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Analyzing The Impact Of Oil And Gas-Contaminated Fluids On Soil In Eddy And Lea Counties Using Sequential Extraction

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ANALYZING THE IMPACT OF OIL AND GAS-CONTAMINATED FLUIDS ON SOIL IN EDDY AND LEA COUNTIES USING SEQUENTIAL EXTRACTION

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DEDICATION

I dedicate this thesis to my mother-in-law and all the mothers who could not realize their full potential because of families and other obligations.

To the Almighty God who has been my savior, nothing would have been possible without him.

Finally, I dedicate this paper to Sophia Otema Adu-Gyamfi, my grandparents, Kweku, and Sarah (R.B.) Acquah, my husband, children, dad, mum, siblings, friends, mentors, and teachers who, have been my guiding light, and it was because of them that I could keep fighting and walk through this journey with strength, patience, and perseverance.

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by

MARY NAADANSWA ADU-GYAMFI, *M.Ed.*

DISSERTATION

Presented to the Faculty of the Graduate School of
The University of Texas at El Paso
in Partial Fulfillment
of the Requirements
for the Degree of

DOCTOR OF PHILOSOPHY

Environmental Science and Engineering Program
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- The National Agricultural Research Center.

Data and results drive decisions, explain concepts, and bring about an understanding of how the world works. Without data and results, there is nothing to substantiate statements made. With your support, I could conclude my findings as you provided me with equipment, a team, expertise, and time to develop my understanding of the work.

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ABSTRACT

The study investigates the impacts of oil and gas-contaminated fluids on soil within the context of Eddy and Lea Counties in New Mexico, the United States. The increase in oil and gas operations has led to enormous wastewater production that is handled, stored, and transported, leading to thousands of spills yearly. The continuous and accidental release of this wastewater poses several risks to the environment due to its high levels of hazardous pollutants. Several studies were conducted on how to reduce the contaminants; however, the impact caused on the environment and the fate of the spilled fluids is unclear due to the complexity of reporting requirements, size, location of the spills, and gaps in research data on spills.

The experimental research design employed as the primary research methodology, involved using sequential extraction techniques and rigorous analysis of the soil's physical characteristics of Eddy and Lea Counties. T-test and spatial analysis were conducted to validate the findings. The study aimed to identify the distribution patterns, behavior, and potential implications of soil contamination resulting from oil and gas wastewater spills and leaks by employing these techniques.

The research findings revealed the existence of soil contaminants attributed to the spills from oil and gas wastewater. They also highlighted the significance of understanding how contaminants interact with soil particles and the subsequent effects on soil quality. Furthermore, the findings highlighted the importance of soil properties in influencing the mobility of contaminants. The insights gained from this research can help policymakers communicate informed policy decisions on oil and gas wastewater management. They are also essential in communicating to stakeholders to conduct an in-depth study on the broader impact of oil and gas wastewater on other ecosystem areas, such as groundwater sources in different regions.

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CHAPTER ONE: INTRODUCTION

With the increase in oil and gas extraction and production activities, the oil and gas sector has faced substantial challenges in maintaining a delicate balance between its operations and mitigating adverse environmental consequences, especially soil. These challenges arise from several factors, such as contamination during extraction, wastewater transportation, and other activities. This chapter discusses interactions between oil and gas activities and wastewater contamination. It also discusses the problem statement, the research question, the research objectives, the statement of purpose, and the study's scope and significance.

1.1 Background

1.1.1 OIL AND GAS EXTRACTION AND PRODUCTION

At the global level, oil and natural gas are the main sectors of the energy market, and as the world's primary fuel source, it plays a critical role in the global economy. They account for nearly 3 percent of the global domestic product, with crude oil trade reaching $640 billion in 2020, making it one of the world's most traded commodities. The high demand has led to a spontaneous rise in the oil and gas extraction and production capacity to clarify the implications of energy transitions worldwide (ILO, 2022; Paulauskiene, 2018).

Shale gas formation and production have transformed the unconventional gas industry due to the substantial advances in extraction technology, which uses a combination of horizontal wells and hydraulic fracturing in a way that optimizes operations by maintaining fracturing and flow of gas much better than before (Arthur et al., 2009). The advances in directional drilling technology in shale reservoirs have allowed hydraulic fracturing to become widespread worldwide (Mahmud et al., 2022).

Hydraulic fracturing is a technique that enhances hydrocarbon extraction from subsurface geological formations by injecting fracturing fluids at a pressure higher than the formation pressure to crack open the hydrocarbon formation rock (Arthur et al., 2009). In the United States, hydraulic fractures have increased dramatically in the extraction of natural gas from shale rock (McKenzie et al., 2012; Reap, 2015) due to the presence of shales as the most abundant sedimentary rocks in the Earth's crust across the country (Arthur et al., 2009) as illustrated in Figure 1.1.

This has created a connection between hydraulic fracturing and the United States' position as the world's leading oil and natural gas producer, with proven reserves of American natural gas expected to increase by 152.1 trillion cubic feet (Tcf) by the end of 2021. (EIA, 2022d). Up to 95 percent of newly drilled wells now, according to the U.S. Energy Department, are hydraulically fractured, which accounts for two-thirds of all the commercial natural gas production in the United States and roughly half of all crude oil output (EIA, 2022b; API, 2017).

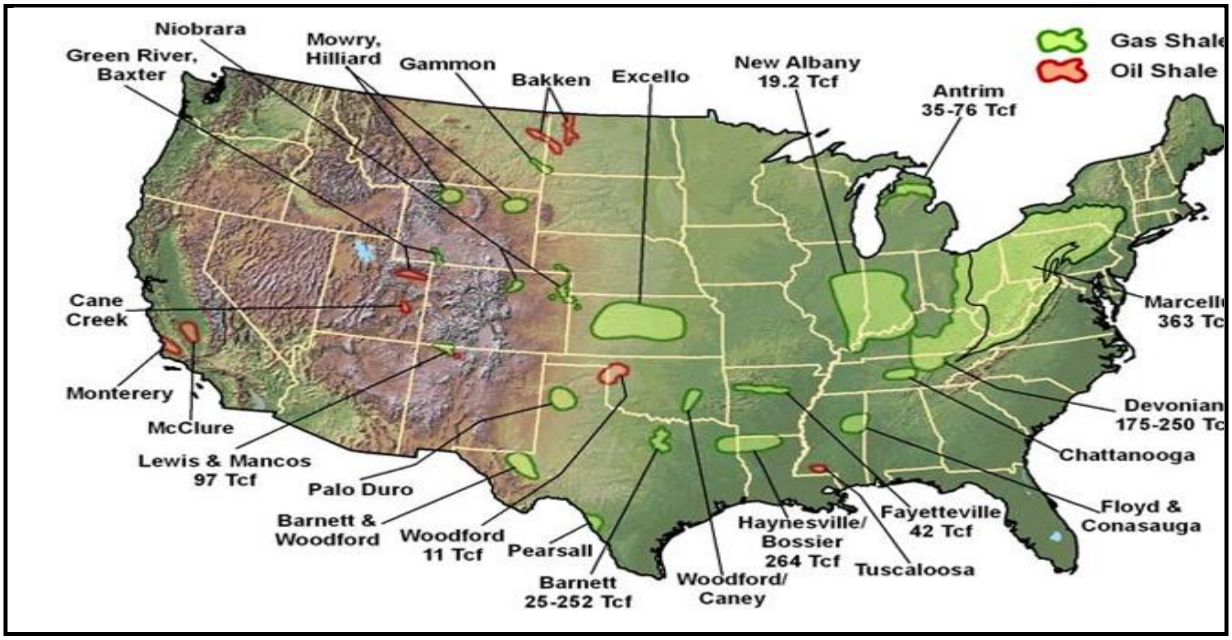


Figure 1.1: Gas Shale Basins of the United States with Estimated Gas Reserves (Arthur et al., 2009; DOE, 2009).

On the other hand, the advances in horizontal drilling ushered in a new era of operational efficiency and environmental stewardship. Horizontal drilling involves guiding a drilling bit to follow a path roughly angled between 85 and 95 degrees away from the vertical direction just above the target oil reservoir (Azar, 2004).

This revolutionary advancement has reinforced the effectiveness of directional drilling by enabling the consolidation of operations at single sites, effectively reducing the ecological 'footprint' of production activities on land and minimizing the need for offshore platforms. Horizontal drilling extends its reach to access reservoirs several kilometers away from the drill rig, a previously unattainable feat. As technology progresses, it has further reduced the need for satellite wells and allowed for more flexibility in selecting a drill site, mainly where environmental concerns are raised (Busahmin et al., 2021; UNEP, 1997).

In addition, horizontal drilling's profound impact is highlighted by its manifold advantages, stemming from heightened wellbore exposure to reservoirs. This technique has shown benefits in a spectrum of scenarios, including the revival of economic production, acceleration of recovery rates, cost reduction, and augmentation of the rate of return. Especially pertinent in an era characterized by surging competition and volatile oil prices, these benefits are of paramount importance for operators striving for viability and success (Stark, 2003).

The widespread adoption of horizontal drilling has led the United States to stand as a testament, boasting an impressive tally of more than 11,344 horizontal wells. In 2021, 81% of US well completions were horizontal or directional. Notably, this implementation has breathed new life into aging fields, propelling economic production and amplifying recovery efforts. Moreover, the accelerated recovery and increased rate of return facets remain potent driving forces for North American ventures, further underscoring the centrality of horizontal drilling in shaping contemporary oil production dynamics (Stark, 2003; EIA, 2021).

While natural gas production has risen due to the oil and natural gas industry's investment in innovative technologies (EIA, 2022c), fracturing fluids have evolved over time (Holditch, 2007). During shale gas development, massive volumes of water, chemicals, and sand are forcefully injected into these underground formations at high pressures. This pressurized injection serves to crack the rock formations, facilitating the release of previously trapped gas and oil reserves. As a result, the once-trapped gas and oil can then be extracted to the surface for further utilization (NRDC, 2019).

The fluids used create additional challenges, such as water availability and disposal (Arthur et al., 2009), that are hazardous to the environment and ecology. Despite previous advances, improvements in the current technology for sustainability and environmental protection are required to improve hydraulic fracturing in tight gas reservoirs and gas shal (Holditch, 2007).

1.1.2 WASTEWATER

As the demand for oil production increases, oil and gas extraction techniques like hydraulic fracturing in shale gas development continue to involve and require hundreds of barrels of water containing sand to be pumped or injected into the desired shale zone (Arthur et al., 2009). These fracture fluids are mainly water-based fluids mixed with additives that help the pressurized water carry sand proppant into the fractures. Water and proppants comprise 98-99% of the total fluid volume, and chemicals compose of the remaining 1- 2%. After the injection process is completed, internal reservoir pressures cause the production of wastewater (Precht & Dempster, 2012).

Wastewater is produced in the form of some of the fracturing fluids remaining in the subsurface while others return to the surface, and this is called flowback water. Other wastewater produced with oil and natural gas during extraction is called produced water. The two kinds of wastewater are highly saline, non-portable, and significantly contaminated (Arthur et al., 2009).

1.1.2.1 Flowback Water (FBW)

Flowback water (FBW) after the completion of hydraulic fracturing is one of the significant waste streams created during the life cycle of a well (Knapik et al., 2021). It constitutes 5 to 10% of the total wastewater generated from a shale gas well (Vengosh et al., 2017). FBW consists of water, the fracturing chemicals injected into the well, and any contaminants that may be present in the rock (Fink, 2021).

Additionally, a significant proportion ranging between 25% and 75% of the injected fluids return to the surface during the production stage of the well, and this depends on the formation properties of a well, the fracturing program design, and the type of fracturing fluid used. Flowback water returns to the surface over the well, mainly occurring in the early production stage. Before treatment, disposal, or recycling, flowback water is customarily stored on-site in tanks and then later sent to a treatment facility or disposed of by injection into a deep formation through a disposal well (Precht & Dempster, 2012). However, proper handling and disposal of this water is still challenging in the US and the world.

1.1.2.2 Produced Water (PW)

Produced Water (PW) refers to naturally occurring water that has already formed in the shale and is typically brought to the surface along with oil and gas during production. PW results from two processes in the oil and gas industry. Firstly, it emerges from the extraction process, where a mixture of water and oil is obtained, and this mixture is often from the seawater that surrounds the oil well. Secondly, the water injected into the oilfield to bring the deep crude to the surface also contributes to PW's composition (Igunnu & Chen, 2014).

Shale development involves water production as residues, which varies between the shale gas plays and notably within regions of each play (Arthur et al., 2009). PW is considered the most significant wastewater generated during oil and gas extraction, and it contains a higher concentration of hydrocarbons, heavy metals, and several other pollutants. Due to the upsurge in industrial activities, produced water amounts have increased drastically globally (Al-Ghouti et al., 2019), with the US alone generating approximately 21 billion barrels of produced water per year (Research and Markets, 2022).

The characteristics and volume of produced water generated for a well can change over time. In addition, periodic well maintenance and stimulation activities can affect produced water characteristics and generation rates. PW production has reached 250 million barrels per day worldwide and is expected to increase (Haneef, Mustafa, Yasin, et al., 2020). 40% of this amount is discharged untreated into the environment (Haneef, Mustafa, Rasool, et al., 2020).

PW can be cleaned and reused, hence offering proper ways to reduce the adverse environmental impacts of drilling and hydraulic fracturing activities. However, on the contrary, it has caused environmental concerns. The prospect of beneficial uses has driven research into the treatment of produced water with current conventional treatment technologies targeting the removal of heavy metals, oil and grease, suspended solids, and desalination, which often lead to the generation of large volumes of secondary waste (Arthur et al., 2011).

1.1.2.3 Contamination of Wastewater

Hydraulic fracturing demands the use of large volumes of water and concurrently generates significant quantities of highly contaminated wastewater (Chang et al., 2019). The production of environmentally hazardous wastewater in hydraulic fracturing is attributed to be partly due to the interaction between chemicals introduced into injected freshwater and saline brine that is naturally present within rock formations (Dartmouth College, 2015; Fink, 2021).

The major constituents of concern in produced water are:

- Salt content expressed as salinity, total dissolved solids, or electrical conductivity.
- Oil and grease identified through analytical tests that measure the presence of various organic chemical compounds.
- Several natural inorganic and organic compounds, such as chemicals that can cause hardness and scaling, such as calcium, magnesium, sulfates, and barium.
- Chemical additives utilized in drilling, fracturing, and operating the well that may have some toxic properties like biocides and corrosion inhibitors, typically at very high concentrations.
- Naturally occurring radioactive material (NORM) (Arthur et al., 2011).

Handling and disposal of wastewater is a normal part of oil and gas drilling operations and is not limited to only hydraulically fractured wells. The hydrocarbons are separated from the returned fluids at the surface, and the flowback and produced water (FPW) are collected in tanks for treatment or injection (Precht & Dempster, 2012). However, there are growing concerns about the management of FPW that both regulatory agencies and the public raised to disposal limitations, induced seismicity that is associated with Class II Underground Injection Control (UIC) wells, and the potential environmental impact on water resources, including injection of fluids into inadequately built wells, spills and leaks (Chang et al., 2019; NRDC, 2019).

1.1.2.4 Spills and Leaks

The rapid growth of hydraulic fracturing for shale gas within the US has triggered public concern regarding the potential hazards linked to industry-related spills and leaks (Clancy et al., 2018). This is because fracking wastewater is occasionally stored in simple pits near the production wells, putting nearby waterways and soil at risk. Available evidence also suggests that fracking wastewater spills occur often, and when they reach water, they can severely harm the ecosystem and wildlife (Environment America, 2019).

By some estimates, up to 5% of the total oil and gas wastewater generated in the United States finds its way into the environment accidentally or through illegal means released into the environment. In addition, there are various potential routes that facilitate the entry of this waste into both the groundwater and the surface. The routes include scenarios such as spills that arise from pipelines or tanker trucks that transport the waste, seepage from wastewater storage pools or tanks at well sites or disposal facilities, and movement of subsurface fluids through failed well enclosures (Konkel, 2016).

Furthermore, spills and leaks can stem from multiple sources, some of which include human error and equipment malfunctions, throughout the multifaceted stages of the hydraulic fracturing process. This can consist of occurrences during the transportation of highly concentrated chemical additives, the mixing and subsequent injection of fracturing fluids into the wellbore, as well as the storage, transportation, and disposal of utilized fracturing fluid and wastewater (NRDC, 2019).

While water pollution from the release of partially treated flowback and produced water into rivers and streams is a severe problem, it is regional in nature. Most US regions with significant shale gas resources also have plentiful deep injection well capacity for liquid waste disposal. Thus, the global impacts of fracking on water quality may be critically dependent on the availability of appropriate treatment and disposal mechanisms for flowback, produced water, fracking fluids, drilling mud, and other waste (Duke, 2016). Furthermore, the full impact can be challenging to measure for many reasons, including that the chemical makeup of the spilled fluid may be unknown or poorly described, and the ultimate fate of the spilled liquids and impacts of the spill are not typically studied (NRDC, 2019).

1.2 Problem Statement

As oil and gas extraction operations are expanding in the US, the volumes of wastewater being generated have increased exponentially in recent years. According to USGS, the increase in these volumes has not only overwhelmed the local infrastructure but strained many parts of the post-fracking water cycle, including the storage, treatment, reuse, transportation, or disposal of the wastewater, resulting in spills, leaks, and other environmental releases (Engle et al., 2014; Ong, 2014).

In the US, spills and leakages occur occasionally, with a 2 to 16% occurrence in well reports yearly (Clancy et al., 2018). Moreover, 151 hydraulic fracturing fluids or additives spills on or near well sites in 11 states were reported between January 2006 and April 2012 (Almaliki et al., 2022). Additionally, the western area reports eight spills per day (Rider, 2020, 2021), with the Eddy and Lea counties in New Mexico, which are part of the Permian basin, being responsible for more than 87% of the spills (Rider, 2021). However, following the analysis of incidents that have occurred, it is concluded that most of the spills are a result of the leakage of waste from the drilling facilities themselves, accidents during drilling such as ruptures of the fracturing fluid storage, and liquid spills during transportation (Clancy et al., 2018) leading to contamination of the soils in areas where they occur (Gilmore et al., 2014).

Contamination of soils can cause severe threats to human health and the ecosystem (Sattar et al., 2022). Despite the level of toxicity of these spills due to their high level of contamination of PW and FBW upon release, little data exists on the potential mechanisms of toxicity (Blewett et al., 2017) and their level of impact on the soils where they occur.

1.3 Statement of Purpose

The western part of the US receives high levels of spills from hydraulic fracking wastewater per day (Rider, 2020a, 2020b), yet these are considered to threaten public health and the environment (Ong, 2014). Nevertheless, studies of the effects of wastewater spills on soil resources are scant in the scientific literature (Pichtel, 2016). Furthermore, the fate of the spilled fluids has not been typically studied (NRDC, 2019). This study aimed to investigate the impact of oil and gas-contaminated fluids on soil quality within the context of Eddy and Lea Counties. By employing sequential extraction techniques and rigorous analysis, this study aimed to identify the distribution, behavior, and potential implications of soil contamination resulting from oil and gas wastewater spills and leaks.

1.4 Research Question

During this study, the following research question was investigated.

How has oil and gas wastewater impacted the soils in Eddy and Lea counties?

1.5 Research Objectives

The following research objectives were considered during the research study.

- To study the characterization of compounds adsorbed on soil particles due to spills in Eddy and Lea Counties.
- To carry out exposure studies that identify the level of toxicity of compounds adsorbed on soil due to spills in the Eddy and Lea counties.
- To investigate the fate and transport of wastewater spills' metals and how they are held up in the soils in Eddy and Lea counties.
- To determine the influence of soil properties on the mobility and persistence of contaminants introduced by oil and gas-related spills in Eddy and Lea Counties.

1.6 Significance of the Study

Due to the dramatic increase in hydraulic fracking activities within the United States, the oil and gas industry is challenged with a massive wastewater problem (Saunders, 2017). However, despite this issue, comprehensive research studies of the plethora of shale oil and gas regions have not been undertaken due to the nature and complexity of the requirements for systematic studies, especially in determining the impact of spills on the environment and the ecosystem (Konkel, 2016). Therefore, there is a need for more research to understand the impact and fate of oil and gas wastewater spills on the environment, especially on the soil.

Additionally, undertaking this study will help operators, stakeholders, policymakers, and the community understand the level of toxicity of spills and guide how to minimize the contamination of these fluids. Furthermore, no research focused on the impact of spills on soil in the New Mexico region of the Permian Basin-Eddy and Lea County, which signified a research gap that needed to be explored and examined.

1.7 Scope of the Study

The study focused exclusively on answering the research question and fulfilling the research objectives by investigating the impact of oil and gas-related contaminated fluids on soil quality within the New Mexico region of the Permian Basin, specifically Eddy and Lea Counties. The study involved targeted sampling and analysis of soil samples from distinct locations within Eddy and Lea Counties. In addition, the research captured a representative illustration of soil contamination situations by strategically selecting sites with varying levels of oil and gas activities and potential spill incidents.

CHAPTER TWO: LITERATURE REVIEW

The era of technological advances has led the oil and gas sector to be one of the fastest-growing sectors in the world. Technologies such as hydraulic fracking and directional drilling have made this kind of growth and development possible but have positively and negatively impacted the ecosystem. This literature review explores the wells in the United States, how shale gas is formed, wastewater fluid composition and how spills happen, and the impacts of hydraulic fracking and directional drilling on the ecosystem. It further covers the research gaps and the related theoretical frameworks that provided a structured and conceptual basis for understanding and analyzing the problems under investigation.

2.1 Shale Gas Formation

Since the successful revolution in North America, shale gas has received significant recognition worldwide, and it is considered to be the most promising replacement for conventional energy in the future (B. Zhang et al., 2020). Shale gas is a conventional gas that exists in highly porous and permeable reservoirs and can be easily tapped by standard extraction techniques. This kind of gas can remain trapped in its source rock, also known as the organic-rich shale that was formed from the sedimentary deposition of mud, silt, clay, and organic matter on the floors of shallow seas (UCS, 2015). Many procedures have been designed and developed to tap shale gas; however, the most commonly employed gas production techniques are hydraulic fracking and horizontal drilling.

The advent of technologies such as hydraulic fracking and horizontal drilling have made shale gas formation possible and more accessible, making the estimated size of the natural gas resources, especially in the US, rise steadily since the 1990s. Today, the US produces over 34.5 trillion cubic feet (Tcf), an average of about 94.6 billion cubic feet per day (EIA, 2022), and this is expected to increase close to double by 2050, as illustrated in Figure 2.1. Furthermore, the technologies have made it simple to extract vast amounts of shale gas that were previously expensive to produce. Because of this, shale gas is considered to be the fastest-growing natural resource in the United States and the world at large.

