Environmental risk factors and cancer incidence in rural central Kansas

by

Luke David Romang

B.S., University of Missouri-Kansas City, 2023

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

Approved by:

Major Professor
Dr. Karin Goldberg

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Abstract

Groundwater contamination is a global concern in agricultural regions and can lead to adverse health effects for affected populations. In central Kansas, three predominantly agricultural counties exhibit notably high cancer incidence rates compared to the state average. This study investigates potential links between land use practices, groundwater contamination, and elevated cancer rates in these counties while also assessing the role of radon exposure. Additionally, we sought to identify factors controlling contaminant occurrence and distribution in local groundwater. We collected 56 groundwater samples, deployed 39 indoor radon tests, and conducted 65 household cancer surveys. A GIS-based buffer analysis using CDL and NLCD land use datasets was performed to explore potential associations between land use and groundwater contamination. Geochemical analyses were used to evaluate possible controls on contaminant occurrence, including pH, redox conditions, and water-rock interactions. Our findings indicate that redox state is the primary control on groundwater geochemistry and contaminant distribution. Evaporation was a key factor influencing groundwater chemistry in Russell County, while water-rock interactions were more significant in Lincoln and Ellsworth County. In the majority of the study area, nitrate and uranium concentrations exceeded EPA and WHO maximum contaminant levels, and 48.7% of radon measurements exceeded the EPA action level of 4 pCi/L. Although no clear correlations were found between agricultural land use and contaminant occurrence, a positive association was observed between open-water land cover and nitrate concentrations. Our cancer data reveals that 64% and 77% of households surveyed in Lincoln and Russell counties, respectively, reported cancer within the household. Additionally, 83% of participants in Lincoln County have a family history of cancer. In Russell County, 6% of cases were in individuals under 20 years old, while in Ellsworth County, 18% were in

individuals aged 20-40. This study provides preliminary correlational evidence linking environmental factors to cancer causation and contributes cancer data for the region, offering a glimpse of potential environmental cancers that might guide future studies and provide a framework for future public health guidelines.

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Acknowledgements

I would like to express my heartfelt gratitude to my family and friends, especially my fiancée, Jillian, whose unwavering support, encouragement, and sense of humor have been a constant source of motivation. I am also deeply grateful to my parents for providing me with every opportunity to succeed and build my career.

A special thank you to Dr. Karin Goldberg for her dedication and hard work in our research, particularly in managing logistics and planning. Her guidance has been instrumental in my professional growth, and I cannot thank her enough. I also extend my sincere appreciation to my committee members, especially Dr. Matt Kirk, who taught me everything I know about hydrogeology and geochemistry, and Dr. Helene Avocat, whose expertise helped me navigate the GIS portion of my studies.

I would also like to acknowledge my field assistants, Sam and Connor, for their invaluable support and companionship during fieldwork. Their professionalism and friendship made the experience all the more rewarding.

Finally, I want to express my gratitude to the people of Russell, Ellsworth, and Lincoln County. Their kindness, hospitality, and willingness to share their lives with me made a lasting impression. They will always hold a special place in my heart.

Dedication

To Jesus Christ, True God and True Man, through Whom all was made,

To the Blessed Virgin Mary, Mother of God,

To St. Joseph, Model of Workers,

To St. Thomas Aquinas, Patron of Students,

To St. Albert Magnus, Patron of the Natural Sciences,

To Bl. Niels Stensen, Pioneer of Earth Science.

Chapter 1 - Introduction

Cancer incidence in agricultural regions has recently raised public health concerns (Skalaban et al., 2024). Globally, groundwater contamination due to agricultural practices is a significant environmental and health issue (Bijay-Singh & Craswell, 2021). Prior research has identified groundwater contaminants, such as nitrate and uranium, as well as airborne pollutants, like radon gas, as risk factors for specific cancer types. These contaminants may originate from natural geologic sources and human activities, particularly agriculture. Many rural communities depend on private domestic wells as their primary source of drinking water. However, these wells are typically unregulated by water quality standards, leaving rural populations vulnerable to long-term exposure to harmful contaminants.

Elevated concentrations of nitrate and uranium in groundwater have been associated with agricultural land use worldwide, primarily due to fertilizer application. For example, a study in Sri Lanka found that phosphate fertilizers applied to rice fields contained high levels of uranium, which easily leached into surrounding soils and water systems (Chandrajith et al., 2010). A systematic review of uranium dissemination from phosphate fertilizers similarly concluded that soils fertilized with phosphorus fertilizers contained significantly higher uranium concentrations than unfertilized areas (Mwalongo et al., 2024). This trend was observed across Europe, Australia/New Zealand, the Middle East, Asia, and Latin America, indicating that uranium contamination in agricultural soils is a global phenomenon.

Nitrate contamination, once considered a problem mainly in developed nations, has become a widespread concern, particularly in East and Southeast Asia, as agricultural intensification spreads globally (Bijay-Singh & Craswell, 2021). These studies provide critical

insight into nitrate and uranium contamination sources and suggest possible links to human health risks. However, few studies have directly examined the relationship between agricultural land use, groundwater contamination, and cancer occurrence. This lack represents an important knowledge gap, especially given the well-documented health risks associated with these contaminants. Nitrate exposure has been linked to methemoglobinemia, neural tube defects, and colorectal cancer (Espejo-Herrera et al., 2016; Schullehner et al., 2018; Skalaban et al., 2024). Uranium exposure has been associated with kidney toxicity, bone toxicity, kidney cancer, breast cancer, and colorectal cancer (Ahmed et al., 2022; Radespiel-Tröger & Meyer, 2013; Wagner et al., 2011). In addition, radon exposure is a well-established risk factor for lung cancer (Darby et al., 2005; Krewski et al., 2005; Rääf et al., 2023; Riudavets et al., 2022; Thompson et al., 2008; US EPA, 2014).

This study investigates potential connections between water quality, radon levels, and the unusually high cancer rates observed in three agricultural counties in central Kansas. We also explore whether land use practices may contribute to elevated cancer rates through groundwater contamination. To address these objectives, we collected 56 groundwater samples, 65 cancer surveys, and 39 radon measurements from multiple sites within the study area. We performed geochemical analysis to characterize local groundwater chemistry, identify possible contaminants, and evaluate the factors influencing contaminant concentrations, distribution, and sources. Additionally, we generated geochemical maps to visualize spatial patterns in groundwater chemistry. We used geospatial analysis to examine how land use may influence groundwater quality and assessed potential associations between land use patterns and specific cancer types. Finally, we compiled cancer data and overlaid cancer-type point data onto maps of

groundwater geochemistry and radon levels to explore possible spatial relationships between environmental contaminants and cancer clusters.

By integrating geochemical, geospatial, and cancer data, this study seeks to improve understanding of the potential environmental drivers of cancer risk in rural communities. The findings may inform future public health initiatives and contribute to broader efforts to address environmental health disparities in agricultural areas.

Chapter 2 - Background

Geology and Groundwater Resources

The study area in Central Kansas has numerous rock units that record sea level variations in the late Cretaceous. More recently, Quaternary terrace deposits and blankets of loess are evidence of glaciation and deglaciation. In this section, the stratigraphy relevant to the study area will be presented in stratigraphic order (from base to top), briefly describing each formation's stratigraphy, occurrence in the study area, and groundwater resources (Figure 2.1). Important groundwater resources in the study area include the Kiowa Formation, Dakota Formation, and Quaternary terrace deposits. The Dakota Formation is the region's most important groundwater aquifer.

Cheyenne Sandstone

The Cheyenne Sandstone does not crop out within the study area but underlies much of Russell, Lincoln, and Ellsworth counties. It is a fine to medium-grained, loosely cemented quartz sandstone with occasional shale and conglomerate lenses (Berry, 1952; Frye & Brazil, 1943). The Cheyenne Sandstone is not utilized for groundwater resources, either in stock or for domestic purposes. The Kansas State Board of Health has approved the Cheyenne Sandstone as a disposal horizon for oil field brines (Frye & Brazil, 1943).

Kiowa Formation

The Cretaceous Kiowa Formation marks the base of the stratigraphic sequence represented in the study area. The Kiowa Formation is a grey-to-black shale with thin lenses of fine-grained sandstone. Minerals such as pyrite and gypsum are commonly found in the Kiowa

Formation. Within the study area, the Kiowa Formation crops out sparingly in the southeastern corner of Ellsworth County and some isolated patches along the Smokey Hill River. The upper contact of the Kiowa Formation is conformable and often observed interfingering with the Dakota Formation (Swineford, 1947).

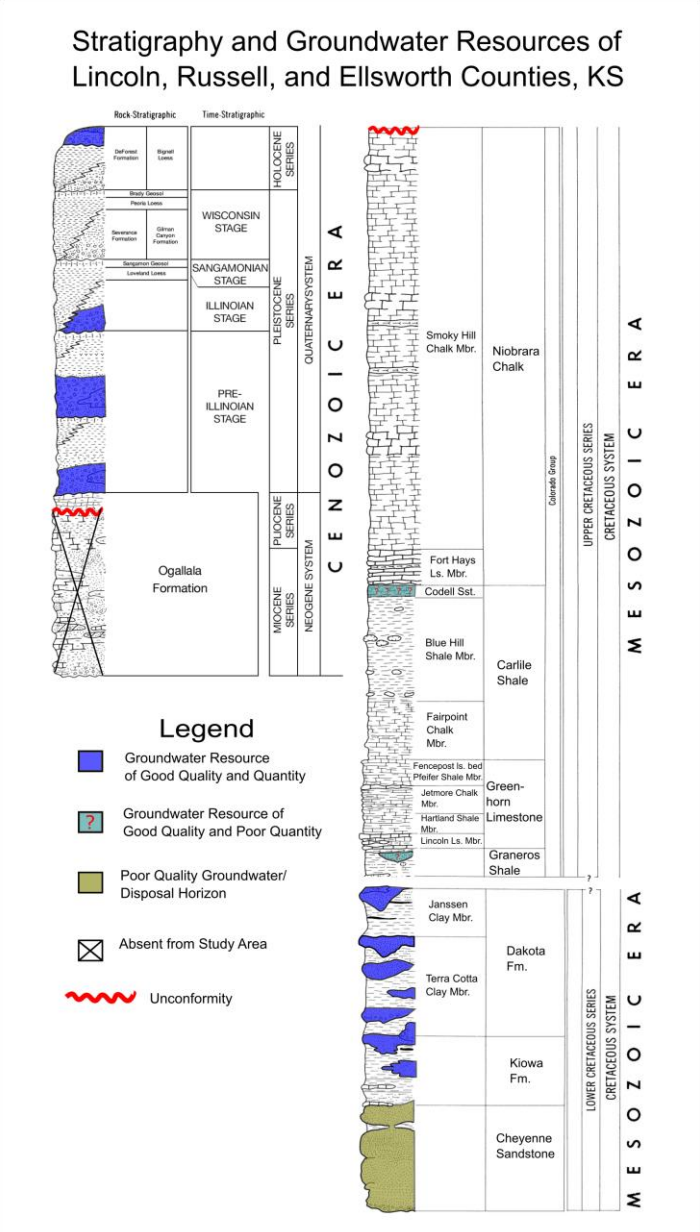

Figure 2.1 Stratigraphy and groundwater resources found within the study area. Modified from Zeller (1968).

The Kiowa Formation is a groundwater source in Lincoln County. Wells that tap the Kiowa Formation are located along the eastern portion of the county and the Smokey Hill River valley (Bayne et al., 1971). Sandstone lenses are more prevalent in the upper section of the Kiowa Formation and serve as the most reliable aquifers, yielding water to central and eastern Ellsworth County (Bayne et al., 1971). Grain size variation in the Kiowa Formation causes the flow rate to vary from well to well, ranging from a few gallons per minute (gpm) to 50 gpm (Bayne et al., 1971). In Lincoln County, the Kiowa Formation produces enough water for domestic and stock purposes if the well taps a sand lens. However, well owners prefer more higher quality, more accessible aquifers, leading to few wells tapping the Kiowa Formation (Berry, 1952). Well owners in Russell County do not utilize the Kiowa Formation (Frye & Brazil, 1943).

Dakota Formation

The general lithology of the Dakota Formation consists of interbedded shales, siltstones, and sandstones (Arbogast & Johnson, 1996; Bayne et al., 1971; Frye & Brazil, 1943; Sawin & Layzell, 2024). Within the Dakota Formation, sandstones are generally weakly consolidated and commonly cemented with iron oxide (Arbogast & Johnson, 1996). Dense, calcite-cemented sandstones are locally present in Lincoln County, where they are quarried and colloquially deemed "Lincoln Quartzite" (Sawin & Layzell, 2024). The Dakota Formation is divided into the Terra Cotta Clay Member and the Janssen Clay Member. The Terra Cotta Clay Member is composed of interbedded claystone, siltstone, and sandstones of various colors (Arbogast & Johnson, 1996; Bayne et al., 1971; Frye & Brazil, 1943). The Janssen Clay Member is composed of light to dark gray siltstone and shale, with occasional sandstone beds (Bayne et al., 1971). The Janssen Clay Member contains more siltstones and claystones and is more poorly sorted than the

Terra Cotta Clay Member (Bayne et al., 1971). However, near the top of the Janssen Clay Member thick beds of friable quartz sandstone with ripples and crossbedding occur (Bayne et al., 1971). Numerous channel sandstones are present at the top of the Janssen Clay Member in Russell County (Arbogast & Johnson, 1996; Frye & Brazil, 1943).

The Dakota Formation in the study area ranges from 100-300 ft thick and crops out in Lincoln, Ellsworth, and eastern Russell County (Arbogast & Johnson, 1996; Sawin & Layzell, 2024). Outcrops are found along hillslopes and major river valleys (Figure 2.2) (Arbogast & Johnson, 1996; Sawin & Layzell, 2024). Lincoln and Ellsworth Counties account for most of the surficial exposure of the Dakota Formation in the study area (Arbogast & Johnson, 1996; Bayne et al., 1971; Sawin & Layzell, 2024).

Figure 2.2 Dakota Sandstone over Hell Creek below Wilson Lake in Russell County. Photographed by Bill Johnson, University of Kansas.

The Dakota Aquifer is the primary groundwater source in the region (Bayne et al., 1971; Berry, 1952; Frye & Brazil, 1943). Poor sorting in the Dakota Formation indicates that groundwater availability will vary spatially, vertically, and with sediment size (Bayne et al., 1971; Berry, 1952). Sandstones within the Dakota Formation are largely lenticular channel deposits, but Bayne (1971) notes that some sandstone layers can range up to 90 ft thick. Higher quantities of groundwater can be obtained by tapping into these coarse, well-sorted channel sandstones (Frye & Brazil, 1943). However, many wells in Russell County utilize groundwater from fine-grained beds of the Dakota Formation, but only in small quantities (Frye & Brazil, 1943). Nonetheless, these small quantities are adequate for domestic and stock purposes. In some locations, hydrostatic head pressure causes artesian conditions in the Dakota Aquifer (Bayne et al., 1971; Berry, 1952). Like water quantity, water quality is highly variable in the Dakota Formation(Bayne et al., 1971). Bayne (1971) notes that well owners in western Ellsworth County report salty water in deeper wells. Chloride concentrations vary dramatically in Russell County, ranging from 23 mg/L to 22,875 mg/L (Bayne et al., 1971; Frye & Brazil, 1943). Iron content ranged dramatically, from 0.07 mg/L to 256 mg/L .

Graneros Shale

The Graneros Shale Formation is a non-calcareous, fissile, gray-colored shale that weathers to shades of grey and yellowish brown. The Graneros Shale grades from an argillaceous shale into a calcareous mudstone. Additionally, thin limestone beds become more frequent towards the upper contact with the Greenhorn Limestone (Hattin, 1965). The Graneros Shale typically forms slopes and is only visible where it is protected from erosion by overlying Greenhorn Limestone. (Sawin & Layzell, 2024). In Russell County, the Graneros Shale ranges

from 20-30 ft thick and crops out in major incised river valleys (Arbogast & Johnson, 1996; Hattin, 1965). The Graneros Shale crops out in the upland areas of north-central and south-central Lincoln County, with thickness ranging from 20 to 45 ft (Sawin & Layzell, 2024). In Ellsworth County, the Graneros Shale ranges from 35-40 ft thick, and crops out in west central and north central Ellsworth County (Bayne et al., 1971). This unit contains occasional sandstone lenses that could be tapped for groundwater if found below the water table. However, even in this case, it is unlikely that the Graneros Shale will be utilized as a water resource due to poor water quality and the availability of shallower groundwater resources (Bayne et al., 1971; Berry, 1952; Frye & Brazil, 1943).

Greenhorn Limestone

The Greenhorn Limestone lies unconformably on the Graneros Shale within the study area (Arbogast & Johnson, 1996). It comprises a sequence of alternating chalk and limestone beds divided into four members (*KGS--Stratigraphic Nomenclature--Strat Chart*, n.d.). The lowermost member is the Lincoln Limestone, consisting of interbedded calcareous mudstones, limestone beds, and occasional bentonite seams (Arbogast & Johnson, 1996; Sawin & Layzell, 2024). Overlying it is the Hartland Shale Member, a calcareous mudstone with occasional bentonite seams and skeletal limestone lenses (Arbogast & Johnson, 1996). Similarly, the Jetmore Chalk Member continues the pattern of interbedded calcareous mudstone and limestone beds (Arbogast & Johnson, 1996; Bayne et al., 1971). The Jetmore Chalk Member has three marker beds: the first is a paired bentonite seam and limestone bed, the second is a calcified bentonite seam, and the uppermost is the notorious fence-post limestone bed, a historical building material in the region (Bayne et al., 1971) (Figure 2.3). The topmost Pfeifer Member

conformably overlies the Jetmore Chalk Member and consists of fine-grained calcareous shale and chalky limestone (Arbogast & Johnson, 1996; Bayne et al., 1971).

The total thickness of the Greenhorn Limestone in Ellsworth County is 76-81 ft, with each member being roughly 20 ft thick (Arbogast & Johnson, 1996; Bayne et al., 1971; Sawin & Layzell, 2024). The Greenhorn Limestone crops out in the upland areas of north-central and west-central Ellsworth County (Bayne et al., 1971). In Lincoln County, the Greenhorn Limestone

Figure 2.3 The Fencepost Limestone Bed. Photographer: John Charlton, KGS.

crops out in the northern upland and the south-central upland areas near Ellsworth County's border, with thickness ranging between 65-90 ft (Berry, 1952; Sawin & Layzell, 2024). The Greenhorn Limestone covers most of Russell County, cropping out in incised river valleys, bluffs, and upland areas, up to 80 ft thick (Arbogast & Johnson, 1996; Frye & Brazil, 1943). The Greenhorn Limestone is not an abundant groundwater source; only a few wells per county utilize it (Bayne et al., 1971; Berry, 1952; Frye & Brazil, 1943). However, the uppermost,

weathered limestone beds can yield small quantities of water (Bayne et al., 1971; Frye & Brazil, 1943).

Carlile Shale

The Carlile Shale is divided into three members: the Fairpoint Chalk Member, the Blue Hill Shale Member, and the Codell Sandstone Member. The lithology of the Fairpoint Chalk Member is a grouping of chalks, marls, calcareous shales, and mudstones. The Blue Hill Shale Member consists of dark gray, fissile, silty shale that weathers into brittle flakes (Hattin, 1962). Additionally, the Blue Hill Shale Member contains septarian calcite concretions, iron carbonate concretions, and small crystalline pyrite nodules (Arbogast & Johnson, 1996; Hattin, 1962). The topmost Codell Sandstone Member consists of two silt-fine-sandstone beds separated by a foot-thick layer of fine sandstone and shale partings (Hattin, 1962).

The Carlile Shale is roughly 300 ft thick in Russell County, occurring in bluffs along river valleys and in the western area of the county (Arbogast & Johnson, 1996). In Lincoln County, only 20 ft of Carlile Shale is present and restricted to upland areas in the south and north of the county (Sawin & Layzell, 2024). The Carlile Shale is 175-200 ft thick in Ellsworth County and occurs in the north-central and southwestern regions (Bayne et al., 1971).

The fine-grained nature of the Carlile Shale prevents it from being an abundant groundwater source. It does not provide water for Ellsworth or Lincoln County (Bayne et al., 1971; Berry, 1952). In Russell County, meager water quantities are found in the topmost, weathered, shallow exposures of Carlile Shale and the Codell Sandstone Member (Frye & Brazil, 1943).

Niobrara Chalk

The Niobrara Chalk lies unconformably on the Carlile Shale and is divided into two members (*KGS--Stratigraphic Nomenclature--Strat Chart*, n.d.). The Fort Hays Limestone Member is the lowermost member of the Niobrara Chalk, comprising a sequence of highly resistant, bioturbated, microcrystalline limestone layers interspersed with shale partings and bentonite seams (Arbogast & Johnson, 1996; Hattin, 1982; Hattin & Siemers, 1987). The Smokey Hill Chalk Member is composed of fissile, shaly chalk (Arbogast & Johnson, 1996; Hattin, 1982). The Niobrara Chalk is exclusively found in the northwest corner of Russell County, reaching a thickness of 100 ft (Arbogast & Johnson, 1996). The Niobrara Chalk is not a groundwater resource in the study area (Bayne et al., 1971; Berry, 1952; Frye & Brazil, 1943).

Ogallala Formation

In Ellsworth County, isolated occurrences of the Miocene Ogallala Formation rest unconformably on the Cretaceous Greenhorn Limestone and Carlile Shale (Arbogast & Johnson, 1996; Bayne et al., 1971). The Ogallala Formation consists of greenish-pink, fine to coarse sands, gravel, ash layers, and bentonite seams. The Ogallala Formation is capped by a 3 ft thick calcrete bed (Arbogast & Johnson, 1996; Bayne & O'Connor, 1968). In Ellsworth County, the Ogallala Formation is the soil caliche displays a distinctive pink banding (Bayne et al., 1971).

The Ogallala Formation is found on the slopes of major river valleys (Arbogast & Johnson, 1996; Bayne et al., 1971). In northwest Russell County and northern Ellsworth County, isolated patches of this unit range from 2.5 to 44 ft thick (Arbogast & Johnson, 1996; Bayne et al., 1971).

The Ogallala Formation is not a groundwater resource in Ellsworth County and Lincoln County (Bayne et al., 1971; Berry, 1952). In Russell County, this unit is composed of unconsolidated sands and gravels and, hence, bears enough water for domestic and stock uses (Frye & Brazil, 1943).

Quaternary Deposits

Quaternary deposits range from pre-Illinoian aged to the Holocene and are derived from fluvial, alluvial, and eolian sources. Fluvial deposits consist of gravel, sand, and silt. Additionally, eolian loess deposits are common within the study area (Arbogast & Johnson, 1996; Bayne et al., 1971; Berry, 1952; Sawin & Layzell, 2024).

Pre-Illinoian Stage

Pre-Illinoian sediments consist of unconsolidated sand, gravel, and occasional silts (Arbogast & Johnson, 1996; Sawin & Layzell, 2024). Generally, the lower portion of the pre-Illinoian sediments is fluvial and composed of gravel and sand. In contrast, the upper half of the pre-Illinoian sediments primarily comprises eolian loess, alluvial silt, and sand (Arbogast & Johnson, 1996; Berry, 1952).

Pre-Illinoian stage sediments range from a thin veneer to 70 ft thick in the study area (Bayne et al., 1971). In Ellsworth County, these deposits are continuous and form terraces along the Saline River and, to a larger extent, the Smokey Hill River (Bayne et al., 1971). Additionally, these sediments are found along the Wilson Valley in northwestern Ellsworth County and southwestern Lincoln County. They are 40 ft thick in places (Sawin & Layzell, 2024).

Pre-Illinoisan sediments are terrace and valley-fill deposits in major river valleys (Arbogast & Johnson, 1996; Sawin & Layzell, 2024). Loess deposits of the Pre-Illinoian stage

often occur along major rivers in the study area, as well as around the Wilson Valley and upland areas (Arbogast & Johnson, 1996; Bayne et al., 1971; Berry, 1952; Frye & Brazil, 1943). These deposits lie above the water table (Bayne et al., 1971; Berry, 1952; Frye & Brazil, 1943). Some localized sections of these terraces may occur under the water table and yield wells that flow up to 10 gpm (Bayne et al., 1971). Lower sand-gravel beds of the Pre-Illinoian sediments produce wells with flow rates up to 50 gpm, with some gravel-rich areas yielding up to 100 gpm (Bayne et al., 1971). Lower Pre-Illinoian deposits are only locally saturated with water along major rivers but unsaturated in tributary streams (Bayne et al., 1971). In Lincoln County, the Upper Pre-Illinoian sediments in Wilson Valley may lend some water to wells. However, Pre-Illinoian sediments are often passed up for the underlying Dakota Aquifer (Berry, 1952).

Illinoian-Recent

The Illinoian Loveland Loess (previously Crete and Loveland Silt Formation) is an unconsolidated alluvial sand and gravel with overlying loess (Arbogast & Johnson, 1996; Sawin & Layzell, 2024). The Sangamon Geosol, a strongly developed paleosol, marks the top of the Loveland Loess and the end of the Illinoian time stratigraphic unit (Arbogast & Johnson, 1996). Wisconsinan deposits include the Gilman Canyon, Peoria Loess, and Brady Geosol. The Gilman Canyon is silty, bioturbated loess, and the Peoria Loess is a massive, calcareous loess, yellow in coloration (Arbogast & Johnson, 1996). The Brady Geosol is a dark gray-brown paleosol that marks the top of Pleistocene-aged deposits. A massive, gray-yellow silt, known as the Holocene Bignell Loess, overlies the Brady Geosol (Arbogast & Johnson, 1996).

