R^2 = 0.25) with vulnerability index. This demonstrates that DRASTIC model can be used to effectively map areas or zones that are prone to surface contamination.

While the model identified potential areas at risk, it does not indicate the source of contamination. By integrating DRASTIC model with advanced tools like machine learning or process-based models like MODFLOW, future work can enhance predictive accuracy and address nonlinear contamination dynamics.

This work provided a preliminary assessment of the Ozark Plateau Aquifer's vulnerability and highlighted the potential for using DRASTIC model to predict aquifer vulnerability, offering a tool for proactive groundwater management not just in Cherokee but also to other areas with similar problems. Collaboration among government agencies, environmental organizations, local communities and academic institutions is crucial to ensure sustainability of groundwater for future generations. To prevent long-term contamination and ensure access to safe drinking water, water quality monitoring programs must be strengthened and targeted remediation effort should be implemented in high-risk zones.

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AI-Assisted Research Disclosure: During the preparation of this report, the authors used ChatGPT (OpenAI) to assist with language refinement and structural organization of the content. However, all technical analyses, data interpretation, and scientific conclusions were independently developed by the authors. The use of AI was limited to improving readability and did not influence the study's methodological approach or findings.

Appendix A-Additional information

Table A.1: Lead data

Lead Conc.	Latitude	Longitude
4.3	37.28117	-95.0327
9.7	37.26034	-94.9589
10.2	37.23062	-94.995
10.6	37.2009	-95.05
7.9	37.18034	-95.07
11.1	37.23728	-94.918
11.3	37.22534	-94.8372
12.9	37.16284	-94.9955
5.2	37.30978	-94.6802
10.2	37.30894	-94.7055
9.6	37.28056	-94.675
9.8	37.04201	-94.643
10.9	37.02368	-94.7211
5.5	36.99896	-94.8513
9.2	37.08206	-94.6488
8.8	37.2495	-94.82
9.3	37.337	-94.8475
3.24	37.12	-94.84
0.83	37.58	-94.81
0.2	37.1	-94.63
0.12	37.63	-94.63
0.06	37.03	-94.64
0.11	37.02	-94.63
0.12	37.02	-94.63
0.11	37.031	-94.67
0.1	37.033	-94.67

0.12	37.02	-94.69
0.09	37.024	-94.62
0.08	37.02	-94.703
0.12	37.01	-95.412
0.25	37.33	-95.01
0.03	37.281	-94.677
0.1	37.282	-94.677
4.59	37.282	-94.678
0.23	37.28	-94.91
0.39	37.16	-95.03
0.06	37.02	-95.73

Table A.2: Zinc data

Zinc conc.	Latitude	Longitude
0.14	37.28117	-95.0327
0	37.26034	-94.9589
0	37.23062	-94.995
0.03	37.2009	-95.05
0.04	37.18034	-95.07
0.02	37.23728	-94.918
0	37.22534	-94.8372
0.03	37.16284	-94.9955
1.5	37.30978	-94.6802
0	37.30894	-94.7055
0.11	37.04201	-94.643
0.15	37.02368	-94.7211
0.03	36.99896	-94.8513
0	37.08006	-94.6488
0	37.2495	-94.82

0.03	37.337	-94.8475
0	37.12	-94.84
0.05	37.58	-94.81
0.03	37.1	-94.63
0	37.63	-94.63
0	37.03	-94.64
0	37.02	-94.63
0.02	37.02	-94.63
0.04	37.031	-94.67
0	37.033	-94.67
0.01	37.02	-94.69
0.45	37.024	-94.62
0	37.02	-94.703
0	37.01	-95.412
0	37.33	-95.01
0.01	37.281	-94.677
0	37.282	-94.677
0.02	37.282	-94.678
0.04	37.28	-94.91
0	37.16	-95.03
0.01	37.02	-95.73

Table A.3: Nitrate data

Nitrate conc.	Latitude	Longitude
2.3	37.28117	-95.0327
3	37.26034	-94.9589
2.4	37.23062	-94.995
0.6	37.2009	-95.05
0	37.18034	-95.07

2.9	37.23728	-94.918
1.3	37.22534	-94.8372
0.2	37.16284	-94.9955
3.7	37.30978	-94.6802
1.3	37.30894	-94.7055
1.5	37.04201	-94.643
2	37.02368	-94.7211
0	36.99896	-94.8513
0.1	37.08173	-94.6513
0.1	37.24839	-94.8077
0.09	37.33783	-94.8441

Table A.4: Well depth

Latitude (Datum NAD 27)	Longitude (Datum NAD 27)	Static water level in (m)
37.3354864	-94.7017	71.0184
37.32911	-94.6927	60.96
37.29877	-94.6546	40.2336
37.0746	-94.9985	39.624
37.28532	-94.909	51.816
37.28355	-94.9249	54.2544
37.17527	-94.8032	64.008
37.15331	-94.8348	45.72
37.17746	-94.7276	36.576
37.16226	-94.7577	54.864
37.14767	-94.7849	46.9392
37.14493	-94.7837	41.4528
37.1261	-94.8028	52.7304

37.12751	-94.7917	7.62
37.12011	-94.7803	7.62
37.16769	-94.669	38.1
37.15235	-94.7118	91.44
37.1493	-94.7099	42.672
37.14813	-94.6401	70.104
37.14816	-94.6428	33.528
37.1412	-94.6483	36.576
37.13573	-94.6736	50.292
37.05147	-94.8654	72.5424
37.04443	-94.8512	51.816
37.04496	-94.8506	46.3296
37.11823	-94.7348	66.4464
37.11827	-94.76	76.2
37.1068	-94.6304	21.336
37.11439	-94.6414	48.768
37.10599	-94.652	15.24
37.1126	-94.6826	26.54198
37.10213	-94.6229	12.192
37.07575	-94.6304	70.104
37.07931	-94.622	64.3128
37.07482	-94.6184	84.7344
37.06122	-94.7209	9.144
37.07283	-94.7066	27.432
37.07394	-94.7055	9.144
37.07394	-94.6986	29.1084
37.06846	-94.7033	38.1
37.07136	-94.7014	45.72
37.04735	-94.6193	24.384
37.05937	-94.6345	18.288