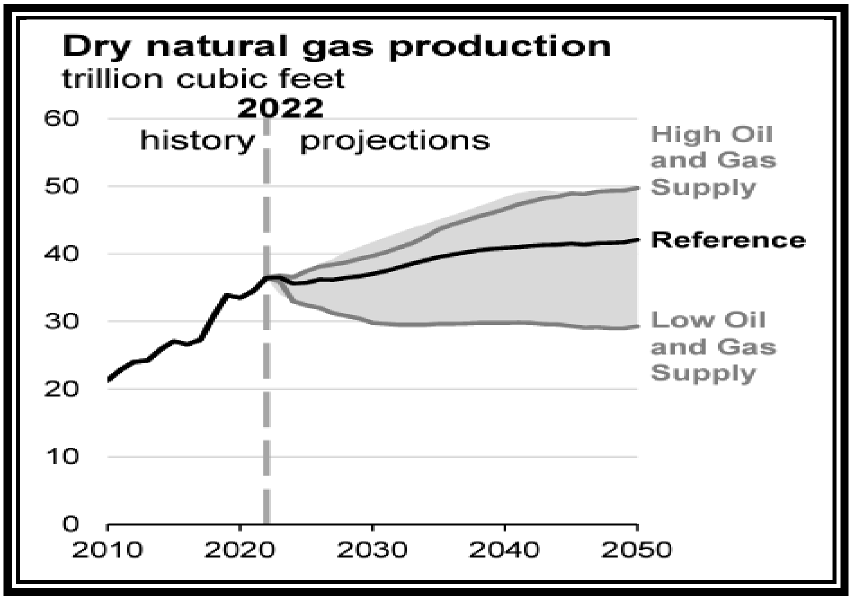


Figure 2.1: Dry natural gas projections (EIA, 2023).

Hydraulic fracking is the most dominant technique in shale gas extraction. In this process, deep holes are drilled into the shale rock, from which pressurized fluids (water) containing sand and chemicals are injected. These fluids, also known as fracking fluids, cause fractures in the rock, enabling the trapped gas to flow into the collection wells, and later, it is piped away for commercial use (LSE, 2022; EIA, 2013). While this method is standard, horizontal drilling is also almost similarly utilized.

The shallow section of shale wells is drilled vertically during the horizontal drilling process. A drill path is then turned horizontally at the target depth, the location where the shale gas formation exists. At this point, the horizontal wells are oriented in a direction that maximizes the number of fractures intersected in the shale once fracturing is to happen. This technique achieves more formation, contact, and vast volumes of oil recovery from a drill hole as it can travel more than a mile (EIA, 2013). Both technologies have been effective and have enhanced the volume of natural gas produced worldwide; however, despite the benefits, they have also caused negative impacts on the environment and ecology.

2.2 Shale Oil Wells in the United States

The development of directional drilling (DD) and hydraulic fracturing (HF) technologies has been aimed at increasing natural gas extraction in the oil and gas sectors. However, they have led to an increase in the number of wells drilled every year around the world. In the United States, there are over 1.6 million wells. According to EIA, hydraulically fractured horizontal wells accounted for 69% of all oil and natural gas wells drilled in the United States and 83% of the total linear footage drilled in 2016 (EIA, 2018).

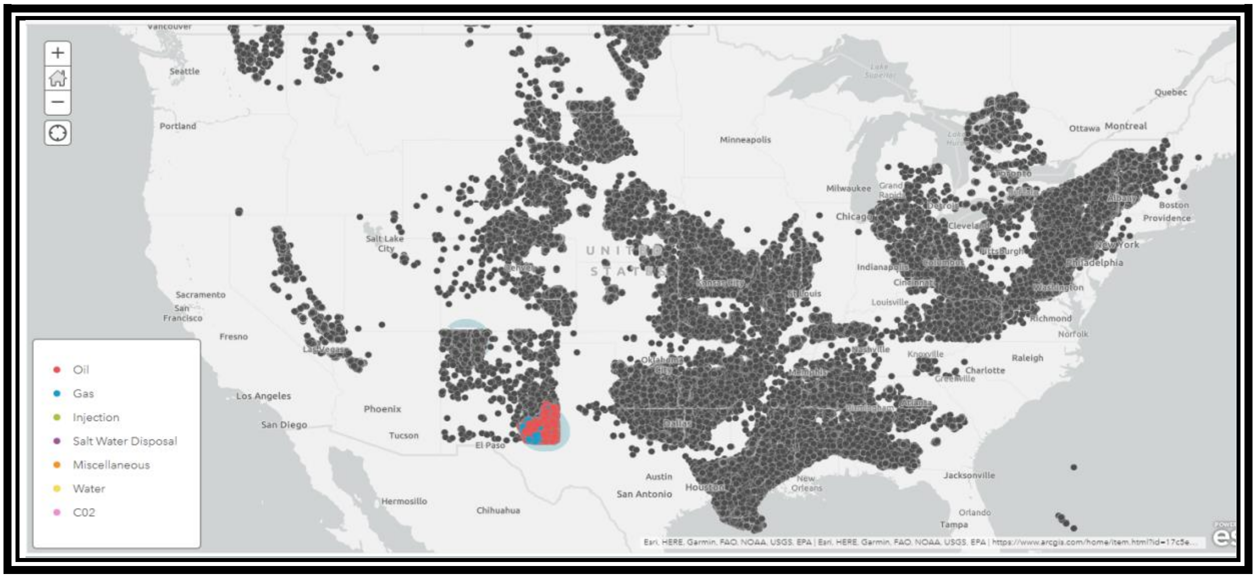


Figure 2.2: Hydraulic Fracturing and Horizontal Drilling Wells in the United States.

Furthermore, a combination of hydraulic fracking and horizontal drilling has directed the United States to produce over 18.88 million barrels of crude oil daily by releasing hydrocarbons buried more than a mile under the surface in shale formations. The amount is expected to rise in record in the coming years (EIA, 2022).

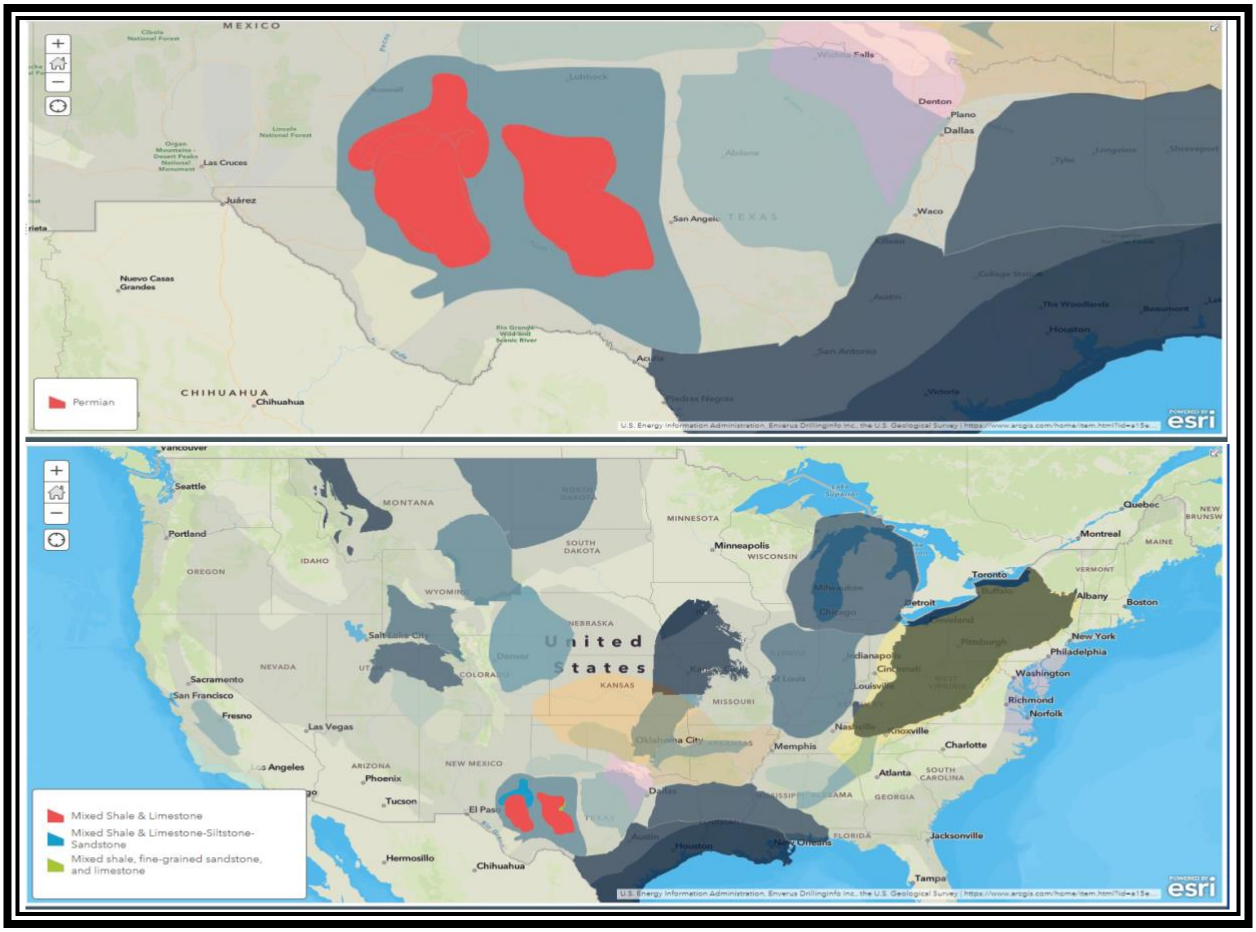


Figure 2.3: Texas and New Mexico Permian Basin Shale Play.

Approximately 71% of the total US oil is produced from five states: Texas at 42.7 %, New Mexico at 11.3%, North Dakota at 9.6 %, Alaska at 3.9% and Colorado at 3.5%) (Galov, 2023). Texas as the leading state with nearly 300,000 wells (Malewitz, 2016), produces over 15,612 million barrels of crude oil and 102,370 billion cubic feet of natural gas on reserve (EIA, 2022), while New Mexico, the second leading state, is reported to produce over 450, 577, 398 barrels of oil, 2, 232, 962, 321 billion cubic feet of gas, and 1, 583,858,038 barrels of produced water in 2021. There are 625,000 active oil and gas wells, with most wells in the southern New Mexico-Permian Basin as in Figure 2.3 above (OCD, 2022).

2.3 Produced Water

Produced water is generated during the oil and gas operations, and the amount of oil and gas produced is directly related to how much produced water can be discharged to the surface. Therefore, for maximum amounts of energy, large volumes of water are utilized, which amount to large volumes of water that are released to the surface in the form of produced water (Salem & Thiemann, 2022). In addition, nearly 1 million oil and gas wells in the US generate vast volumes of produced water (EIA, 2022).

Table 2.1: Production of water, gas produced, and oil produced in 15 years span.

Types of Production	2002-2007	2007-2012	2012-2017
The volume of Water Produced (bbl/year)	21,000,000,000	21,200,000,000	24,400,000,000
The volume of Gas produced (Mmcf/year)	24,500,000	29,000,000	35,182,000
The volume of oil Produced (bbl/year)	1,700,000,000	2,300,000,000	3,300,000,000

(bbl is for barrel, and 1bbl = 42 US gallons)

Table 2.1 shows that the total volume of produced water estimated for 2017 increased by 16.2% over ten years (2007 to 2017) to about 24.4 billion bbl due to increased gas production (Balboa, 2020).

2.4 Fluid Composition

2.4.1 INJECTED WATER COMPOSITION

The geologic structure, formation pressure, particular geologic formation, and the goal for a well significantly impact the kind and composition of fracking fluids to be injected (EIA, 2013). The liquids are always a mixture of water, sand, and a chemical additive pumped under extremely high pressure to more than 9,000 pounds per square inch into fissures in the rock to increase the permeability flow path (Kuwayama et al., 2015). Figure 2.4 below shows the typical composition of the mixtures needed to fracture the shale rock.

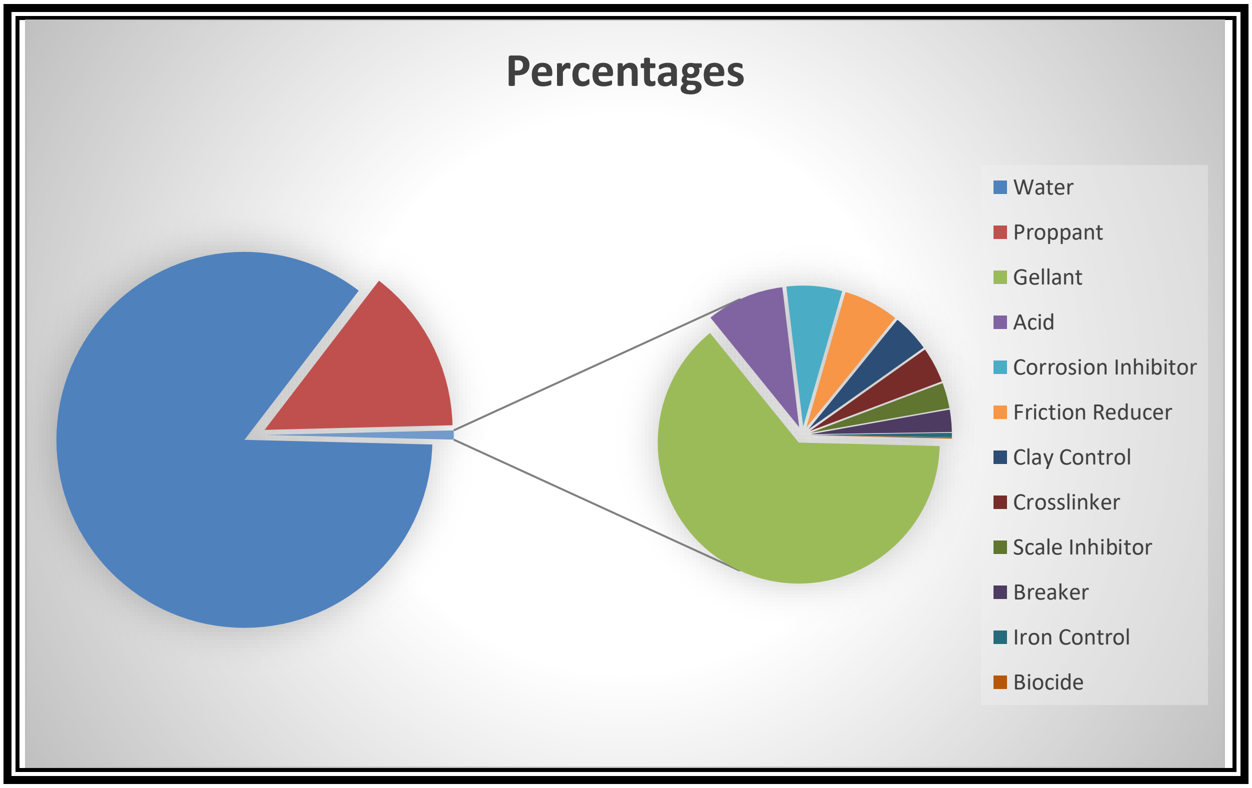


Figure 2.4: Typical fluid for the Hydraulic Fracturing Process (FracFocus, n.d.).

The primary composition of the fracturing mixture is always about 98-99% of the total volume consisting of fresh water or treated produced water, and the remaining 1-1.9 % of the total volume consists of sand or ceramic particles that help to keep the fissures open during fracturing and chemical additives (Fontaine et al., 2008). Below is a table that illustrates the various chemical additives used for fracking.

Table 2.2: Typical Chemical Additives for Hydraulic Fracturing Water (Carman & Cawiezel, 2007; Craddock, 2018; Fontaine et al., 2008; Hoeman et al., 2011).

Compound	**Purpose**	**Common Application**
Polyacrylamide or Mineral oil (Friction Reducer)	0.025% of the total volume reduces the friction from the fluid and the pipe	The adsorbent in baby diapers, water treatment, or soil conditioner

Disinfectant (biocide)	0.005%-0.05% of total volume-removes or eliminates bacteria from the water	Disinfectant or sterilizer for medical and dental instruments
KCl (potassium chloride)	Creates a brine carrier fluid	Low sodium table salt
Oxygen Scavenger (ammonium bisulfite)	Removes oxygen from the water to prevent corrosion from the pipe	Cosmetics, Food and beverage, processing, water treatment
Borate salts (crosslinker)	Maintain fluid viscosity as temperature increases	Cosmetics, detergent, and soap
pH adjusting agent (Sodium or potassium) carbonate)	Maintains the effectiveness of other components like crosslinkers	Detergent, soap, water softener, glass and ceramics and washing soap
Surfactants	Breaks and prevents emulsion; surface tension reducer	Shampoos, toothpaste, paints, etc
Gelation chemicals (thickeners)	Gel the water to suspend and carry the sand	Food additives, toothpaste, sauces, baked products, ice cream, cosmetics
Scale inhibitors (ethylene glycol)	Prevent mineral precipitate	Automotive anti-freeze, deicing agent, household cleaners
Ammonium persulfate (breaker)	Slowly breaks down the gel polymer chains	Bleaching agents found in hair and detergent products and household plastics.
Hydrochloric acid or muriatic acid	Reduces the initiation pressure and helps to break down minerals and start cracks in the rocks	Swimming pool or cleaning agents
Corrosion inhibitor	Used to reduce corrosion of metals	Toxic to the environment

2.4.2 WASTEWATER COMPOSITION

Produced and flowback water generated as wastewater during the oil and gas operations is usually contaminated due to contact with hydrocarbons. The physical and chemical properties of the wastewater vary considerably depending on the geological location and the type of hydrocarbon being produced (CSM, 2016).

The significant wastewater constituents are:

- **Salt content**: Salt content is also expressed as salinity, total dissolved solids, or electrical conductivity. The salt content in produced water varies widely from nearly freshwater to salt levels up to ten times higher than seawater.
- **Oil and grease**: Oil and grease are not individual chemicals. They can be distinguished as a test method that measures many types of organic chemicals that collectively lend an oily property to the water.
- **Inorganic and organic chemicals**: These chemicals are found naturally in the formation and are transferred to the water through long-term contact with the hydrocarbon, or they can be chemical additives used during the drilling and operation of the well.
- **Naturally occurring radioactive material** (NORM): Some of the formations holding oil and gas have small concentrations of natural radioactivity. Low levels of radioactivity can be transferred into the produced water. Generally, the radiation levels in the produced water are minimal and pose no risk. However, scale from pipes and sludge from tanks holding produced water can concentrate NORM.

This makes this kind of water hazardous to human life and other aspects of the ecosystem once an encounter occurs, especially in the form of spills (CSM, 2016).

2.5 Risk Assessment

2.5.1 RISK ASSESSMENT: WATER QUALITY

Since wastewater spills occur at any point of oil and gas exploration, they heavily impact water quality once in contact with surface water. Studies indicate that wastewater spills can lead to trace metal accumulation or naturally occurring radioactive material in surface water. These can be mobilized through flood events or anthropogenic activities (Lauer et al., 2016; Steding et al., 2000), causing massive contamination and changes in water quality. In the US, it is estimated that most shallow drinking water aquifers are contaminated by methane, faulty casing, migration of greenhouse gases from fractures or abandoned wells, brine spills, and other oil and gas fluids (Brittingham et al., 2014; Huang et al., 2017; Li et al., 2021; Soares et al., 2021; Vidic et al., 2013; Woda et al., 2018) which are assumed to be as a result of hydraulic fracking and horizontal directional drilling.

However, other studies indicated that there were no statistically significant correlations between groundwater methane levels and proximity to hydraulic fracturing oil and gas wells (Li et al., 2021). Assessing risk this kind of risk is complicated due to the lack of predrilling baseline measurements, insufficient access to well sites, lack of industry data, the constant introduction of new chemical additives to fracturing fluids, and difficulties in associating data sets obtained through various sampling and analytical methods (Stroebel et al., 2019; Wilson & Varma-Nelson, 2019).

2.5.2 RISK ASSESSMENT: SEISMICITY

There is supposedly an increasing correlation between earthquakes and oil and gas operations (Krupnick & Echarte, 2017; DOE, 2016). Earthquakes may be induced by the wide range of oil and gas operations, such as mining and hydraulic fracturing (HF). Additionally, studies carried out in Oklahoma acknowledged that between 2010 and 2016, more than 75% of seismicity was correlated with approximately 300 HF wells (Ries et al., 2020). However, the response differs from basin to basin. For instance, despite the thousands of wells in the Barnett area in Texas, Bakken in North Dakota, and Marcellus in Pennsylvania, there was little to no hydraulic fracturing-induced seismicity (Verdon & Bommer, 2021).

2.5.3 RISK ASSESSMENT: ECOLOGY

Studies indicated that the expansion of wind turbines and unconventional oil and gas drilling influence the number of wildlife living on the land and the expense of maintaining the environment (EIA, 2022b). Another study on the US's most complex and extensive stream network assesses stream contamination close to shale gas development with a new geospatial tool.

Results showed that out of the 1300 national spills that occurred, only 20 (2%) had data, and 3 (0.2%) of the 1300 national spills were detected to be contaminated streams with NaCl-rich spills (Agarwal et al., 2020). The spills are assumed to be very dangerous to the ecosystem in the long term. Another study found that Mahi-Mahi (Coryphaena hippurus), Cardiomyocyte Contractile Function, and swimming performance were impacted for 24 hours due to 2.75% of flowback water from hydraulic fracturing (Folkerts et al., 2020). Other research has also shown the potential negative impact on many forms of aquatic organisms due to hydraulic fracturing wastewater (Nagel et al., 2020).

2.5.4 RISK ASSESSMENT: WASTEWATER

Wastewater has an impact on both the environment and human health. According to a Cornell University study (Pollution Solutions, 2014), the occurrence of spills and leaks caused by hydraulic fracturing (HF) and horizontal drilling activities has the potential to cause a high level of soil contamination. Some contaminants such as salts, ammonium, and other toxic substances can release heavy metals like arsenic, barium, cadmium, chromium, lead, selenium, and mercury into the soil (Duke, 2016). Some of the metals, such as arsenic, cadmium, chromium, lead, and mercury, have a high level of toxicity and are classified as carcinogens that can cause multiple organ damage when exposed to humans.

2.6 Sequential Extraction

Sequential extraction is applied to estimate the chemical association of trace elements in soils and sediments and to determine the mobility, availability, distribution, and possible toxicity of chemical elements in soils as well as predict their bonding type in individual fractions (Tack & Verloo, 1999; Vollprecht et al., 2020). The technique represents a robust and systematic approach to characterizing the distribution and speciation of contaminants within soil particles. It involves a series of selective chemical treatments designed to mimic different environmental conditions, thereby simulating the potential fate of contaminants in soil. The technique dwells on the varying degrees of chemical bonding and affinity between contaminants and soil phases, allowing for the fractionation of contaminants into discrete operationally defined pools (C. Wang et al., 2013).

2.7 Theoretical Framework

2.7.1 THEORY OF BEHAVIORAL CHANGE

Anthropogenic activities have significant impacts on the environment. According to Hasnas (2009), the exploitation of ecosystems by humans has long-lasting consequences for the future provision of natural resources and ecosystem services. This is clearly witnessed by the fact that oil and gas reservoirs are being heavily exploited to increase the amount of natural gas extraction. While the US has abundant oil reservoir resources, the availability of these reservoirs in the future will depend on how much oil is currently being explored.

Additionally, there are many anticipated negative impacts of using HF and Horizontal Drilling (HD) technologies in the US. Some of these include contamination of water sources, soil, and plants and a cause of climate change. While there isn't much correlation to some negative issues, such as seismicity, Earth's surface contact with wastewater from both technologies is highly hazardous to the ecosystem. Many laws and regulations have been enacted to prevent severe negative ecological impacts; nonetheless, it would appear they are not followed rigorously by many oil companies due to exemptions and weak enforcement.

For instance, the Halliburton Loophole from the 2005 Energy Policy Act blocks the US Environmental Protection Agency (EPA) from regulating HF as part of the 1972 Clean Water Act as well as the 1974 Safe Drinking Water Act (Cronshaw & Grafton, 2016). As a result, the health and welfare of the public and environmental impacts have been left to individual state governments, which address the issues differently (Centner & O'Connell, 2014). Neglect to activate ecological regulations can be assumed to be neglect to change social activities for positivity. Therefore, there is a need for behavioral change.