Loess within the study area (Loveland Loess, Gilman Canyon, Peoria, Bignell) is mapped as a single unit in the geological maps (Arbogast & Johnson, 1996; Bayne et al., 1971; Sawin & Layzell, 2024). In Ellsworth County, loess deposits are restricted to the southwest uplands, and

in Lincoln County, loess is mapped in upland areas in the north and in the south to a lesser extent (Bayne et al., 1971; Sawin & Layzell, 2024). In Russell County, it occurs everywhere except incised river valleys (Arbogast & Johnson, 1996) as terrace deposits. These terraces cover a smaller area than similar pre-Illinoian deposits and range in thickness from a thin veneer to 50 ft thick (Arbogast & Johnson, 1996; Bayne et al., 1971; Berry, 1952; Sawin & Layzell, 2024). Loveland Loess fluvial deposits occur as terraces along major rivers and are more proximal to modern river channels than Pre-Illinoisan deposits. This proximity brings Loveland Loess in contact with the water table (Arbogast & Johnson, 1996). These fluvial deposits are the principal alluvial aquifers in Ellsworth County and serve as the primary source of domestic/stock water resources in river valleys within the study area (Bayne et al., 1971; Berry, 1952). Illinoian deposits in the Smokey Hill River Valley often comprise fine-grained material such as silt and sand and do not yield abundant water (Bayne et al., 1971).

Loess deposits are a poor groundwater reservoir because of their fine-grained nature and upland occurrence. Recent alluvium is utilized for domestic/stock purposes along major river valleys (Berry, 1952).

Land Use

National Land Cover Database (NLCD)

Land use in the study area varies county by county despite shared borders. All three counties are primarily used for cultivation and pasture. According to 2021 land use data from the National Land Cover Database (Jin et al., 2023), the land coverage class "cultivated crops" accounts for 44% of Lincoln County's land use, 31% for Russell, and 34% for Ellsworth County (Figure 2.4). Raising livestock is practiced in all three counties. However, it is difficult to

distinguish between grassland, idle cropland, and pasture-based on NLCD data alone, as they are all combined into the “Grassland/Herbaceous” land coverage class. According to 2023 estimates from the USDA, Lincoln has a cattle population of 34,500, Ellsworth 32,500, and Russell has a population of about 29,500 cattle (*USDA - National Agricultural Statistics Service - Kansas - County Estimates*, n.d.).

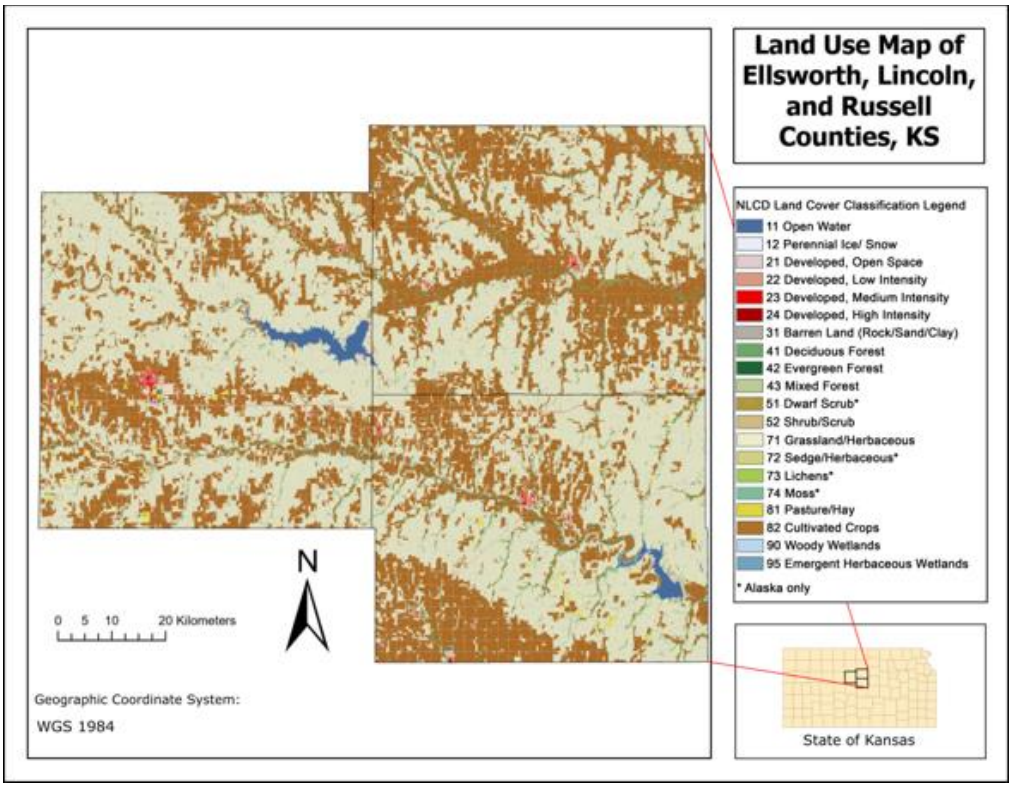

Figure 2.4 Land Use Land Cover (LULC) map of Ellsworth, Lincoln, and Russell Counties.

Crop Data Layer (CDL)

Despite its smaller area, Lincoln County has the highest cattle and crop production of the three counties (*USDA - National Agricultural Statistics Service - Kansas - County Estimates*, n.d.). According to George Mason University's Crop Data Layer (CDL), crop types are similar in all three counties, while the areas of these crops differ (Han et al., 2012). According to the CDL, the primary crop type is winter wheat, followed by sorghum and soybeans. Lincoln County has

the highest percentage area of significant crop types in the study area, with 17.4% winter wheat, 10.8% soybeans, and 9.0% sorghum. 15.1% of Ellsworth County's area is used for winter wheat, 5.4% as soybeans, and 7.66% as sorghum. 11.9% of Russell County is used for winter wheat, 2.82% soybeans, and 8.46% sorghum. Each county has a high percentage of its area as grassland/pasture, ranging from 48% to 58%. Lincoln County is 48.3% grassland/pasture, Ellsworth is 55.7%, and Russell is 58.7% grassland/pasture (Han et al., 2012).

Oil and Gas Operations

Russell is the sixth-highest oil-producing county in the State, producing 1,083,886 barrels in 2024 (Figure 5) (*KGS--Top Ten Lists--Oil and Gas Production*, 2023). Oil and gas extraction operations are present in Ellsworth County (Figure 2.5), but to a much smaller extent, producing only 178,320 barrels in 2024 (*Ellsworth County--Oil and Gas Production*, n.d.). Lincoln County does not produce oil or gas (*Lincoln County--Oil and Gas Production*, n.d.).

The presence of oil and gas extraction operations is likely an important factor to consider when evaluating groundwater chemistry. Numerous crude oil and brine spills have been reported to the KDHE in areas with the highest density of oil and gas wells, which can impact redox conditions and add ions to groundwater.

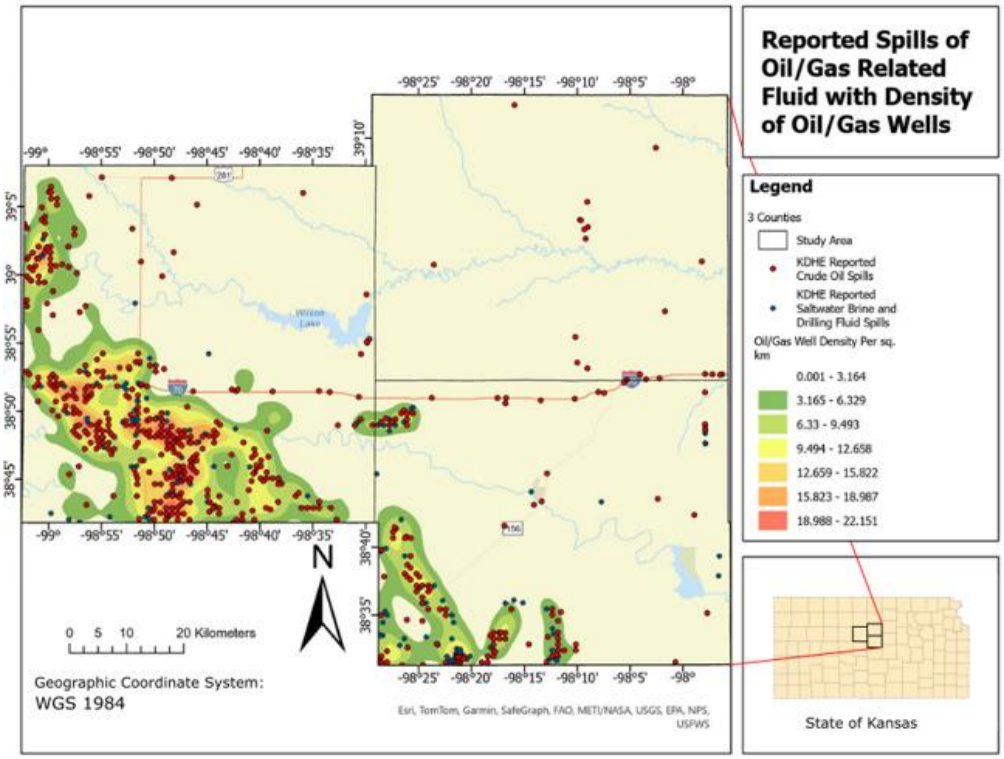

Figure 2.5 Map displaying Kansas Department of Health and Environment reported spills of crude oil and related products (red points), produced brine water and drilling fluid (blue points). An underlying heat map displaying density of oil and gas wells.

Relevant Contaminants

Ammonia

Ammonia (NH_4^+, NH_3) is a compound found in nature through organic matter decomposition and nitrogen fixation. At higher pH, ammonia occurs as NH_3, and in acidic pH, ammonia is protonated to NH_4^+ (US EPA, 2015a). During nitrification, ammonia oxidation converts it into bioavailable nitrite and nitrate (Figure 2.6) (Kirk, 2023). Because nitrification occurs in oxic environments, ammonia accumulates in anoxic conditions. Background ammonia concentrations are typically below 0.2 mg/L, but anoxic groundwater can contain up to 3 mg/L for the reasons discussed above (World Health Organization, 2017). Ammonia is easily metabolized by mammals in higher quantities than found in the groundwater (World Health

Organization, 2017). For this reason, ammonia is not considered a primary contaminant and is unregulated by government agencies (US EPA, 2015b; World Health Organization, 2017). However, ammonium in oxic environments can increase nitrate and nitrite concentrations, two primary contaminants (US EPA, 2015b). Additionally, ammonia is an indicator of fecal contamination of groundwater, which leads to the spread of pathogens (World Health Organization, 2017). Ammonia is known to harm aquatic environments due to its link to eutrophication and oxygen removal during nitrification (Kirk, 2023; US EPA, 2015a).

Nitrate

Nitrate, frequently used to increase crop yield, is a common groundwater contaminant and commonly observed in Kansas (Lane et al., 2020; Whittemore et al., 2014); Whittemore et al., 2014). In addition to nitrate fertilizers, other sources include animal manure, leaky sewage systems, wastewater disposal systems, and leaky solid waste landfills, making nitrate contamination common in urban and rural communities (Wakida & Lerner, 2005).
Nitrate contamination occurs when concentrations exceed the maximum contaminant level (henceforth referred to as MCL) determined by the Environmental Protection Agency (EPA), which is 10 mg/L as Nitrogen (US EPA, 2015b). A variety of adverse health effects follow nitrate contamination, of which methemoglobinemia is the most well-known. Methemoglobinemia affects infants more acutely because infant formula requires a mixture of water and formula powder; if nitrate-contaminated groundwater is used for the mixture, it can lead to high exposure among infants (Greer et al., 2005). Nitrate converts to nitrite in the infant's stomach, which binds to hemoglobin and impairs the ability of the blood to transport oxygen to the infant's body. This impaired oxygen delivery commonly causes a blue tinge to the infant's

skin (Greer et al., 2005). Ward (2018) notes that nitrate MCL was determined to prevent infant methemoglobinemia and fails to consider the risk of cancer and reproductive harm (Ward et al., 2018). A recent review of thirty epidemiological studies on drinking water, nitrate and human health found that the most common adverse health effects were neural tube defects and cancers of the colon, bladder, breast, and thyroid (Ward et al., 2018). These cancers are positively associated with nitrate consumption below MCL concentrations (Ward et al., 2018). Long-term exposure to nitrate and trihalomethanes in groundwater can be a risk factor for prostate cancer (Donat-Vargas et al., 2023).

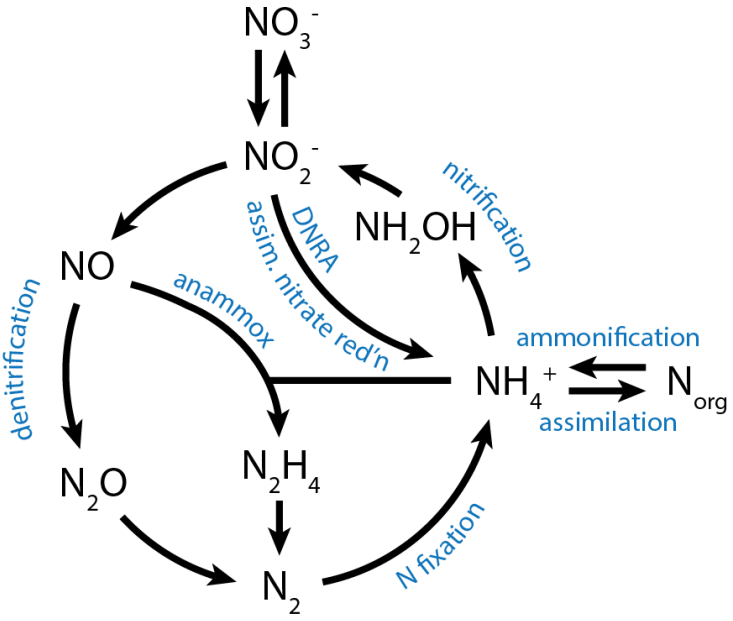

Figure 2.6 The Nitrogen Cycle, from Kirk (2023).

Uranium

Uranium occurs in groundwater worldwide and is recognized as a primary contaminant by the WHO and EPA. Uranium exists in several isotopic states, all radioactive. The most abundant isotope is U^{238}, which accounts for 99.284% of uranium on Earth; the second is U^{235}, which has an abundance of 0.711%; and lastly, U^{234}, with an abundance of 0.005% (ATSDR,

2013). Uranium has a range of oxidation states which are 0, 2+, 3+, 4+, 5+, and 6+. However, natural uranium occurs in 4+, 5+, and 6+ oxidation states (Langmuir, 1997). Uranium is incompatible with major rock-forming elements, leading to incorporation in minor phase minerals and mineral grain boundaries (Liesch et al., 2015) (Porceli & Swarzenski, 2003). Uranium is a lithophile element that gravitates towards oxide formation, such as uranite (UO_2) (Bjørklund et al., 2017). Other mineral groups include silicates (zircon, coffinite), phosphates (monazite, autunite), and vanadates (carnotite) (Liesch et al., 2015). Igneous rocks and black shales contain the highest concentration of uranium (Liesch et al., 2015). According to a recent review of uranium occurrence in geologic materials, granite contains 3-4 mg/kg U, shale contains 3.7 mg/kg and carbonates 2.2 mg/kg U; unconsolidated sediments contain 1.4-53 mg/kg, and igneous rock can range from 0.53-5 mg/kg U (Liesch et al., 2015). Phosphate minerals and their derived fertilizers contain 30-200 mg/kg U (Liesch et al., 2015). These high concentrations occur because of uranium substitution for calcium in apatite (Liesch et al., 2015). Primary uranium undergoes various changes, including weathering to secondary minerals, mobilization into groundwater, or sorption onto sediment grains (Liesch et al., 2015). Uranium readily sorbs onto soil particles, organic matter, and mineral grain surfaces.

Uranium is present in soil and sediment as U(IV) minerals, immobile in reducing conditions (Nolan & Weber, 2015). In reducing environments, the uranous ion (U^{4+}) and other U(IV) minerals dominate U occurrence. In oxidizing environments, the uranous ion is oxidized to the uranyl ion (UO_2^{2+}) and its corresponding U(VI) minerals, which are highly soluble (Langmuir, 1997). The uranyl ion complexes with bicarbonate, significantly increasing its mobility in groundwater. Many factors influence uranium mobilization, the strongest factor being redox geochemistry. Additionally, carbonate alkalinity (bicarbonate) controls uranium

mobilization in groundwater (Nolan & Weber, 2015; Tisherman et al., 2023)). Other parameters associated with uranium mobilization are salinity and calcium concentration (Nolan & Weber, 2015; Tisherman et al., 2023). Nitrate concentrations positively correlate with uranium concentrations in groundwater (Bonotto et al., 2019) and correlate spatially (Nolan & Weber, 2015). Nitrate's effect on the oxidation state of the groundwater is the cause for uranium mobilization through intermediate reactions and direct oxidation of uranous ions.

The link between nitrate to uranium mobilization indicates that elevated nitrate in groundwater could lead to secondary co-contamination of uranium. Uranium contamination is well known to accompany industrial activities, such as nuclear waste disposal, nuclear testing, and mining, but a lesser-known source is fertilizers. As stated above, phosphate fertilizers are known to range from 30-200 mg/kg uranium. Uranium concentrations in groundwater are slightly higher than average in agricultural land (Liesch et al., 2015).

Uranium oral exposure is typically low, but when uranium is elevated in groundwater, it can comprise the majority of uranium intake (World Health Organization, 2017). Uranium is known for its kidney toxicity (US EPA, 2015b), and prolonged ingestion of uranium in groundwater could predispose someone to kidney damage (Vicente-Vicente et al., 2010). A German study in Bavaria, comparing uranium groundwater levels to adverse health effects (tumors/growths, liver, thyroid, musculoskeletal and genito-urinary diseases, and congenital malformations), found weak positive correlations between uranium concentrations >10 µg/L and incidence of tumors/growths and liver diseases (Banning & Benfer, 2017). Another Bavarian study found a significant increase in the risk of leukemia in men who lived in regions containing 1-4.99 µg/L uranium in groundwater (Radespiel-Tröger & Meyer, 2013). Additionally, women were found to be at a higher risk of kidney cancer and lung cancer (Radespiel-Tröger & Meyer,

2013). A study on uranium exposure through drinking water from domestic wells has shown that uranium accumulates in bone tissue and increases bone turnover, possibly resulting in osteotoxicity (Kurttio et al., 2005). A study in South Carolina found that colorectal, breast, kidney, and total cancer occurrence were elevated in regions with high groundwater use and regions with higher uranium concentrations in groundwater (Wagner et al., 2011). The EPA and WHO set an MCL value of 30 µg/L. It should be noted that this MCL is provisional due to a poor understanding of the effects of uranium on human health (US EPA, 2015; World Health Organization, 2017). In the past, a 20 µg/L MCL was proposed for the EPA, and Germany recently lowered its MCL to 10 µg/L. Due to apparent toxicity at levels far below the WHO's MCL, it is understandable that the maximum contaminant level goal (MCLG) for uranium is zero (EPA, 2015).

Radium & Radon

Radon is a gas produced by the radioactive decay of radium-226 within the uranium-lead decay chain. Uranium-238 and radium-226 are found in high concentrations in igneous rocks such as granite and basalt and in sedimentary rocks such as black shale and limestone. Black shales contain the highest concentrations of radium at 1.1 µg/kg, followed by limestones, with radium concentrations of 0.4 µg/kg (Bowen, 1979; Krewski et al., 2005). Due to the lack of igneous rocks in central Kansas, aside from occasional ash layers, the primary source of uranium, radium, and radon is black shale. Radon is not harmful when exposed to the atmosphere, as radon is dispersed and quickly decays (Radon's half-life = 3.8 days). However, radon gas is hazardous when trapped and allowed to accumulate. High radon concentrations occur along subsurface structures and conduits, which catalyze movement and accumulation of

radon gas (Figure 2.7). These structures include mining chambers, oil and gas wells, groundwater wells, faults, joints, fractures, plumbing, and basements. In residential areas, radon can travel through plumbing and exit through shower heads, exposing residents to radon. Additionally, basements allow for accumulation and exposure to radon. The EPA suggests acting when radon levels reach four pCi/L (US EPA, 2019). Radon gas damages cellular DNA when inhaled, increasing lung cancer risk (Krewski et al., 2005). Radon gas is a well-studied human carcinogen. It has been proven to be carcinogenic through studies on subsurface mine workers and proven to be a risk to residential citizens (*Health Effects of Exposure to Radon*, 1999; Krewski et al., 2005). Behind smoking, radon exposure is the leading cause of lung cancer in the United States (*Health Effects of Exposure to Radon*, 1999) .

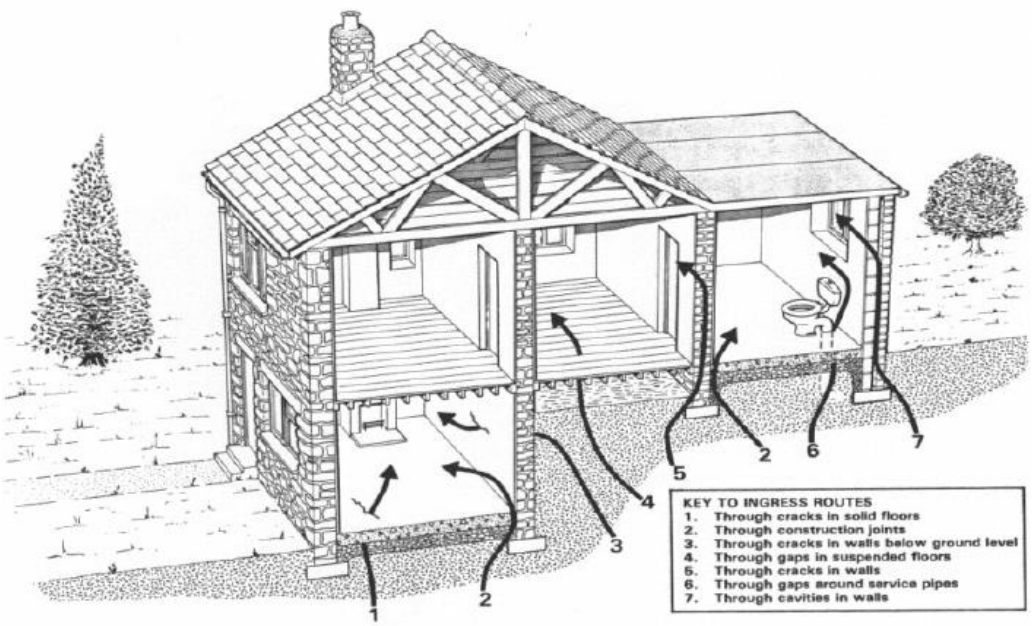

Figure 2.7 Common radon pathways into homes. Figure from (Lecomte 2014).

Existing Cancer Data

According to 2014-2018 data from the Kansas Department of Health and Environment, Russell County had the fourth highest cancer rate in the State for colorectal cancer (65.1 cases out of

100,000 people). This cancer rate is significantly higher than the Kansas State average of 39.2 cases per 100,000 individuals (*Kansas Health Matters,* n.d.-b). Low colon screening rates can be ruled out as a cause of this higher rates because Russell County has a screening rate of (62.2%) which is higher than the Kansas median screening rate (61.8%) (*Kansas Health Matters*, n.d.-b). This suggests that there could be an extraordinary cause for high colorectal cancer rates in Russell County. In Lincoln County, the colorectal cancer rate is 51.4, also higher than the average Kansas colorectal cancer rate of 39.2 per 100,000 population (*Kansas Health Matters*, n.d.-b). Lincoln County also boasts a higher-than-average colon cancer screening rate of 63.7% (*Kansas Health Matters*, n.d.-b). These elevated colorectal cancer rates for Lincoln and Russell Counties contrast with the neighboring Ellsworth County, which has a low colorectal cancer rate of 36.5 per 100,000 population but similar screening rates (*Kansas Health Matters,* n.d.-b). Lincoln County has the third highest lung and bronchus cancer rate, with 87.6 cases per 100,000 population, compared to the State average of 54.0 (*Kansas Health Matters*, n.d.-b). Similarly, Russell County has a lung and bronchus cancer rate of 64.1. Ellsworth County has a lower-than-average lung and bronchus cancer rate 37.5 (*Kansas Health Matters*, n.d.-b). Tobacco smoking can be ruled out as a cause of elevated lung and bronchus cancer rates because the average rate of adult smokers in Lincoln County is 16.8 percent compared to the State median value of 17.2 percent (*Kansas Health Matters*, n.d.-b). Likewise, smoking rates for Russell County are slightly above average (18.1%), about the same as in Ellsworth County (Figure 2.8). The latter, however, has one of the lowest lung and bronchus cancer rates in Kansas (37.5 cases per 100,000 population), significantly lower than the state average of 54.0 (*Kansas Health Matters*, n.d.-b).

County	Adult Smokers (% Population)	**Lung and Bronchus Cancer Rate	Colon Cancer Screening (% Population)	**Colorectal Cancer Rate	**Prostate Cancer Rate	Mammogram in Last Two Years (% Population)	**Breast Cancer Rate	**Age Adjusted Cancer mortality rate
Lincoln	16.8	**87.6**	63.7	**51.4**	**228.7**	72.8	**135.1**	104.2
Russell	18.1	**64.1**	62.2	**65.1**	106.9	71.2	124.7	**185.5**
Ellsworth	18.2	37.5	61.6	36.5	**128.2**	71.7	**147.4**	**205**
Kansas Average/Median *USA National Average	17.2	54	61.8	32.9	109.8	*76.5	129	148.3
**Cancer and mortality rates represent the age-adjusted cancer/mortality rate per 100,000 citizens								

Figure 2.8 Table comparing cancer rates between counties. Ordinary contributing factors such as low screening and smoking are compared as well. Red boxes highlight similar rates of screening and smoking, and bold numbers emphasize abnormally high cancer rates despite these similarities.