37.05012	-94.6984	35.052
37.05844	-94.6379	36.576
37.05934	-94.6941	48.768
37.04461	-94.7005	24.384
37.03906	-94.6869	24.384
37.0372	-94.6753	12.192
37.03545	-94.641	36.576
37.03677	-94.6453	6.7056
37.03178	-94.6456	15.24
37.03178	-94.6256	82.296
37.02108	-95.0085	30.48
37.00547	-94.9961	3.048
37.00356	-94.9848	45.72
37.02996	-94.7664	22.86
37.01426	-94.758	21.336
37.00048	-94.7574	24.384
37.01812	-94.6289	15.24
37.02444	-94.6233	18.288
37.0299	-94.625	38.1
37.02631	-94.6363	18.288
37.02268	-94.6363	45.72
37.02267	-94.6317	48.768
37.02268	-94.6478	24.384
37.02268	-94.6409	18.288
37.02177	-94.6421	27.432
37.02449	-94.6317	21.336
37.0254	-94.6329	15.24
37.02003	-94.663	38.7096
37.02086	-94.6501	15.24
37.02447	-94.6569	21.336

37.02854	-94.6666	51.816
37.02995	-94.6318	12.192
37.02173	-94.6645	48.768
37.02446	-94.6592	15.24
37.02601	-94.6624	42.672
37.02989	-94.666	24.384
37.02464	-94.6922	22.2504
37.0154	-94.6845	38.7096
37.01551	-94.6485	28.3464
37.00853	-94.6213	21.336
36.99897	-94.629	18.288
37.0004	-94.6501	60.96
37.00162	-94.6958	12.192
36.99928	-94.7213	27.432
37.00269	-94.6317	18.288
37.00359	-94.642	24.384
37.00995	-94.6501	18.288
37.01539	-94.657	30.48
37.01086	-94.6833	38.1
37.0154	-94.6822	26.2128
37.00981	-94.6681	19.812
37.01086	-94.6833	15.24
37.02812	-94.6822	22.86

Table A.5: Recharge data

Latitude (Datum NAD 27)	Longitude (Datum NAD 27)	Net Recharge (gpm)
37.3354864	-94.7017	400
37.32911	-94.6927	50
37.29877	-94.6546	40
37.0746	-94.9985	
37.28532	-94.909	300
37.28355	-94.9249	
37.17527	-94.8032	150
37.15331	-94.8348	20
37.17746	-94.7276	1200
37.16226	-94.7577	15
37.14767	-94.7849	50
37.14493	-94.7837	50
37.1261	-94.8028	70
37.12751	-94.7917	30
37.12011	-94.7803	25
37.16769	-94.669	150
37.15235	-94.7118	1000
37.1493	-94.7099	75
37.14813	-94.6401	950
37.14816	-94.6428	400
37.1412	-94.6483	700
37.13573	-94.6736	40
37.05147	-94.8654	45
37.04443	-94.8512	300
37.04496	-94.8506	25
37.11823	-94.7348	30

37.11827	-94.76	35
37.1068	-94.6304	20
37.11439	-94.6414	15
37.10599	-94.652	20
37.1126	-94.6826	300
37.10213	-94.6229	15
37.07575	-94.6304	750
37.07931	-94.622	80
37.07482	-94.6184	50
37.06122	-94.7209	35
37.07283	-94.7066	1000
37.07394	-94.7055	60
37.07394	-94.6986	533
37.06846	-94.7033	625
37.07136	-94.7014	650
37.04735	-94.6193	15
37.05937	-94.6345	20
37.05012	-94.6984	30
37.05844	-94.6379	60
37.05934	-94.6941	15
37.04461	-94.7005	50
37.03906	-94.6869	15
37.0372	-94.6753	15
37.03545	-94.641	20
37.03677	-94.6453	60
37.03178	-94.6456	25
37.03178	-94.6256	30
37.02108	-95.0085	60
37.00547	-94.9961	3
37.00356	-94.9848	60

37.02996	-94.7664	15
37.01426	-94.758	40
37.00048	-94.7574	20
37.01812	-94.6289	30
37.02444	-94.6233	8
37.0299	-94.625	20
37.02631	-94.6363	15
37.02268	-94.6363	12
37.02267	-94.6317	15
37.02268	-94.6478	15
37.02268	-94.6409	25
37.02177	-94.6421	30
37.02449	-94.6317	25
37.0254	-94.6329	20
37.02003	-94.663	140
37.02086	-94.6501	25
37.02447	-94.6569	25
37.02854	-94.6666	30
37.02995	-94.6318	30
37.02173	-94.6645	20
37.02446	-94.6592	25
37.02601	-94.6624	30
37.02989	-94.666	30
37.02464	-94.6922	40
37.0154	-94.6845	30
37.01551	-94.6485	3
37.00853	-94.6213	100
36.99897	-94.629	30
37.0004	-94.6501	2
37.00162	-94.6958	20

36.99928	-94.7213	12
37.00269	-94.6317	25
37.00359	-94.642	40
37.00995	-94.6501	12
37.01539	-94.657	7
37.01086	-94.6833	20
37.0154	-94.6822	25
37.00981	-94.6681	20
37.01086	-94.6833	20
37.02812	-94.6822	30