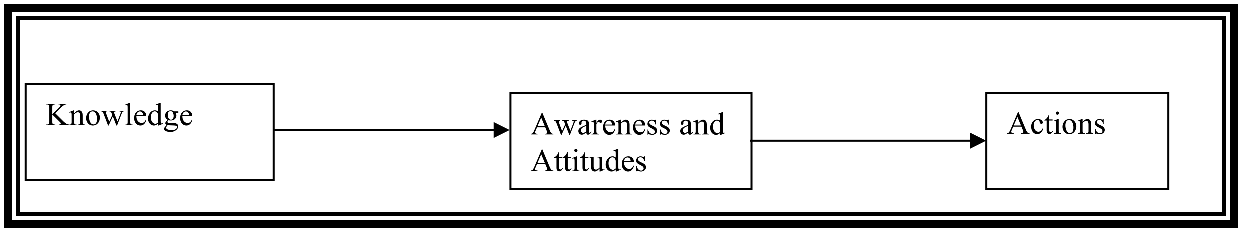


Figure 2.5: Theorized behavioral change model (Ramdas & Mohamed, 2014)

As illustrated in Figure 2.5, the theory of behavioral change proposes that the level of knowledge influences the awareness or attitude of an individual, hence leading to responsible actions. From the perspective of environmental protection, it can be assumed that an individual with increased knowledge of the environment and its issues will lead to increased awareness and positive attitudes towards the environment. In the long run, this will lead to responsible actions in protecting and conserving the environment.

However, studies by Hungerford & Volk (1990) suggest that a linear relationship cannot evidently represent behavior towards the environment. Instead, it is the basis of providing the relationship between knowledge and attitude. Therefore, the existence of several regulations and environmental protection laws won't necessarily protect the environment. It is within the acts of humans that will depend on whether the laws are heavily enforced.

2.7.2 THEORY OF ENVIRONMENTAL PROTECTION

In the era of technological advances, people have become highly aware of the importance of environmental protection and green living. A series of federal laws govern that most environmental aspects of shale development in the oil and gas sector exist. For instance, in the US, the Clean Water Act regulates surface discharges of water associated with shale gas drilling and production, as well as stormwater runoff from production sites. At the same time, the Safe Drinking Act aims to regulate the underground injection of fluids from shale gas activities (DOE, 2009).

Environmental protection is theorized to involve political, social, and economic aspects. Politicians and academics emphasize the importance of economic security, environmental safety, and relations to environmental issues. Developed countries like the US are making stricter environmental measures to protect the ecosystem. Additionally, it is assumed that consumers' and communities' awareness of environmental hazards is continuing to improve hence advocating for more environmentally friendly actions (L. Wang, 2016).

On this accord, the use of regulations can act as tools to minimize damage from unconventional oil and gas extraction activities (Esterhuyse et al., 2022). In the US, there are eight federal laws under which oil and gas development can be regulated. Table 2.3 shows the eight key Federal Laws that fall under the Environmental and Public Health Laws.

Table 2.3: Federal Laws and their exemptions to HF and DD companies.

Key 7 Federal Law	**Applicable to Oil and Gas Development**	**Exemption or Limitation**	**Source of exemption Exemption or Limitation**
Safe Drinking Water Act (SDWA)	Underground Injection Control Program	Hydraulic fracturing fluids other than diesel fuel do not require an	Statutory-2005 Energy Policy Act

	Imminent and Substantial Endangerment Provision	Underground Injection Control Permit.	
Clean Water Act (CWA)	National Pollutant Discharge Elimination System program Spill Reporting and spill prevention and response planning requirements	Federal stormwater permits are not required for uncontaminated stormwater at oil and gas construction or well sites	Statutory-1987 Water Quality Act and 2005 Energy Policy Act
Resource Conservation and Recovery Act (RCRA)	Non-exempt wastes present at well sites may be regulated as hazardous. Imminent and Substantial Endangerment Provision	Petroleum and gas exploration and production wastes are not regulated as hazardous waste	1988 Regularity EPA decision
Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)	Hazardous Substance Release Report Imminent and substantial endangerment provision for release of a pollutant or contaminant	Liability and reporting provisions do not apply to the injection of fluids authorized by state law for production, enhanced recovery, or water production.	Statutory -1980

		Petroleum releases not covered.	
Emergency Planning and Community Right-to-Know Act	Reporting on use, inventories, and releases into the environment of hazardous and toxic chemicals above threshold quantities	Oil and gas well operations are not required to report the release of listed chemicals to the Toxic Release Inventory	1997 Regulatory/EPA decision
Toxic Substances Control Act (TSCA)	Requiring reporting, record keeping, testing, and restrictions associated with chemical substances or mixing	Most of the chemicals are on the list.	
Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA)	Used to kill bacteria or organisms that may prevent the hydraulic fracturing process		

Although some limitations and exemptions exist that make the laws ineffective (Esterhuyse et al., 2022), EPA oversees environmental contamination under Federal Law (EPA, 2022). Additionally, ecological vulnerability is still a significant challenge for countries worldwide. The over-exploitation of resources combined with a lack of proper handling of waste and lack of laws or weak governing laws are substantial reasons why the ecosystem is highly impacted by oil and gas operations.

CHAPTER THREE: METHODOLOGY

This chapter discusses the study location considered during the study and the systematic approach undertaken to answer the research question and objectives by thoroughly describing the experimental research design employed, the units of analysis, the sample size, and the data collection and analysis techniques.

3.1 Study Area

The research was conducted in Eddy and Lea counties in the United States, in the southeastern part of the New Mexico region. Eddy County is located at 32.4171° N and 104.4723° W. It is 10,870 km^2 in area and home to over 58,000 people. Lea County is located at 32.8969° N and 103.3587° W. It has an area of 11,380 km^2 and is home to over 72000 people. The selected areas are the most prominent oil-producing counties in the New Mexico region, accounting for about 96% of New Mexico's entire oil production (Hedden, 2019).

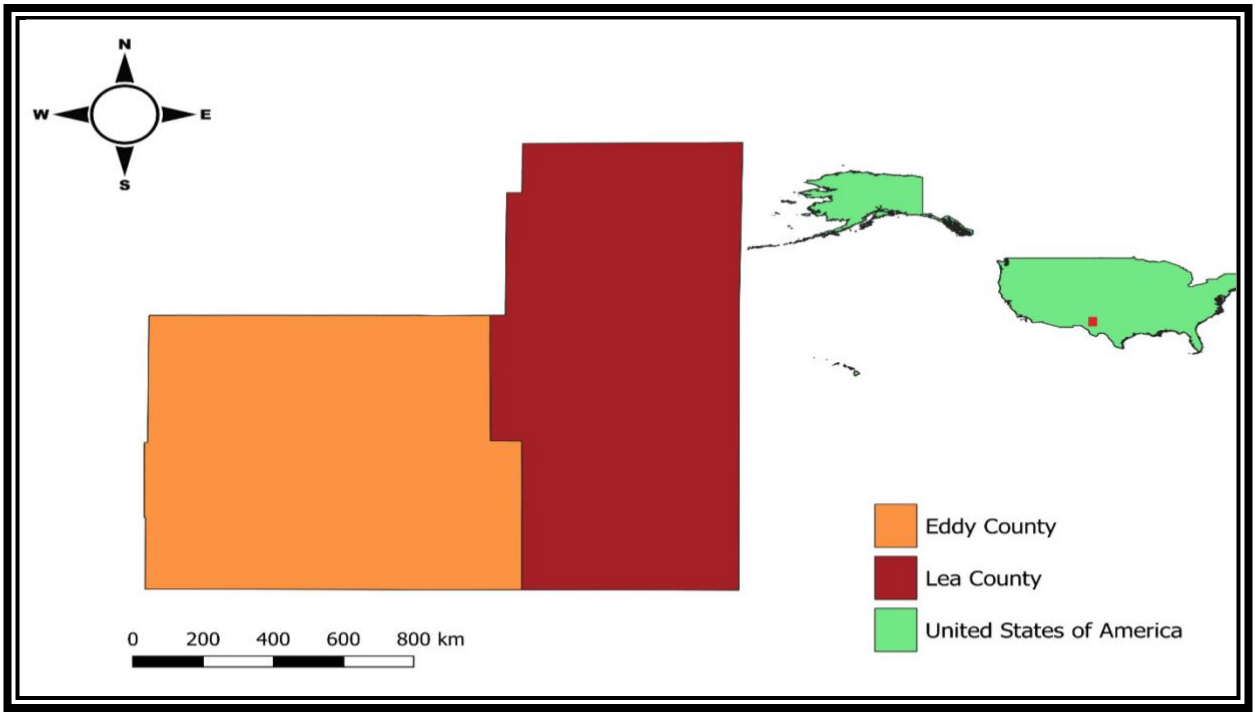


Figure 3.1: Location of Eddy and Lea counties.

3.1.1 GEOLOGY OF EDDY AND LEA COUNTY

Eddy County consists of Piedmont Alluvial Deposits (23%), Eolian and piedmont deposits (17%), older alluvial deposits of the highland plains and piedmont areas, and calcic soils and eolian cover sediments of the highland regions (8%), Queen and Grayburg Formations (7%) Artesia Group (7%), and San Andres Formation (6%), the Rustler Formation (5%), Yates and Tansill Formation (5%), Seven River Formation (4%), Castile Formation (3%), Salado Formation (3%), Eolian deposits (2%), Quartermaster and Rustler Formations (0.6%), Lacustrine and playa-lake deposits (0.4%), Quartermaster Formation; red sandstone and siltstone, Upper Permian (0.3%), Ogallala Formation (0.2%), Upper Chinle Group, Garita Creek through Redonda Formations, undivided (0.1%), Bell Canyon Formation (0.1%), Santa Rosa Formation (0.1%), and Santa Rosa Formation (0.1%) (USGS n.d.-a).

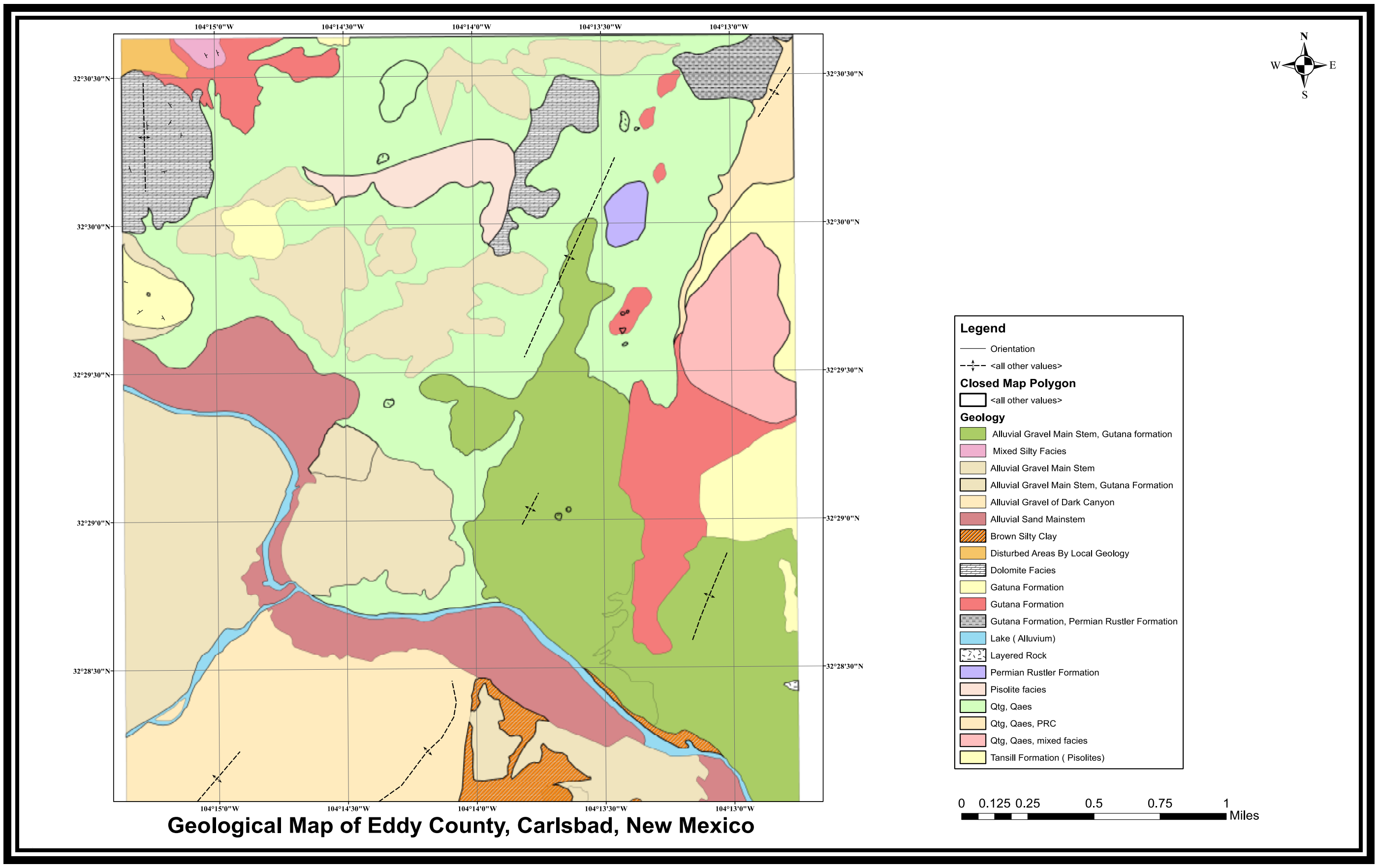


Figure 3.2: Geology of Eddy County.

Lea County comprises the Ogallala Formation (48%), Eolian, and Piedmont deposits (32%). Older alluvial deposits of the high plains and sediments of Piedmont are calcic soils and eolian cover of the High Plains region (8%), Eolian deposit (5%), Piedmont alluvial deposits (5%), Alluvium (0.4%), Blackwater draw formation (0.1%), Sand sheet deposit (0.1%), Playa (0.1%), Sand deposit, undivided (0.1%), Ogallala formation (0.1%), Lower Cretaceous, undivided (0.1%), Leona Formation (0.1%), and Alluvium (0.1%) (USGS n.d.-b).

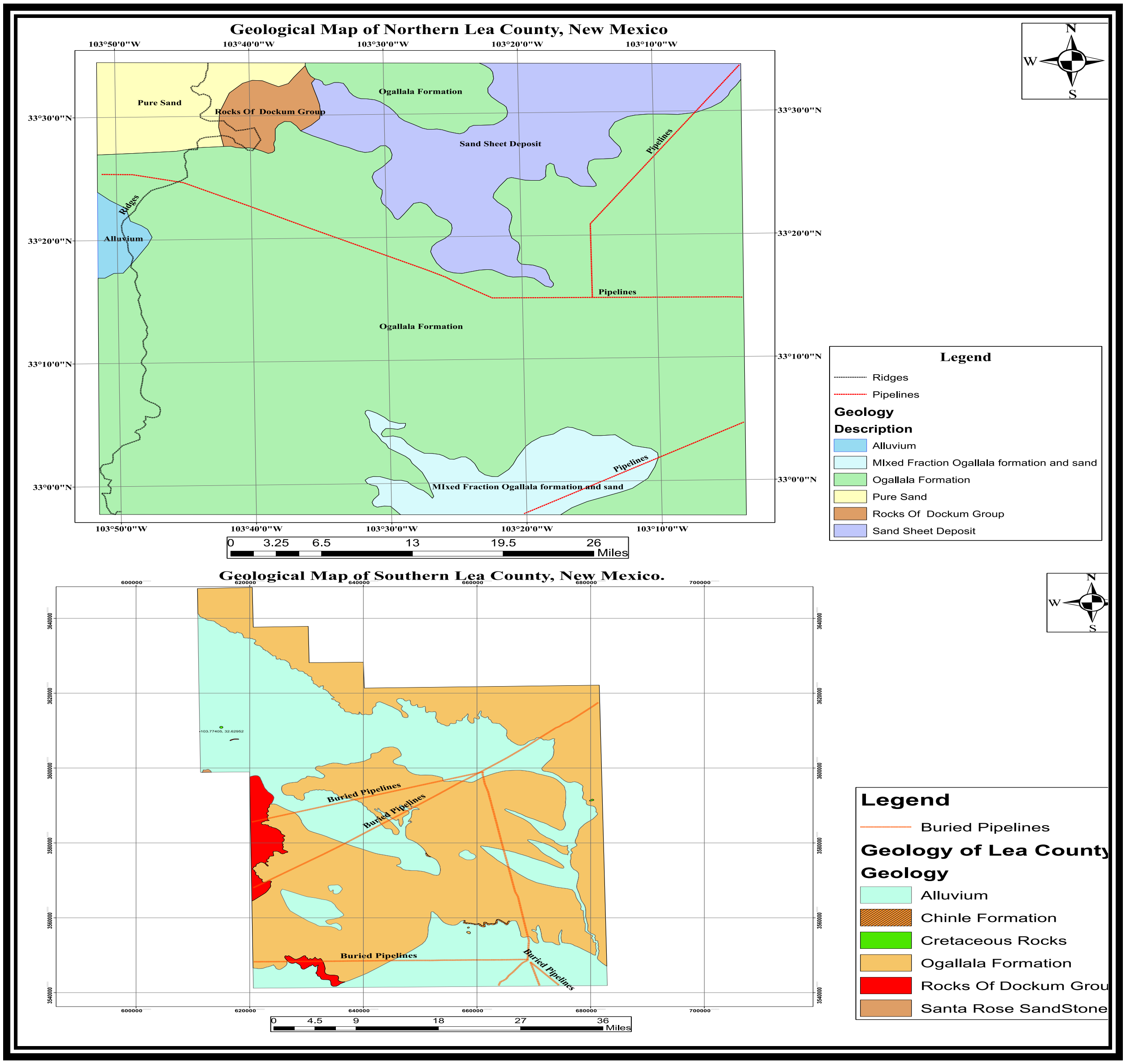


Figure 3.3: Geology of Lea County.

3.1.2 OIL AND GAS ACTIVITIES IN EDDY AND LEA COUNTIES

Eddy and Lea are the top two oil-producing counties in New Mexico (Hedden, 2019). They account for 29% of the Permian crude oil production. In southeastern New Mexico, horizontal wells in Lea and Eddy counties drove much of the recent Permian Basin crude oil output growth. Output from horizontal wells in the two counties averaged 1.7 million barrels per day (b/d) in the first quarter of 2023 (EIA, 2023).

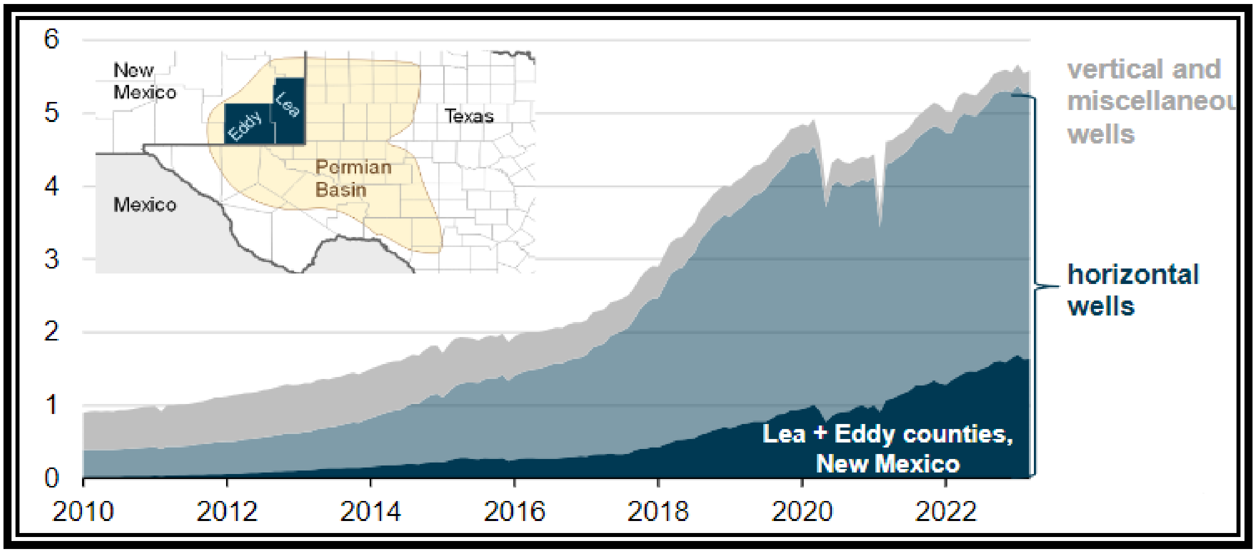


Figure 3.4: Permian crude oil production between January 2010 to March 2023 ((EIA, 2023).

3.2 Research Design

An experimental research design was employed to fully explore the following research questions: a) To study the characterization of compounds adsorbed on soil due to spills in Eddy and Lea Counties. b) To carry out exposure studies that identify the level of toxicity of compounds adsorbed on soil due to spills in the Eddy and Lea counties. c) To investigate the fate and transport of wastewater spills' metals and how they are held up in the soils in Eddy and Lea counties, and d) To determine the influence of soil properties on the mobility and persistence of contaminants introduced by oil and gas-related spills in Eddy and Lea Counties. Experimental research is characterized by a notably higher level of control over the research situation, enabling the deliberate manipulation of certain variables to observe and analyze their subsequent impact on other related variables (Kothari, 2004).

The use of experimental research designs in modern science studies is heavily increasing as they can accurately provide information about the variables and units of analysis under consideration. Experimental research designs also permit authentication by many users, and they have substituted for unreasonable prejudice, a definite sort of proof that has attained sufficient certainty to justify prediction. The methods further allow cause-and-effect relation s to be more clearly and rapidly assessed than any other method, and the results are delivered credibly (Chapin, 1917, p. 133). Additionally, results from the selected research design have low bias, high precision, and widely applicable results (Lazic, 2016).

3.3 Units of Analysis and Variables

Soil was selected as the unit of analysis. Soil analysis allows in-depth analysis of the various factors that influence the soil properties at different spatial and sequential dimensions, hence acknowledging a thorough understanding of all the soil dynamics. It also permits an accurate and detailed examination of all the factors that may cause contamination (Dawson, 2023). The dependent and independent variables that were measured were the soil properties and heavy and hazardous metals in the soil as illustrated in Table 3.1 below.

Table 3.1: The Unit of analysis and Variables

Unit of Analysis	**Variables**
Soil	Soil Texture – Clay, Silt, and Sand
	Soil pH – Acidic or Alkaline
	Soil Conductivity – High or Low
	Soil Organic Matter – High or Low
	Soil Organic Carbon – Low or High
	Cation Exchange Capacity (CEC) – Low or High

3.4 Sample Selection and Size

To avoid experimental bias, the samples were randomly selected from various areas of the study areas. In each county, two sites were chosen for sampling and a total of eight soil samples were collected, and they comprised two sub-samples from each site. The collected soil samples under consideration were obtained from both contaminated and uncontaminated site areas and these were collected under the guidance of The Bureau of Land Management (BLM) personnel (petroleum engineering technician). Additionally, a soil depth between 0 to 20cm was considered during the sample collection process.