Lincoln County also has the highest prostate cancer rate in the State of Kansas, 228.7 cases per 100,000 population. This cancer rate is over double the average rate for the State of Kansas, which is 109.8 per 100,000 people (*Kansas Health Matters*, n.d.-b). Ellsworth County has a significantly lower prostate cancer rate of 128.2, although it is higher than the State average rate of 109.2 (*Kansas Health Matters*, n.d.-a). Both Ellsworth County and Lincoln County have breast cancer incidence rates that exceed the Kansas state average of 129 cases per 100,000 population. Lincoln County reports a rate of 135.1 cases per 100,000, while Ellsworth County has an even higher rate of 147.4 cases per 100,000. In contrast, Russell County has a slightly lower breast cancer rate of 124.7 cases per 100,000, falling just below the Kansas average (*Kansas Health Matters*, n.d.-b).

When evaluating mammography rates, all three counties in the study area report lower screening rates than the U.S. national average of 76.5 percent. In the past two years, Lincoln County reported a mammography rate of 72.8 percent, Russell County reported 71.2 percent, and Ellsworth County reported 71.7 percent. These similar mammography rates across the three counties, however, do not fully explain the wide discrepancy in breast cancer incidence,

particularly the elevated rates in Lincoln and Ellsworth Counties (*Kansas Health Matters*, n.d.-b).

Further concern arises when considering the age-adjusted cancer mortality rates in the study area. Lincoln County has a mortality rate of 104.2 deaths per 100,000, Russell County has a rate of 185.5 deaths per 100,000, and Ellsworth County has a rate of 205 deaths per 100,000 (*Kansas Health Matters*, n.d.-b).

The combination of high cancer incidence rates and elevated mortality rates in these rural Kansas counties is alarming and warrants further investigation. Given that mammogram, smoking, and colorectal screening rates are relatively consistent across the counties and do not account for the disparity in cancer outcomes, it is essential to examine potential environmental contributors to these patterns. Identifying possible environmental exposures and risk factors is critical to making informed public health decisions, reducing risk, and preventing future illnesses within these communities.

Chapter 3 - Methods

Study Design

This study investigates the relationships between land use, groundwater chemistry, radon gas occurrence, and high cancer rates in central Kansas. Our specific objectives were to (1) determine the groundwater quality in domestic wells, (2) determine the role of industrial processes and waste management on groundwater quality, (3) determine the role of land use on groundwater quality, (4) measure radon levels in homes in Lincoln, Ellsworth, and Russell counties; and (5) determine whether land use and radon levels can be related to the rates of specific cancer types in Lincoln, Ellsworth, and Russell counties.

To achieve these objectives, we conducted groundwater sampling, radon testing, and distributed cancer surveys throughout the study area. We made maps comparing geochemistry (and contamination) to clusters of various types of cancer and analyzed statistically the relationship between land use and groundwater chemistry (Figure 3.1).

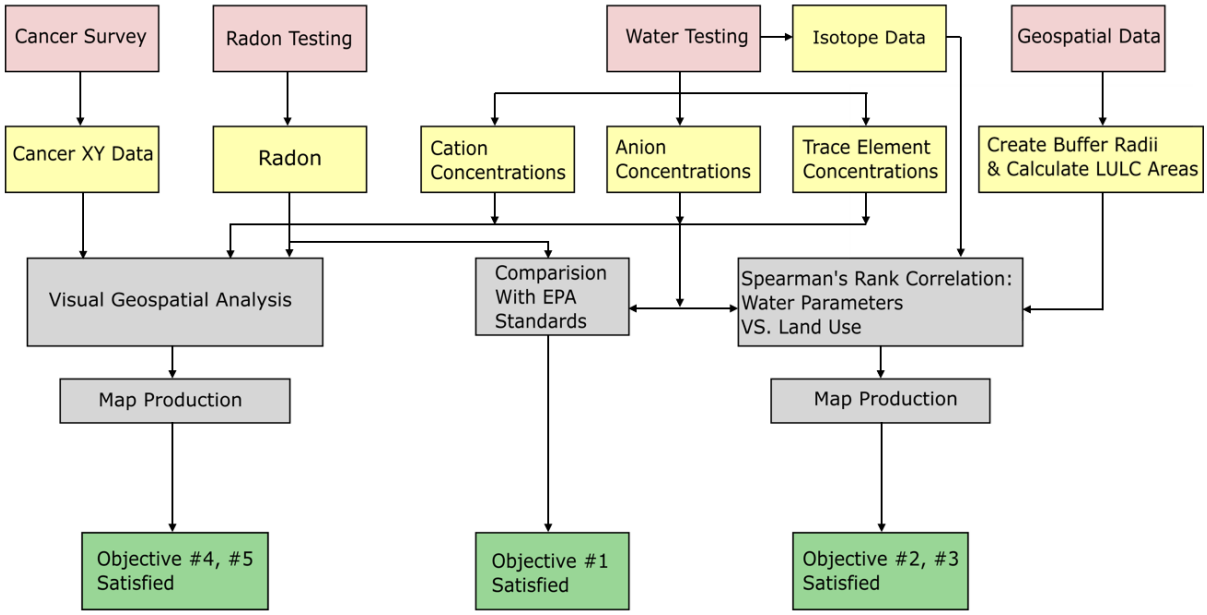

Figure 3.1 Study design schema. Red-colored boxes indicate field methods, yellow boxes represent data obtained from field methods, grey boxes represent analysis techniques, and green boxes represent the desired outcome (objectives satisfied).

Additionally, we analyzed geochemical data to understand further what geochemical parameters (such as pH and dissolved oxygen) might control contaminant occurrence, as well as the spatial distribution of these parameters.

Fieldwork

Groundwater Sampling

We obtained 56 groundwater samples (24 in Lincoln County, 18 in Ellsworth County and 14 in Russell County) over two fieldwork periods: March 11-15 and June 3rd through 21st, 2024. Selection of the sampling sites was intended to cover the broadest geographical extent of the study area, but it was restricted by the agreement of volunteer participants.

Before any data was collected, we calibrated the field probes. We calibrated the Oakton pH probe using a three-point calibration with pH 4, 7, and 10 standards. Additionally, we

calibrated the YSI Pro dissolved oxygen (Henceforth referred to as DO) probe using a 1413 us/cm (at 25 degrees C) solution of potassium chloride to calibrate electrical conductivity. The YSI Pro DO probe is calibrated inside the cover tube with reverse osmosis water (henceforth referred to as RO water) before removing the sensor to calibrate the dissolved oxygen sensor. We rinsed the probes with RO water before and after calibration.

After locating a spigot at the well owner's property, a splitter is screwed onto the spigot. The splitter directs water out of two hoses and controls the flow rate through each hose (Figure 3.2). The first hose is a higher-diameter garden-style hose called the purging hose, used to purge water at a high flow rate. The second hose has a smaller diameter, called the sampling hose. The sampling hose runs into the bottom of a 1000 ml plastic graduated cylinder used for data and sample collection. The water from the sampling hose enters the bottom of the graduated cylinder and overflows from the top; pH and DO probes hang halfway into the overflowing cylinder; this ensures fresh groundwater flows past the probes, allowing for accurate groundwater measurements before interaction with the atmosphere. To ensure representative groundwater sampling, we purged the well of stagnant water by directing water out of the purge hose, where we measured the flow rate by recording the time it took to fill a 5-gallon bucket. After recording the flow rate, we continue to let water flow through the purge hose for 10 minutes to ensure the removal of stagnant water.

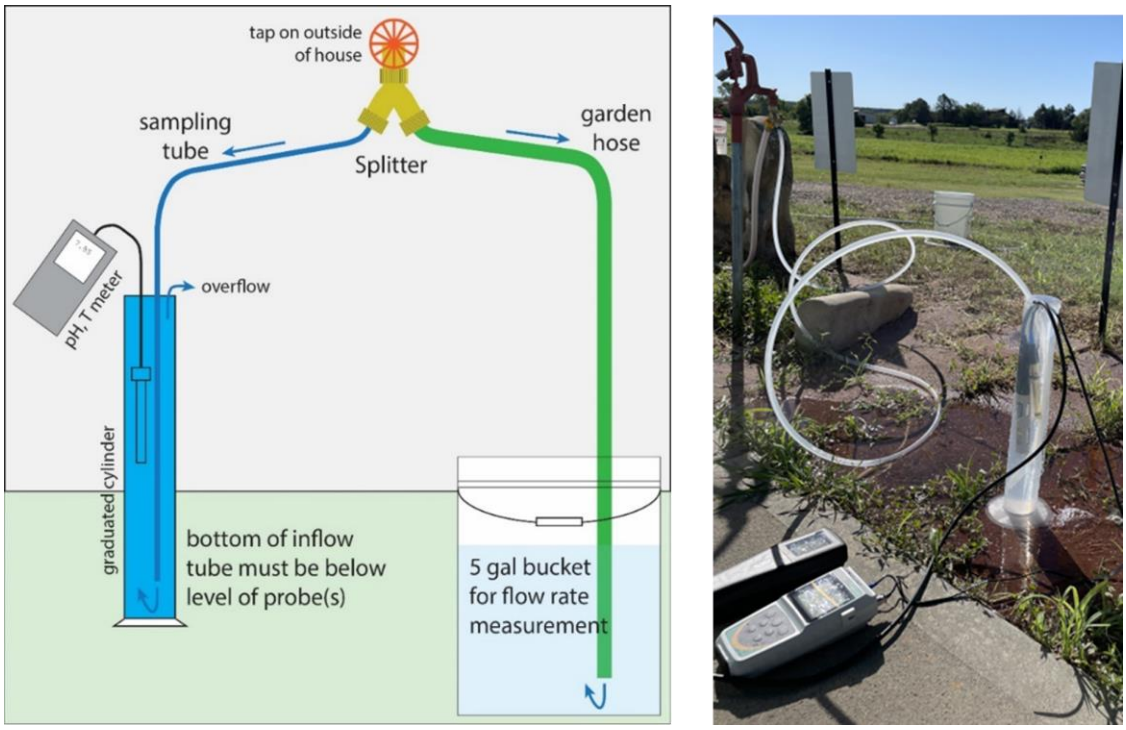

Figure 3.2 Left: groundwater sampling schematic, used with permission from Dr. Matthew Kirk, Groundwater sampling during fieldwork.

While purging the well, pH and dissolved oxygen concentration are recorded from the hanging probes at zero, five, and ten minutes to ensure parameter stabilization. Stabilized parameters indicate the absence of stagnant water, and that sampling can begin. Before sampling, final field parameters, such as pH, DO, electrical conductivity, and specific conductance, are recorded on paper and in the ArcGIS Pro field app. We used plastic syringes to extract samples from the graduated cylinder and rinsed syringes with groundwater from the sampling site before taking samples. We screwed 0.45 um filters onto the syringes to filter out particulate matter from groundwater. Additionally, we rinsed sampling bottles with filtered groundwater from the sampling site before collecting samples. We filled two 60 ml Nalgene bottles for cation and anion samples, one 30 ml Nalgene bottle for trace element samples, one 60 ml amber glass bottle

for non-purgeable organic carbon (NPOC) samples, and one 1 ml glass bottle for water stable isotope analysis (Figure 3.3).

Figure 3.3 Filtering groundwater through 0.45um screw-on filter into a sample bottle.

When sampling was complete, we organized samples into a single plastic bag for each site and stored them in a cooler with ice until the end of the day, when samples were transferred to a refrigerator. We rinsed field probes with RO water before and after data collection.

We prepared all sample bottles prior to fieldwork to prevent contamination. All Nalgene bottles are prepared by acid washing them in a 2% HCl and water solution, rinsing them with 18 megaOhm deionized water (henceforth referred to as DI water), and air drying them. Amber glass bottles used to collect NPOC were acid-washed like the plastic Nalgene bottles and baked overnight to remove residual carbon.

Radon Testing

We performed 39 radon tests in the study area (15 in Lincoln County, 14 in Ellsworth County and 10 in Russell County). The testing sites were selected based the same criteria described in the groundwater sampling section. The goal was to collect radon data in the same households where we collected groundwater samples. However, technical difficulties inherent to the testing (e.g., insufficient exposure to absorb radon gas, or excessive time to reach the lab for analysis) rendered some of the tests invalid.

We administered the radon test on the same day as groundwater sample collection. Each radon test, consisting of a charcoal pack that absorbs air when unsealed, was left undisturbed for at least 48 hours to absorb radon and retrieved within 7 days. The radon testing kits were placed at the lowest level and frequently accessed by residents (i.e., basements and living rooms). After retrieving a radon test after 48 hours, they were carefully sealed and mailed to Alpha Energy laboratories in Texas for analysis.

Cancer Data

We obtained cancer data from 65 households (25 in Russell County, 24 in Lincoln County and 16 in Ellsworth County) via optional, anonymous, and confidential surveys distributed during radon and groundwater sampling. The survey form approved by the Institutional Board Review (#IRB-12052) provided standardization of the collected data and written consent to utilize the data in this research project. The survey form contained questions that record name, household address, number of residents diagnosed with cancer (if any), and for each cancer patient, sex, type of cancer, age diagnosed, smoker (yes or no), and colon screening (yes or no). A section was left blank for participants to list any risk factors or family history of

cancer. The goal was to collect cancer data from residents in the same households where groundwater samples and radon data were collected. However, the total number of respondents exceeded the collection of the other data due to the eagerness of Russell residents to contribute to the research. Surveys were collected, stored in a secure location, and uploaded to a secure drive to ensure confidentiality of data.

Lab Work

Sample Preparation

Upon returning to the lab, we stored all water samples inside a refrigerator set to 4 degrees Celsius. In the week following summer fieldwork, we preserved our cation and NPOC samples through acidification. We preserved cation samples by pipetting 120 µl Trace Element grade nitric acid to each sample bottle. We did not acidify anion samples to prevent sample destruction, but they were analyzed as quickly as possible. We preserved NPOC samples by pipetting 120 µl of HCl to each bottle. We did not acidify isotope samples.

Alkalinity Titrations

Following sample preservation, samples from both spring and summer fieldwork sessions were titrated. We used anion samples for alkalinity titrations and performed titrations using the Thermo scientific OrionStar T910 automatic alkalinity titrator (Figure 3.4). We calibrated the instrument in a similar manner to the field pH probe, using pH 4, 7, and 10 solutions in a three-point calibration. Next, we diluted samples by a factor of 1 part sample to 4 parts of deionized water. After completing titrations, we logged the data in the laboratory logbook and transferred it to a spreadsheet.

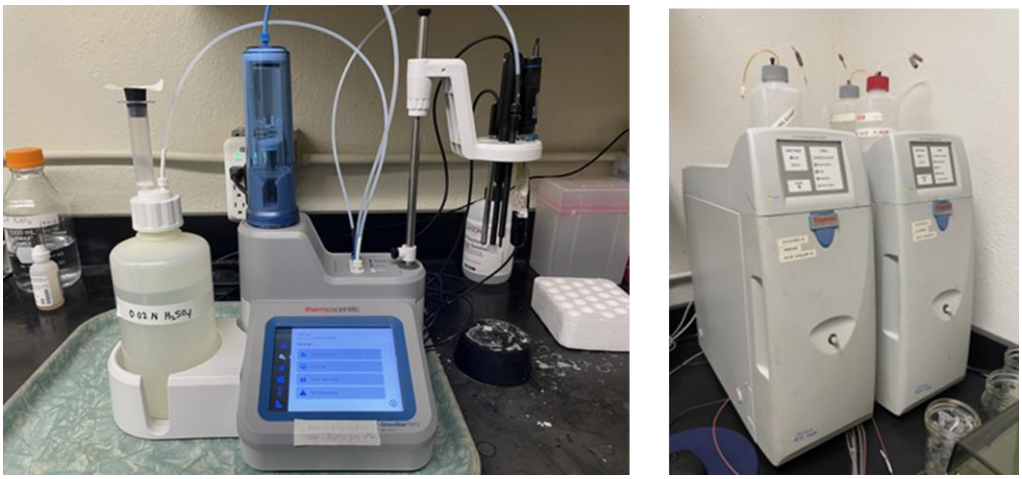

Figure 3.4 Instruments used at Kansas State University, aqueous geochemistry laboratory. Left: Thermo scientific OrionStar T910 automatic alkalinity titrator. Right: Dionex ICS-1100 Ion Chromatograph.

Ion Chromatography

We analyzed samples for cations such as sodium, ammonium, potassium, magnesium, calcium, and strontium. Additionally, we analyzed samples for anions such as fluoride, chloride, bromide, nitrite, nitrate, and sulfate. Ions were analyzed at Kansas State University in the Aqueous Geochemistry laboratory using the Dionex ICS-1100 Ion Chromatograph (Figure 3.4). After analyzing samples, we checked data quality in Chromeleon software; if samples fell above the upper detection limits (due to high concentrations), we diluted and reanalyzed samples until they fell within the lower and upper detection limits. Once samples met this criterion, we transferred data to the Geochemist's Workbench software, where we calculated the charge imbalance to ensure data quality. We reanalyzed any samples with a charge balance error greater than 5 percent. We repeated this process until the charge balance error fell below the 5% threshold. There were only two samples that had a charge imbalance error higher than 5 percent, the highest being 6.54%

Trace Element Analysis

We shipped trace element samples to the University of Nebraska-Lincoln Redox Biology Center for analysis. Samples were analyzed for Cu, Zn, Hg, Pb, U, Li, B, Co, Ni, As, Se, Mo, and Cd using an inductively coupled plasma mass spectrometer (ICPMS).

Isotope Analysis

Stable isotope analysis was performed at the Stable Isotope Mass Spectrometry Laboratory at the Kansas State University Division of Biology. The laboratory utilized a Picarro L-i2130 water analyzer. Results are presented in permille notation relative to Vienna Standard Mean Ocean Water (VSMOW).

Cancer Data Analysis

We compiled the cancer data collected during fieldwork into an Excel spreadsheet and categorized cancer cases based on age brackets, risk factors, and types of cancer. Cases were categorized into 5 age brackets, 1 = 0-20 years old, 2 = 21-40 years old, 3 = 41-60 years old, 4 = 61-80 years old, and 5 = 81+ years old. We also categorized cases into four risk factor classes: 0 =, no known risk; 1 = known genetic marker for cancer; 2 = one family member diagnosed with cancer; and 3 = 2+ family members diagnosed with cancer. Some cancer types (as described by the survey respondents) were combined to simplify and standardize data; combined cancers were as follows: bone = myeloma, sarcoma; lymphatic = lymphoma, lymph; skin = melanoma; intestinal = colorectal, small intestine; gynecological = cervix, endometrial, ovarian. Other cancers were left ungrouped, such as bile duct, bladder, brain, breast, esophagus, eye, kidney, leukemia, lung, prostate, stomach, and thyroid.

We used Microsoft Excel to calculate and display data for the study area and each county separately. Data includes the percentage of households with cancer, the percentage of cases for

each age bracket and risk factor class, the percentage of cases per sex, percentage of colon cancer screening and smokers, as well as the percentage for each cancer type.

Geospatial Analysis

During fieldwork, we recorded the longitude, latitude, and field parameters of each sample site in the ArcGIS Field Maps app. We uploaded this data to ArcGIS Pro and created multiple ring buffers for the well coordinates. We performed a buffer analysis to extract land use areas to calculate correlations between land use and geochemical data. These correlations help us to investigate statistical relationships between land use parameters and groundwater geochemistry. This methodology is commonly used with surface water but has been applied sparingly to understanding groundwater chemistry. We created geochemical maps of the study area through interpolation. These interpolated maps help us understand the hydrogeology and hydrochemistry of the study area.

After compiling geochemical data into a spreadsheet, we imported the data as XY data points into ArcGIS Pro. From there, we performed inverse distance-weighted interpolations to produce geochemical maps of the study area. Additionally, we imported cancer data into ArcGIS Pro as separate XY data layers. We overlayed cancer data onto geochemical maps to visually determine spatial relationships between groundwater chemistry and cancer occurrence.

We created buffers to analyze the statistical relationship between land use and groundwater chemistry. We used the most recent available land use data from NLCD 2021 and CDL data from 2015. We used TIGER boundaries for our county boundaries. All data layers were reprojected to NAD Alber's 1983 equal area projection (continuous United States) to preserve accurate geometries. All data layers were also limited to the extent of the study area (Lincoln, Ellsworth, Russell Counties) via clipping and masking. We used the multiple-ring

buffer tool to create concentric circular buffers radiating from each well location. Buffer radii were 100, 250, 500, 1000, and 2000 meters to explore relationships over various spatial scales. Once we created these ring buffers, we used the tabulate area tool to calculate the area of each land use type within each ring buffer (Figure 3.5). We converted land use areas into a tabular format using the "zonal statistics as table" tool. Next, we exported the table as an Excel file for further calculations, such as conversion into percentages.

We combined some individual land use classes to create a single combined class; for example, high-intensity, medium-intensity, low-intensity developed land, and barren land were added together and treated as a single class titled "total developed land." We used the same process to aggregate evergreen, deciduous, and mixed forest types into a single "total forest" class. Wetland classes such as woody wetlands and emergent herbaceous wetlands were combined into a single "total wetlands" class.

We used additional geospatial data, such as KGS well data, to make groundwater flow maps and depth-to-groundwater maps. We also used KGS oil and gas well location data to make heat maps of oil and gas well density in the study area. We used KDHE-reported spill data to investigate contamination and groundwater chemistry links. We also compiled KGS geologic units and USSURGO soil data to create geologic and soil maps.

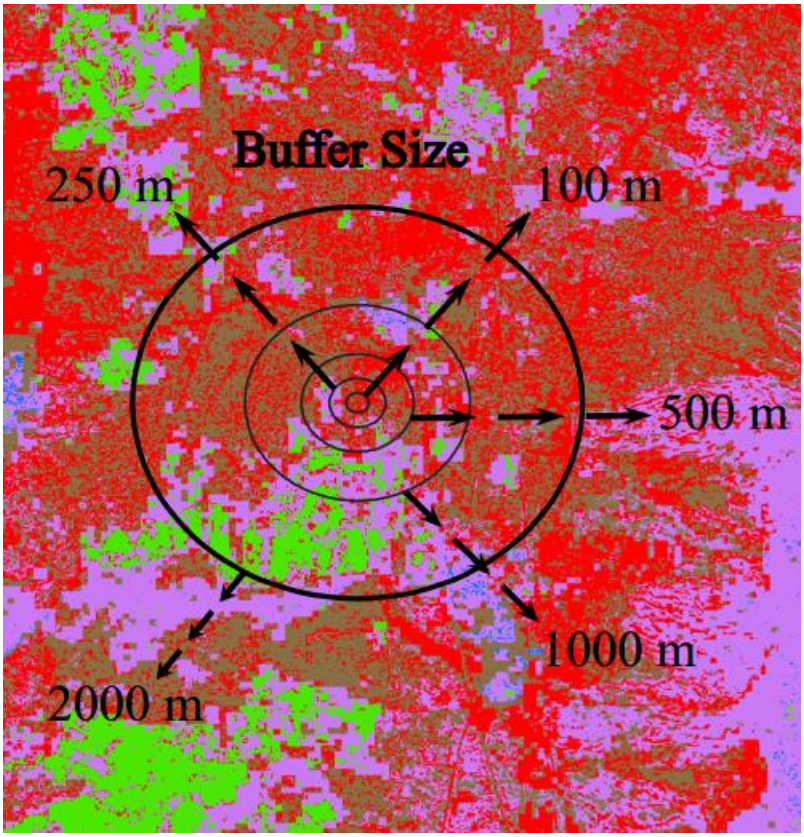

Figure 3.5 Example of buffer analysis from Rasool et al. (2023). Circular rings indicate buffers of various radii. Different colors represent different land use classes or crop types. Percent coverage is calculated for each buffer ring.

Statistical Analysis

We analyzed data to determine the statistical relationships between geochemistry and land use, as well as relationships between geochemical parameters. First, we loaded a spreadsheet containing field parameters, radon, major ion, and trace element concentrations into R. Then, we calculated Spearman's rho and P values for all parameters and created a matrix containing both. We considered P values above 0.05 statistically significant for this study.

We separately uploaded land-use areas to R for each buffer radii to determine relationships between land use (NLCD, CDL) and geochemistry (radon, major ions, trace elements) for each spatial scale. We calculated Spearman's rho and P values between each

geochemical parameter and land use class of the desired buffer ring for CDL. We repeated this process for NLCD.

We created a Spearman's rho and P value matrix between field parameters, major ions, and trace elements. P values above 0.05 were considered statistically significant. This analysis gave us insights into what controls geochemistry in the study area.

Chapter 4 - Results

Geochemistry

Within the study area, the groundwater temperature ranged from 10.1 to 18.8 degrees Celsius, with a median of 15.4 degrees Celsius, and the pH ranged from 6.34 to 7.81, with a median of 6.82 (Figure 4.1). Dissolved oxygen ranged from 0.03 to 13.23 mg/L, with a median of 2.05 mg/L, and the median value for alkalinity was 5.75 meq/L, ranging from 1.83 to 8.25 meq/L (Figure 4.1).