3.5 Apparatus and Instrumentation

Inductive Coupled Plasma Mass Spectroscopy (ICP-MS) is an instrument consisting of an ion source, a sampling interface, an ion lens, a mass spectrophotometer, and a detector. The instrument is used to determine the concentration of rare earth elements (REEs) in plants and soils (Nuttall et al., 1995). During the study, a high-speed, precise, and sensitive instrument was used to measure the number of atoms in the soil. It was also used for measuring trace, ultra-trace metals, and some non-metals at extremely low detection limits for a wide range of elements (Nasirian et al., 2014).

3.6 Data Collection Methods

The methods employed for data collection included Desk, Field, and Laboratory studies.

3.6.1 DESK STUDIES

Desk-based studies involved relevant literature review to draw conclusions from the available resources as well as identify gaps that required further analysis. During the research, the information was derived from validated online document databases, online government websites, and study area-based websites. Utilizing desk studies prevents more time and resource consumption that could be directed toward primary data collection as they illuminate the context of principal data research, define the depth and extent required, and formulate suitable research questions.

3.6.2 SITE OBSERVATIONS

Site visits were carried out to gain an understanding of the contamination sources and the physical environment of the counties. These were planned and carried out to ensure coverage and representation of the study area. Site observations were also used to validate the fidings from other data collection methods.

3.6.3 LABORATORY EXPERIMENTS

Laboratory experiments were employed to measure the soil properties that could be used to determine the level of soil contamination. Using this method can provide accurate measurements of the influencing factors and their variables hence evaluating the cause-and-effect relationship accurately. Laboratory experiments also allowed the measured variables to be tested under controlled conditions (Lazic, 2016).

3.7 Data Analysis

Soil analysis was conducted using standard laboratory methodologies (Page et al., 1982; Sparks et al., 1996). Further analysis was carried out using the T-test method and sequential extraction. "Sequential extraction is a common analytical method used to identify elements associated with solid phases in environmental media based on their reactivity with a specific solution" (Rodgers et al., 2015).

Spatial analysis was used to identify the hotspot and cold spot areas within Eddy and Lea counties. The procedure aimed at identifying regions that are potentially more susceptible to the impact of oil and gas spills as well as oil and gas-contaminated fluids by identifying areas exhibiting higher concentrations or, diminished occurrences of contamination, and providing insights into the varying degrees of risk and vulnerability of the areas across the counties (Cheng & Washington, 2005; Stopka et al., 2014). Furthermore, all statistical analyses were computed by using Microsoft Excel software for Windows.

3.8 Quality Assurance and Safety

To avoid inaccurate results and contamination during the laboratory analysis and sample collection, all equipment was thoroughly cleaned. The specimens were further inspected, and transcription measures were thoroughly reviewed through report verifications and reliable tests. Uncontaminated samples were collected and analyzed to act as comparative results for the contaminated ones.

All technicians and sample handlers maintained high levels of accuracy and proficiency and ensured proper storage and handling of specimens and equipment at all stages of research. Additionally, safety precautions were followed at all points right from sample collection, testing, storage, and analysis as well as disposal of wastes.

3.9 Ethical Considerations

The study fulfilled all the necessary ethical considerations. During the research, all parties who were involved received informed consent requests. These were through oral and written communication. The information was aimed at explaining to the parties what the study was about, the benefits of the study, the period through which the study was to be conducted, and all other necessary information.

CHAPTER FOUR: DATA

This chapter discusses the process of collecting and analyzing data used to answer the research questions and objectives under investigation. It details the process of on-site observations process, laboratory procedures, measurements, and analysis.

4.1 Site Observation

The physical condition of the study area and sample collection was assessed under the guidance of the Bureau of Land Management (BLM) personnel. During the site visits, the study area was thoroughly inspected using the key parameters in Table 4.1 below. The key parameters helped to thoroughly examine and provide valuable insights that would be used for further analysis.

Table 4.1: Key parameters considered during site observation

Site	**Eddy Site 1**	**Eddy Site 2**	**Lea Site 1**	**Lea Site 2**
Cause of Spill				
Spill size				
Age of spill				
Coordinates				
Comments				

4.2 Laboratory Experimentation

4.2.1 SOIL SAMPLE

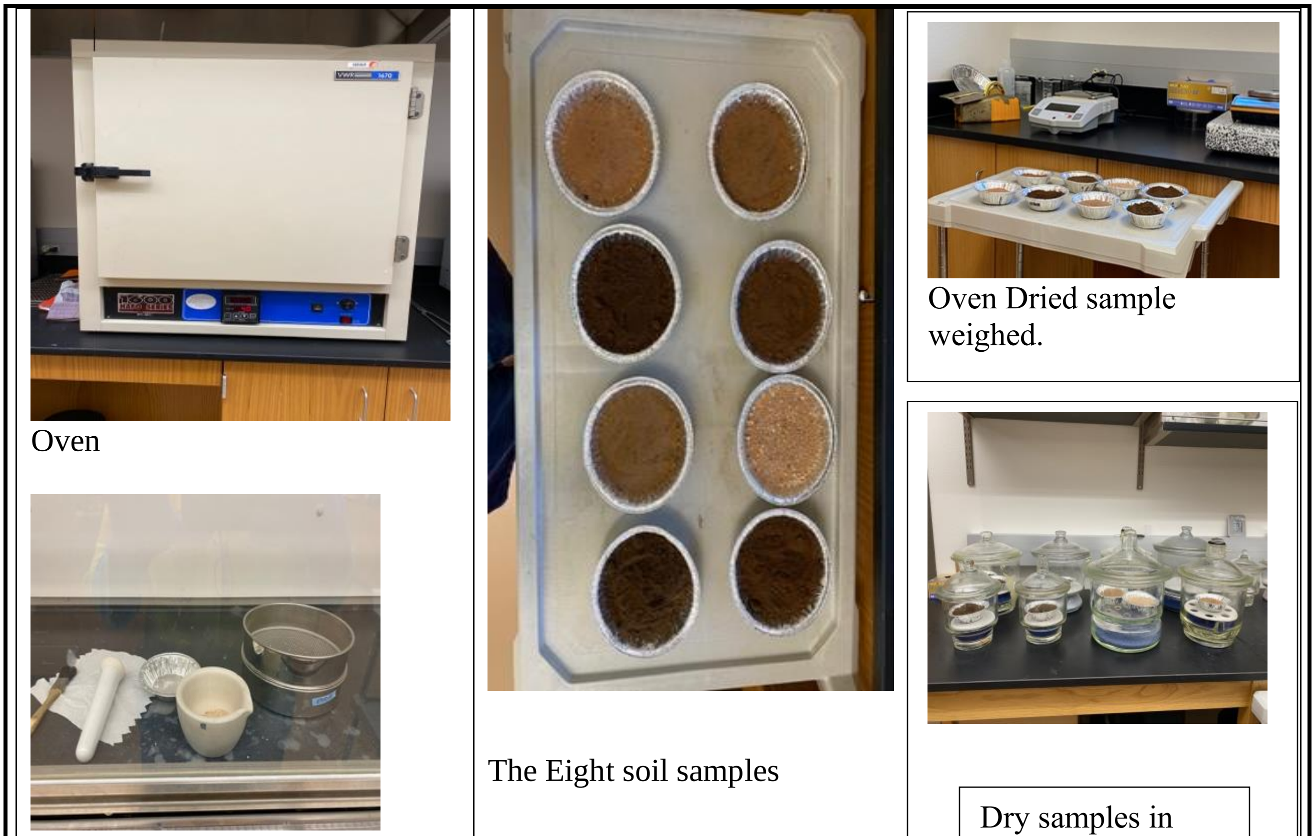
4.2.1.1 Soil Sample Collection

The surface soil at a depth of 0-20cm was collected using an appropriate shovel tool and placed in plastic bags with labels, yielding a total of 1 kg (total). A Survey 123 app was used as a soil field data sheet and a GPS was used to collect the necessary field information.

4.2.1.2 Soil Sample Preparation and Preservation

200 grams of each sample was weighed and then ground with a mortar and pestle to reduce soil aggregates. The samples were passed through a 2 mm sieve and then oven-dried at 40^0C or

less in a clean aluminum foil dish to remove moisture and then stored. The set drying temperature of 40^0C is to ensure that extractable cations will not be changed, unlike temperatures above 48.9 degrees Celsius.



Oven

Mortar and Pestle and 2mm sieve

The Eight soil samples

Oven Dried sample weighed.

Dry samples in desiccant

Figure 4.1: Soil sample preparation and preservation.

4.2.2 CHEMICAL AND PHYSICAL ANALYSIS OF SOIL SAMPLES

4.2.2.1 Materials and Apparatus

Reverse osmosis (RO) water and analytical grade chemicals were used, and all the clean apparatuses were rinsed with de-ionized water and then 1% nitric acid before use. The following in Tables 4.2, 4.3, and 4.4, were the equipment, chemicals, and instruments that were used during the examination of the chemical and physical analysis of soil samples.

Table 4.2: Equipment and materials used during the experimentation procedure

Equipment and Materials			
Burette	Erlenmeyer flask (250 ml)	Funnels	Mm Sieve (No.10)
Burette Clamp	Erlenmeyer flask 500 ml	Buchner funnel	Polyethylene Bottles
Beaker (50ml)	Centrifuge tubes, 50 ml	Funnel Stand	
Graduated Cylinder	Ceramic Pestle and Mortar	Polyethylene bags	Weighing Papers
Volumetric Flask 250 ml	Steering rod	Whatman Filter Paper 42	Tape and markers for labeling
Volumetric Flask 50 ml	2-millimeter (mm) Sieve	2 sheets of Whatman filter paper	5-10 ml micropipette and tips
Micropipette and tips (500/100 uL)	Tray: aluminum		

Table 4.3: Chemicals used during the experimentation procedure

Chemicals	
Ammonium Acetate ($C_2H_7NO_2$)	Hydroxylammonium Chloride ($HONH_2.HCl$)
Potassium Dichromate ($K_2Cr_2O_7$)	Concentrated Nitric Acid
Potassium Chloride (KCl)	Concentrated Hydrochloric Acid (HCl)
95% Ethanol (CH_3CH_2OH)	Hydrogen Fluoride (HF)
Ferrous Sulfate Heptahydrate ($FeSO_4.7H_2O$)	Citric Acid ($C_6H_8O_7$)
O-Phenanthroline Monohydrate ($C_{12}H_{10}N_2O$)	Sulfuric Acid (H_2SO_4)
Acidic Glacial Water ($C_2H_4O_2$)	Phosphoric Acid (H_3PO_4)
Hydrogen Fluoride (HF)	Hydrogen Peroxide (H_2O_2)
Nitric Acid (HNO_3)	

Table 4.4: Instruments used during the experimentation procedure

Instruments	
Oven	Hot Plate/Magnetic Stirrer
A pH Meter	Conductivity Meter with Standard Calibration Solution.
Desiccant	Microwave Digestion (ETHOS UP)
Centrifuge	A Mass Spectrometer
Titration apparatus	

4.2.2.2 Laboratory Preparation

The data was prepared as below.

a) **pH 7.01, 1M Ammonium Acetate**

Approximately 77.08g of ammonium acetate was completely dissolved in 100 mL of distilled water and made up to 1 liter in a volumetric flask. A pH meter was immersed in the solution and the pH was adjusted to 7.00 with dropwise additions of ammonium hydroxide.

b) **Potassium dichromate ($K_2Cr_2O_7$) 1 M**

Potassium dichromate (1 M) was prepared by weighing 294g of $K_2Cr_2O_7$ in a 1-liter volumetric flask. 100 ml of distilled water was added to dissolve it and prepared until the flask was filled.

c) **Potassium Chloride (KCl) 1 M**

A portion of KCl (74.5 g) was dissolved in 30 ml of distilled water and prepared to fill a 1-liter volumetric flask.

d) **95% Ethanol (CH_3CH_2OH)**

A 10ml portion of distilled water was added to 190 ml of 100% ethanol in a volumetric flask to obtain a volume of 200 mL of 95% ethanol solution.

e) Ferrous Sulphate ($FeSO_4.7H_2O$) 0.1 M

A ferrous sulfate solution was prepared by weighing 18.2g of $FeSO_4.7H_2O$ in a volumetric flask. A minimum volume of 50 ml of distilled water was added to dissolve the ferrous sulfate and diluted to 250 ml with distilled water.

f) Solution Ferrocyanide Indicator

6.95 g of $FeSO_4.7H_2O$ was then added and dissolved in RO water. The resulting solution was transferred to a 1000 mL volumetric flask and diluted to the mark with distilled water.

g) Acetic Acid (CH_3COOH) 0.11 M

1.6 ml of glacial acetic acid was added to 100 ml of RO water in a 250 ml polyethylene bottle. The bottle was then filled to the mark with distilled water in a fume cupboard to make an acetic acid solution of 0.11 M.

h) Hydroxylammonium Chloride ($HONH_2.HCl$) pH 2.00, 0.5 M

A small portion of hydroxylammonium chloride (34.75g) was dissolved in 400 ml of distilled water. The resulting solution was transferred to a 1-liter volumetric flask and filled with RO water. A pH meter was immersed in the solution and the pH of the solution was adjusted to 2.00 with a dropwise addition of 2 M concentrated HNO3.

i) Aqua Regia (HNO_3+3HCl)

Approximately 83.34 mL of concentrated nitric acid was added to 250 mL of concentrated hydrochloric acid in a conical flask to obtain a volume of 333.34 mL of aqua-regia. This was done in a fume cupboard since strong acids are involved.

j) Citric acid ($C_6H_8O_7$) 0.05 M

The citric acid solution of 0.05 M was prepared by weighing 19.2 g of citric acid powder in a volumetric flask. 500 mL of RO water was added to completely dissolve the powder and diluted to 2 liters with RO water.

k) 1% HCl

A solution of 1% HCl was prepared by adding 1 ml of concentrated HCl to a 100 mL volumetric flask and diluting to the mark with RO water.

l) 1% HNO_3

Approximately 1 ml of concentrated HNO_3 was added to a 100 mL volumetric flask and diluted to the mark with RO water.

4.2.3 EXPERIMENTATION PROCEDURE

4.2.3.1 Soil pH and Soil Electrical Conductivity

The pH is important for determining the soil characteristics of the collected samples. Soil pH influences the degree of adsorption, mobility, and bioavailability of contaminants, including heavy metals and organic compounds. Contaminants can become more soluble and mobile under certain pH conditions, potentially facilitating their transport through the soil profile, and increasing the risk of groundwater and soil contamination The soil nutrients are considered to be leached out if the soil pH falls outside the optimum range. In addition, a low pH is a good indication of oxidation and generation of acids that take place, whereas a higher pH is anticipated in dry areas due to the presence of calcium carbonate ($CaCO_3$) (Bakshi et al., 2018).

Soil electrical conductivity (EC) is important in determining the health of the soil as it indicates the soil's capacity for nutrient retention and loss, soil texture, and available water capacity. It is also a valuable indicator of soil salinity, which can be influenced by the presence of contaminants in the soil (USDA, 2014).

To calculate the pH and conductivity of the soil, 25 grams of soil were weighed and placed into a beaker. 25 ml of RO water was added to each beaker and the suspension was stirred with a spatula to form a paste or slurry. The slurry was left to sit for 10 minutes. The calibrated conductivity probe was dipped into the slurry, and the meter was allowed to stabilize, then the reading was recorded. Afterward, the pH meter was used to record the pH values of the suspension. An illustration of the conductivity and pH of soil sample preparation is shown in Figure 4.4 below.

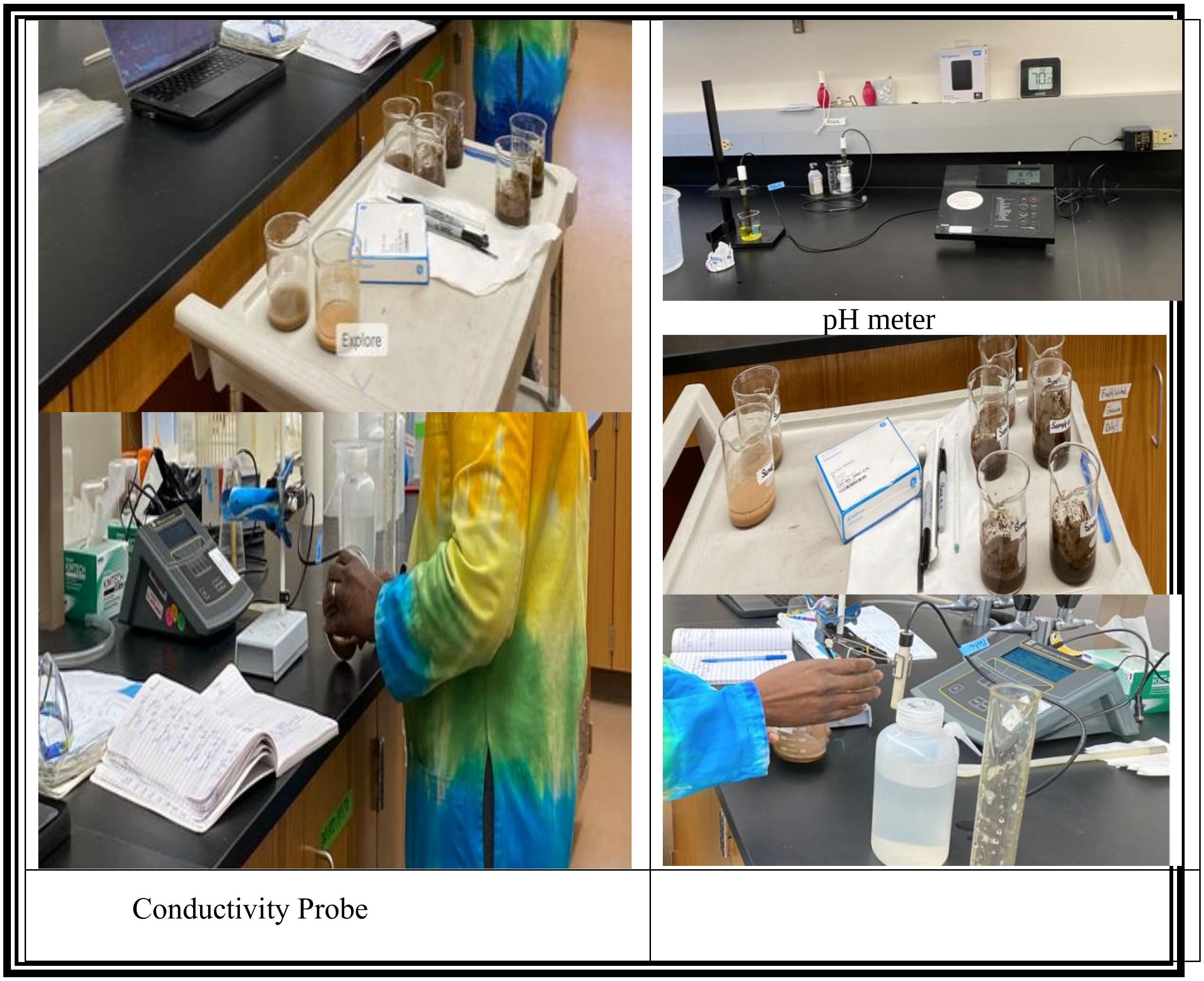


Figure 4.2: Conductivity and pH of soil samples.

4.2.3.2 Total Organic Carbon (TOC) Content

The organic carbon of soil is a most important and crucial component in soils as it affects almost all soil properties. It determines how well the soil can hold water, produce good crop yields, minimize soil erosion, increase plant nutrient retention, and increase biological diversity. It also ensures soil structure so that air, water, and movement are possible (FAO, 2019). When 0.167M of Potassium Dichromate ($K_2Cr_2O_7$) in concentrated sulfuric acid (H_2SO_4) was added to the soil, the organic carbon got oxidized. According to the following equation below:

$$2Cr_2O_7^{2-} + 3CO + 16H + 4Cr_3 + + 3CO_2 + 8H_2O$$

The $Cr_2O_7^{2-}$ was reduced, and C was oxidized. The remaining unreduced dichromate was re-titrated using ferrous sulfate or ammonium ferrous sulfate with the complex indicator-o-phenanthroline-ferrous complex (FAO, 2019).

One gram of dry soil was weighed and placed into a 500 mL Erlenmeyer flask. A 10 mL of 0.167 molar of $K_2Cr_2O_7$ was added to the flask, gently for soil dispersion. After, 20 ml of concentrated H_2SO_4 was added and swirled again to mix the solution first gently and then vigorously for a minute. The solution was allowed to sit in the hood for 30 minutes. Then 200 mL of RO water was added to the flask.

A 10M of 85% H_3PO_4 consisting of two to three drops of the o-phenanthroline indicator was finally added. The titration started with a solution of 0.5 molar (M) $FeSO_4$ or $(NH_4)_2Fe(SO_4)_2.6H_2O$ as the titrant in the burettes. During titration, the initial color of the solution was greenish cast, then changed to green as the ferrous sulfate heptahydrate was added drop, and by drop, as it reached the end of the titration, the color drastically changed from blue to finally red (maroon color).

The percentage of TOC was computed using the following equation below where;

Soil Organic Matter = 1.724 * Total organic carbon (%)

4.2.3.3 Soil Organic Matter (SOM)

Soil organic matter (SOM) makes up about 1-5% of the organic materials in the soil as a result of living organisms such as plant, animal, and microbial residues during the many processes of decomposition (Department of Crop and Soil Science, 2008; Weil & Bradly, 2017). SOM includes a wide variety of compounds containing carbon, sulfur, hydrogen, and oxygen. In this research, determining the SOM helped to identify and examine Eddy and Lea soils' capacity to resist water and wind erosion, water holding capacity, water infiltration, and water movement in soil. It was also used to determine the soils' capacity to retain and release nutrients for plant growth (Sullivan et al., 2019).

To determine SOM, the soil samples were oven-dried, weighed, and then heated to 400°C; at this temperature, the organic matter was burned off. The weight lost from heating the samples was then calculated as a percentage using the formulas below.

Mass of organic matter = Mass of the dry soil – Mass of the burned soil

SOM = (Mass of Organic matter/ Mass of the dry soil) x 100

4.2.3.4 Soil Organic Texture

Soil texture is an important parameter in measuring the health of the soil as it significantly influences water retention, drainage, nutrient availability and fixation, strength, and other soil behaviors (Tiwari, 2020). In this research, the collected samples inhabited coarse characteristics; hence the sieve analysis method was employed as an appropriate method to determine the texture of the soils (Hossain et al., 2021).

As illustrated in Table 4.5 below, the sieve analysis process involved sieving the eight collected samples through a series of sieves with varying standard US mesh sizes

Table 4.5: US standard sieve numbers and their opening sizes (Hossain et al., 2021).

Sieve No.	Opening (mm)	Sieve No.	Opening (mm)	Sieve No.	Opening (mm)
4	4.75	18	1.00	70	0.212
5	4.00	20	0.85	80	0.180
6	3.35	25	0.71	100	0.150
7	2.80	30	0.60	120	0.125
8	2.36	35	0.500	140	0.106
10	2.00	40	0.425	200	0.075
12	1.70	45	0.355	270	0.053
14	1.40	50	0.300	400	0.038
16	1.18	60	0.250		

The retained particles on each sieve were weighed and the particle size distribution was determined. For this research, 100 g of each of the eight collected soil samples was oven-dried to remove any excess moisture. Their dry mass was recorded and then they were passed through different sieve sizes starting from the largest one. The samples in the largest sieve were shaken over the second-largest sieve. The remaining soil in the largest sieve was weighed to determine its mass.

The soil in the second largest sieve was also shaken over the smallest sieve and the remaining soil in the second largest sieve was weighed and recorded. The soil in the smallest sieve was weighed to determine its mass. The relative percentage of the soil composition was calculated with sand being the remaining soil in the largest sieve, silt the remaining soil in the second largest sieve, and clay in the smallest sieve. The type of soil was then determined from the relative calculated percentages using the USDA soil texture calculator (USDA, n.d.).

4.2.3.5 Cation Exchange Capacity (CEC)

The Cation Exchange Capacity (CEC) parameter assesses the ability of soils to allow the exchange of cations from their surface and in solution. It is an indicator of soil fertility or soil's ability to hold essential nutrients-calcium, magnesium, potassium ammonium, hydrogen, and sodium. It also provides a buffer from soil acidification (Brown & Lemon, 2016). To determine the CEC, the Ammonium Acetate Method was used and the procedure is as below.

A 125 ml of the 1molar (M) Ammonium Acetate was added to 25.0 g of the soil sample in a 500 mL Erlenmeyer flask. Then it was thoroughly shaken and allowed to stand overnight. A 5.5 cm Buchner funnel was fitted with retentive filter paper. The paper was moistened with a minimum amount of Ammonium Acetate and inserted into a 500 ml suction flask; the vacuum pump was turned on to hold the moistened filter. The soil-ammonium Acetate mixture was stirred and filtered. The filtrate was re-filtered to obtain a very clear solution.

The soil was gently washed four times with 25 ml of the Ammonium Acetate then eight separate additions of 95% ethanol to remove excess ammonia and the leachate was discarded. The adsorbed Ammonia was extracted by leaching the soil with eight separate 25 mL additions of 1 M KCl. The soil was discarded, and the leachate was transferred to a 250 ml volumetric flask and subsequently diluted to the mark with additional KCl. The concentration of NH_4-N in the KCl extract was determined with Inductive Couple Plasma Mass Spectrometer (ICPMS).

4.3 Experimental Analysis

4.3.1 SEQUENTIAL EXTRACTION

Understanding the chemical speciation of metals in solution is necessary for evaluating their toxicity and mobility in soils. "Sequential extraction is a common analytical method used to identify elements associated with solid phases in environmental media based on their reactivity with specific solution" (Kiri et al., 2019). However, due to experimental problems with it (K. H. Okoro et al., 2012; Tessier et al., 1979), the sequential extraction of metals from soil based on Tessier's procedure was modified was modified to a 3-step extraction (Tukur Rumah, 2017). In this research, the Bureau Commune de Reference of the European Commission (BCR) Sequential extraction procedure (SEP) was employed, and the following steps were taken to conduct it.

a) Step 1: Exchangeable fractions

A 40mL of 0.11 molar of Acetic Acid at pH 2.8 was added to 1.0000 grams of soil and shaken for 16 hours. The sample was centrifuged at 10,000 rpm for 20 minutes to separate the extract from the solid residue. The solution was filtered from the residue using Whatman filter No. 42 in a 50 mL centrifuge tube. RO water was used to rinse the filter paper a few times for any remaining sample left on it. The RO water was added to the supernatant to the 50mL mark on the tube. The solid residue was washed with 20mL reverse osmosis (RO) water and shaken for 20 minutes, centrifuged and the supernatant was discarded leaving behind all the solid residues.

b) Step 2: Reducible iron/manganese oxides

40 ml of 0.5 molars of hydroxyl ammonium chloride at a pH of 2 was added to the residue in step 1. The extraction procedure in steps a) was followed.

c) Step 3: Oxidizable organic matter and sulfides

A 10ml of 30% Hydrogen Peroxide solution was added to the residue from step 2 and left to digest for 1 hour at room temperature. The digested content was heated to 85 degrees Celsius for an hour to bring the volume to approximately 3 ml. Another 10mL of 30% hydrogen peroxide solution was added to the solution and the previous step was repeated. 50 mL of 1.0 molar Ammonia Acetate at a pH of 2 was added to the cool moist residue. The sample was then shaken, centrifuged, and the extract was separated as in step a).

d) Step 4: Residual

12 mL of aqua regia (21 mL of HCl) and 7 mL of HNO_3 were added to the solid residue from step c), digested the sample, and analyzed using the Inductive Coupled Plasma Mass (ICPMS).

4.3.2 INDUCTIVE COUPLED PLASMA MASS SPECTROSCOPY (ICP-MS)

4.3.2.1 Sample Preparation

0.250g of soil sample was placed into an acid-cleaned microwave vessel. The sample was placed under a fume hood and then 7 mL of nitric acid (HNO_3) was pipetted into the vessel. Then a clean watch lens was used to cover the ajar vessel so that evaporation was reduced. The pre-digestion process was completed in 45 minutes with the cap ajar. 1 ml of hydrogen peroxide (H_2O_2) was added, and the process took another 45 minutes to complete. Finally, 3mL of hydrogen fluoride (HF) was added, and waited 45 minutes for the total breakdown of the soil sample, and the vessel was then sealed. The vessels were placed in the microwave cartridge and the run cycle in the microwave was set at 25 min ramp to 200 degrees Celsius and held for 15 minutes to cool.

After the sample cooled, the 50 mL centrifuge tube was labeled, and the sample was filtered with the Whatman filter paper and poured into the centrifuge tube. Before discarding the filter paper, RO water was used to rinse any remaining samples back into the tub for analyses in the ICP-MS.

Figure 4.3: Pseudo-Total Determination of Heavy Metals in the soil.

4.3.2.2 ICP-MS Procedure

ICP-MS is an instrument consisting of an ion source, a sampling interface, an ion lens, a mass spectrophotometer, and a detector. This high-speed, precise, and sensitive instrument was used to measure the number of atoms and they were then filtered according to their masses. After the samples were ionized at 10000 degrees Celsius, they were directed into a magnetic field where lighter isotopes deflect more and the mass-to-charge ratio (m/z) was measured, followed by targeting them into an electron multiplier tube detector. Each ion was then identified and quantified (Nasirian et al., 2014).

As illustrated in Figure 4.6, below is the major component of an instrument used to measure the elemental component of a substance. The analytical technique uses argon (Ar) plasma for the conversion of samples into ions.

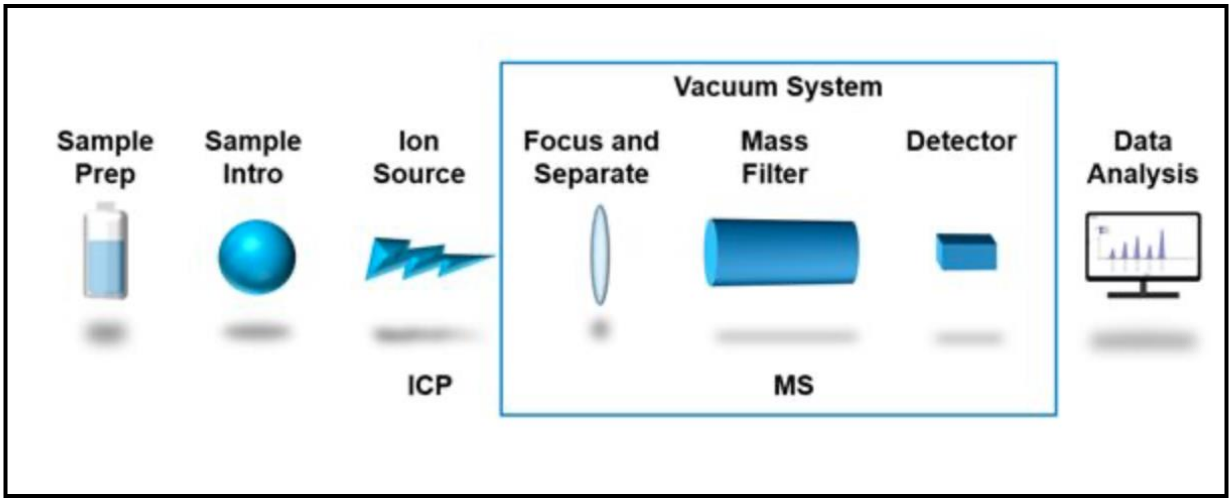


Figure 4.4: Major components of ICP-MS.

4.3.3 THE T-TEST

To assess the level of contamination in the different site locations in Eddy and Lea counties, the t-test was used to determine the differences in means between the two groups. This analytical method stands as a robust means of discerning whether the observed variations in contaminant levels between two groups are statistically significant or merely due to random chance (Bevans, 2020).

To determine whether the observed difference was statistically significant, the calculated t-statistic was correlated to a critical value from the t-distribution. The results were then interpreted, and a conclusion was drawn based on the findings of the calculated t-statistics.

4.4 Spatial Analysis

Spatial analysis was used to validate results from the experimental, T-test, and statistical analyses. Spatial analysis was conducted to identify patterns of contamination distribution across the study areas. This was done to examine the spatial extent and intensity of the impact of the oil and gas-contaminated fluids. The contaminated samples were analyzed using hotspot analysis, the buffer tool.

During spatial analysis, the required data on oil and gas wells in Eddy and Lea counties was extracted from the USA oil and gas wells dataset by clipping using the respective location maps. The soil map was extracted from the FAO soil map database and the produced water data was extracted from the USGS-produced water database. The produced water data was sorted and filtered to remove repeated information and to consider only the data with coordinates.

4.4.1 BUFFER ANALYSIS

Buffer analysis is a geoprocessing procedure that buffers polygons around input features to a specified distance (Mitchell, 2005). The buffer tool in GIS was used to identify buffers around oil and gas wastewater locations. The buffer distance of 500 meters was chosen based on the desired result and the standard software guidelines. The buffered zones were overlayed against the sample location points. This was used to map the potential impact radius of potential spill areas as well as oil and gas operations.

4.4.2 HOTSPOT ANALYSIS

Hotspot analysis is a statistical-based method that was used to assess the geographic clustering of the oil wells in Eddy and Lea counties. The Getis-Ord Gi* statistic tool in GIS was used to identify locations with statistically significant high and low-value clusters by evaluating each of the analyzed oil and gas features within the context of their neighboring features and against all other features in the dataset (Mitchell, 2005).

4.5 Limitations

Research shows that there are two experimental problems associated with the sequential extraction method. Firstly, reabsorption and redistribution of metals occur in the solution and finally, the particular nature of the material being separated is unknown (H. Okoro et al., 2017; Tessier et al., 1979). Therefore, the 5-step Tessier sequential extraction method was modified to a 3-step extraction for efficiency (Tukur Rumah, 2017).

Furthermore, there was limited data on oil and wastewater transportation data that would be beneficial to carry out a comprehensive analysis of data concerning contaminants.

CHAPTER FIVE: FINDINGS

This chapter discusses the details of the spatial analysis of data from the contaminated site locations using GIS and the findings from the different data analysis methods that were employed to provide insights into the possible interactions of contaminants with soil.

5.1 Observation Results

The site selection for collecting soil samples was a critical aspect of conducting spatial analysis. The choice of site locations in Figures 5.1 and 5.2 was guided by various factors that aimed to ensure the representativeness and relevance of the collected data and the results are represented in Tables 5.1 and 5.2 below. In addition, the selection of soil samples for analysis was based on observations, field visits, and historical knowledge of the site location.

Table 5.1: Eddy Counties Sites Visit: Field Notes of Sites 1 and 2.

Site ID	**Eddy Site 1 (Flowline Joint)**	**Eddy Site 2 (Old Battery Facility)**
Cause of Spill	Corroded Joint	Unknown
Spill Size	Length 125.10 feet Width 84.0 feet	Length 124. 7 feet Width 84.0 feet
Age of Spill	5-10 years	5-10 years
Coordinates	Latitude: 32.708, Longitude: -103.851	Latitude: 32.708, Longitude: -103.851
Comments	Evidence of hydrocarbon, smell, dead plants and animals are visible	Salt crust evidence seen, visible dead plants and animals

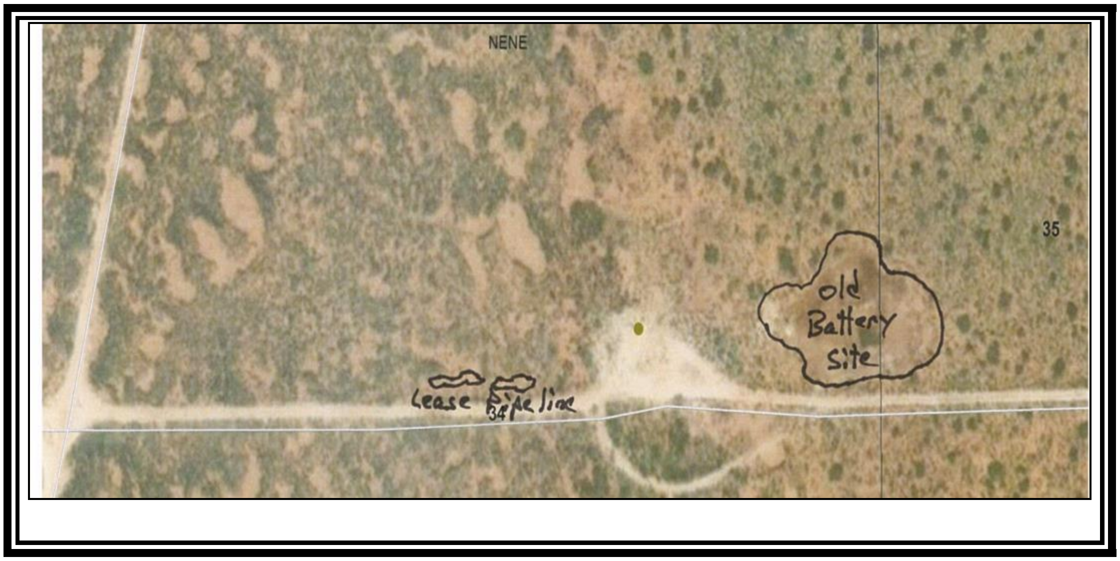


Figure 5.1: Eddy County sites 1(flowline) and 2 (battery site).

Table 5.2: Lea County's Sites Visit Field Notes of Sites 3 and 4.

Site ID	**Lea Site 3 (Well 3 and 3Y)**	**Lea Site 4 (Pipeline)**
Cause of Spill	Inaccurate plug of wells	Corroded joints
Spill Size	Length 91.9 feet Width 33.5 feet	Length 118.0 feet Width 27.0 feet
Age of Spills	22	10-15
Coordinates	Latitude: 37.708 Longitude: -103.851	Latitude: 37.798 Longitude: -103.851
Comments:	Leaking due to Well 3 not being plugged and Well, 3Y plugged inaccurately.	Jackrabbit, cattle, coyote birds, dead vegetable plants and animals

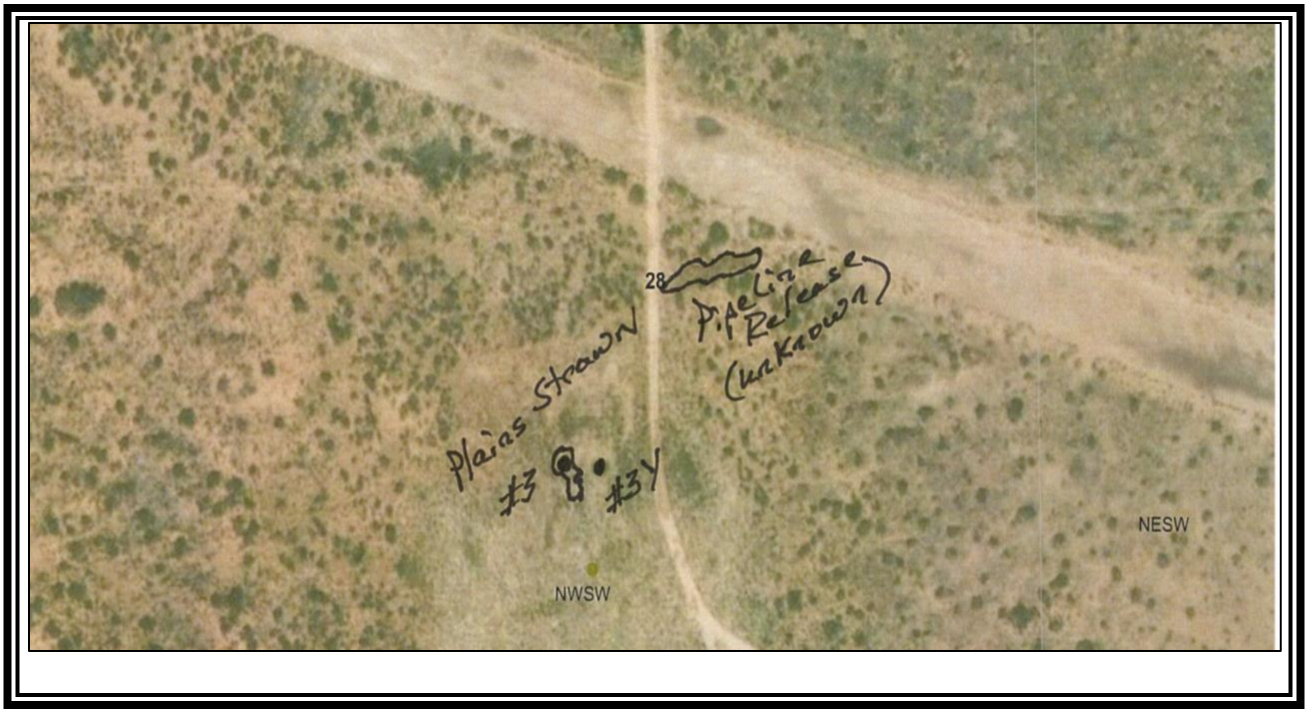


Figure 5.2: Lea county site 3(well 3 and 3Y) and 4 (pipeline site)

Results from observations, field visits, and historical data indicated that the contaminated samples of Eddy and Lea counties exhibited visible characteristics such as discoloration, staining, or unusual coloration in the soil. There was the presence of an unusual odor that was attributed to oil and gas smells. In addition, there was the presence of salt crusts, dead animals, oil and gas residues, and the observed vegetation was of poor health while some areas had little to no vegetation as illustrated in Figures 5.3, 5.4, and 5.5 below. In comparison to the uncontaminated areas, there was a significant difference in soil coloration, vegetation, and site odor.

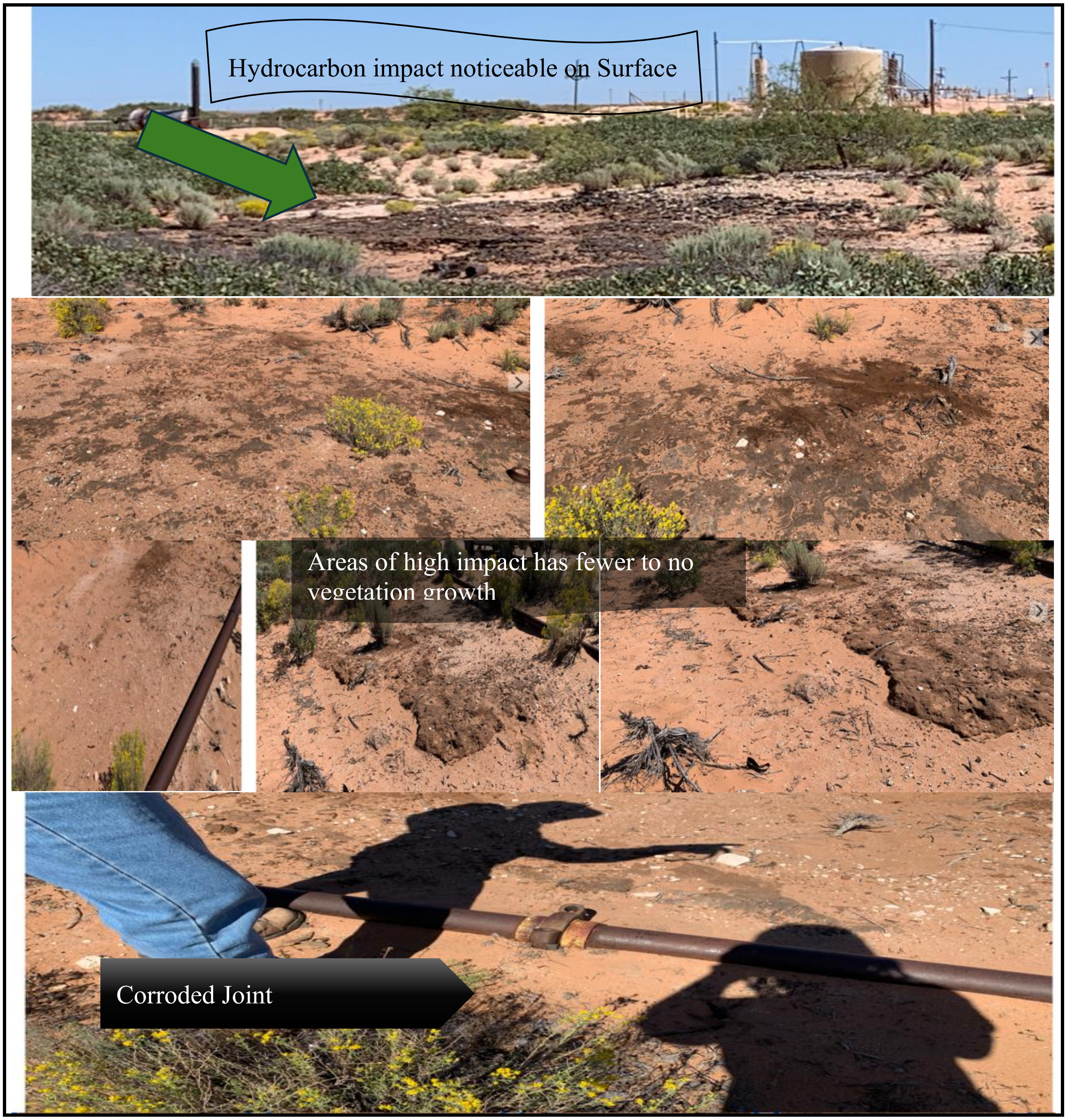


Figure 5.3: Site observation pictures from the study area.

Figure 5.4: Site Area where two well ruptures occurred leaving behind, oil, fracturing fluids, and underground toxicants.

Figure 5.5: Large area that is heavily contaminated with oil and gas residues

5.2 Soil Characteristics

From analysis and experimentation, the findings indicate that the soils in the selected sites in Eddy and Lea counties had the following characteristics. The results from the various measured soil characteristics were aimed at understanding the health of the soils in both Eddy and Lea counties.

5.2.1 SOIL TEXTURE

The characterization of soil was an important parameter to help recognize the nature and extent of contamination in the soil. The USDA textual triangles helped to determine the relative proportions of soil fractions (USDA, 1998). The results were concluded by combining the estimated proportions of sand, silt, and clay from the sieve analysis method of the samples collected and in the field. In addition, previous data on the soil taxonomy of Eddy and Lea counties was used to validate the findings. From analysis, three types of soils were identified in Eddy and

Lea counties, and these are represented in Table 5.3 and the results were further graphically represented as shown in Figure 5.6 below.