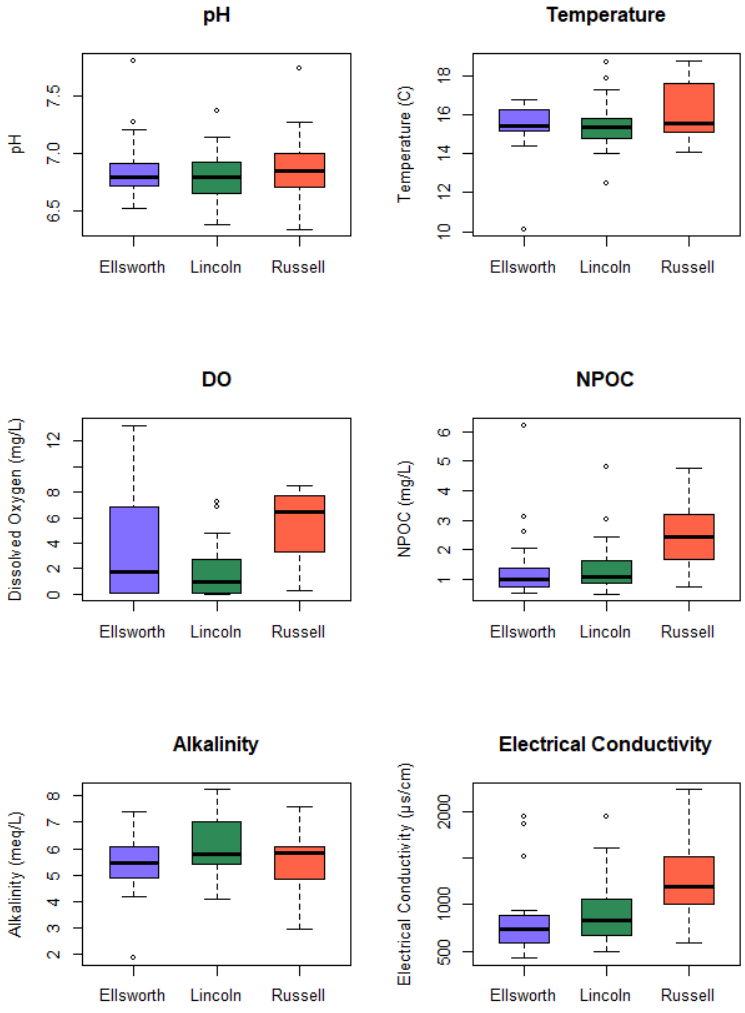

Figure 4.1 Box and whisker plots for each field parameter, as well as alkalinity.

Major Ions

We analyzed fluoride (F^-), chloride (Cl^-), nitrite (NO_2^- as NO_2^-), Nitrate (NO_3^- as N), bromide (Br^-), and sulfate (SO_4^{2-}) concentrations (Figure 4.2). The fluoride concentration in the study area ranged from 0.130 mg/L to 2.06 mg/L, with a median of 0.469 mg/L. Chloride ranged from 7.92 mg/L to 434.6 mg/L, with a median of 68.56 mg/L. Nitrite ranged from 0.164 mg/L to 0.547 mg/L, with a median of 0.164 mg/L. Nitrate ranged from 0.0633 mg/L to 45.62 mg/L, with a median of 0.903 mg/L. Bromide has a median of 0.105 mg/L and ranged from 0.0093 mg/L to 0.800 mg/L. Sulfate has a median value of 141.45 mg/L and ranged from 21.58 mg/L to 1007.4 mg/L.

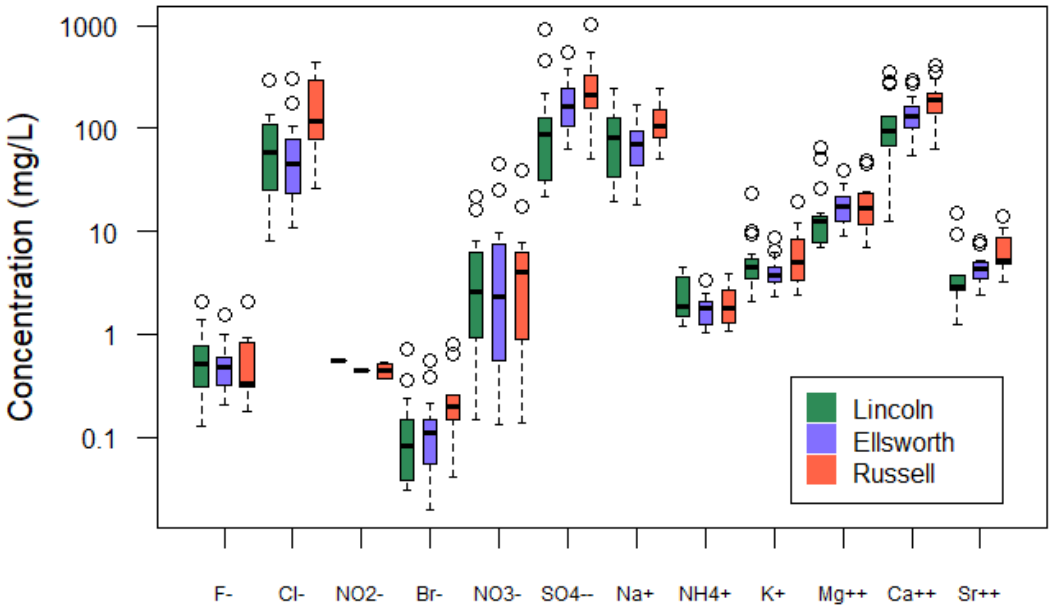

Figure 4.2 Box and whisker plot displaying the distribution of major anions and cations in samples from each county.

We analyzed cations such as sodium (Na^{2+}), ammonium (NH^{4+}), potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}) and strontium (Sr^{2+}) (Figure 4.2). Sodium ranged from 17.83 mg/L to 246.5 mg/L, with a median value of 83.92 mg/L. Ammonium ranged from 0.52 mg/L to

4.55 mg/L, with a median of 1.29 mg/L. Potassium ranged from 0.994 mg/L to 23.52 mg/L, with a median value of 4.21 mg/L. Magnesium has a median value of 14.42 mg/L, ranging from 0.982 mg/L to 64.03 mg/L. Calcium ranged from 1 mg/L to 410.49 mg/L and has a median of 130.66 mg/L. Strontium ranged from 1.23 mg/L to 14.94 mg/L and has a median of 4.29 mg/L in the study area.

Trace Elements

Additionally, we analyzed the concentration of various trace elements in our samples, including phosphorus (P), manganese (Mn), iron (Fe), copper (Cu), zinc (Zn), mercury (Hg), lead (Pb), uranium (U), lithium (Li), boron (B), cobalt (Co), nickel (Ni), arsenic (As), selenium (Se), molybdenum (Mo), and cadmium (Cd). The median concentrations are 2.15 mg/L for P, 0.00677 mg/L for Mn ,0.0337 mg/L for Fe ,0.00377 mg/L for Cu, 0.0663 mg/L for Zn, 0.00145 mg/L for Hg ,0.000367 mg/L for Pb ,0.00475 mg/L for U ,0.0544 mg/L for Li, 0.104 mg/L for B,0.000219 mg/L for Co ,0.00159 mg/L for Ni ,0.000186 mg/L for As, 0.00056 mg/L for Se,0.00146 mg/L for Mo, and 0.0000628 mg/L for Cd respectively (Figure 4.3). Most of these elements were below any regulatory limit, so they will not be discussed in depth in the water quality section. Trace elements that exceed water quality guidelines were manganese, iron, mercury, and uranium, and hence will be included in the section below.

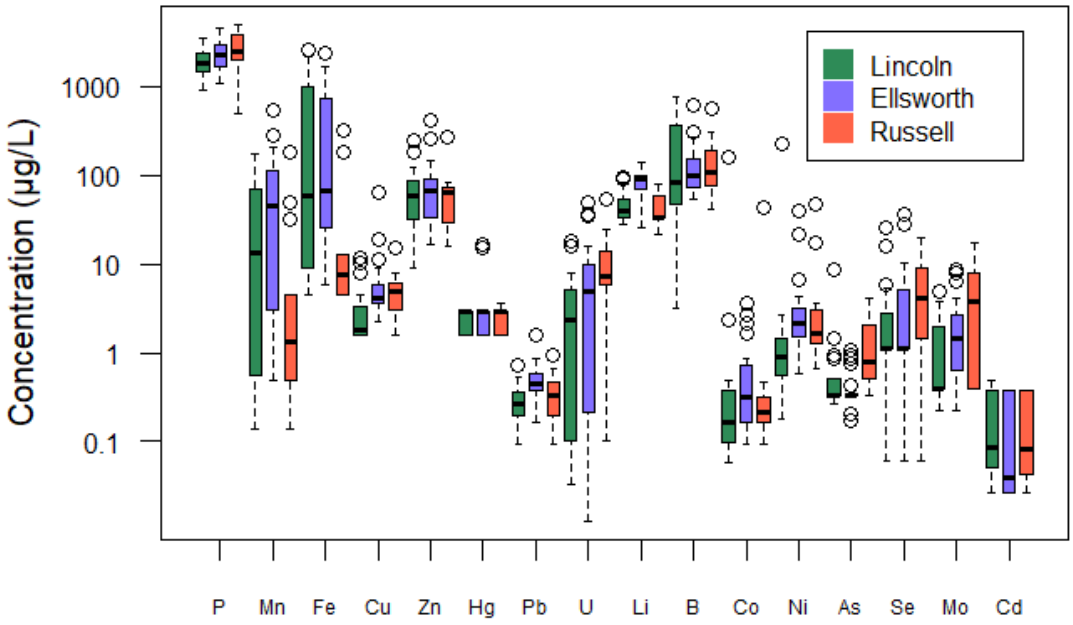

Figure 4.3 Box and whisker plot displaying the distribution of major anions and cations in samples from each county.

Water Quality

Groundwater in the study area contained three primary contaminants that exceed EPA maximum contaminant levels (MCL) and seven secondary contaminants that exceed EPA secondary contaminant levels (SMCL). SMCL and MCL values relevant to this study, along with a summary of violations for the study area are listed in figure 4.4.

Primary contaminant violations include nitrate, uranium, and mercury. The MCL for nitrate is 10 mg/L as N. Six samples violated this standard, two samples from each county. The highest concentration was 45.62 mg/L as N, found in Lincoln County. Nitrate has a moderate positive correlation with phosphorus (rho=0.48) and strontium (rho=0.47), weak positive correlations with DO (rho=0.36) and uranium (rho=0.33), and a moderate inverse relationship with dissolved iron (rho=-0.47) (Figure 4.5).

Contaminants					
Anions					
Primary Contaminants			**Secondary Contaminants**		
Anions	**MCL**	**% Samples over**	**Anion**	**SMCL**	**% Samples over**
NO3-	10 mg/L as N	10.71	SO4--	250 mg/L	25
			Cl-	250 mg/L	14.3
			Fl-	2 mg/L	3.57
Cations & Trace Elements					
Primary Contaminants			**Secondary Contaminants**		
Ion	**MCL**	**% Samples over**	**Ion**	**SMCL**	**% Samples over**
Uranium	0.30 µg/L	7.14	Fe++	0.3 mg/L	26.79
Mercury	2 µg/L	5.36	Mn++	0.05 mg/L	37.5
Other					
Parameter			**SMCL**		**% Samples over**
TDS			500 mg/L		98.2
Ph			<6.5 or >8.5		8.93
Non-water Contaminants					
Gas contaminant			**EPA Action Level**		**% Samples over**
Radon			4 pCi/L		48.7
Radon			*2 pCi/L		69.2
*EPA recommends that Americans consider fixing their home for radon levels between 2 pCi/L and 4 pCi/L					

Figure 4.4 Table summarizing regulatory limits and violations within the study area for primary, secondary, and non-water contaminants such as radon gas.

The second primary contaminant violation was uranium. The EPA and WHO both set the uranium MCL at 30 ug/L. Within the study area, we found four violations, the highest being 54.07 µg/L. It should be noted that Germany has an MCL at 10 µg/L; in that case, there are 15 violations of the water quality standard. Uranium strongly correlates with calcium (rho=0.75), strontium (rho=0.76), NPOC (rho=0.65), and TDS (rho=0.65) (Figure 4.5). Uranium has a moderate positive correlation with phosphorus (rho=0.55), sulfate (rho=0.55), and a moderate inverse relationship with dissolved iron (rho=-0.46) (Figure 4.5). Uranium has weak correlations with chloride (rho=0.39), DO (rho=0.30), and nitrate (rho=0.33) (Figure 4.5).

Only three samples violated the EPA and WHO MCL for mercury (0.002 mg/L). The highest concentration we found was 0.01543 mg/L in Lincoln County. The low numbers of samples with violating Hg concentrations precluded a correlation with other parameters.

Secondary contaminants cause degradation of water aesthetics, such as smell, coloration, and taste, but they do not pose serious health risks. The EPA SMCL for total dissolved solids (TDS) is 500 mg/L, 98.2% of samples exceed this limit (Figure 4.4).

The SMCL for pH has two limit values: a lower limit of 6.5 and an upper limit of 8.5. Samples below 6.5 and above 8.5 violate the SMCL standard. We found five samples that fell below 6.5 (Figure 4.4).

Fluoride has an SMCL value of 2 mg/L, and we found two violations in the study area. Chloride has a SMCL value of 250 mg/L, and we found eight violations in the study area, the highest value being 558.2 mg/L in Russell County. Sulfate has a SMCL value of 250 mg/L, and we found two samples violating this level, the highest being 1007 mg/L in Russell County.

Chloride strongly correlates with calcium (rho=0.61), strontium (rho=0.70), specific conductivity (rho=0.81), TDS (rho=0.69), and NPOC (rho=0.71) (Figure 4.5). Chloride also has a moderate correlation with sulfate (rho=0.55) and a weak inverse relationship with manganese (rho=-0.41) and iron (rho=-0.30) (Figure 4.5).

Sulfate strongly correlates with SpC (rho=0.84), TDS (rho=0.91), NPOC (rho=0.61), calcium (rho=0.74), and strontium (rho=0.80), with moderate correlations with chloride (rho=0.55), alkalinity (rho=0.43), and uranium (rho=0.55) (Figure 4.5).

The final SMCL violations were manganese and iron. The manganese SMCL is 0.05 mg/L; in the study area, we found 20 violations (Figure 4.4), the highest value found in 0.55

mg/L in Lincoln County. The iron SMCL is 0.3mg/L; we found 15 violations, the highest being 2.57 mg/L in Ellsworth County.

Manganese has a strong correlation with iron (rho=0.71) and moderate inverse relationships with DO (rho=-0.53), phosphorus (rho=-0.44), NPOC (rho=-0.49), and chloride (rho=-0.41) (Figure 4.5). Manganese also has a weak inverse relationship with radon (rho=-0.37). Iron has a strong relationship with manganese, moderate inverse relationships with DO (rho=-0.55), nitrate (rho=-0.47), phosphorus (rho=-0.58), and uranium (rho=-0.46), and weak negative relationships with NPOC (rho=-0.35) and chloride (rho=-0.30) (Figure 4.5).

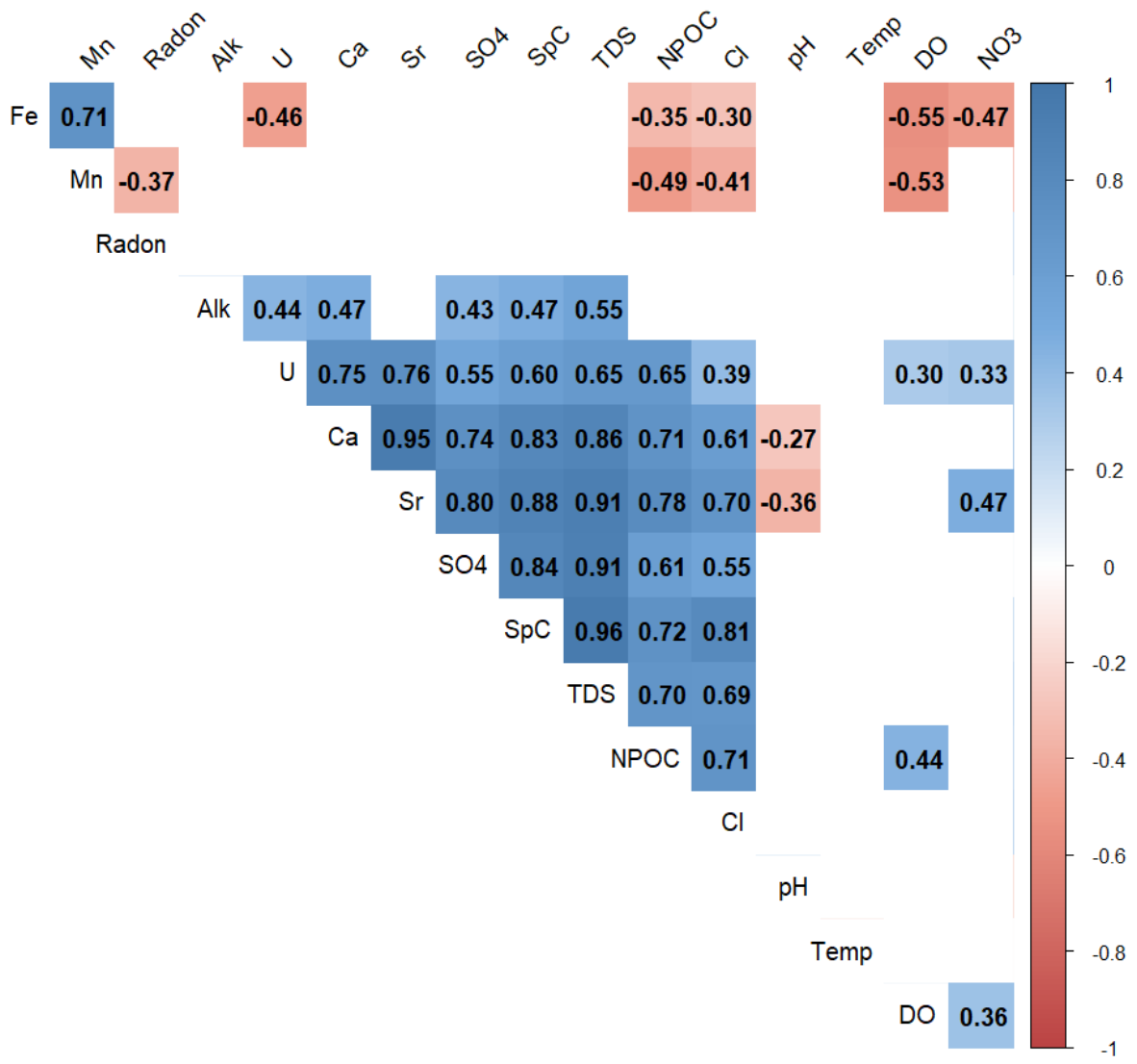

Figure 4.5 Correlogram displaying statistically significant (p values<0.05) Spearman's correlations. Blue colors indicate a positive correlation and red colors a negative relationship. Spearman's rho inside each box indicates the strength of the correlation.

Radon

The EPA recommends that homeowners take immediate action to lower radon levels when radon levels exceed 4 pCi/L. However, because there is no known safe radon level, the EPA strongly encourages action if levels exceed 2 pCi/L. Over the sampling periods, we performed 39 radon tests: 10 in Russell, 14 in Ellsworth, and 15 in Lincoln County. 19 tests

exceeded the upper action level of 4 pCi/L, and 8 exceeded the lower action level of 2 pCi/L. This finding amounts to 69.2% of radon tests exceeding 2 pCi/L and 48.7% exceeding 4 pCi/L (Figure 4.4). We found the highest radon concentration in Lincoln County at 36.2 pCi/L, nine times the upper action level. The median radon concentrations for Lincoln, Russell, and Ellsworth counties were 2.5 pCi/L, 7.6 pCi/L, and 4.4 pCi/L, all exceeding the EPA action level of 4 pCi/L except for Lincoln County. The maximum radon concentrations for Lincoln, Russell, and Ellsworth counties are 36.2 pCi/L, 25.5 pCi/L, and 13.1 pCi/L, respectively. Figure 4.6 summarizes the range of radon concentrations for each county in the study area (Figure 4.6).

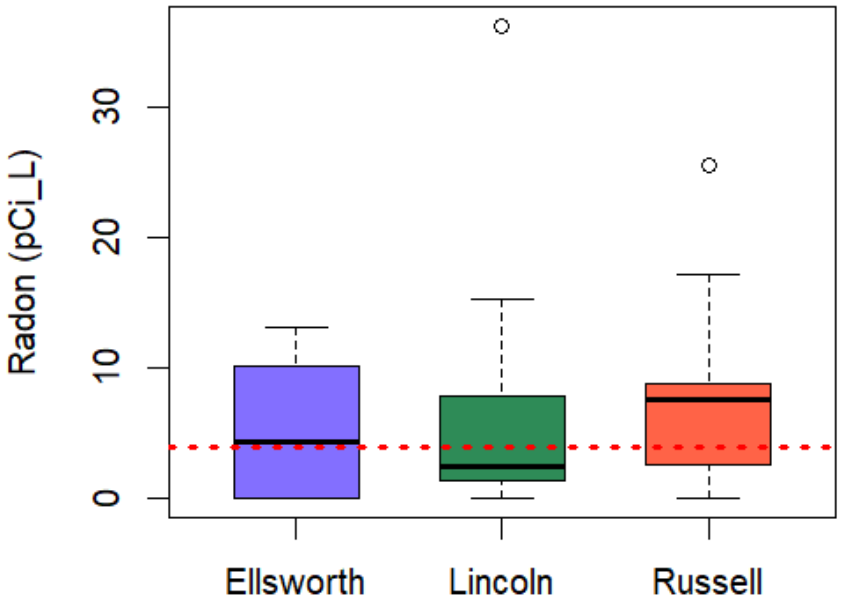

Figure 4.6 Box and whisker plot summarizing the distribution of radon concentrations for each county. The red line indicates a radon concentration of 4pCi/L, the upper EPA action level.

Geospatial analysis

Within the study area, we discovered zones of varying groundwater chemistry. pH was statistically similar between all three counties. The average pH values for Lincoln, Ellsworth,

and Russell counties were 6.80, 6.89, and 6.90, respectively. DO concentrations varied significantly between Lincoln County and Russell County (p=0.000147). The average DO value in Lincoln County is 1.83 mg/L, 3.67 mg/L in Ellsworth, and 5.60 mg/L in Russell County. Generally, Russell County had the highest DO values, and Lincoln had the lowest DO values (Figure 4.7A). Regarding NPOC, Lincoln County and Ellsworth County are statistically similar, while both are statistically distinct from Russell County (p= 0.02481 for Ellsworth, Russell. P= 0.004106 for Lincoln, Russell) (Figure 4.5). The average NPOC concentrations for Lincoln, Ellsworth, and Russell counties were 1.38 mg/L, 1.49 mg/L, and 2.55 mg/L, respectively. Spatially, NPOC is highest in Russell County, with elevated patches in Lincoln County (Figure 4.7B).

Regarding electrical conductivity in the study area, Lincoln and Ellsworth County are similar, while Russell County has a statistically significant difference with Ellsworth County (p=0.0137) and Lincoln County (p=0.0139) (Figure 4.7C). The average conductivity values for Lincoln, Ellsworth, and Russell counties were 903.2 µs/cm, 859.2 µs/cm, and 1313.9 µs/cm, respectively. TDS in the study area followed a similar pattern (Figure 4.7D). Lincoln and Ellsworth counties were statistically similar, and Russell County was statistically distinct from Ellsworth County (p= 0.040). Russell County and Lincoln County were not statistically distinct (p= 0.084). Average TDS values for Lincoln, Ellsworth, and Russell counties were 995 mg/kg, 859.2 mg/kg, and 1314 mg/kg, respectively. Generally, TDS was higher in Russell County than in Ellsworth and Lincoln counties (Figure 4.7D).

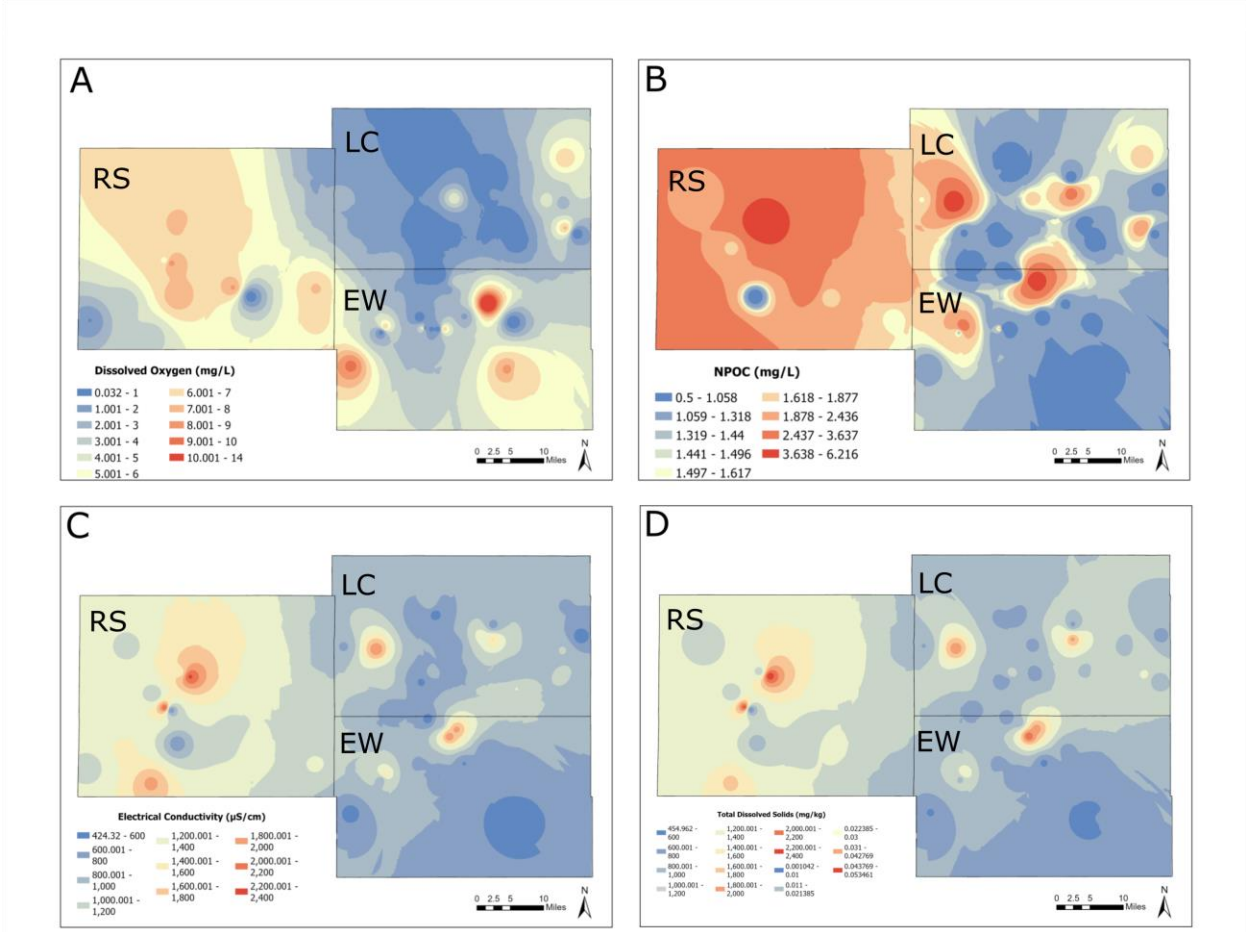

Figure 4.7 Spatial variation in major geochemical parameters in the study area. A) Dissolved oxygen, B) NPOC, C) Electrical Conductivity, and D) TDS.

Stable isotope data show a statistically significant difference in δD (deuterium) in all three counties and a significant difference in $\delta^{18}O$ in all three counties (Figure 4.8). For this study, we consider a relationship statistically significant when the p-values fall below 0.05. Generally, we found lower δD and $\delta^{18}O$ values in western Lincoln County and west-central Ellsworth County. We found the most positive values of both isotopes in Russell County and northeastern Lincoln County. δD average values for Lincoln, Ellsworth, and Russell counties

were -48‰, -51.9‰, and -41.4‰, respectively. $\delta^{18}O$ average values were -7.24‰, -7.28‰, and -5.97‰ for Lincoln Ellsworth and Russell counties, respectively.

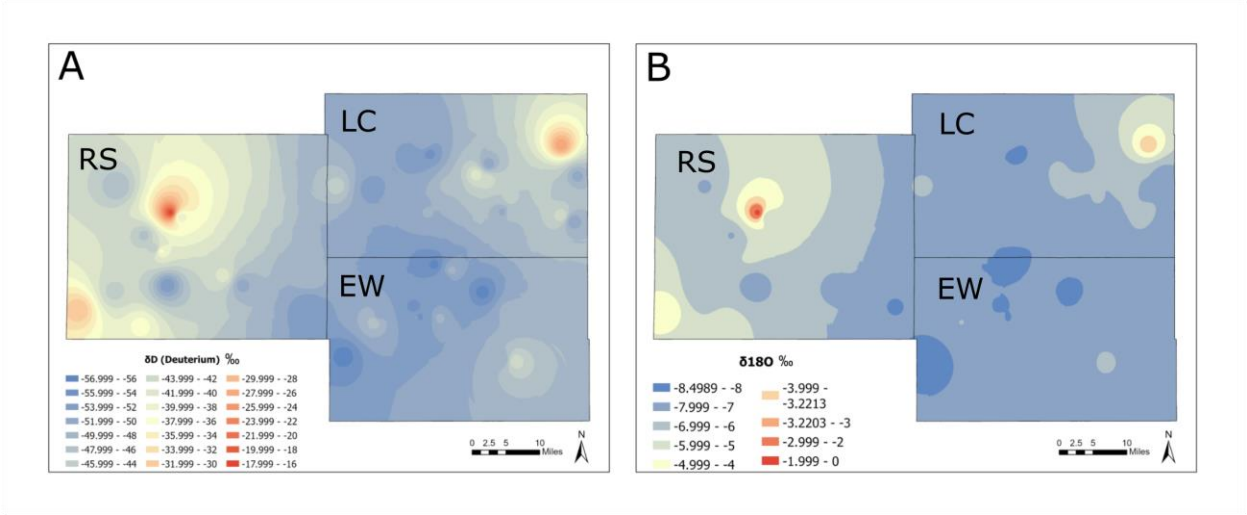

Figure 4.8 IDW map displaying spatial isotopic variations in δD (A) $\delta^{18}O$ (B).

Nitrate was statistically similar between all three counties. Groundwater with high nitrate contamination was primarily in isolated patches rather than following county-wide patterns like other parameters (Figure 4.9A). However, Russell has a higher nitrate concentration on average. The average nitrate concentrations in Lincoln, Ellsworth, and Russell counties were 4.92, 3.32, and 6.55 (mg/L as N), respectively. Median values were 0.70, 0.43, and 3.55 (mg/L as N), respectively.

Uranium was statistically distinct between Ellsworth and Russell (p=0.0374) but not between Russell and Lincoln counties (p=0.0723). High uranium concentrations are isolated occurrences, but background levels are higher in Lincoln and Russell counties (Figure 4.9B). The average concentrations in Lincoln, Ellsworth, and Russell counties are 9.35 µg/L, 3.79 µg/L, and 12.80 µg/L, respectively. The median values for uranium concentrations in Lincoln, Ellsworth, and Russell counties were 4.88 µg/L, 2.33 µg/L, and 7.43 µg/L, respectively.

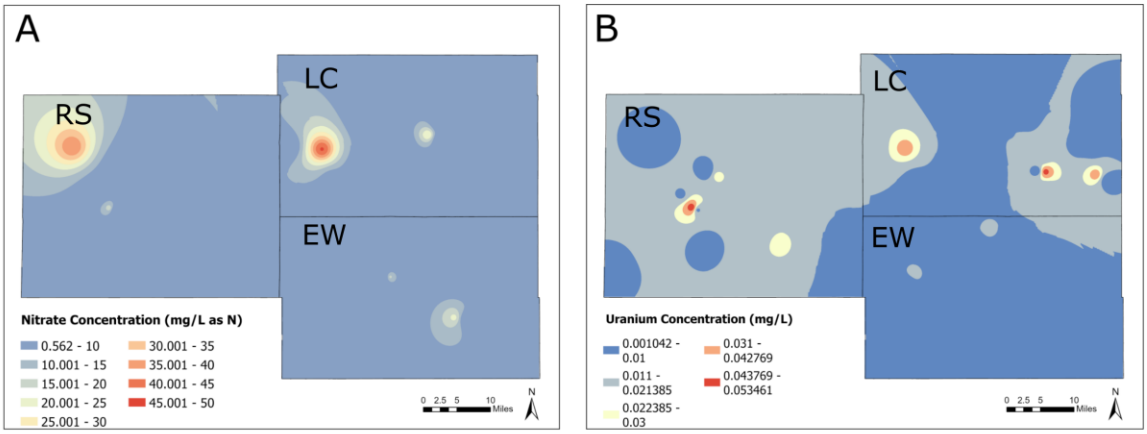

Figure 4.9 Primary contaminant concentrations across the study area. A) Nitrate, and B) Uranium.

Chloride concentrations in groundwater were statistically similar between Lincoln and Ellsworth counties. Russell County was statistically different than Lincoln (p=0.00630) and Ellsworth (p= 0.0286) counties. Generally, chloride is higher in Russell County and southwest Ellsworth County, with some isolated occurrences in Lincoln County (Figure 4.10A). The average chloride concentration for Lincoln, Ellsworth, and Russell counties was 62.49 mg/L, 83.79 mg/L, and 177.2 mg/L, respectively. The median values were 45.29 mg/L, 58.70 mg/L, and 116.1 mg/L respectively.

Sulfate is statistically similar across the study area. Generally, sulfate is highest in north-central Russell County, western Russell County, and isolated patches in northern Ellsworth County and southern Lincoln County (Figure 4.10B). The average concentrations for Lincoln, Ellsworth, and Russell counties are 187.46 mg/L, 88.16 mg/L, and 211.62 mg/L, respectively. Median values were 165.89 mg/L, 88.16 mg/L, and 211.62 mg/L respectively.

Iron varies significantly between Russell and Lincoln County (p=0.0073) and Russell and Ellsworth County (p=0.024). We found the highest iron concentrations in Lincoln and Ellsworth

County, specifically, northern Ellsworth County, southern Lincoln County, and Eastern Lincoln County (Figure 4.10C). Iron is nearly absent from Russell County. The average iron concentrations for Lincoln, Ellsworth, and Russell counties are 0.44 mg/L, 0.52 mg/L, and 0.042 mg/L, respectively. Median values for Lincoln, Ellsworth, and Russell counties are 0.07mg/L, 0.06 mg/L, and 0.007 mg/L, respectively.

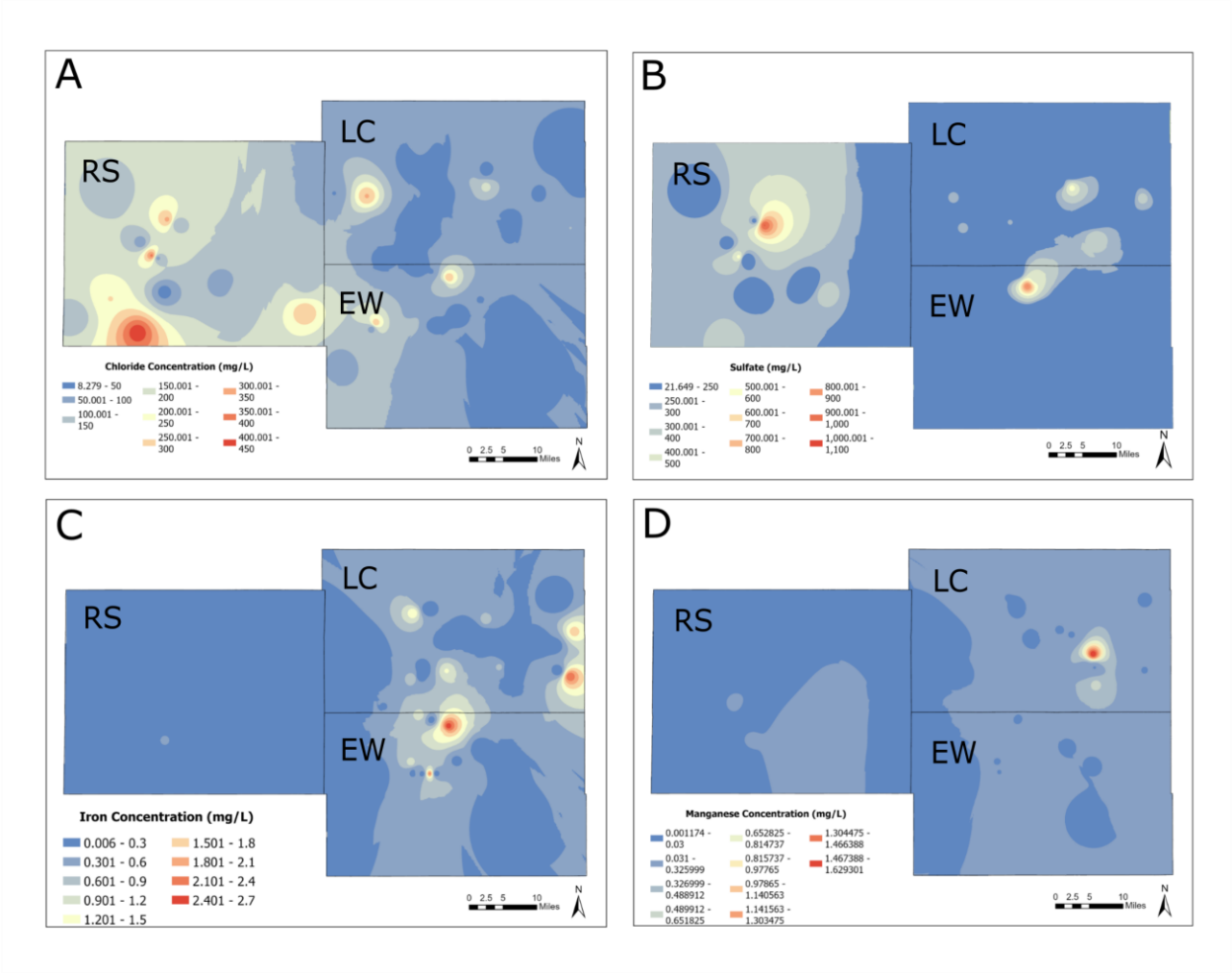

Figure 4.10 Secondary contaminant concentrations across the study area. A) Chloride, B) Sulfate, C) Iron, and D) Manganese.

Manganese displays a pattern similar to iron. Manganese varies significantly between Lincoln County and Russell County (p=0.034). The highest manganese concentrations in the

study area are in eastern Lincoln County and extend into western Lincoln County and central Ellsworth County (Figure 10D). In Russell County, manganese concentrations are much lower. The average manganese concentrations for Lincoln, Ellsworth, and Russell counties are 0.082 mg/L, 0.040 mg/L, and 0.019 mg/L, respectively. Median values are 0.046mg/L, 0.014mg/L, and 0.013mg/L for Lincoln, Ellsworth, and Russell counties.

Land Use Relationships

NLCD

Nitrate correlates with various land-use classes from NLCD on different scales (Figure 4.11). Nitrate shows weak positive correlations with developed land for the 1000m buffer (rho=0.27) and open water for the 2000m buffer (rho=0.32). Nitrite displays weak positive correlations with developed land for the 250m (rho=0.33) and 1000m buffer (rho=0.31). Uranium also positively correlates with the natural land cover class for the 500m (rho=0.31) and 1000m (rho=0.37) buffer sizes. Uranium has a weak positive correlation with the hay/pasture land-use class for the 2000m buffer (rho=0.26). Iron content positively correlates with the cultivated crops land-use class at the 2000m buffer size (rho=0.29), and chloride positively correlates with the open water class (rho=0.33) on the 2000m scale.

NLCD						
Species	Buffer	Cultivated Crops	Hay/Pasture	Natural Land	Developed Land	Open Water
NO_3^-	1000m				0.27	
	2000m					0.32
NO_2^-	250m	-0.31			0.33	
	500m	-0.35		0.31		
	1000m	-0.37		0.37	0.31	
U	2000m		0.26			
Cl^-	500m	-0.35	-0.28			
	1000m	-0.35				
Mn^{++}, Fe^{++}	1000m					Fe -0.31
	2000m	Fe 0.29				Fe -0.28

Figure 4.11 Spearman's correlations between NLCD land-use classes and primary and secondary contaminants. Red indicates a positive relationship, and blue indicates an inverse relationship. Spearman's rho inside each box indicates relationship strength.

CDL

Using CDL data, nitrate positively correlates with the total developed land use class at 500m (rho=0.27) (Figures 4.12, 4.13). Nitrate also positively correlates with open water at 2000m (rho=0.27). Nitrite positively correlates with the total developed land use class at the 250m (rho=0.31) and 500m (rho=0.33) buffer scale. Nitrite also correlated with open water at the 500m buffer (rho=0.34). At the 1000m scale, nitrite correlates with rye (rho=0.33) and grassland/pasture (rho=0.30). At the 2000m scale, nitrite correlates with rye (rho=0.35) and the total wetland class (rho=0.32).

CDL								
Species	Buffer	Corn	Sorghum	Soybeans	Winter Wheat	Rye	Oats	Alfalfa
NO_3^-	250m						0.28	
	500m			-0.33				
	1000m			-0.32		0.33		
NO_{2-}	2000m					0.35		-0.32
	250m				-0.3			
	500m				-0.27			
U	1000m	-0.32			-0.3			
	250m			-0.32				
	500m		-0.28	-0.37				-0.29
	1000m			-0.31				
Cl^-	2000m			-0.31				
	100m			Mn 0.33				Mn 0.28
	250m			Mn 0.41 Fe 0.36				
	500m			Mn 0.39 Fe 0.38				Mn 0.29
	1000m			Mn 0.32				
Mn^{++}, Fe^{++}	2000m			Mn 0.31 Fe 0.39	Fe 0.26			Mn 0.41 Fe 0.29

Figure 4.12 Spearman's correlations between CDL crop land use classes and primary and secondary contaminants. Red indicates a positive relationship, and blue indicates an inverse relationship. Spearman's rho inside each box indicates relationship strength.

Uranium had no positive correlations with CDL land use classes (Figure 4.12). Iron had positive correlations with soybeans in the 250m (rho=0.36), 500m (rho=0.38),1000m (rho=0.35), and 2000m (rho=0.39) buffer sizes (Figure 4.12). At the 2000m buffer scale, iron correlates positively with winter wheat (rho=0.26), alfalfa (rho=0.29), and non-alfalfa hay (rho=0.48) (Figure 4.13). Manganese positively correlates with soybeans in the 100m (rho=0.33), 250m (rho=0.41), 500m (rho=0.39), 1000m (rho=0.32) and 2000m (rho=0.31) (Figure 4.12). Manganese correlates with alfalfa in the 100m (rho=0.28), 500m (rho=0.29), 2000m (rho=0.41). Manganese correlates with non-alfalfa hay at the 2000m scale (rho=0.42) (Figure 4.13).

		CDL						
Species	Buffer	NonAlfalfa_Hay	Fallow Land	Open Water	Total Developed	Total Forest	Total Wetlands	Grassland/Pasture
	250m						0.36	
	500m				0.27			
NO_3^-	2000m			0.27				
	250m				0.31			
	500m			0.34	0.33			
	1000m							0.3
NO_2^-	2000m						0.32	
	100m					-0.36		
	250m					-0.27		
	1000m	-0.29						
Cl^-	2000m	-0.32				-0.27		
	100m		Fe -0.29					
	1000m			Fe -0.31				
Mn^{++}, Fe^{++}	2000m	Mn 0.42 Fe 0.48		Fe -0.32				

Figure 4.13 Spearman's correlations between CDL crop land use classes and primary and secondary contaminants. Red indicates a positive relationship, and blue indicates an inverse relationship. Spearman's rho inside each box indicates relationship strength.

Cancer Data

Age and Risk Factors

We analyzed cancer surveys from 65 households within the study area. 68% of households in the study area reported at least one cancer case. In Russell County, 88% of the households surveyed reported cancer cases. Cancer incidence in Lincoln was 58 % and 55% in Ellsworth County. Regarding sex, cancer incidence in males was 71% in Ellsworth County, 53% in Russell County and 44% in Lincoln County. In other words, most cancer cases in Ellsworth County were in females, and most cancer cases in Ellsworth County were in males. Russell County has roughly equal amounts of cancer per sex.

When analyzed per age bracket, overall in the study area most cancer cases occur in individuals between the ages of 61-80 years old (47%) and 41-60 years old (41%). However, in Russell County 6% of cancer cases were in children (<20 years old), in Ellsworth County 18% were in individuals aged 21-40 years old and in Lincoln County 53% were in individuals aged

41-60 years old. The overall percentage of cancer cases within the study area in smokers was 23%, much higher than the state incidence of 15%. In Russell County, 27% of individuals with cancer were smokers, in Ellsworth, 18%, and in Lincoln 23% were smokers.

According to our data, 65% of individuals were screened for colon cancer within the study area. Colon cancer screening percentages were 76%, 57%, and 69% in Lincoln, Russell, and Ellsworth counties, respectively.

Our survey revealed that, overall, 41% of the individuals with cancer had no (known) risk factor, and, from those tested for genetic markers associated with cancer, none displayed genetic predisposition for cancer. However, 83% of individuals diagnosed with cancer have at least one other family member also diagnosed with cancer.

Cancer Types

We identified the six most common types of cancer within the study area. The first is prostate cancer, which accounts for 17% of cancer occurrences (Figure 4.14). Russell and Ellsworth County had 5 cases each, and Lincoln County had 4.

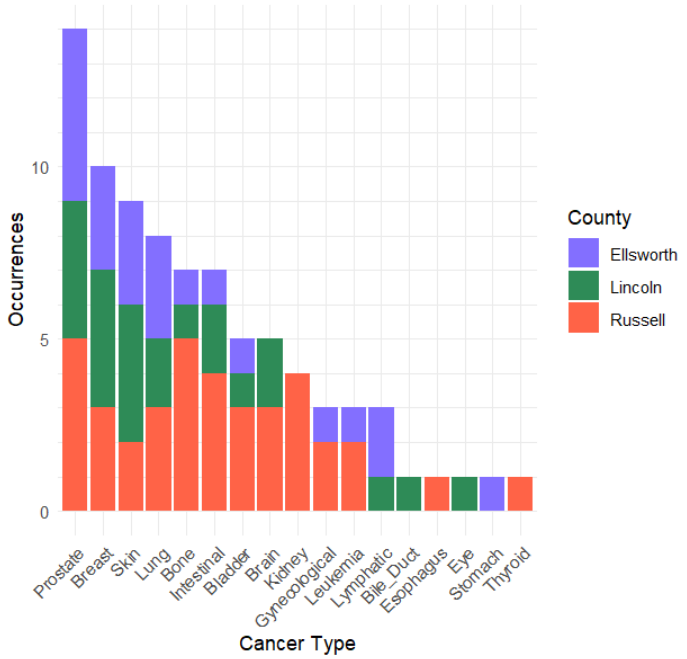

Figure 4.14 Number of occurrences of various cancer types reported in our cancer surveys. The colors indicate the numbers per county.

Breast cancer accounts for 12% of reported cancer in the study area, with 4 cases in Lincoln County and three cases in Russell and Ellsworth counties each (Figure 4.15). Skin cancer is the third most common type at around 11% of cases. Lincoln County has 4 cases, Ellsworth County 3 cases and Russell County 2 cases. Lung cancer is the next highest, accounting for roughly 10% of cases. Ellsworth and Russell Counties have three cases each, and Lincoln County has 2 cases. Bone cancer accounts for 8% of reported cases, with 5 cases reported in Russell County, and Ellsworth and Russell counties with only one case each. Lastly, intestinal cancers account for 8% of cases, with Russell County recording 4 cases, Lincoln 2 cases, and Ellsworth County one case. Kidney cancer, despite representing only 5% of cases, was only reported in Russell County (4 cases). Brain cancer makes up 6% of cases and is restricted to Lincoln County (2 cases) and Russell County (3 cases), not being reported in Ellsworth County.

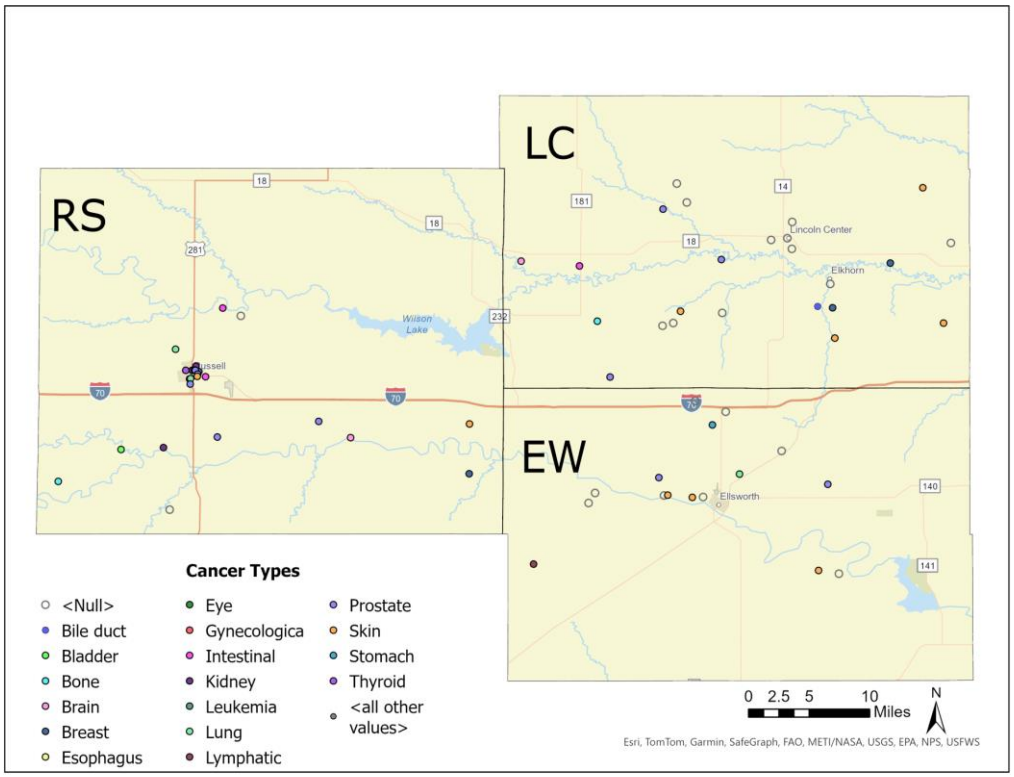

Figure 4.15 Spatial distribution of all cancer data collected across the study area. Open circles indicate surveyed households that reported no cancer cases.

Chapter 5 - Discussion

Geochemistry

Aquifer Characteristics

We found two distinct groundwater redox zones within the study area, based on the DO concentrations. The boundary between these redox zones is along the western border of Ellsworth and Lincoln counties (Figure 4.7A). Generally, Russell County has oxygen-rich, oxidizing groundwater (>0.96mg/L) indicated by a median DO concentration of 6.49 mg/L, whereas Lincoln and Ellsworth County have groundwater closer to sub-oxic conditions (<0.96 mg/L), with median DO concentrations of 0.98 mg/L and 1.75 mg/L respectively. Additionally, Russell County has higher concentrations of NPOC (median = 2.44 mg/L), in contrast with Ellsworth and Lincoln County, which have median values of 0.973 mg/L and 1.07 mg/L respectively.

Redox heterogeneity across the study area is likely related to well depth, as dissolved oxygen is most abundant in shallower wells. KGS WWC5 well data suggests that most of Russell County has wells drilled to depths of 35 ft, while areas of Lincoln and Ellsworth County (especially in highland areas) reach depths of 60-250 ft (Figure 5.1). This discrepancy of well depths to water is likely due to topographic variations across the study area. Additionally, Russell County is located further up the flow pathway of the Dakota aquifer, which could result in the removal of dissolved oxygen before it reaches Lincoln and Ellsworth counties.