Table 5.3: Soil texture analysis for the selected sites

Soil Composition	Eddy (Uncontaminated)	Eddy (Contaminated)	Lea (Uncontaminated)	Lea (Contaminated)
Clay (%)	12.8	10.8	16.8	10.8
Silt (%)	8	10	8	30
Sand (%)	79.2	79.2	75.2	59.2

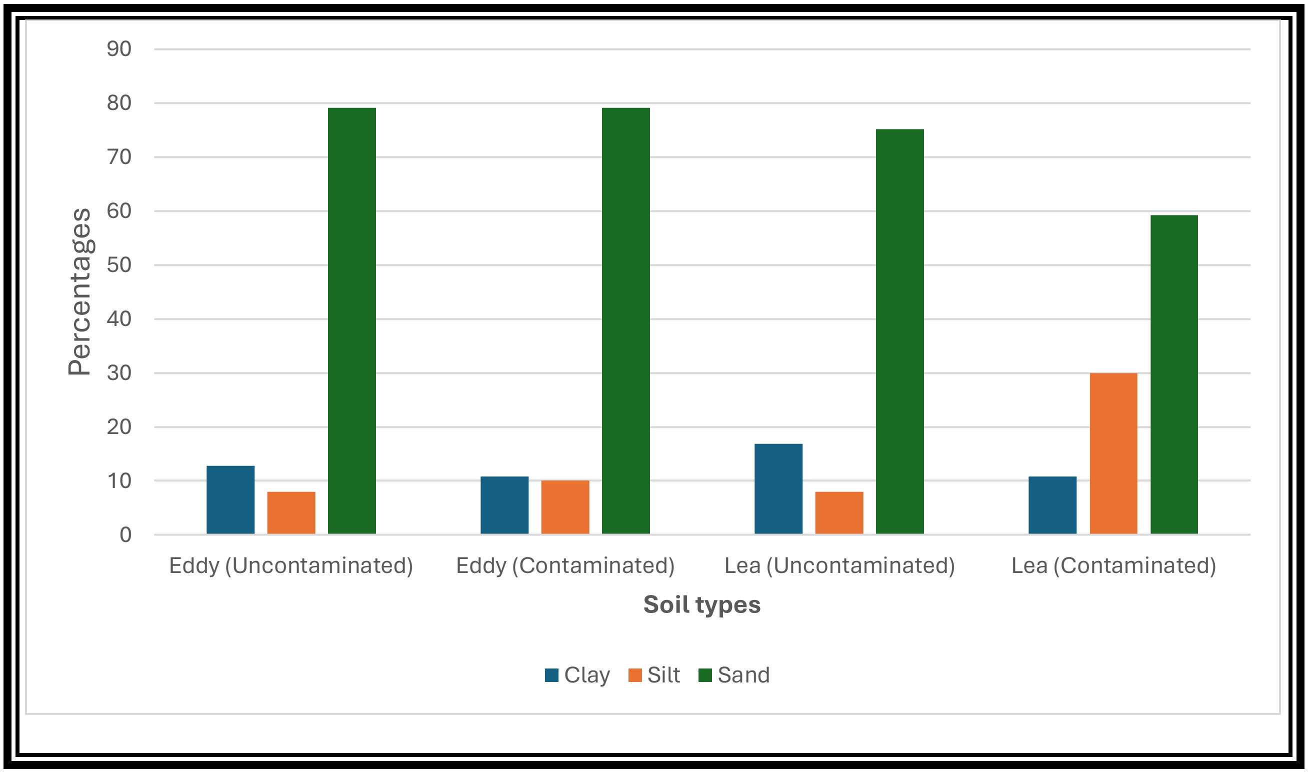


Figure 5.6: Soil texture percentages of Eddy and Lea counties.

The table and the graph show that the composition of sand in Eddy and Lea counties was greater than 50%, a value higher than all the other soil compositions combined. From the soil textural calculator (USDA, n.d.), all the soils were analyzed and the percentages were calculated from which the results indicated that all the soils from the selected site locations were of sandy loam type.

5.2.2 SOIL PH

The pH results obtained from soil sampling of both the contaminated and uncontaminated sites in Eddy and Lea Counties show an evident comparison in soil acidity levels. These are illustrated in the table 5.4 below.

Table 5.4: Soil pH analysis for the selected sites.

Site Name	pH
Contaminated Lea County (1)	7.54
Contaminated Lea County (2)	6.00
Uncontaminated Lea County (1)	8.49
Uncontaminated Lea County (2)	8.53
Contaminated Eddy County (1)	7.63
Contaminated Eddy County (2)	5.66
Uncontaminated Eddy County (1)	8.35
Uncontaminated Eddy County (2)	8.01

In comparison to the pH values of the uncontaminated areas which range from 8.01 to 8.53 and the pH scale, the pH values of the contaminated area which range between 5.66 to 7.63 signify a slightly acidic to neutral pH environment in the soil. The pH values further indicate a potential influence of the oil and gas-contaminated fluids on soil pH within a relatively narrow span. Therefore, the soils in the contaminated areas of Eddy and Lea are moderately acidic.

5.2.3 SOIL ELECTRICAL CONDUCTIVITY

The comparison of the soil-to-water suspension ratio was 1:1 to determine the electrical conductivity of the soil. The conductivity values for the uncontaminated soils ranged from 7.89 to 82.74 μS/cm and the contaminated soils ranged from 19.65 to 100.10 μS/cm and these are tabulated in Table 5.5.

Table 5.5: Soil Electrical Conductivity analysis for the selected sites.

Site ID	**Electrical Conductivity (μS/cm)**
Contaminated Lea County (1)	19.65
Contaminated Lea County (2)	35.00
Uncontaminated Lea County (1)	12.70
Uncontaminated Lea County (2)	17.22
Contaminated Eddy County (1)	12.06
Contaminated Eddy County (2)	100.10
Uncontaminated Eddy County (1)	7.89
Uncontaminated Eddy County (2)	82.74

From the above results, it is evident that the uncontaminated areas have relatively low values of electrical conductivity compared to the contaminated areas. The varied values of electrical conductivity in both the contaminated and uncontaminated areas signify the varying degrees of soil mineralization and ion content. The higher conductivity value of 100.10 μS/cm in the contaminated samples is higher than that of the highest value in the uncontaminated area and this can be associated with the soil salinity differences in the sampled locations.

Additionally, the differences in conductivity values between contaminated and uncontaminated sites indicate potential changes in soil mineralization and ion concentrations that could arise from oil and gas-related contaminants.

To compare the EC results with the standard EC values and their corresponding degrees of salinity which are illustrated in the table below, the EC results were converted from to dS/m which is at a ratio of 1: 0.001 (1 μS/cm = 0.001 dS/m). The changed EC values were then matched to their corresponding salinity values.

Table 5.6: Soil Salinity classes and their relationship between $EC_{1:1}$ and EC_e values (Smith & Doran, 2015; USDA, 2014).

Texture	**Degree of Salinity (salinity classes)**					
	Nonsaline	**Slightly saline**	**Moderately saline**	**Strongly Saline**	**Very strongly saline**	**The ratio of $EC_{1:1}$ to EC_e**
$EC_{1:1}$ method (dS/m)						
Coarse sand to loamy sand	0-1.1	1.2-2.4	2.5-4.4	4.5-8.9	9^+	0.56
Loamy fine sand to loam	0-1.2	1.3-2.4	2.5-4.7	4.8-9.4	9.5^+	0.59
Silt loam to clay loam	0-1.3	1.4-2.5	2.6-5.0	5.1-10.0	10.1^+	0.63
Silty clay loam to clay	0-1.4	1.5-2.8	2.9-5.7	5.8-11.4	11.5^+	0.71
EC_e method (dS/m)						
All textures	0-2.0	2.1-4.0	4.1 -8.0	8.1-16.0	16^+	N/A

Based on Table 5.6, the $EC_{1:1}$ values from soil analysis of the collected soil samples in Eddy and Lea counties were within the saline section of standard values which indicates that indicate that the soil samples are non-saline.

5.2.4 SOIL ORGANIC MATTER

From the analysis of the collected soil samples in Eddy and Lea counties, the results of organic matter are tabulated in Table 5.7 below.

Table 5.7: Soil Organic Matter (SOM) in mg/kg.

Eddy Sites (%)			**Lea Sites (%)**		
Contaminated		Uncontaminated	Contaminated		Uncontaminated
Site 1	4.36	2.10	Site 1	5.86	2.72
Site 2	3.86	1.63	Site 2	5.36	2.63

The sites that are contaminated have higher organic matter values than the soils that are not contaminated. An increase in heavy metal pollutants means the organic matter and its proportions in total soil organic carbon also increase (M.-K. Zhang & Wang, 2007).

The recorded values of 3.86 to 5.86 in the contaminated sites are higher than those in the uncontaminated areas which indicate relatively lower to moderately low organic matter in the uncontaminated areas. The differences in the results of both the uncontaminated and contaminated soil samples indicated a potential alteration in the contaminated sites' soil characteristics which can be attributed to the presence of contaminants and their interactions with soil microorganisms. Additionally, the increase in organic matter can be associated with an increase in hydrocarbons such as sulfur (Kaiser, 2018) and boron which arise from the contaminated oil and gas fluids.

5.2.5 TOTAL ORGANIC CARBON

The results from the computation of the Total Organic Carbon are tabulated in Table 5.8 below.

Table 5.8: Table showing the Total Organic Carbon results for the uncontaminated and contaminated soil samples in both Eddy and Lea counties.

Eddy Sites (%)			**Lea Sites (%)**		
Contaminated		Uncontaminated	Contaminated		Uncontaminated
Site 1	2.529	1.218	Site 1	3.399	1.578
Site 2	2.239	0.945	Site 2	3.109	1.526

The findings indicate that the contaminated soil samples have a range of 2.239 to 3.399 while the uncontaminated soil samples have a range of 0.945 to 1.578. With comparison to the table below which illustrates the semi-quantitative source richness interpretation of total organic carbon (TOC) by K. E. Peters (2), (1986). The contaminated soils have excellent richness in TOC while the uncontaminated soil samples have good to very good richness levels.

Table 5.9: The standard TOC richness values (K. E. Peters (2), 1986).

Generation potential	**Wt % TOC carbonates**
Poor	0.0 – 0.2
Fair	0.2 – 0.5
Good	0.5 – 1.0
Very good	1.0 – 2.0

Excellent	> 2.0

From Table 5.9, the results in Table 5.8 indicate that the higher the values of TOC, the higher the potential for the presence of oil and gas contaminants. Additionally, the difference in TOC values of the uncontaminated and contaminated soil samples indicates the potential influence of oil and gas-contaminated fluids on the soil characteristics of Eddy and Lea counties.

5.2.6 CATION EXCHANGE CAPACITY (CEC)

The results from the computation of the values for CEC are tabulated in Table 5.10 below.

Table 5.10: Eddy and Lea counties Soil Cation Exchange Capacity (CEC) in Milli-equivalent (mEq/100g).

Eddy Sites			**Lea Sites**		
Contaminated		Uncontaminated	Contaminated		Uncontaminated
Site 1	3.893	1.341	Site 1	4.317	2.297
Site 2	3.591	1.214	Site 2	4.109	2.453

The contaminated soil content had higher CEC which ranged from 3.591 to 4.317 mEq/100g while the uncontaminated soil samples had lower CEC value ranges of 1.214 to 2.453 mEq/100g. The higher values of CEC signify that the contaminated soils can retain nutrients than the uncontaminated ones. The nutrient retention capacity further signifies a potential for oil and gas-contaminated fluids since organic matter is usually high in areas where there is oil and gas contamination (Egobueze et al., 2019; Ssenku et al., 2022).

5.3 Heavy Metal Soil Analysis

5.3.1 PSEUDO HEAVY METAL SOIL ANALYSIS

From analysis, the Pseudo Total Metal Content in both the contaminated and uncontaminated soils compared to the Total Metal Concentration with BCR sequential extraction are tabulated in Table 5.11 below.

Table 5.11: Eddy and Lea counties Pseudo total metal content (mg/kg).

Sample ID	**Site Name**	**52 Cr (mg/kg)**	**53 Cr (mg/kg)**	**111 Cd (mg/kg)**	**208 Pb (mg/kg)**
1	Contaminated Lea County (1)	5.01	2.16	46.01	2.18
2	Contaminated Lea County (2)	2.26	4.00	126.89	1.54
3	Uncontaminated Lea County (1)	3.61	7.13	110.47	1.71
4	Uncontaminated Lea County (2)	2.84	3.32	112.65	4.28
5	Contaminated Eddy County (1)	2.52	6.71	83.95	0.67
6	Contaminated Eddy County (2)	1.28	3.76	124.33	1.30
7	Uncontaminated Eddy County (1)	1.77	2.24	103.67	2.24
8	Uncontaminated Eddy County (2)	2.07	6.14	168.42	1.33

The table shows that the Chromium (Cr) 52 and 53 levels in both the uncontaminated and contaminated soil samples ranged between 1.77 to 5.01 and 2.16 to 7.13 respectively, and the Cadmium (Cd) levels for all the soil samples ranged from 46.01 to 126.89 mg/kg while the lead (Pb) levels in all the soil samples ranged 0.67 to 4.28 mg/kg.

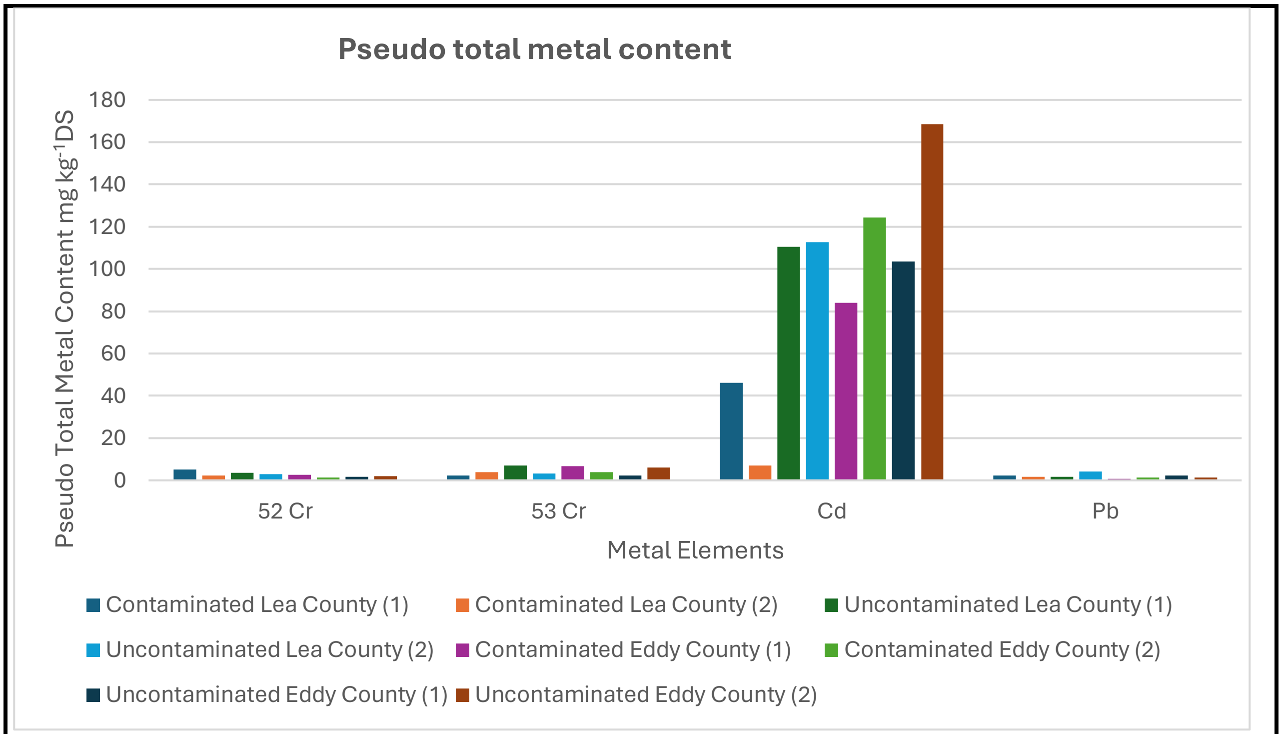


Figure 5.7: Graph showing the pseudo metal content in the soil samples.

In comparison to the WHO's standard minimum heavy metal permissible levels in soil that are illustrated in Table 5.12 below, the values of 52 Cr, 53 Cr, and Pb of all the soil samples are below the limits. However, the values of Cd were higher where its measured concentrations surpassed the permitted thresholds. This particular observation served as a significant indicator of potential contamination from oil and gas-contaminated fluids.

Table 5.12: WHO permissible limits for heavy metals in soil (Ogundele et al., 2015; WHO, 1996).

Elements	***Target value of soil (mg/kg)**
Cd	0.8
Zn	50
Cu	36
Cr	100
Pb	85
Ni	35

5.3.2 BCR SEQUENTIAL EXTRACTION

The total metal content with the BCR sequential extraction method revealed an evident divergence from the measurements attributed to the pseudo-total content and the results are illustrated in Table 5.13 below.

Table 5.13: The total heavy metal concentration using BCR sequential extraction.

Sample ID	**52 Cr (mg/kg)**	**53 Cr (mg/kg)**	**111 Cd (mg/kg)**	**208 Pb (mg/kg)**
1	6.12	4.32	48.54	5.28
2	3.26	4.99	136.89	4.25
3	4.61	7.83	114.51	4.82
4	4.79	3.96	122.65	5.64
5	6.16	6.87	113.95	4.55
6	5.17	3.15	124.34	4.27
7	5.34	2.61	110.67	5.17
8	4.03	3.81	169.22	5.75

The results in Table 5.13 show the nature of metal distribution and speciation within the soil matrix, signifying that the accumulation patterns and potential reactivity of metals are not solely summed up within the pseudo-total analysis. In addition, the table also shows that different elements in the same soil samples behaved differently. To determine the potential behavior, fate, and impact of the metals within sampled soils, the distribution of heavy metal concentrations across different fractions was analyzed and the metal partitions in the soil samples are illustrated in Table 5.14 and Figures below. In addition, the mobility of metals in soil samples was assessed based on the absolute and relative content of fractions that are weakly bound to soil components.

Table 5.14: The metal partitions in the soil samples

Sample ID	**52 Cr**				**53 Cr**			
	S1	**S2**	**S3**	**S4**	**S1**	**S2**	**S3**	**S4**
1	1.15	0.77	1.87	2.33	1.99	0.16	0.74	1.43
2	1.16	0.20	0.39	1.51	1.79	0.22	1.38	1.60
3	0.31	0.39	0.93	2.98	0.76	0.17	0.68	6.22
4	0.99	0.76	2.49	0.55	1.94	0.18	0.85	0.99
5	1.53	0.83	1.47	2.33	3.08	0.22	0.56	3.01
6	0.79	1.15	0.73	2.50	0.91	0.22	0.94	1.08
7	1.57	1.98	0.71	1.08	0.98	0.22	0.07	1.34
8	1.25	1.29	0.47	1.02	1.46	0.25	1.11	0.99
Sample ID	**111 Cd**				**208 Pb**			
	S1	**S2**	**S3**	**S4**	**S1**	**S2**	**S3**	**S4**
1	16.63	4.72	6.36	20.83	1.26	0.64	1.29	2.09
2	34.98	16.12	3.80	81.99	1.02	0.49	0.89	0.89
3	16.16	17.28	5.15	75.92	0.51	1.27	0.47	2.57
4	8.75	10.36	2.90	100.64	0.50	3.21	0.70	1.23
5	18.19	27.36	7.67	60.73	0.52	0.74	0.42	2.87
6	11.67	10.86	9.12	92.69	1.00	0.73	0.97	1.57
7	14.07	16.94	9.64	70.02	0.59	2.09	0.52	1.97
8	18.24	10.42	1.02	139.54	0.49	1.37	1.14	2.75
S1: Step 1 Exchangeable Fraction		S2: Step 2 Reducible iron\Manganese Oxides		S3: Step 3 Oxidizable-Organic Matter and Sulfides			S4: Step 4 Residual	

The results were further graphically represented in the form of speciation percentages for both the contaminated and uncontaminated soil samples and these are illustrated in Figures 5.8 and 5.9.

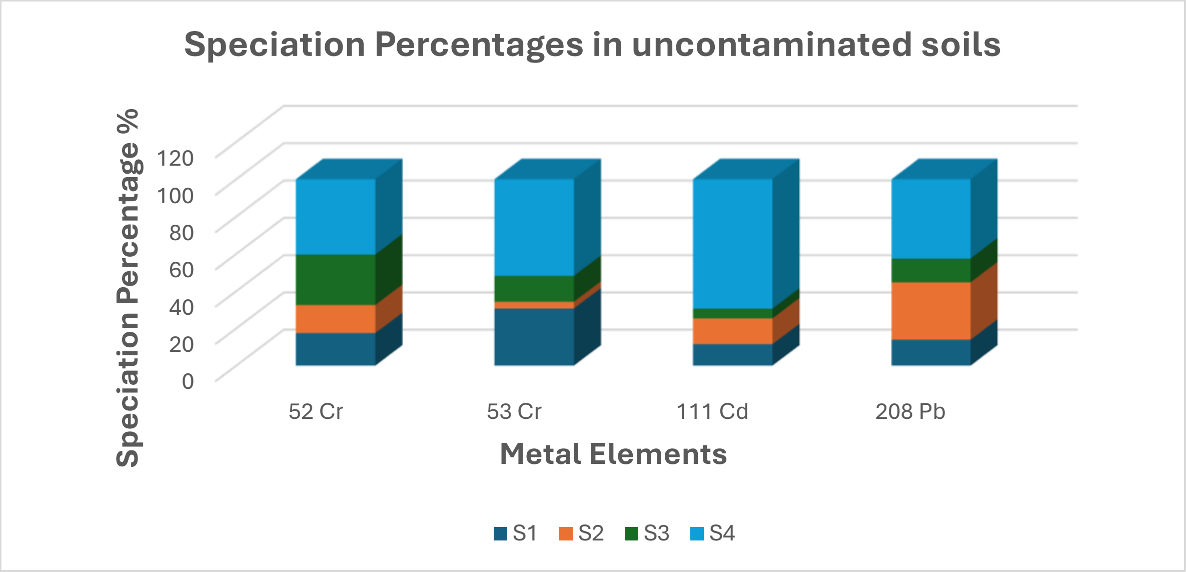


Figure 5.8: Distribution of the heavy metals among the operationally defined fractions in the uncontaminated soil samples.

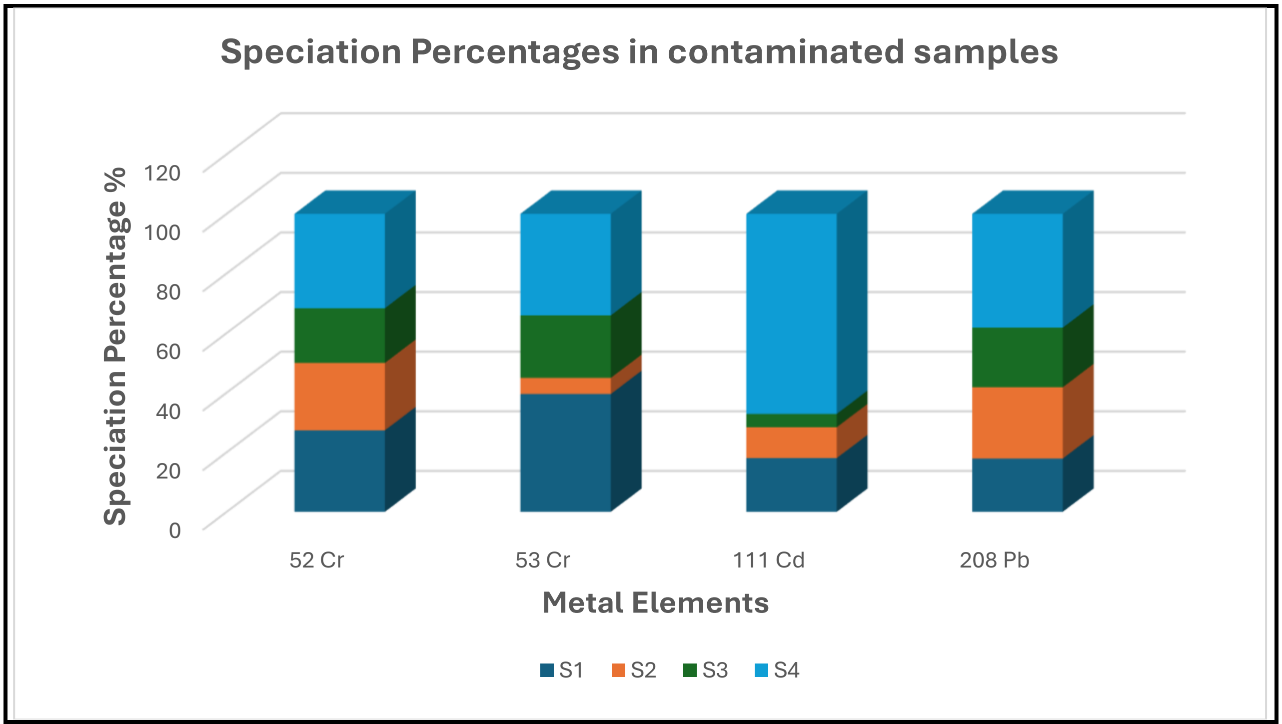


Figure 5.9: Distribution of the heavy metals among the operationally defined fraction in the contaminated soil samples.