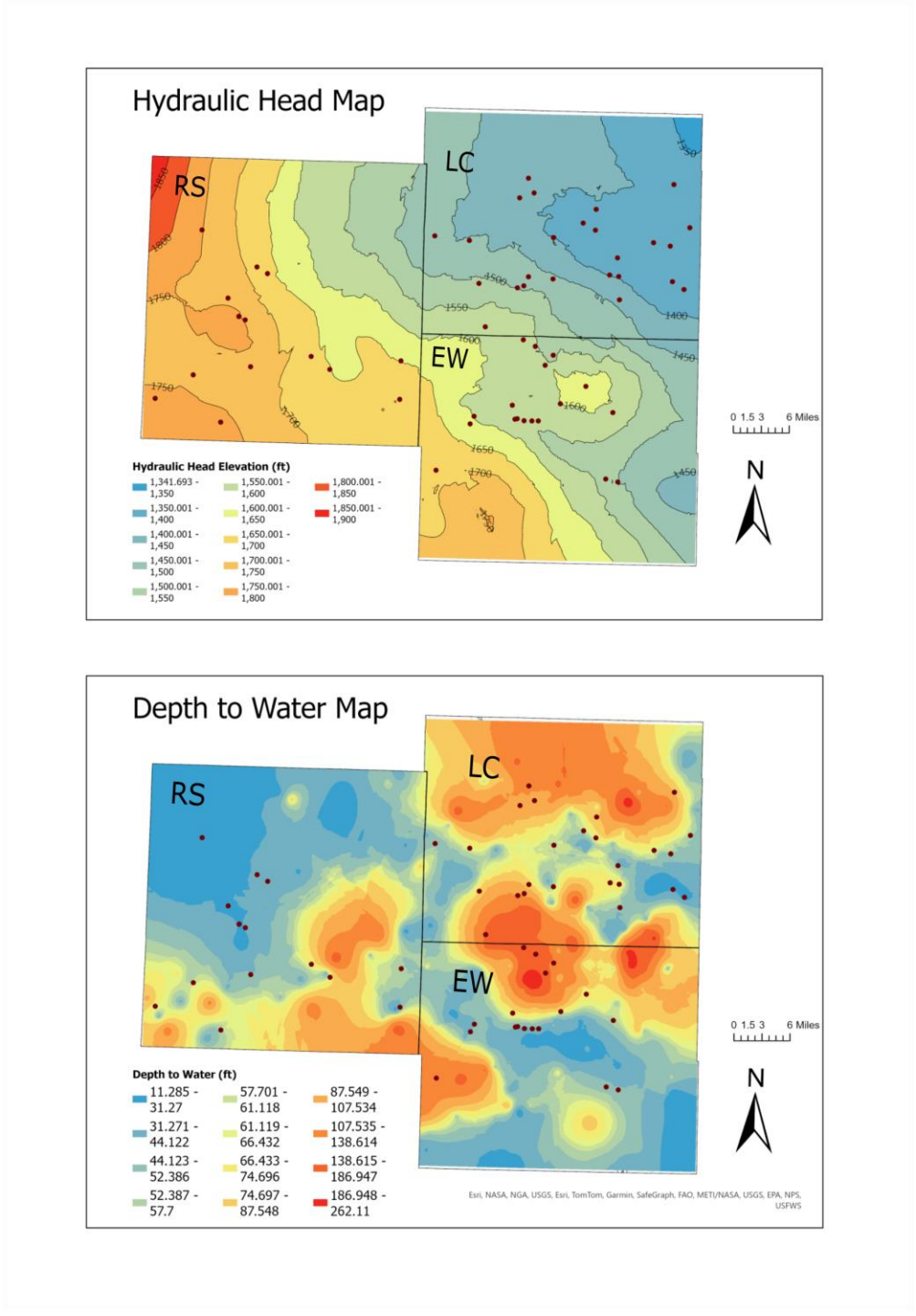

Figure 5.1 Maps showing hydraulic head elevation (top) and depth to water (bottom) as reported in well construction records across the study area (KGS WWC5 wells).

Stable isotope analysis in water showed that Russell County has the isotopically heaviest water of the three counties (Figure 5.2). Variation in isotopic data could be a result of evaporation, recent recharge from precipitation, or mixing of groundwater sources. Divergence of samples from the global meteoric water line (GMWL) indicates that some samples have undergone evaporation on the surface prior to infiltration into the groundwater, and it only includes samples from Russell County plus one sample from Lincoln County. Irrigation flowback could explain this evaporation signature for samples in Russell County.

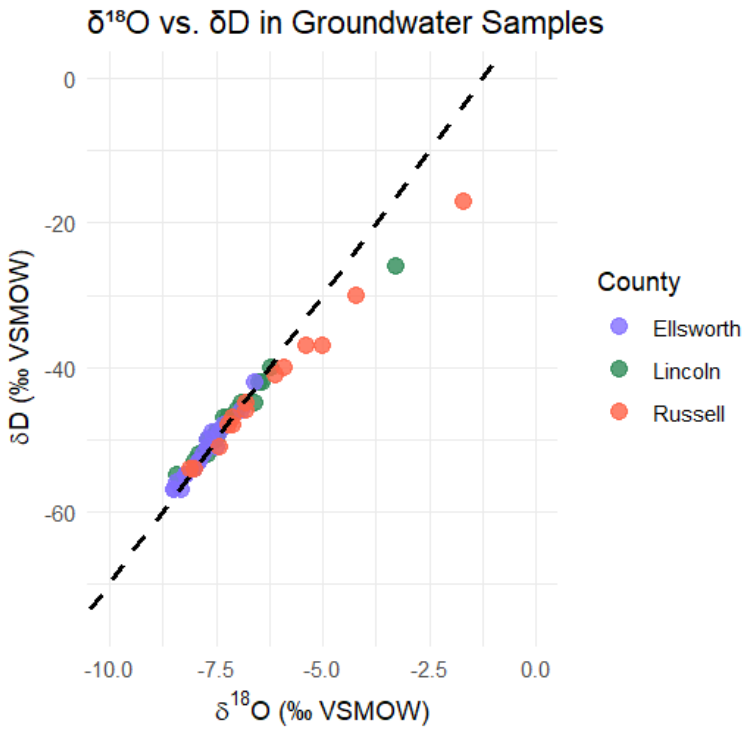

Figure 5.2 Cross plot between δ18O and δD. with samples color-coded by county. The dark dashed line is the GMWL (global meteoric water line). Divergence from this line indicates evaporation.

The deuterium excess (D-excess) parameter provides insight into the role of evaporation in influencing the geochemistry of water samples. In the study area, most samples cluster around D-excess values of approximately 10‰, consistent with unaltered meteoric water and minimal

evaporative effects. However, as shown in Figure 5.3, several samples from Russell and Lincoln counties exhibit significantly lower D-excess values, ranging from about -3‰ to 5‰. These depleted D-excess values suggest that evaporation has played a substantial role in modifying the isotopic composition of water in these areas, which could result from irrigation flowback. Additionally, irrigation flow back explains the positive relationship between sulfate and chloride with D-excess as irrigation and salt-based fertilizers often occur together.

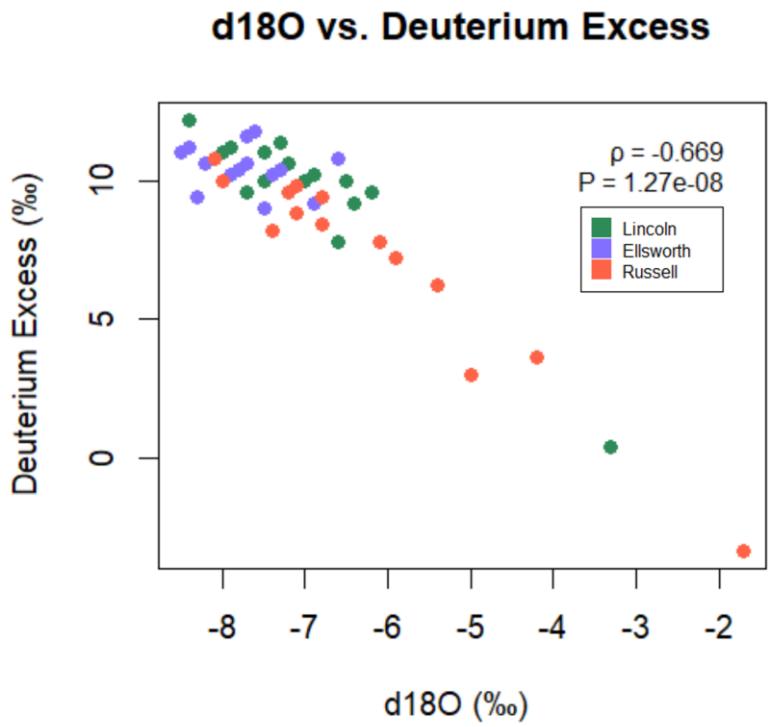

Figure 5.3 D-excess vs. d18O. Figures plotting towards the bottom right display signs of evaporation, while samples plotting towards top right indicate unaltered meteoric water.

Nitrate

Nitrate positively correlates with DO, NPOC, Ca, and Sr. The correlations with DO and NPOC (Figure 5.4) indicate that nitrate occurrence in the study area depends on redox conditions. Redox conditions depend upon well depth, location along the groundwater flow path,

and heterogeneity within geologic units. In oxygen-rich environments, microbes use oxygen during cellular respiration. Oxygen is the most efficient electron acceptor, which explains why organisms prefer it over other electron acceptors. Nitrate is also an electron acceptor, albeit not as efficient as oxygen, and is the next preferable option for microbes. Because oxygen is preferred to nitrate, nitrate accumulates in oxygen-rich groundwater, as oxygen is depleted by organisms before nitrate. In oxygen-poor groundwater, nitrate is used as an electron acceptor and is removed from the solution. These processes explain why nitrate and dissolved oxygen have a positive correlation.

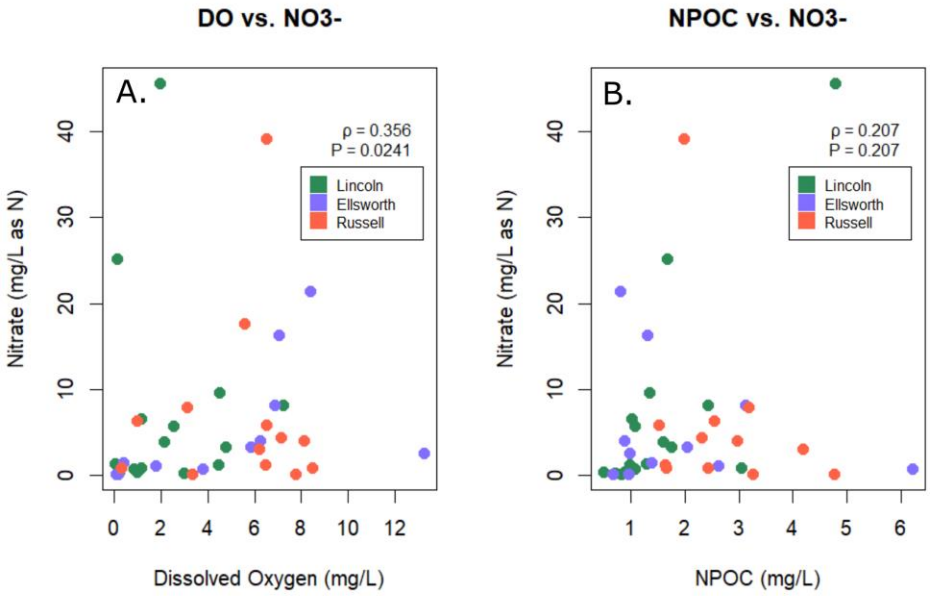

Figure 5.4 Cross plots between nitrate and dissolved oxygen (A), and NPOC (B). Spearman's rho and its corresponding p-value are printed on the plot.

The two samples with the highest nitrate concentrations were found near cattle feeding/watering/sheltering areas. This field observation suggests that cattle

feeding/watering/sheltering areas can contribute to nitrate contamination in shallow, nearby wells.

Uranium

Uranium is likely derived from black shales, but other contributing sources could be phosphate fertilizers, local ash deposits, and detritus derived from igneous rocks. Redox conditions within the groundwater control uranium mobility across the study area. Uranium mobilization under oxidizing conditions explains positive relationships between uranium, DO (0.30), and nitrate (0.33) (Figure 5.5A and B). These relationships suggest that redox processes, nitrate and organic matter (NPOC) concentrations, and carbonate alkalinity control uranium mobility. Most notable is the strong relationship with NPOC (rho=0.65) and moderate relationship with alkalinity (rho=0.41) (Figure 5.5C and D). These findings reinforces our current knowledge of uranium mobility in groundwater as several studies have found that uranium mobility is largely dependent upon redox conditions, bicarbonate content, and nitrate concentration (Banning et al., 2013; Bonotto et al., 2019; Liesch et al., 2015; Nolan & Weber, 2015).

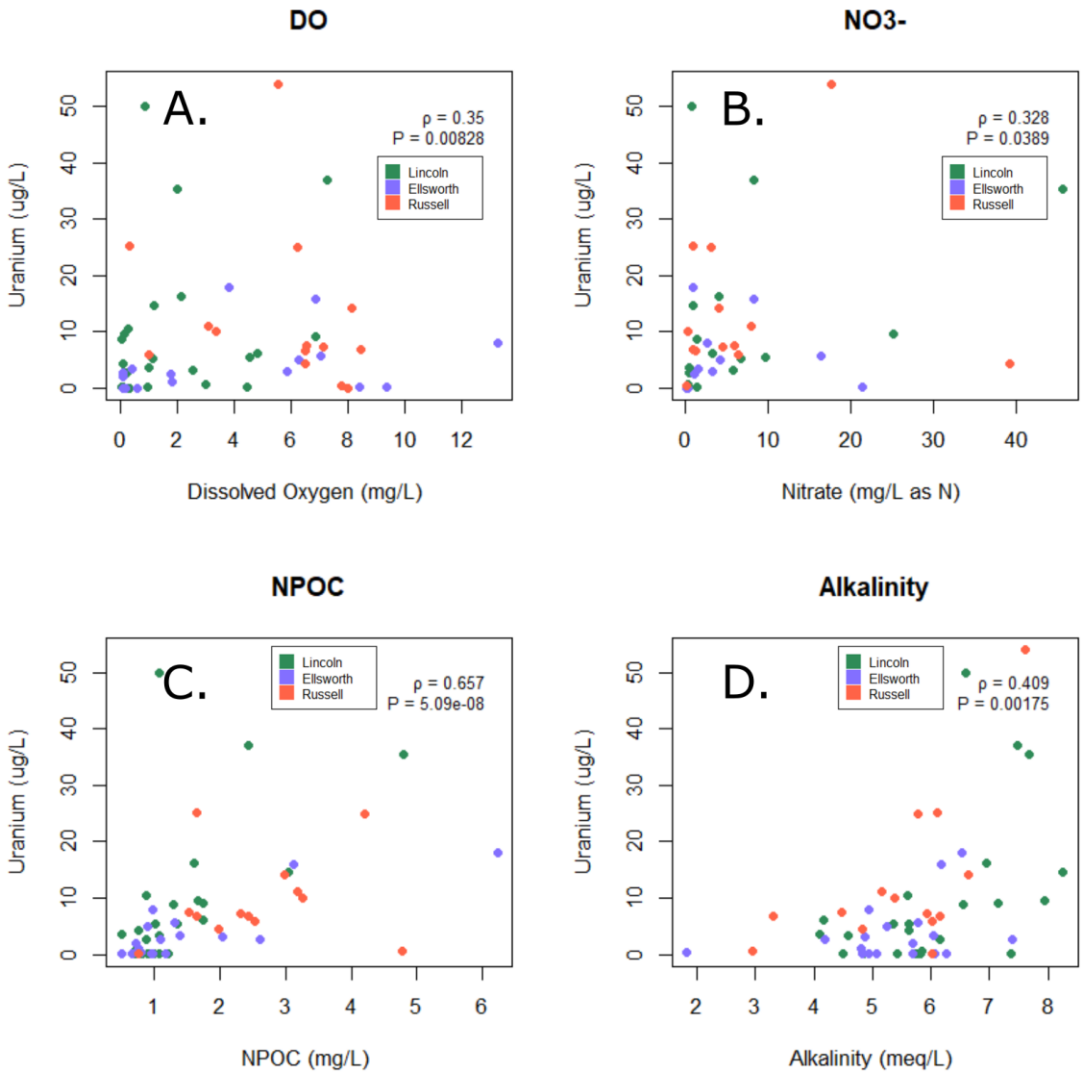

Figure 5.5 Cross plots between uranium and DO (A), nitrate (B), NPOC (C), and Alkalinity (D).

Additionally, uranium mobilization under oxidizing conditions explains uranium's inverse correlation with iron (-0.46) (Figure 4.5), as iron precipitates under reducing conditions. Under oxygen-rich conditions like those found in Russell County, uranium readily desorbs from mineral surfaces, organic matter, and soil surfaces and mobilizes into the groundwater as the uranyl iron (UO_2^{2+}). Carbonate alkalinity, NPOC (organic matter), calcium, and nitrate increase uranium mobility by complexing with the uranyl ion; these relationships are consistent with our

findings. In oxygen-poor groundwater, uranium stays sorbed to mineral surfaces, organic matter, and soil particles. This tendency for uranium to stay immobile under reducing conditions explains uranium's absence in parts of Lincoln and Ellsworth County.

Iron and Manganese

The iron source for groundwater is likely iron minerals within the subsurface. According to the literature, pyrite occurs in the Kiowa Formation, Dakota Formation, Graneros Shale, and Niobrara Chalk (Berry, 1952; Frye & Brazil, 1943; Hattin, 1982; Swineford, 1947). The Dakota Formation has primarily cement (Berry, 1952; Frye & Brazil, 1943; Sawin & Layzell, 2024)l. In deeper wells, dissolved oxygen is depleted, and suboxic conditions dominate. In suboxic and anoxic conditions, ferric iron (solid iron within minerals) is reduced and mobilized as soluble ferrous iron, resulting in elevated iron concentrations in groundwater. This process explains the higher iron concentrations in Lincoln and Ellsworth counties, where suboxic and anoxic conditions dominate. In Russell County, dissolved oxygen is abundant, which ensures the oxidation of soluble ferrous iron, and subsequent removal from the solution through mineral precipitation. Manganese could be derived from manganese oxide minerals within marine sedimentary rocks. And would be mobilized by reduction from insoluble Mn (IV) to soluble Mn (II). This behavior mirrors iron, as both manganese and iron are inversely correlated with dissolved oxygen, NPOC, and nitrate (Figure 5.6), suggesting that iron and manganese mobility is controlled by redox state of the groundwater.

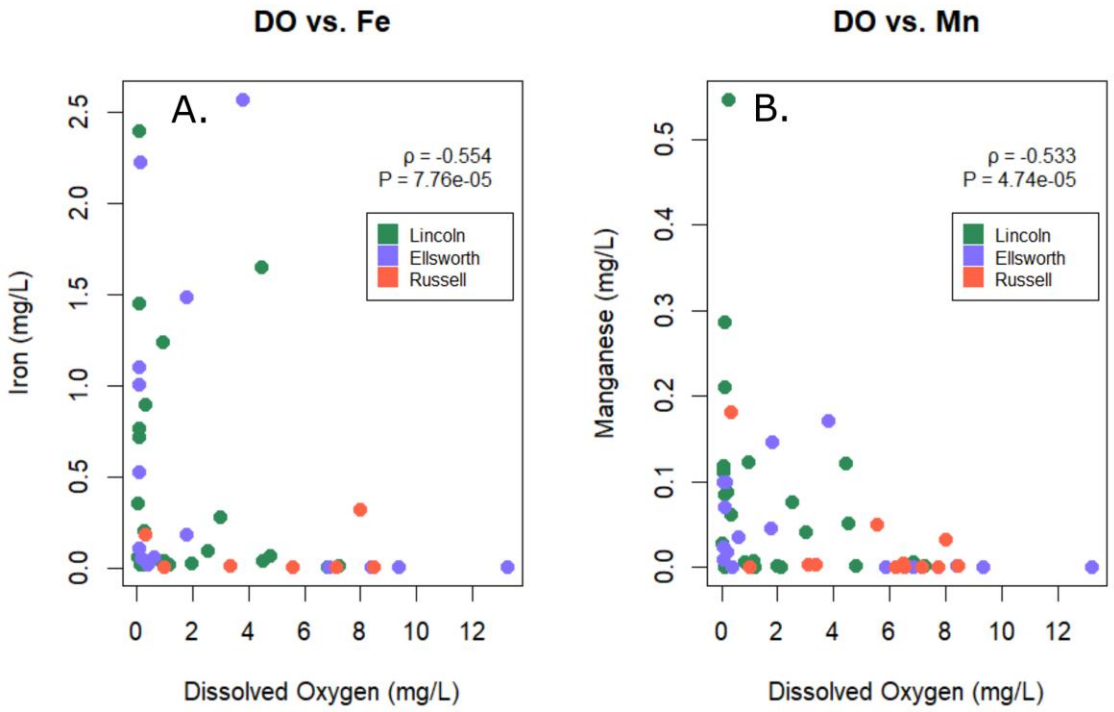

Figure 5.6 Cross plots between dissolved oxygen and iron (A), and manganese (B). Spearman's rho and its corresponding p-value are printed on the plot.

Chloride and Sulfate

We observed elevated chloride concentrations in Russell County, with patches above the EPA SMCL in southern and central Russell County and western Lincoln and Ellsworth counties (Figure 4.10A). Likewise, sulfate is present in high concentrations in Russell County. Most of Russell County's groundwater exceeds the EPA's SMCL of 250 mg/L for sulfate (Figure 4.10B). North-central Ellsworth County has a small area of groundwater with sulfate concentrations exceeding the SMCL. However, most samples from Lincoln and Ellsworth counties have sulfate concentrations below the sulfate SMCL. This finding is consistent with previous reports, which indicate that Russell County has higher chloride and sulfate concentrations than Lincoln and Ellsworth County (Whittemore et al., 2014). Reducing conditions present in Lincoln and

Ellsworth counties explain low sulfate in groundwater. Under reducing conditions, sulfide oxidation within pyrite can increase sulfate concentrations in groundwater. When high calcium concentrations (from carbonate weathering) are present alongside increased sulfate (from sulfide oxidation), gypsum can reach saturation and precipitate as secondary gypsum. This phenomenon is reported by (Whittemore et al., 2014) in their study on the Dakota aquifer. Gypsum precipitation could explain the lack of sulfate in Ellsworth and Lincoln counties.

Additionally, microbial sulfate reduction could explain the lack of sulfate in Lincoln and Ellsworth County. In Russell County, oxidizing conditions dominate, which leads to sulfide mineral oxidation, which then increases sulfate and ferrous iron concentration in the groundwater. However, ferrous iron derived from sulfide oxidation immediately oxidizes to form iron (III) oxide minerals, resulting in low iron concentrations in groundwater. This process accounts for high sulfate and low ferrous iron concentrations in Russell County. High chloride and sulfate concentrations could indicate a more arid climate than Lincoln and Ellsworth counties. Russell County received an average of 25.98 inches of rainfall per year over 1991-2020 (*Kansas Office of the State Climatologist · Kansas Drought*, n.d.). This average is several inches lower than Lincoln County, which received 28.24 inches, and Ellsworth County, which received 29.38 inches annually. Elevated chloride and sulfate concentrations could also be related to surficial inputs such as applying salt-based fertilizers. The weak-moderate negative relationship between chloride and sulfate with D-excess supports this interpretation (Figure 5.7).

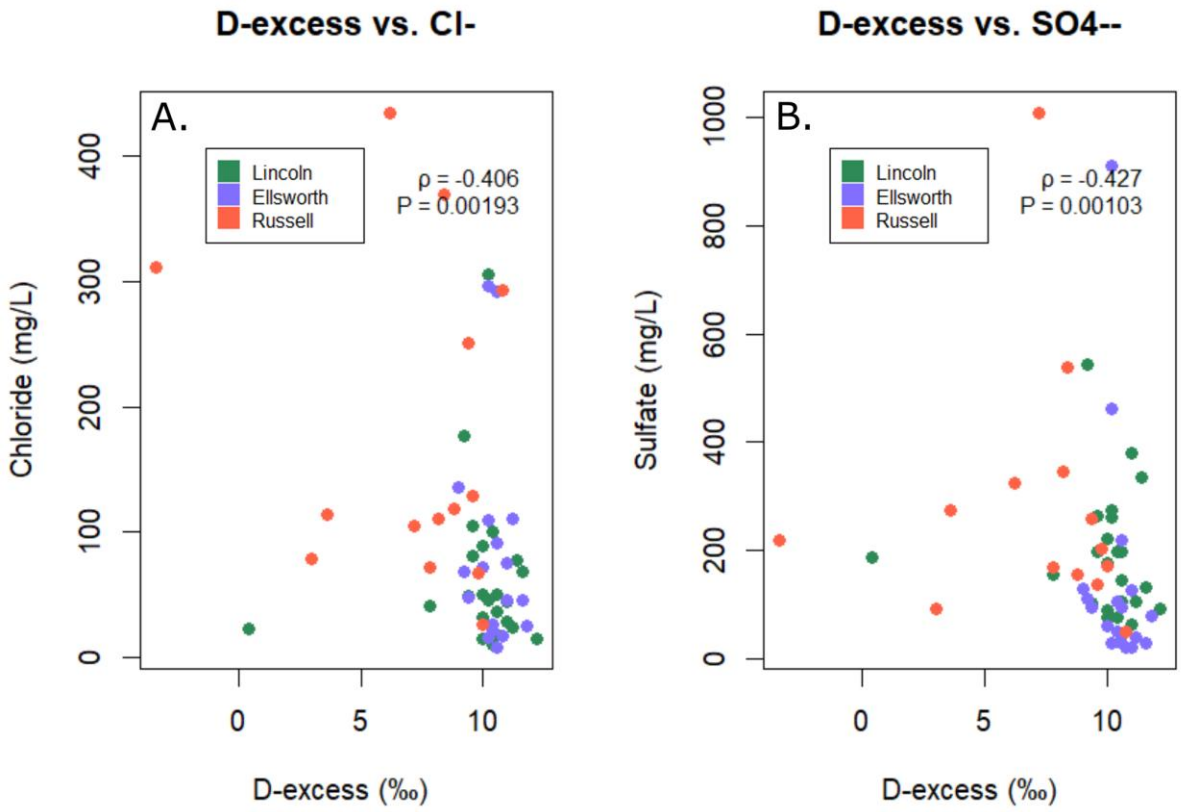

Figure 5.7 Cross plots between D-excess and chloride (A), and sulfate (B). Spearman's rho and its corresponding p-value are printed on the plot.