The results in the graphs indicate a varying distribution of the tested metals across different fractions within the BCR sequential extraction. In the exchangeable fraction step (S1), 53 Cr at 39.6 % in the contaminated samples at 30% in the uncontaminated samples had the highest percentages which indicated an elevated risk of this metal being readily accessible to plants, microorganisms, and potential leaching into groundwater. On the contrary, the lower percentages of Pb metal at 17.9% and Cd at 11.5% in the exchangeable fraction of the contaminated and uncontaminated samples respectively indicated reduced immediate mobility and lower bioavailability of the metals in the soil.

In the reducible Iron/ Manganese Oxides (S2), Pb had 23.9% and 30.8% as the highest percentages in the contaminated and uncontaminated soil samples respectively. The higher percentages of metals in this fraction signified the potential for these metals to be released under certain conditions, contributing to their medium-term mobility. In the Oxidizable-Organic Matter and Sulfides (S3), 27.1% and 21% of 52 Cr were the highest percentages in this fraction for both the contaminated and uncontaminated samples. The higher percentages indicated the metal's association with organic matter.

In the residual fraction (S4), the higher percentages of Cd at 67.1% and 69.4% in the contaminated and uncontaminated samples indicated that the metal has limited mobility and reduced immediate risk as the metals are securely bound to the soil matrix. In addition, the differences in fractionation percentages between contaminated and uncontaminated samples highlighted metal speciation and association with soil components.

5.3.3 T-TEST ANALYSIS RESULTS

To conduct the t-test analysis, the mean concentrations of the metals in both the uncontaminated and contaminated samples were compared. In addition, the test was carried out at a 95% confidence interval. Using the Excel software, a p-value of 0.027 was obtained. The p-value was less than the hypothesized alpha value of 0.05 which indicated that there was a significant difference in the metal concentrations in the contaminated and uncontaminated soil samples. The findings emphasize the influence of oil and gas-contaminated fluids on soil contamination in both Eddy and Lea counties.

5.4 Spatial Analysis

5.4.1 LOCATION OF THE SOIL SAMPLES

Multiple locations of both uncontaminated and contaminated points were collected and mapped however, the eight site locations in Eddy and Lea counties were selected for soil sample collection and these were mapped and located using QGIS and these are illustrated in the maps in Figures 5.10 and 5.11 below.

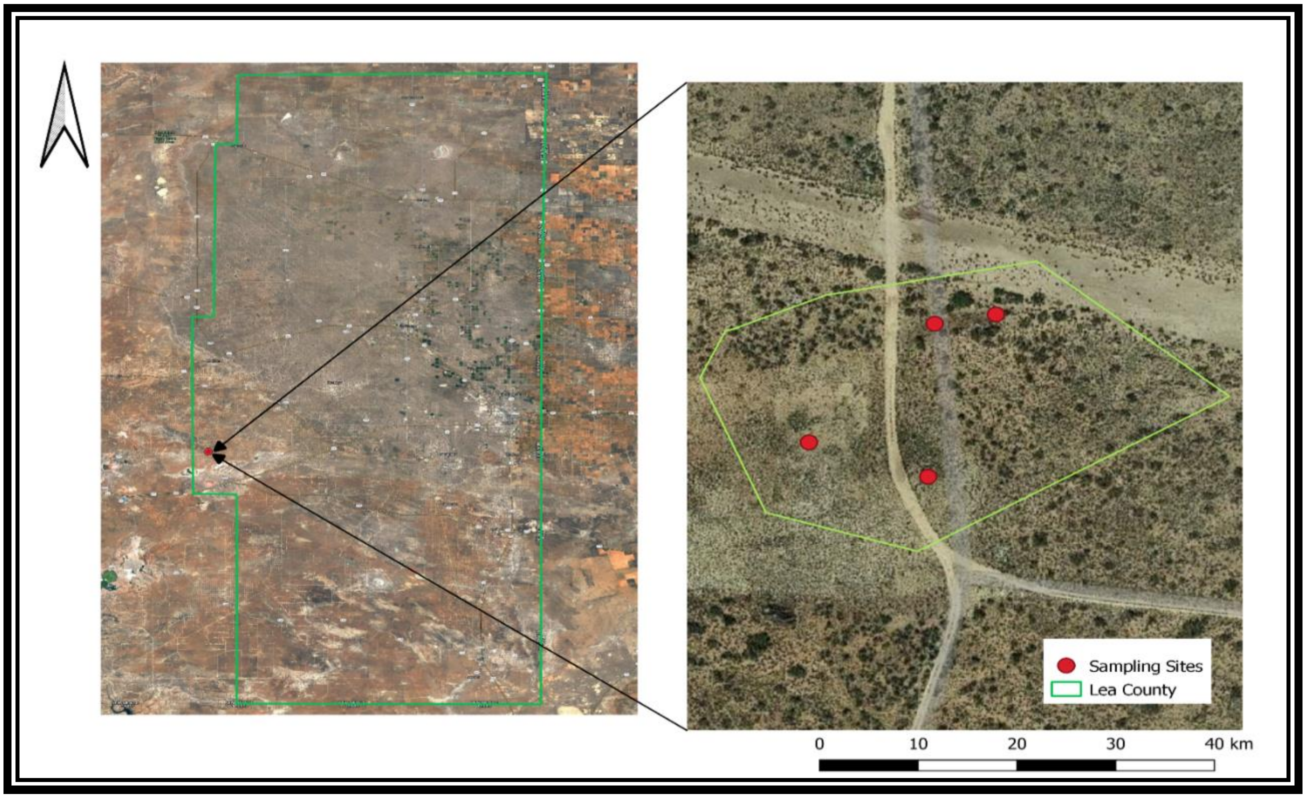


Figure 5.10: Location of the four collected samples in Lea County.

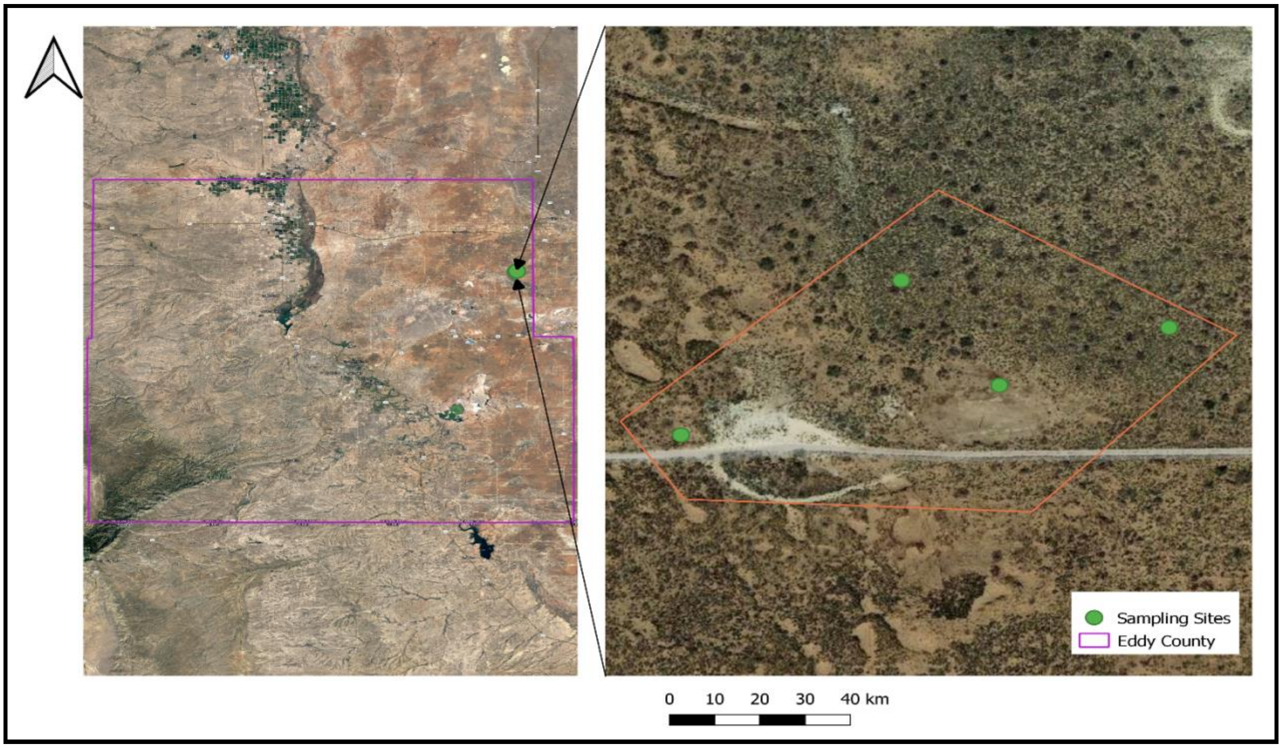


Figure 5.11: Location of the four collected samples in Eddy County.

5.4.2 BUFFER ANALYSIS

During the Hotspot analysis process, the oil and gas wastewater data was extracted in GIS from the USGS-produced water database and the extracted map is illustrated in Figure 5.12. The buffer zones were obtained from the extracted maps using the buffer tool in GIS at a distance of 500 meters. The spatial join was done on the obtained maps and the location points of the soil sample. This was done using the overlay tool in GIS and the obtained maps are illustrated in Figures 5.13 and 5.14 below.

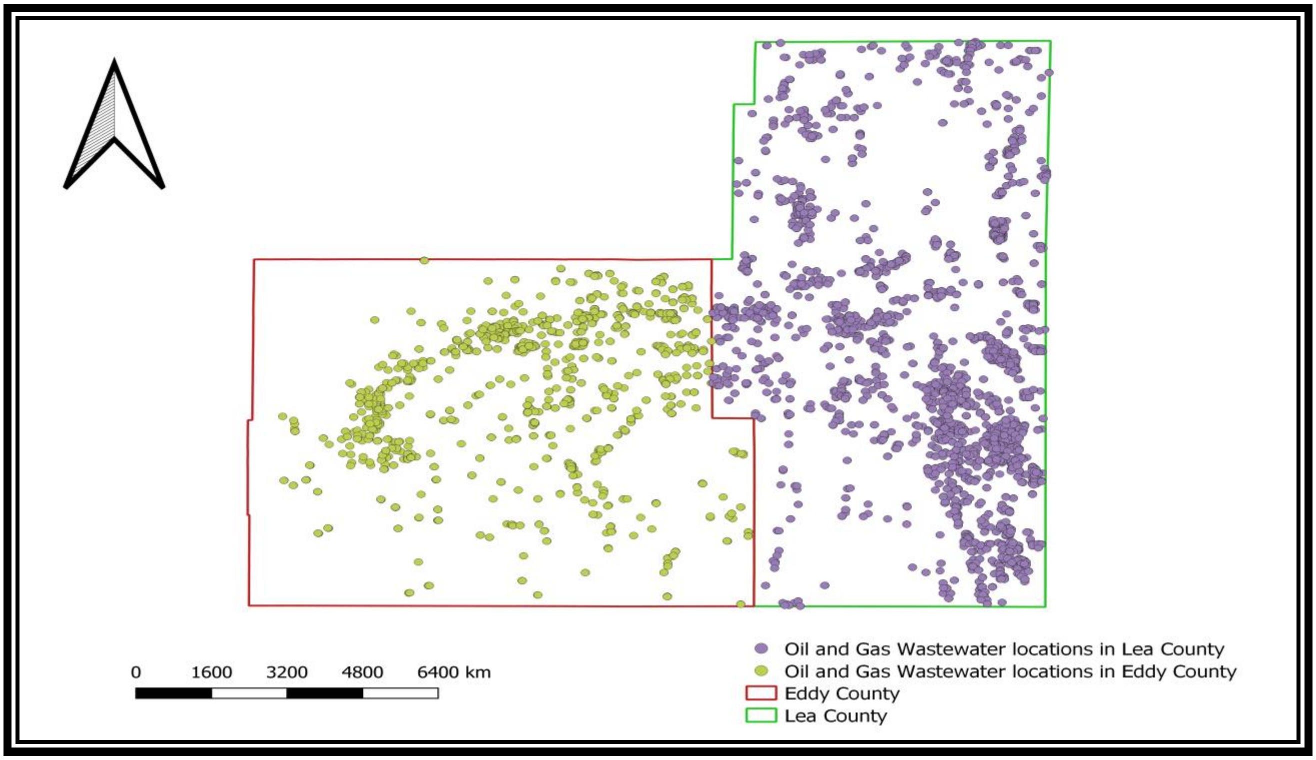


Figure 5.12: Oil and gas wastewater locations in Eddy and Lea counties.

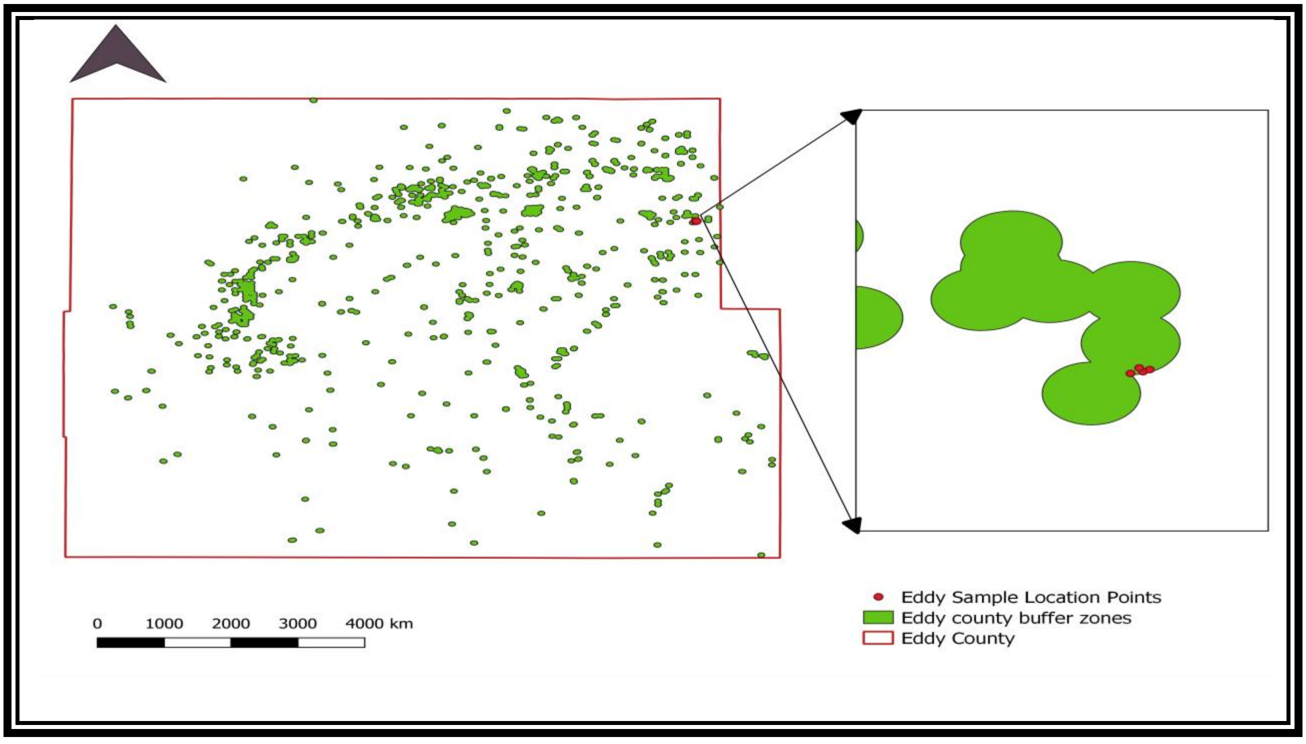


Figure 5.13: Buffer zones in Eddy County.

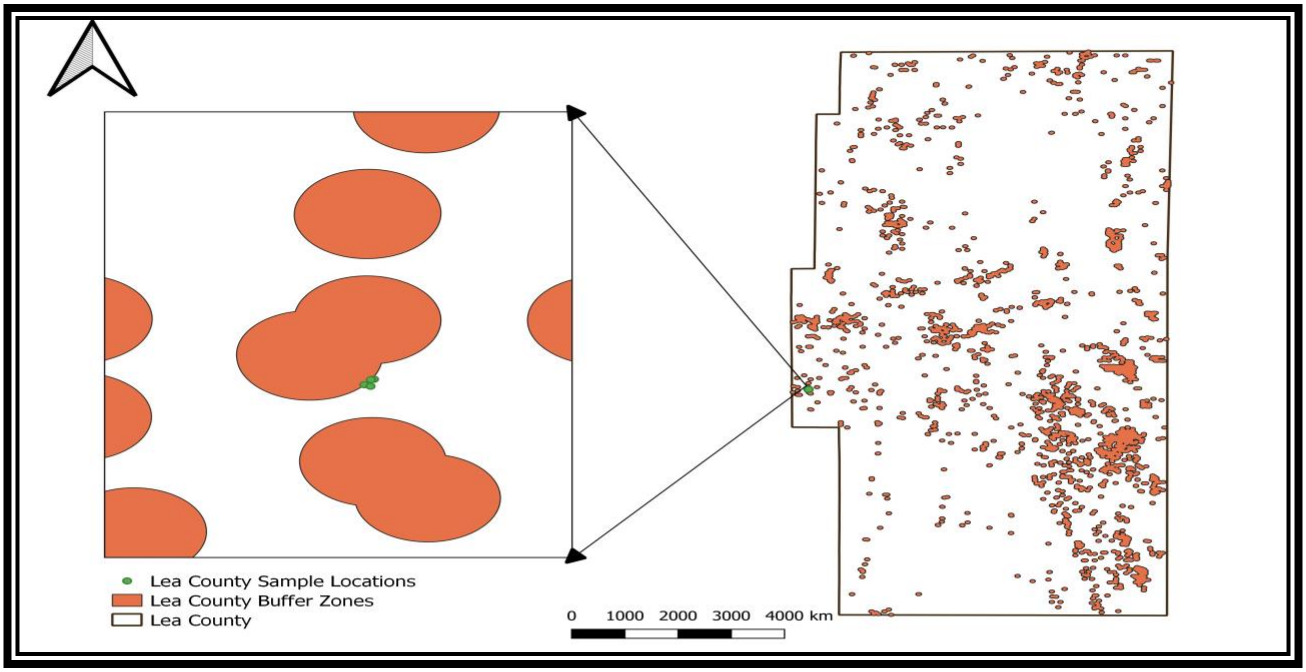


Figure 5.14: Buffer zones in Lea County.

The results from buffer analysis indicated a significant spatial overlap between the wastewater data and the soil sample location points in Eddy County while in Lea County, there was a slight overlap between the wastewater data and the soil sample location points which indicates a potential impact of the produced water spills on the sample location points in the study area.

5.4.3 HOTSPOT ANALYSIS

During the Hotspot analysis process, the oil and gas wastewater data was used to identify coldspots and hotspots around the sampling locations. Using the hotspot analysis tool and the Inverse Distance Weight tool in GIS, insights on the potential impact of the wastewater locations on the sampling locations were provided and these are illustrated in Figures 5.15 and 5.16.

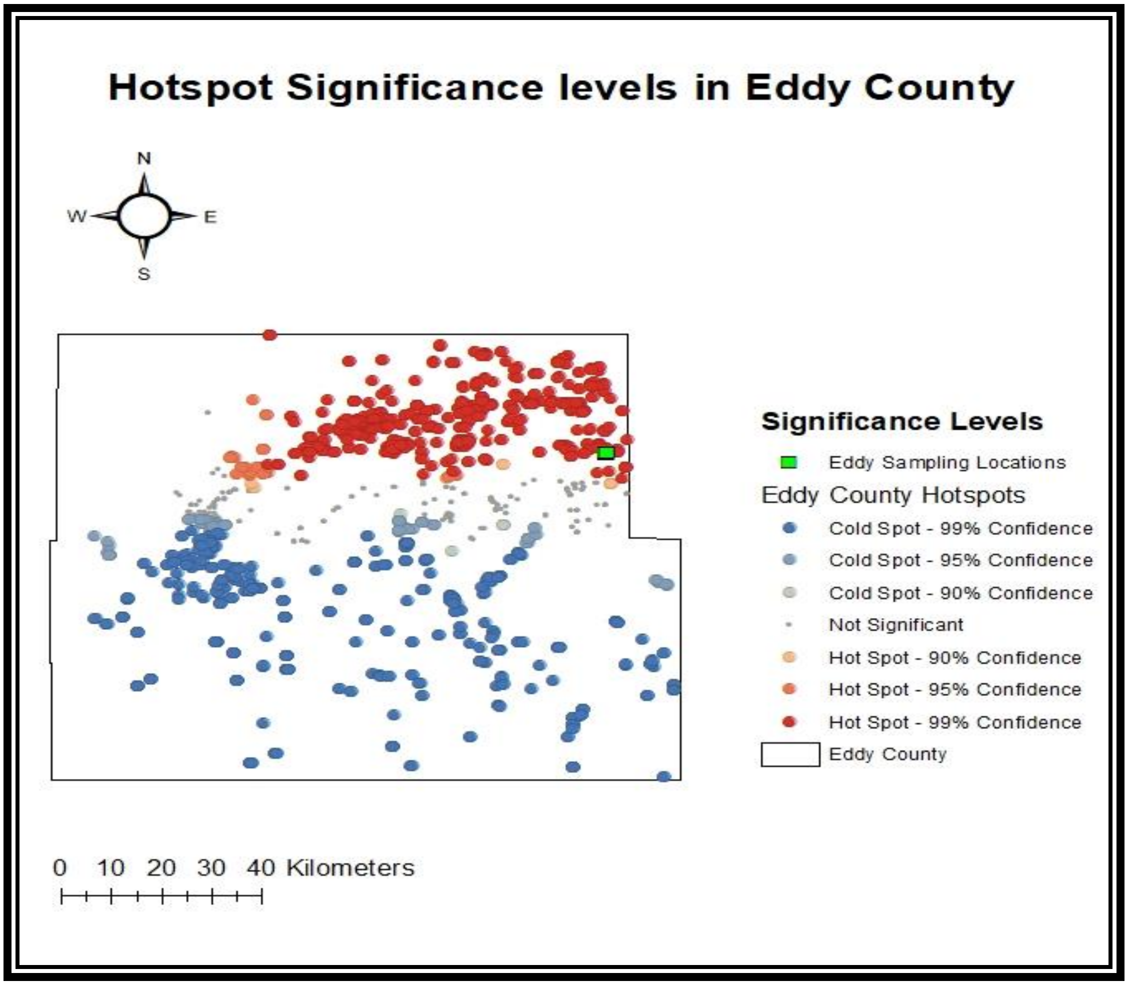


Figure 5.15: hotspots and Coldspots in Eddy County.