Additionally, when plotting δD vs. $\delta^{18}O$, we found an evaporation line containing only samples from Russell County (Figure 5.2), suggesting that samples from Russell County underwent evaporation prior to infiltration. This finding, along with the inverse relationship with D-excess supports the interpretation that irrigation flowback could explain both the evaporation signature and the high concentrations of chloride and sulfate. Groundwater could become enriched in chloride and sulfate as irrigation water passes through high-salinity soils or is sprayed alongside fertilizers directly. The positive correlation between chloride and sulfate with potassium, nitrite, and ammonium (Figure 5.8) lends additional credibility to this interpretation.

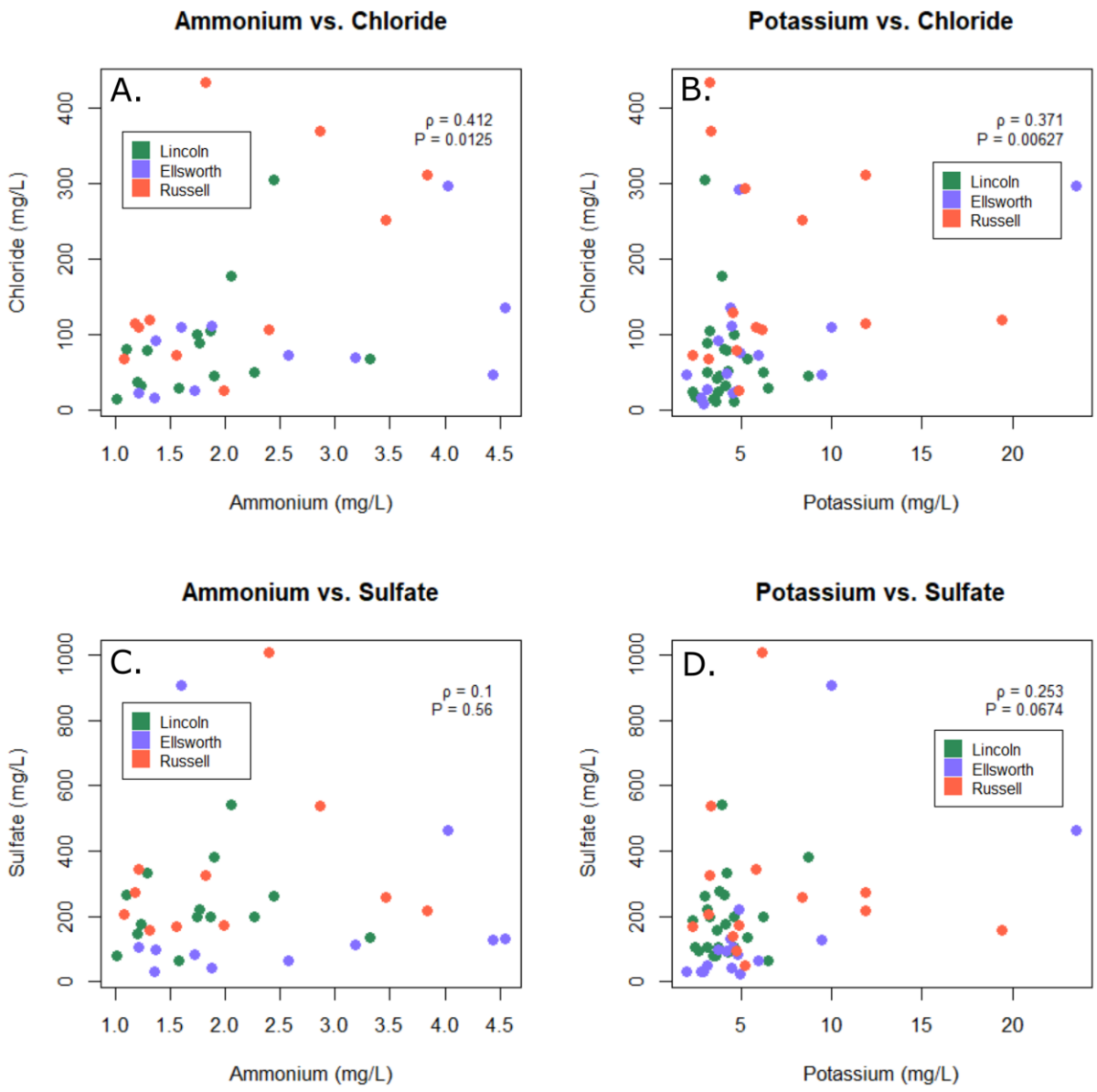

Figure 5.8 Cross plots between ammonium and chloride (A), sulfate (C), and sulfate (B). Additional cross plot between potassium and chloride (B), and sulfate (D). Spearman's rho and its corresponding p-value are printed on the plot.

Water-rock interactions primarily influence Ellsworth County groundwater, whereas Russell and Lincoln counties are primarily influenced by evaporation. Thus fertilizer inputs might be the primary contributing factor to high ion concentrations in Russell and Lincoln

County. Russell County is the 6th highest-producing county in terms of oil and gas in Kansas, and there are hundreds of KDHE-reported brine spills in Russell County. These spills in Russell County could also influence chloride and sulfate concentrations in the groundwater. However, we did not observe evidence of brine mixing in our samples. The most likely sources of sulfate and chloride in the study area are bedrock weathering (sulfide oxidation), dissolution, evaporation, and fertilizer application.

Radon

Radon gas originates from the decay of geogenic uranium into radium, radon, and lead. The primary source of uranium is marine sedimentary rocks, notably black shales, located within the study area. Uranium could also originate from phosphate-based fertilizers, as phosphate minerals used for fertilizers often contain trace amounts of uranium. Most of the study area shows radon concentrations above the EPA limit of 4pCi/L (Figure 5.9), except for some localized areas in southwest Lincoln, southeast Ellsworth and subordinately central-east Russell County, where the concentration is below the limit. The very high radon concentrations in western and southeastern Russell County, western Ellsworth and northeast Russell County are truly alarming, reaching levels that are at least 3 times higher than the EPA limit.

Cancer Data

Lung Cancer

While direct links remain elusive, some spatial variations hint at possible relations between environmental contaminants and cancer incidence within the study area. The strongest link is between radon occurrence and lung cancer, as radon has been demonstrated by numerous

studies to be related to lung cancer (Darby et al., 2005; Krewski et al., 2005; Li et al., 2020; Messier & Serre, 2017; Rääf et al., 2023; Riudavets et al., 2022). Six of seven lung cancer cases were within the 8-12 pCi/L zone, which is 2-3 times higher than the EPA upper action level, indicating a serious health risk (Figure 5.9). One case of lung cancer is located on a property where radon levels reached 9 times the EPA upper action level of 4 pCi/L. Because radon is the leading cause of lung cancer among nonsmokers (US EPA, 2014), and smoking rates cannot account for the widespread elevated lung cancer levels within the study area, radon is likely a contributing cause of lung cancer within the study area. Three of seven cases of lung cancer were from nonsmokers, which suggests lung cancer is related to radon within the study area or, at the minimum, a contributing factor alongside smoking.

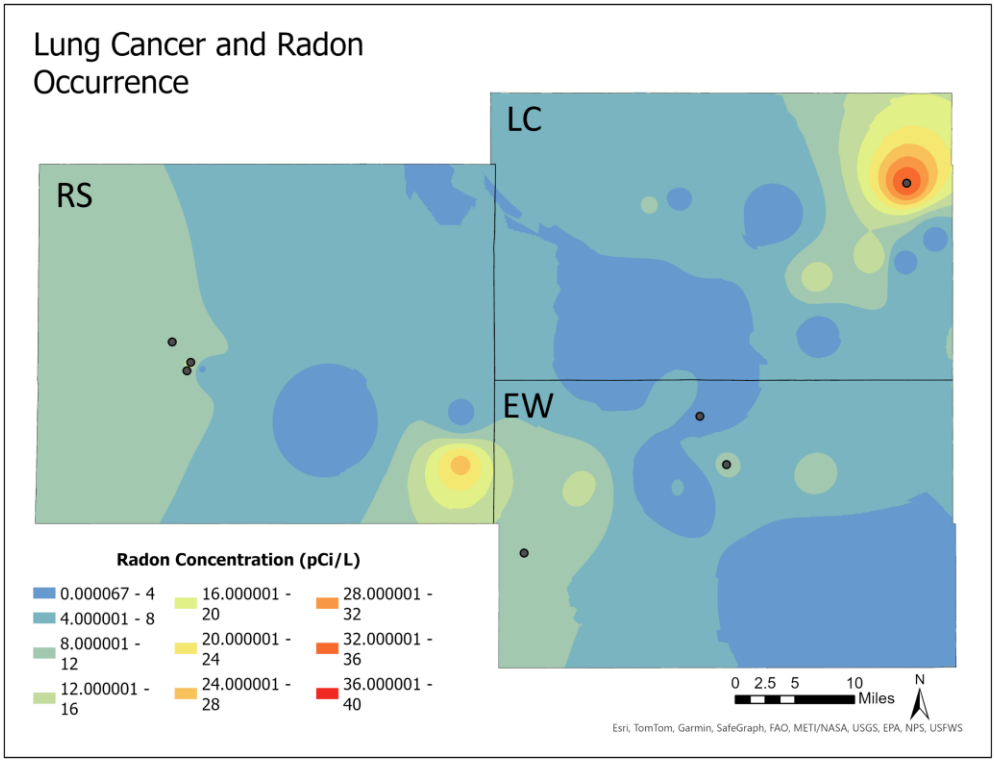

Figure 5.9 Map displaying radon concentration across the study area, overlain with reported lung cancer cases (black circles).

Intestinal Cancer

We found seven cases of intestinal cancer within the study area; four of those cases are in areas with nitrate (as N) concentrations exceeding the EPA MCL of 10 mg/L (Figure 5.10). One of these cases occurs alongside nitrate concentrations reaching 45.62 mg/L, 4.5 times the EPA MCL. Three cases of intestinal cancer occur where nitrate (as N) levels are below 5 mg/L. This pattern reveals that the relationship between nitrate and intestinal cancer is possible but complex. Considering the cases located near groundwater with concentrations exceeding the EPA regulatory limit, studies have shown that adverse health effects can arise from ingestion of water with concentrations much lower than 10 mg/L for nitrate as N (Espejo-Herrera et al., 2016; Schullehner et al., 2018; Ward et al., 2018), What opens the possibility that nitrate contamination contributes to intestinal cancer to some degree.

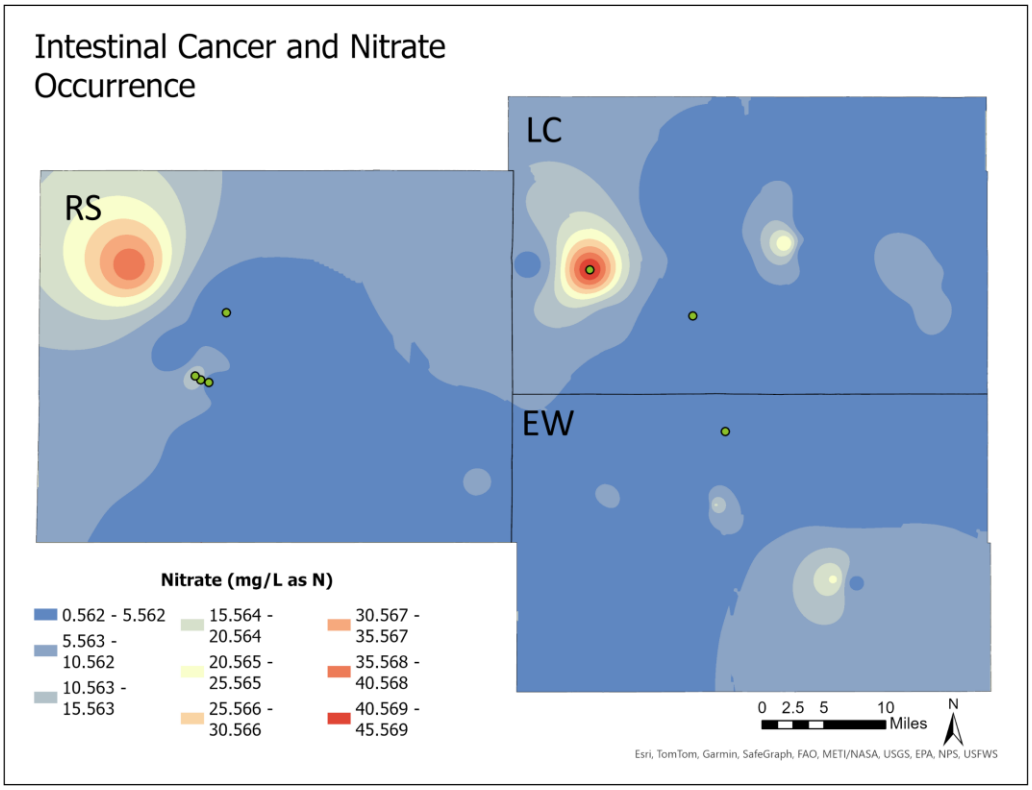

Figure 5.10 Map displaying nitrate concentration across the study area overlain with reported intestinal cancer cases (green circles).

Prostate Cancer

Prostate cancer is the most prevalent type of cancer, with fourteen cases spread throughout the study area. Prostate cancer appears to have no positive relationship with water quality parameters. Eight of fourteen cases of prostate cancer were in areas with radon concentrations above the EPA action level of 4 pCi/L. Prior studies (VoPham et al., 2017) linked long-term radon exposure to cancers related to the endocrine system, such as breast cancer. However, there are little to no studies that link prostate cancer to radon occurrence, making this connection unlikely. A non-significant but suggestive link between elevated uranium and prostate cancer was discovered by (Wagner et al., 2011). This connection is unlikely in our study

area, as only four of fourteen prostate cancer cases are located near groundwater with uranium exceeding the EPA's MCL of 30 µg/L for uranium. Therefore, a possible cause for prostate cancer cases remains unknown.

Breast Cancer

Breast cancer cases are relatively widespread in Ellsworth and Lincoln counties, but concentrated in Russell County (Figure 5.11). Four out of ten cases lie in areas with groundwater uranium concentrations exceeding the EPA MCL of 30 µg/L. Several studies have shown a link between uranium and breast cancer. Studies comparing total cancer incidence with groundwater uranium have shown that populations which utilized groundwater with high uranium had an increased risk for colorectal, breast, kidney, and prostate cancer (Wagner et al., 2011). Another study in Iraq found that women who had breast cancer had higher levels of uranium in their blood, compared to those in the control group (Ahmed et al., 2022). However, more research is needed to investigate the relationship between uranium and breast cancer. Additionally, four of ten cases were in areas with low uranium, which could indicate that uranium is not the only (or primary) contributing factor. A study utilizing data from the Nurses' Health Study II found an association between long-term radon exposure and estrogen receptor negative/progesterone receptor negative breast cancer (VoPham et al., 2017). Radon and uranium seem to be the most likely environmental factors influencing breast cancer in the study area.

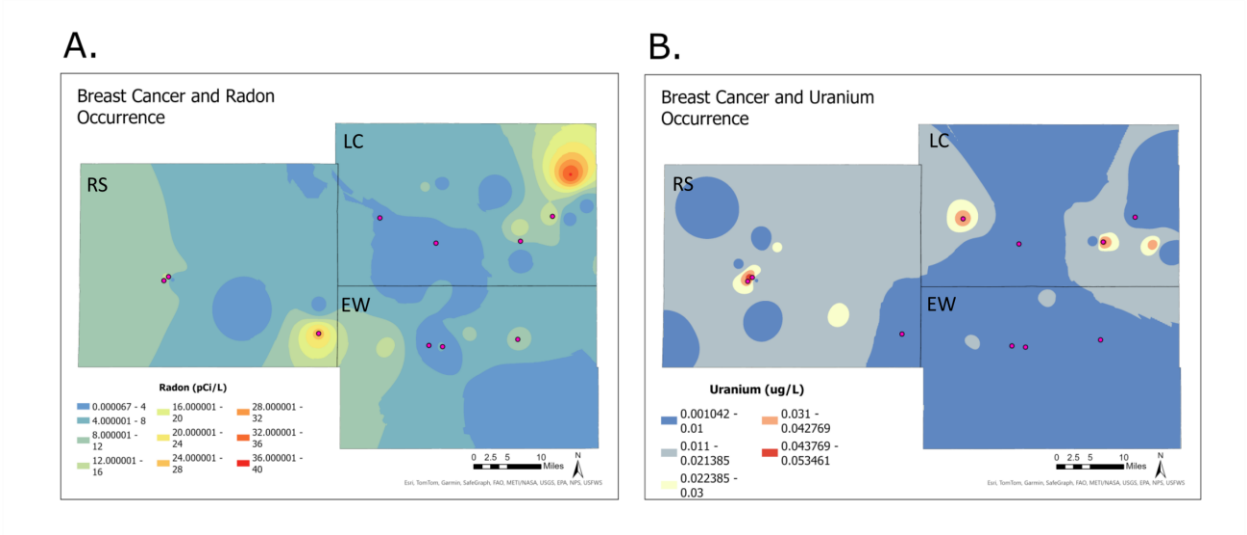

Figure 5.11 Maps displaying radon concentration (A) and uranium (B) overlain with breast cancer cases (red circles).

Skin Cancer

Skin cancer is widespread across the study area and is likely not related to environmental contaminants, but to extended sun exposure during outdoor work. This situation is common in the study area, which is dominated by farming and ranching.

Bone Cancer and Leukemia

Bone cancer cases occur predominantly in Russell County, where five of seven cases are. These cases seem to occur alongside high radon concentrations. Six out of seven bone cancer cases are found in areas with radon concentrations exceeding 4 pCi/L (Figure 5.12). Four cases occur in areas where radon concentrations are between 8 and 12 pCi/L, one in an area with 12-16 pCi/L radon and one case where it is 25.5 pCi/L radon. While radon is not known to cause bone cancer, radium is a known cause of bone cancer, as attested to in numerous studies on drinking water radium and bone cancer (Finkelstein, 1994; Finkelstein & Kreiger, 1996). While we do not

have direct evidence of radium's presence in the groundwater, high radon gas inherently implies the presence of radium in the bedrock, since radium decays to radon.

Radium is also known to cause leukemia (Auvinen et al., 2002; Lyman et al., 1985; O'Brien et al., 1987), along with uranium (Radespiel-Tröger & Meyer, 2013; Wagner et al., 2011). All three leukemia cases occur in areas with high radon (8-28 pCi/L) and roughly occur alongside bone cancer cases. Two of three leukemia cases occur near groundwater with uranium concentrations that exceed the regulatory levels. These observations provide indirect evidence of radium occurrence, which could contribute to leukemia and bone cancer.

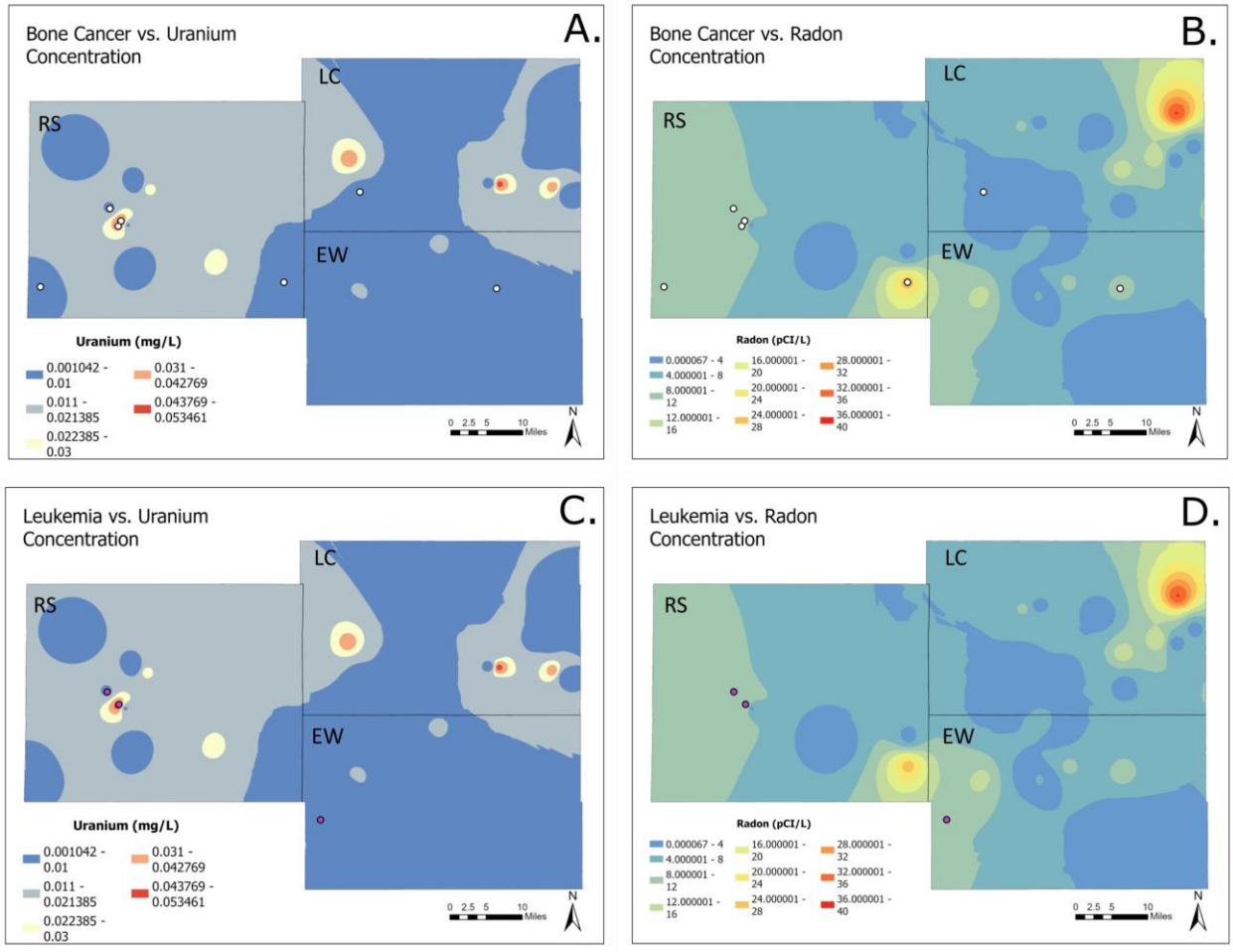

Figure 5.12 Maps displaying uranium concentration (A, C) and radon (B, D) overlain with bone cancer and leukemia cases (bone cancer = white circles, leukemia = purple circles).

Kidney Cancer

Kidney cancer cases only occurred in Russell County (Figure 5.13). Out of the four cases reported, three are inside the city of Russell. The environmental contaminant most likely linked to kidney cancer is uranium (Radespiel-Tröger & Meyer, 2013; Wagner et al., 2011). Incidentally, three of four kidney cancer cases were found in regions with uranium concentrations above EPA's MCL of 30 µg/L uranium, and one where it violates Germany's conservative standard of 10 µg/L. This observation is consistent with findings from other studies on the geographical distribution of cancer and its relation to groundwater quality that indicate a positive relationship between uranium concentration and kidney cancer (Wagner et al., 2011; Radespiel-Tröger & Meyer, 2013).

Three of four cancer cases also lie in areas with radon concentrations reaching 12-16 pCi/L, and one is near an area with 8-12 pCi/L radon. All kidney cancer cases are found in areas where radon is 2-4 times higher than the EPA action level of 4 pCi/L. Since uranium decays to radon, these findings suggest that uranium is the most probable environmental contaminant influencing kidney cancer incidence within the study area.

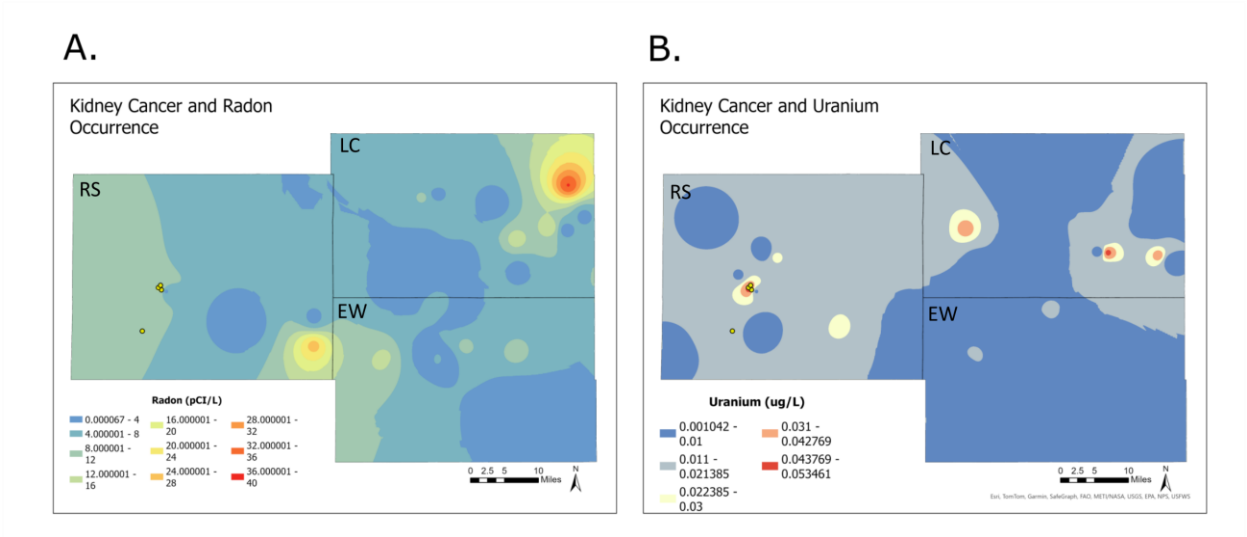

Figure 5.13 Maps displaying radon concentration (A) and uranium (B) overlain with kidney cancer cases (yellow circles).

Land Use Relation to Cancer

The link between cancer and land use is complex and difficult to discern. High concentrations of radon, nitrate, and uranium were discovered within the study area, all known to cause cancer. Nitrate specifically can be linked to land use in certain circumstances. Intestinal cancer cases occur near two locations with the highest nitrate contamination. One case is on the same property where the highest nitrate concentration within the study area was found. This sample was collected adjacent to an area used to feed, shelter, and water cattle. In this case, the most probable cause of nitrate contamination is from the nearby cattle feeding/sheltering/watering facility. Because nitrate is a known cause of colorectal cancer, nitrate contamination of this magnitude could be related to intestinal cancer, effectively linking this case to nearby cattle-born nitrate contamination.

Additionally, in the city of Russell, there were three cases of intestinal cancer reported near groundwater containing nitrate above the MCL. The positive correlation between nitrate and

developed land could suggest that leaky septic systems could contribute to nitrate contamination, a known cause of colorectal cancer. It is important to note that we did not find any statistically significant correlation with agricultural land use. However, our analysis does not rule out nitrate contamination from agricultural sources or suggest that agricultural land is unrelated to cancer within the study area. Cattle feeding, watering, and sheltering areas and leaky septic systems are unlikely to explain the totality of widespread colorectal cancer within the study area. These cases reinforce our understanding of nitrate contamination, namely that shallow, oxygen-rich wells are the most prone to contamination from surficial inputs, as discussed above.

Additionally, our analysis found that phosphate fertilizers, especially in Russell County, could be a potential source of uranium. If this is the case, then the practice of using phosphate fertilizers could be related to kidney, bone, leukemia, and breast cancer. This link is highly tentative, as the most common source of uranium in groundwater is the underlying geology.

Limitations

While this study provides insights into potential environmental contributions to cancer in rural environments, several limitations must be considered when discussing our findings. Some well owners indicated that they did not drink raw groundwater from their domestic wells, but filtered their drinking water through RO filtration systems instead, or used rural water provided by public sources. Additionally, some participants indicated that they had not always lived in the location where radon and water samples were collected, having relocated from another area in, or outside the study area. These limitations complicate our spatial and statistical analysis.

Cancer surveys also relied on participant memory, which could lead to recall errors. Other cancer-causing contaminants were not accounted for in this study, such as PFAs, and

organic contaminants, such as pesticides and herbicides, which are exceedingly common in rural environments.

The amount of data was also limited by operational circumstances. In our analysis of radon, some radon tests were delayed in shipping, invalidating the tests and reducing our amount of data for radon. For our analysis of major cations and anions, some concentrations of sulfate, calcium, and chloride were so high that they could not be measured accurately by the Ion Chromatography instrument. To solve this problem we diluted samples, which could introduce minor errors into our analysis. By calculating charge imbalance errors, we effectively safeguarded our data quality from errors introduced by dilutions. Additionally, some trace elements and major ions fell beneath our detection limits; in this case, the detection limit was used as the actual concentration in geospatial and statistical calculations; this introduces error into our analyses as the actual concentration could be zero or below the detection limit. However, this error is unlikely to significantly harm our analysis.

Water samples were obtained over two sampling periods, the first in March and the second in June of 2024. This could introduce variation in geochemistry due to seasonal land use practices or seasonal-dependent changes in the environment. Finally, samples collected in spring were preserved immediately upon returning to the lab but were not analyzed until June with the rest of our samples, what could have introduced error into our geochemical results.

The hydraulic head map (Figure 5.1) was created using KGS water well completion records (WWC5). All records available within the study area were used to make this map regardless of temporal variation. However, hydraulic head changes over time, and water depth measurements are often inaccurately reported. Therefore, the map does not represent the present-day hydraulic head but approximates the hydraulic head and regional flow direction.

Interpretation of groundwater chemistry did not incorporate lithology and well-construction data for the wells. A more detailed examination of lithology and well-construction records is essential to explain contaminant occurrence on a well-by-well basis, as localized variations in sediment grain size or well-construction practices might have a large impact on local groundwater chemistry.

Our statistical analysis relied heavily on the strength of Spearman's correlations to investigate relationships between groundwater constituents, land use, and groundwater quality. Given the many correlations performed for this purpose, significant correlations could be encountered by chance (multiple comparisons problem). Future studies should apply the Bonferroni correction to account for the multiple comparisons problem to account for the likelihood of finding false positives. The Bonferroni correction divides the significance level by the total number of tests conducted. This adjustment helps correct the risk of mistakenly identifying a correlation as significant due to random chance, ensuring that the relationships detected are more likely to reflect true associations.

Future Work

Future studies should account for these limitations by eliminating cancer data obtained from participants who do not drink water from domestic wells. Future studies should calculate the dose received of various contaminants over the time they have lived in the location where samples are collected, effectively accounting for participant relocation. Water samples should also be obtained within the same season to reduce variation in geochemistry related to natural or anthropogenic factors. Water samples should be analyzed immediately upon return to reduce the

degradation of water samples. Additionally, future studies should consider other contaminants linked to cancer, such as PFAs, herbicides, and pesticides.

Despite these limitations, this study provides high-level reconnaissance into possible environmental contributions to cancer in rural environments and provides a critical launching point for future studies.

Chapter 6 - Conclusions

This study investigated potential links between environmental factors (such as water quality from domestic wells and radon levels) and high cancer rates in an agricultural setting in central Kansas. Additionally, we explored the possibility of land use contributing to high cancer rates through groundwater contamination. Our findings revealed concentrations of nitrate and uranium in the groundwater that exceed EPA/WHO regulations in most of the study area. Even where the concentrations are below these regulatory limits, their levels are associated with adverse health effects.

We found that groundwater redox states control the occurrence of uranium and nitrate, and that NPOC and alkalinity enhance uranium mobility. Within the study area, we generally observed reducing conditions in Ellsworth and Lincoln counties, preventing nitrate accumulation and limiting uranium mobilization. In contrast, Russell County exhibited predominantly oxidizing conditions, which allowed uranium mobilization and nitrate accumulation.

Additionally, we found that 48.7% of radon tests exceeded 4 pCi/L, the threshold at which the EPA recommends immediate action to lower radon levels. This finding is crucial, as radon is the second leading cause of lung cancer in the United States. The EPA recommends radon levels remain below 2.0 pCi/L, yet 69.2% of radon samples in our study exceeded this recommendation.

Regarding cancer data, we found that 83% of participants in Lincoln County had a family history of cancer. In Russell County, 6% of cases were in individuals under 20 years old, while in Ellsworth County, 18% were in individuals aged 20-40. Additionally, 64% and 77% of households surveyed in Lincoln and Russell counties, respectively, reported cancer within the household.

Our study found no positive correlation between nitrate and uranium levels and specific agricultural crop type. This lack of correlation suggests that the relationship between groundwater chemistry and land use is complex and cannot be predicted based on land use alone. Nitrate concentration was positively associated with the open-water land cover class, which confirms that surface water environments are the most prone to nitrate contamination.

Although the relationship between land use, groundwater quality, and cancer incidence remains challenging to predict, our study highlights several environmental factors—nitrate, uranium, radium, and radon—that may contribute to cancer in the region.

Our study contributes valuable cancer data for the region, which can inform future public health research. The multidisciplinary approach, combining geochemical, geospatial, and statistical analyses, provides a comprehensive investigation of potential environmental causes of cancer in rural areas and serves as a foundation for future studies in similar settings.

Chapter 7 - References

Ahmed, R. S., Mohammed, R. S., Mahdi, K. H., Mahdi, Q. A., Mostafa, M. YA., & Khalaf, H. NB. (2022). Evaluation of uranium concentration in the blood breast cancer women with CR-39 detector. *Applied Radiation and Isotopes*, *182*, 110120. https://doi.org/10.1016/j.apradiso.2022.110120

Arbogast, A. F., & Johnson, W. C. (1996). *Surficial Geology and Stratigraphy of Russell County, KS*. Kansas Geological Survey.

ATSDR. (2013). *Toxicological Profile for Uranium* [Toxicological Profile]. U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES Agency for Toxic Substances and Disease Registry.

Auvinen, A., Kurttio, P., Pekkanen, J., Pukkala, E., Ilus, T., & Salonen, L. (2002). Uranium and other natural radionuclides in drinking water and risk of leukemia: A case-cohort study in Finland. *Cancer Causes & Control: CCC*, *13*(9), 825–829. https://doi.org/10.1023/a:1020647704999

Banning, A., & Benfer, M. (2017). Drinking Water Uranium and Potential Health Effects in the German Federal State of Bavaria. *International Journal of Environmental Research and Public Health*, *14*(8), Article 8. https://doi.org/10.3390/ijerph14080927

Banning, A., Demmel, T., Rüde, T. R., & Wrobel, M. (2013). Groundwater Uranium Origin and Fate Control in a River Valley Aquifer. *Environmental Science & Technology*, *47*(24), 13941–13948. https://doi.org/10.1021/es304609e

Bayne, C. K., Franks, P. C., & Ives, W. (1971). *Geology and Ground-water Resources of Ellsworth County, Central Kansas*. https://www.kgs.ku.edu/General/Geology/Ellsworth/index.html

Berry, D. W. (1952). *Geology and Ground-Water Resources of Lincoln County, Kansas*. https://www.kgs.ku.edu/General/Geology/Lincoln/index.html

Bijay-Singh, & Craswell, E. (2021). Fertilizers and nitrate pollution of surface and ground water: An increasingly pervasive global problem. *SN Applied Sciences*, *3*(4), 518. https://doi.org/10.1007/s42452-021-04521-8

Bjørklund, G., Christophersen, O. A., Chirumbolo, S., Selinus, O., & Aaseth, J. (2017). Recent aspects of uranium toxicology in medical geology. *Environmental Research*, *156*, 526–533. https://doi.org/10.1016/j.envres.2017.04.010

Bonotto, D. M., Wijesiri, B., & Goonetilleke, A. (2019). Nitrate-dependent Uranium mobilisation in groundwater. *Science of The Total Environment*, *693*, 133655. https://doi.org/10.1016/j.scitotenv.2019.133655

Bowen, H. J. M. (Humphry J. M. (with Internet Archive). (1979). *Environmental chemistry of the elements*. London ; New York : Academic Press. http://archive.org/details/environmentalche0000bowe

Chandrajith, R., Seneviratna, S., Wickramaarachchi, K., Attanayake, T., Aturaliya, T. N. C., & Dissanayake, C. B. (2010). Natural radionuclides and trace elements in rice field soils in relation to fertilizer application: Study of a chronic kidney disease area in Sri Lanka. *Environmental Earth Sciences*, *60*(1), 193–201. https://doi.org/10.1007/s12665-009-0179-1

Darby, S., Hill, D., Auvinen, A., Barros-Dios, J. M., Baysson, H., Bochicchio, F., Deo, H., Falk, R., Forastiere, F., Hakama, M., Heid, I., Kreienbrock, L., Kreuzer, M., Lagarde, F., Mäkeläinen, I., Muirhead, C., Oberaigner, W., Pershagen, G., Ruano-Ravina, A., … Doll, R. (2005). Radon in homes and risk of lung cancer: Collaborative analysis of individual data from 13 European case-control studies. *BMJ (Clinical Research Ed.)*, *330*(7485), 223. https://doi.org/10.1136/bmj.38308.477650.63

Donat-Vargas, C., Kogevinas, M., Castaño-Vinyals, G., Pérez-Gómez, B., Llorca, J., Vanaclocha-Espí, M., Fernandez-Tardon, G., Costas, L., Aragonés, N., Gómez-Acebo, I., Moreno, V., Pollan, M., & Villanueva, C. M. (2023). Long-Term Exposure to Nitrate and Trihalomethanes in Drinking Water and Prostate Cancer: A Multicase–Control Study in Spain (MCC-Spain). *Environmental Health Perspectives*, *131*(3), 037004. https://doi.org/10.1289/EHP11391

Ellsworth County—Oil and Gas Production. (n.d.). Retrieved February 20, 2024, from https://www.kgs.ku.edu/PRS/County/def/ellsworth.html

Espejo-Herrera, N., Gràcia-Lavedan, E., Boldo, E., Aragonés, N., Pérez-Gómez, B., Pollán, M., Molina, A. J., Fernández, T., Martín, V., La Vecchia, C., Bosetti, C., Tavani, A., Polesel, J., Serraino, D., Gómez Acebo, I., Altzibar, J. M., Ardanaz, E., Burgui, R., Pisa, F., … Villanueva, C. M. (2016). Colorectal cancer risk and nitrate exposure through drinking water and diet. *International Journal of Cancer*, *139*(2), 334–346. https://doi.org/10.1002/ijc.30083

Finkelstein, M. M. (1994). Radium in drinking water and the risk of death from bone cancer among Ontario youths. *CMAJ: Canadian Medical Association Journal = Journal de l'Association Medicale Canadienne*, *151*(5), 565–571.

Finkelstein, M. M., & Kreiger, N. (1996). Radium in drinking water and risk of bone cancer in Ontario youths: A second study and combined analysis. *Occupational and Environmental Medicine*, *53*(5), 305–311. https://doi.org/10.1136/oem.53.5.305

Frye, J. C., & Brazil, J. J. (1943). *Ground Water in the Oil-field Areas of Ellis and Russell Counties, Kansas*. https://www.kgs.ku.edu/Publications/Bulletins/50/04_form.html

Greer, F. R., Shannon, M., the Committee on Nutrition, & and the Committee on Environmental Health. (2005). Infant Methemoglobinemia: The Role of Dietary Nitrate in Food and Water. *Pediatrics*, *116*(3), 784–786. https://doi.org/10.1542/peds.2005-1497

Han, W., Yang, Z., & Di, L. (2012). *CropScape—NASS CDL Program*. https://nassgeodata.gmu.edu/CropScape/

Hattin, D. E. (1962). Stratigraphy of the Carlile Shale (Upper Cretaceous) in Kansas. *University of Kansas Publications*, *Bulletin 156*.

Hattin, D. E. (1982). Stratigraphy and Depositional Environment of the Smokey Hill Chalk Member, Niobrara Chalk (Upper Cretaceous), of the Type Area, Western Kansas. *University of Kansas Publications*, *Bulletin 225*.

Health Effects of Exposure to Radon: BEIR VI. (1999). National Academies Press. https://doi.org/10.17226/5499

Jin, S., Dewitz, J., Danielson, P., Granneman, B., Costello, C., Smith, K., & Zhu, Z. (2023). National Land Cover Database 2019: A New Strategy for Creating Clean Leaf-On and Leaf-Off Landsat Composite Images. *Journal of Remote Sensing*, *3*, 0022. https://doi.org/10.34133/remotesensing.0022

Kansas Health Matters: Indicators :: Male Prostate Cancer Rate :: County : Ellsworth. (n.d.-a). Retrieved January 27, 2024, from

https://www.kansashealthmatters.org/?module=indicators&controller=index&action=view&comparisonId=&indicatorId=7571&localeId=966

Kansas Health Matters: Indicators :: Search. (n.d.-b). Advanced Search: Build a Custom Dashboard. Retrieved March 29, 2025, from https://www.kansashealthmatters.org/indicators/index/indicatorsearch?module=indicators&controller=index&action=indicatorsearch&doSearch=1&i=&l=1023&t%5B%5D=109&primaryTopicOnly=&subgrouping=1&card=0&handpicked=0&resultsPerPage=150&showComparisons=1&showOnlySelectedComparisons=&showOnlySelectedComparisons=1&includeArchivedIndicators=&includeArchivedIndicators=1&grouping=1&ordering=1&sortcomp=0&sortcompIncludeMissing=

Kansas Office of the State Climatologist · Kansas Drought. (n.d.). Retrieved March 26, 2025, from https://mesonet.k-state.edu/climate/precip/county/

KGS--Stratigraphic Nomenclature—Strat Chart. (n.d.). Retrieved February 7, 2025, from https://www.kgs.ku.edu/General/Strat/Chart/index.html

KGS--Top Ten Lists—Oil and Gas Production. (2023). https://www.kgs.ku.edu/PRS/Info/topTen.html

Kirk, M. (2023). Microbiology for Earth Scientists. *NPP eBooks*. https://newprairiepress.org/ebooks/53

Krewski, D., Lubin, J. H., Zielinski, J. M., Alavanja, M., Catalan, V. S., Field, R. W., Klotz, J. B., Létourneau, E. G., Lynch, C. F., Lyon, J. I., Sandler, D. P., Schoenberg, J. B., Steck, D. J., Stolwijk, J. A., Weinberg, C., & Wilcox, H. B. (2005). Residential Radon and Risk of Lung Cancer: A Combined Analysis of 7 North American Case-Control Studies. *Epidemiology*, *16*(2), 137–145.

Kurttio, P., Komulainen, H., & Leino, A. (2005). Bone as a Possible Target of Chemical Toxicity of Natural Uranium in Drinking Water. *Environmental Health Perspectives*, *113*(1), 68–72. https://doi.org/10.1289/ehp.7475

Lane, A. D., Kirk, M. F., Whittemore, D. O., Stotler, R., Hildebrand, J., & Feril, O. (2020). Long-term (1970s–2016) changes in groundwater geochemistry in the High Plains aquifer in south-central Kansas, USA. *Hydrogeology Journal*, *28*(2), 491–501. https://doi.org/10.1007/s10040-019-02083-z

Langmuir, D. (with Internet Archive). (1997). *Aqueous environmental geochemistry*. Upper Saddle River, N.J. : Prentice Hall. http://archive.org/details/aqueousenvironme0000lang

Li, C., Wang, C., Yu, J., Fan, Y., Liu, D., Zhou, W., & Shi, T. (2020). Residential Radon and Histological Types of Lung Cancer: A Meta-Analysis of Case–Control Studies. *International Journal of Environmental Research and Public Health*, *17*(4), Article 4. https://doi.org/10.3390/ijerph17041457

Liesch, T., Hinrichsen, S., & Goldscheider, N. (2015). Uranium in groundwater—Fertilizers versus geogenic sources. *The Science of the Total Environment*, *536*, 981–995. https://doi.org/10.1016/j.scitotenv.2015.05.133

Lincoln County—Oil and Gas Production. (n.d.). Retrieved February 21, 2024, from https://www.kgs.ku.edu/PRS/County/klm/lincoln.html

Lyman, G. H., Lyman, C. G., & Johnson, W. (1985). Association of Leukemia With Radium Groundwater Contamination. *JAMA*, *254*(5), 621–626. https://doi.org/10.1001/jama.1985.03360050059026

Messier, K. P., & Serre, M. L. (2017). Lung and stomach cancer associations with groundwater radon in North Carolina, USA. *International Journal of Epidemiology*, *46*(2), 676–685. https://doi.org/10.1093/ije/dyw128

Mwalongo, D. A., Haneklaus, N. H., Lisuma, J. B., Mpumi, N., Amasi, A. I., Mwimanzi, J. M., Chuma, F. M., Kivevele, T. T., & Mtei, K. M. (2024). Uranium Dissemination with Phosphate Fertilizers Globally: A Systematic Review with Focus on East Africa. *Sustainability*, *16*(4), Article 4. https://doi.org/10.3390/su16041496

Nolan, J., & Weber, K. A. (2015). Natural Uranium Contamination in Major U.S. Aquifers Linked to Nitrate. *Environmental Science & Technology Letters*, *2*(8), 215–220. https://doi.org/10.1021/acs.estlett.5b00174

O'Brien, T. R., Decouflé, P., & Rhodes, P. H. (1987). Leukemia and groundwater contamination. *JAMA*, *257*(3), 317.

Rääf, C. L., Tondel, M., Isaksson, M., & Wålinder, R. (2023). Average uranium bedrock concentration in Swedish municipalities predicts male lung cancer incidence rate when adjusted for smoking prevalence: Indication of a cumulative radon induced detriment. *Science of The Total Environment*, *855*, 158899. https://doi.org/10.1016/j.scitotenv.2022.158899

Radespiel-Tröger, M., & Meyer, M. (2013). Association between drinking water uranium content and cancer risk in Bavaria, Germany. *International Archives of Occupational and Environmental Health*, *86*(7), 767–776. https://doi.org/10.1007/s00420-012-0806-0

Riudavets, M., Garcia de Herreros, M., Besse, B., & Mezquita, L. (2022). Radon and Lung Cancer: Current Trends and Future Perspectives. *Cancers*, *14*(13), Article 13. https://doi.org/10.3390/cancers14133142

Sawin, R. S., & Layzell, A. L. (2024). *Surficial Geology of Lincoln County, Kansas*. Kansas Geological Survey.

Schullehner, J., Hansen, B., Thygesen, M., Pedersen, C. B., & Sigsgaard, T. (2018). Nitrate in drinking water and colorectal cancer risk: A nationwide population-based cohort study. *International Journal of Cancer*, *143*(1), 73–79. https://doi.org/10.1002/ijc.31306

Shukla, S., & Saxena, A. (2020). Sources and leaching of nitrate contamination in groundwater. *Current Science*, *118*(6), 883–891.

Skalaban, T. G., Thompson, D. A., Madrigal, J. M., Blount, B. C., Espinosa, M. M., Kolpin, D. W., Deziel, N. C., Jones, R. R., Beane Freeman, L., Hofmann, J. N., & Ward, M. H. (2024). Nitrate exposure from drinking water and dietary sources among Iowa farmers using private wells. *Science of The Total Environment*, *919*, 170922. https://doi.org/10.1016/j.scitotenv.2024.170922

Swineford, A. (1947, November 15). *Cemented Sandstones of the Dakota and Kiowa Formations in Kansas*. State Geological Survey of Kansas.

Thompson, R. E., Nelson, D. F., Popkin, J. H., & Popkin, Z. (2008). CASE-CONTROL STUDY OF LUNG CANCER RISK FROM RESIDENTIAL RADON EXPOSURE IN WORCESTER COUNTY, MASSACHUSETTS. *Health Physics*, *94*(3), 228–241. https://doi.org/10.1097/01.HP.0000288561.53790.5f

Tisherman, R. A., Rossi, R. J., Shonkoff, S. B. C., & DiGiulio, D. C. (2023). Groundwater uranium contamination from produced water disposal to unlined ponds in the San Joaquin Valley. *Science of The Total Environment*, *904*, 166937. https://doi.org/10.1016/j.scitotenv.2023.166937

US EPA, O. (2014, August 14). *Health Risk of Radon* [Overviews and Factsheets]. https://www.epa.gov/radon/health-risk-radon

US EPA, O. (2015a, November 4). *Ammonia* [Data and Tools]. https://www.epa.gov/caddis/ammonia

US EPA, O. (2015b, November 30). *National Primary Drinking Water Regulations* [Overviews and Factsheets]. https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations

US EPA, O. (2019, February 19). *What is EPA's Action Level for Radon and What Does it Mean?* [Overviews and Factsheets]. https://www.epa.gov/radon/what-epas-action-level-radon-and-what-does-it-mean

USDA - National Agricultural Statistics Service—Kansas—County Estimates. (n.d.). Retrieved February 20, 2024, from https://www.nass.usda.gov/Statistics_by_State/Kansas/Publications/County_Estimates/index.php

Vicente-Vicente, L., Quiros, Y., Pérez-Barriocanal, F., López-Novoa, J. M., López-Hernández, F. J., & Morales, A. I. (2010). Nephrotoxicity of uranium: Pathophysiological, diagnostic and therapeutic perspectives. *Toxicological Sciences: An Official Journal of the Society of Toxicology*, *118*(2), 324–347. https://doi.org/10.1093/toxsci/kfq178

VoPham, T., DuPré, N., Tamimi, R. M., James, P., Bertrand, K. A., Vieira, V., Laden, F., & Hart, J. E. (2017). Environmental radon exposure and breast cancer risk in the Nurses' Health Study II. *Environmental Health*, *16*(1), 97. https://doi.org/10.1186/s12940-017-0305-6

Wagner, S. E., Burch, J. B., Bottai, M., Puett, R., Porter, D., Bolick-Aldrich, S., Temples, T., Wilkerson, R. C., Vena, J. E., & Hébert, J. R. (2011). Groundwater uranium and cancer incidence in South Carolina. *Cancer Causes & Control*, *22*(1), 41–50.

Wakida, F. T., & Lerner, D. N. (2005). Non-agricultural sources of groundwater nitrate: A review and case study. *Water Research*, *39*(1), 3–16. https://doi.org/10.1016/j.watres.2004.07.026

Ward, M., Jones, R., Brender, J., de Kok, T., Weyer, P., Nolan, B., Villanueva, C., & van Breda, S. (2018). Drinking Water Nitrate and Human Health: An Updated Review. *International Journal of Environmental Research and Public Health*, *15*(7), 1557. https://doi.org/10.3390/ijerph15071557

Whittemore, D. O., Macfarlane, P. A., & Wilson, B. B. (2014). *Water Resources of the Dakota Aquifer in Kansas*.

World Health Organization. (2017). *Guidelines for drinking-water quality: Fourth edition incorporating first addendum* (4th ed + 1st add). World Health Organization. https://iris.who.int/handle/10665/254637