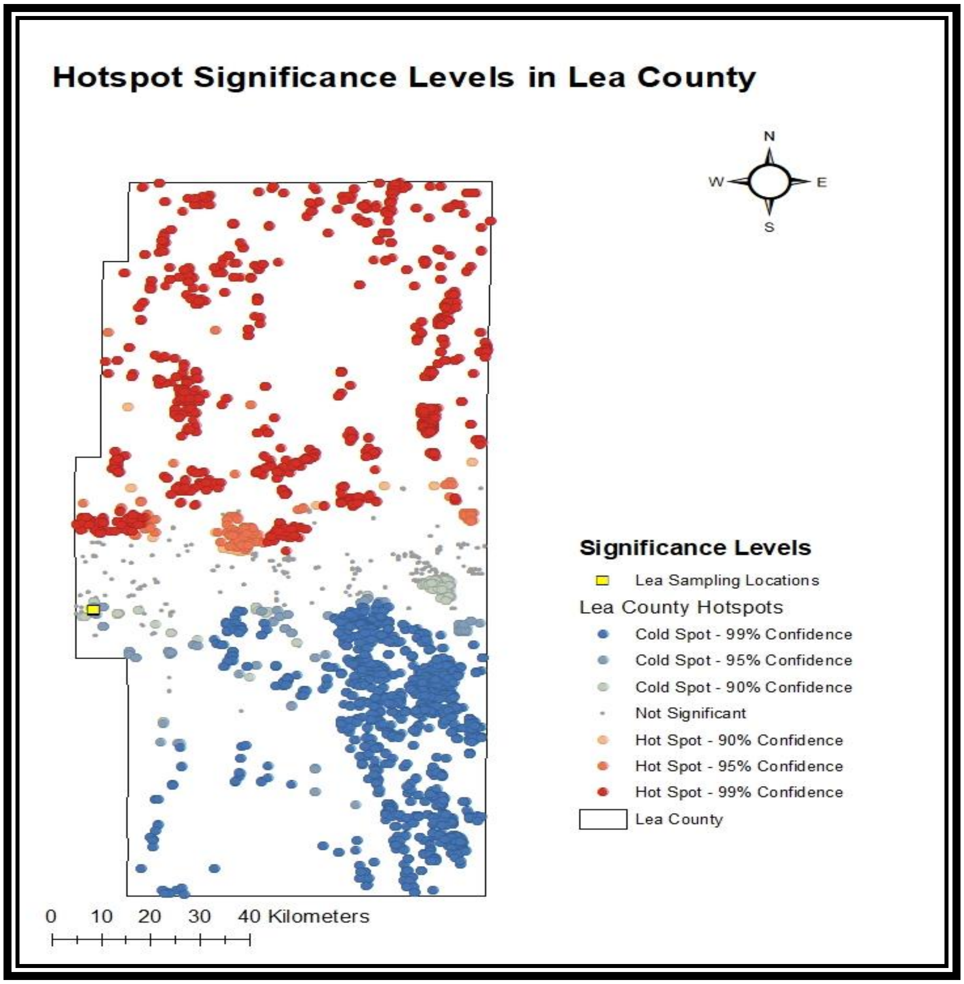


Figure 5.16: Hotspots and Coldspots in Eddy County.

Hotspot analysis was able to delineate spatial patterns around the sampling locations. The maps in Figures 5.15 and 5.16 indicate that there is a statistical significance between the distribution and clustering patterns of produced water locations and the sampling sites. The maps also highlight areas where statistically significant clustering occurs.

In Figure 5.15, the sampling site locations of Eddy county are located with in areas with a 99% confidence level of hotspot significance meaning that the sampling locations are located in areas with high concentrations of clustering. In Figure 5.16, the sampling locations are within a 90% - 95% confidence level of coldspot significance which indicates low levels of concentrations of oil and gas wastewater clustering.

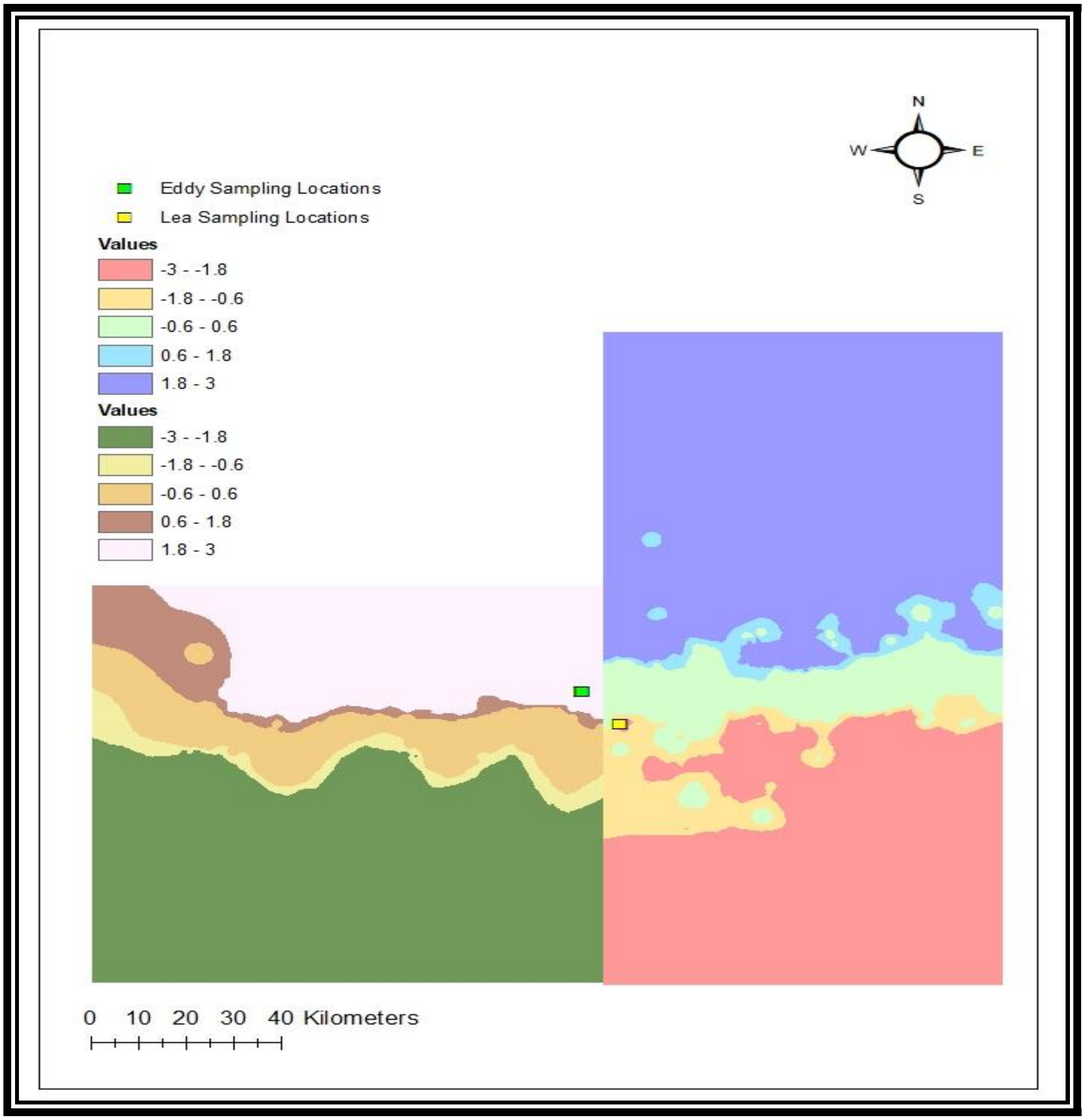


Figure 5.17: Inverse Distance weighted Interpolation results for Eddy and Lea Counties.

In addition, results in Figure 5.17 from carrying out Inverse Distance Weighting show that the sampling locations in Eddy are within the positive values of 1.8 and 3 and those of Lea county are within the negative values of -1.8 and -0.6. The higher positive values indicate a higher concentration of the oil and gas wastewater locations in Eddy county and the negative values in Lea county indicate low concentrations of oil and gas wastewater locations.

CHAPTER SIX: DISCUSSION, IMPLICATIONS AND RECOMMENDATIONS

This chapter summarizes the findings from the research and provides meaningful insights into the implications of the results as well as providing an understanding of the impact of oil and gas-contaminated fluids on soil in Eddy and Lea Counties.

6.1 Discussion

In the analysis of the soil samples' physical characteristics, the soil samples were found to have a sand percentage of over 50%. With further calculation using the soil texture calculator (USDA, n.d.), the soil texture of Lea and Eddy sampled areas was found to be sandy loam. Soil compositions have an influence on hydraulic conductivity, porosity, and adsorption capacities. Since sandy loam has a large percentage of sand in composition, it plays a central role in influencing the distribution, retention, and mobility of the oil and gas-contaminated fluids.

The pH values of the uncontaminated areas range from 8.01 to 8.53 and on the pH scale, the pH values of the contaminated area range between 5.66 to 7.63 indicating a slightly acidic to neutral pH environment in the soil. In addition, there was significance in unraveling the potential impact of oil and gas-related contamination on the soil due to the changes in pH levels between uncontaminated and contaminated soils of Eddy and Lea counties.

Furthermore, the findings indicated that there were disparities in organic matter content between contaminated and uncontaminated sites which signified a potential presence of oil and gas-related contaminants, especially with the higher values in the contaminated soil samples (Egobueze et al., 2019; Ssenku et al., 2022). Results from data analysis showed that the differences in values of soil characteristics in both the contaminated and uncontaminated soil samples of Eddy and Lea counties signified a potential influence of the oil and gas-contaminated fluids on the soil properties.

In pseudo metal analysis, Cadmium had higher concentrations in the soil with values ranging from 46.01 to 126.89 mg/kg. The values were over the standard permissible value of 0.8 mg/kg in soil (Ogundele et al., 2015; WHO, 1996). Additionally, the bioavailability of Cd is affected by soil organic matter (SOM) because of the formation of various complexes with Cd in the soil solution where a high SOM causes more sorption potential (Zulfiqar et al., 2022). In analysis of the soil samples, the contaminated samples had a higher SOM which indicated the availability of the metal for uptake.

Cadmium is considered to be one of the most toxic non-essential trace elements that is widely distributed in the environment. The higher concentrations of cadmium in soil can be linked to the abundance of clay minerals, carbonates, organic matter, and hydrous oxides (Kubier et al., 2019; Page et al., 1987). Oil and gas-contaminated fluids are always characterized by several toxics with cadmium being one of them. The higher concentrations can also be attributed to not separating the metal from the wastewater before transportation or disposal (Villa Nova et al., 2020). This signifies potential spills that may have occurred from oil and gas-contaminated fluids leading to soil contamination in the study location.

To determine the fate of transportation of the heavy metals in the oil and gas-contaminated fluids, the results from sequential extraction were analyzed. The findings indicated that 53 Cr in both the contaminated and uncontaminated samples had the highest percentage at 39.6% of exchangeable fractions which indicated an elevated risk of the metal being readily accessible to plants, microorganisms, and potential leaching into groundwater. In the reducible Iron/ Manganese Oxides (S2), Pb had 23.9% and 30.8% as the highest percentages in the contaminated and uncontaminated soil samples respectively. In the Oxidizable-Organic Matter and Sulfides (S3), 27.1% and 21% of 52 Cr were the highest percentages in this fraction for both the contaminated and uncontaminated samples. While in the residual fraction (S4), the higher percentages were of Cd at 67.1% and 69.4%.

The results from exchangeable fractions and oxidizable organic matter fractions indicated that 53Cr and 52 Cr had the highest speciation percentages which indicated that the metal was potentially mobile and readily available for intake (Demir, 2021). However, the mobility of Cr also depends on the soil characteristics with the pH playing a bigger role. pH controls the soil Cr dynamics such as its oxidation or reduction and adsorption or desorption where a low pH promotes its mobilization, availability, and release (Gustafsson et al., 2014; Pradhan et al., 2017).

In the analysis, the pH levels of the soil samples were slightly acidic which makes Cr still adsorbable (Sintorini et al., 2021; Venditti et al., 2010) posing a potential danger of contamination to soil, plants, groundwater, and ecosystem.

In the reducible Iron/ Manganese Oxides (S2), Pb had 23.9% and 30.8% as the highest percentages in the contaminated and uncontaminated soil samples respectively. Since the dissolution of Pb is not dependent on chemical reduction (Tai et al., 2013), the metal is considered to be less mobile despite its presence in the second fraction. In addition, Cd is considered the least mobile element due to its high percentage of over 60% in the residual fraction.

The results from the t-test also indicated that the p-value was less than the alpha value of 0.05% which indicated that there was a significant difference in the contaminated and uncontaminated samples results. This indicates the presence of statistically significant variations in the distribution of metals among different soil fractions due to contamination.

Under spatial analysis, the results from buffer analysis indicated a significant spatial overlap between the wastewater data and the soil sample location points in Eddy County while in Lea County, there was a slight overlap between the wastewater data and the soil sample location points which indicates a potential impact of the produced water spills on the sample location points in the study area. The proximity of the location points and buffer zones highlights and validates the possibility of contamination of contamination from the oil and gas-contaminated fluids that may be a result of spills or leaks.

Findings from Hotspot analysis and carrying out the Inverse Distance weighted interpolation indicated that there was a high level of wastewater locations clustering close to the sampling locations in Eddy County. This shows that there is a statistical potential impact of the wastewater locations on the sampling locations in Eddy County. In Lea County, the findings indicated a low level of clustering of wastewater locations. The coldspots in Lea County may not necessarily indicate low levels of impact of the oil and gas wastewater locations on the sampling locations since the findings from other methods of analysis indicated that Lea County's sampling locations had higher levels of contamination than those of Eddy County. Rather, the impact may be of a different nature other than the statistical kind. Furthermore, the cold spot results in the underrepresentation of data in Lea County.

6.2 Conclusion

The study aimed to analyze the impact of oil and gas-contaminated fluids on soil. The findings were to fully explore the research objectives and research question. The findings from the spatial analysis indicated that Eddy and Lea's sampling locations were within the analyzed buffer distance and there was a statistical significance between the clustering patterns of wastewater locations and the sampling locations in both counties. In addition, there were hotspots close to the sampling locations in Eddy and coldspots close to the sampling locations in Lea County. The hotspots in Eddy County indicated a higher level of clustering close to the respective sampling locations hence a higher statistical potential impact of the oil and wastewater locations on the sampling locations.

However, in Lea County, there were cold spots close to the sampling locations, This indicated low levels of clustering of oil and gas wastewater locations hence the lower statistical potential impact of the oil and wastewater locations on the sampling locations. The low statistical impact can be highly associated with the difference in nature of impact and the possible underrepresentation of data in Lea County.

The analysis of the soil characteristics of both the uncontaminated and contaminated soil samples in Eddy and Lea County indicated that there was potential contamination that can be attributed to the presence of oil and gas-contaminated fluids in the soil.

Additionally, the results from total metal concentration indicated that Cd had the highest concentrations which were higher than the maximum permissible standards. The higher concentrations indicated that the metal was present in large amounts however, due to its high presence in the residual fraction after the sequential extraction process, Cd is considered to be less mobile.

Furthermore, both 53Cr and 52Cr were present in higher percentages in the exchangeable fractions and oxidizable organic matter. The higher Cr's presence in the exchangeable fraction of sequential extraction signified its availability and higher mobility than other metals in soil. While lead was high in the oxidizable manganese oxide fraction. Therefore, it was considered to be less mobile. The findings also indicated that there were differences in values of soil characteristics and sequential extraction results of Eddy and Lea counties where Lea had higher values. This indicated that Lea had higher contaminated soils with higher metal concentrations, mobility, and availability.

Oil and gas-contaminated fluids contain a number of toxicants and from analysis, the research findings underscored the significance of understanding how contaminants interact with soil particles and the subsequent effects on soil quality. In addition, the study has highlighted the importance of soil properties in influencing the mobility and persistence of contaminants.

6.3 Implications and Recommendations

Based on the findings from an analysis conducted in this study area regarding the impact of oil and gas-contaminated fluids on soil in Eddy and Lea Counties, several recommendations emerged that could guide future actions and initiatives to reduce adverse effects on soil and the environment and these include the following:

In-depth analysis and continuous analysis of the study region: Soil contamination is the primary source of heavy metal uptake in plants which can then reach humans and animals. The uncontaminated samples were randomly sampled with the guidance of the Bureau of Land Management (BLM) personnel however there were no previous studies conducted to confirm that the area was totally uncontaminated. Additionally, the results from soil characteristics indicated a slight difference in the values of the uncontaminated and contaminated samples. The slight difference could indicate that there is possible slight contamination in the uncontaminated area. Conducting a thorough in-depth analysis of the site location is advised. This involves increasing sample size and the depth of the collected samples to detect the possibility of leaching and the effect on groundwater, the use of advanced testing mechanisms and remediation techniques, and continuous monitoring to track the soil quality and contamination levels in the counties, especially in areas prone to spills from oil and gas contaminated fluids.

Best Practices for Waste Management: Oil and gas industries best adopt as a high priority, deliberate, innovative and eco-friendly disposal techniques such as Cd separation (Villa Nova et al., 2020) and other heavy metal separation practice before disposal. In addition, it would be valuable to develop comprehensive guidelines for the management and disposal of wastewater and byproducts to complement those currently available. These can include fostering community awareness about the potential impacts of oil and gas activities on soil quality and environmental health, and strategies to minimize spills, leaks, and contamination events to reduce the environmental footprint of these activities.

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GLOSSARY

List of Abbreviations

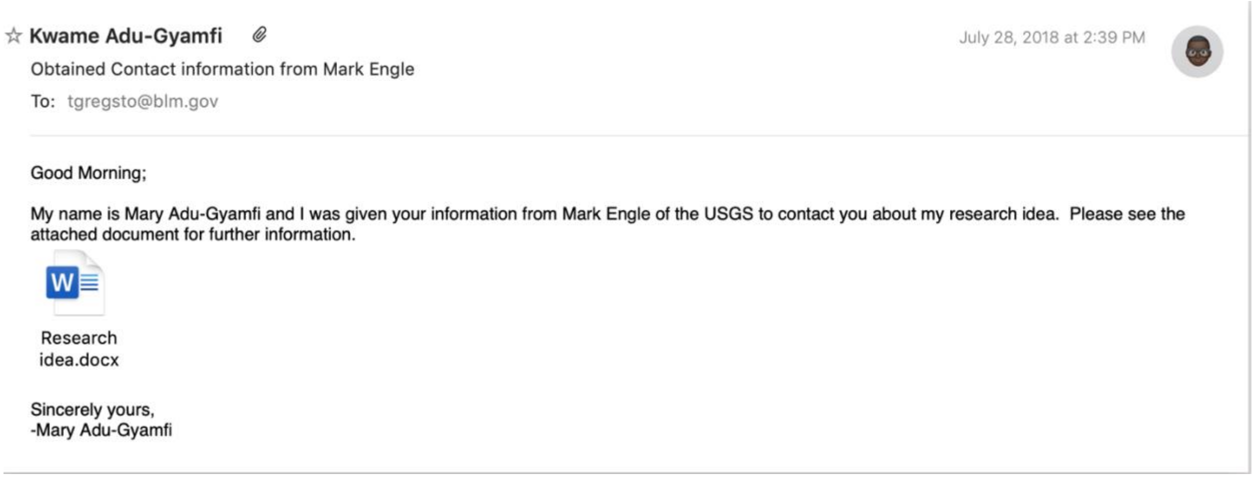
Ar	Argon
bbl	Barrel
BCR	Bureau Commune de Reference
BLM	Bureau of Land Management
CH_3CH_2OH	Ethanol
CH_3COOH	Acetic Acid
$C_2H_4O_2$	Acidic Glacial Water
$C_2H_7NO_2$	Ammonium Acetate
$C_6H_8O_7$	Citric Acid
$C_{12}H_{10}N_2O$	O-Phenanthroline Monohydrate
$CaCO_3$	Calcium Carbonate
Cd	Cadmium
CEC	Catio Exchange Capacity
Cr	Chromium
DD	Directional Drilling
EC	Electrical Conductivity
EPA	Environmental Protection Agency
FBW	Flowback Water
$FeSO_4.7H_2O$	Ferrous Sulfate Heptahydrate
FPW	Flowback and Produced Water
GIS	Geographic Information System

(HF)	Hydrogen Fluoride
H_2O_2	Hydrogen Peroxide
H_2SO_4	Sulfuric Acid
H_3PO_4	Phosphoric Acid
HCl	Concentrated Hydrochloric Acid
HF	Hydraulic Fracturing
HNO_3	Nitric Acid
HNO_3+3HCl	Aqua Regia
$HONH_2.HCl$	Hydroxylammonium Chloride
ICP-MS	Inductive Coupled Plasma Mass Spectroscopy
ICPMS	Inductive Couple Plasma Mass Spectrometer
$K_2Cr_2O_7$	Potassium Dichromate
KCl	Potassium Chloride
NaCl	Sodium Chloride
NORM	Naturally occurring radioactive material
Pb	Lead
PW	Produced Water
QGIS	Quantum Geographic Information System
REEs	Rare Earth Elements
RO	Reverse Osmosis
SEP	Sequential Extraction Procedure
SOM	Soil Organic Matter
Tcf	Trillion cubic feet

TOC	Total Organic Carbon
UIC	Underground Injection Control
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WHO	World Health Organization

APPENDIX

A. Emails regarding Planning for Soil Sample Collection with the Bureau of Land Management (BLM)



☆ **Kwame Adu-Gyamfi**

July 28, 2018 at 2:39 PM

Obtained Contact information from Mark Engle

To: tgregsto@blm.gov

Good Morning;

My name is Mary Adu-Gyamfi and I was given your information from Mark Engle of the USGS to contact you about my research idea. Please see the attached document for further information.

Research idea.docx

Sincerely yours,
-Mary Adu-Gyamfi

August 24th 2018

To whom it May Concern;

Hello, My name is Mary Adu-Gyamfi. I am a graduate student at the university of Texas at El Paso. I am interested in doing research related to oil and gas.

I have been in touch with Mark Engle from the USGS who has an office at the University of Texas at El Paso. He recently gave me your email upon my request to reach out to you to see if there is a possibility I can come and collect some samples for my research. Since this research is outside the scope of USGS, I thought it would be best to reach out to you personally.

My university does not have anyone who is an expert in this area and I have been working on getting someone outside the school to work with me, which the school allows, but currently, I do not have anyone yet. I hope that I can find a professor or a professional in this field who would be willing to guide me to completion of my work with the University.

Currently, the research that I want to do is a 3-part study, which Mark Engle helped me to choose through a series of papers he assigned for me to read over a specified time period:

1- looking at the characterization of compounds sorbed to soil and possibly into plants due to apparent illegal or accidental dumping of produced water;

2- looking at sequential extraction of sediments to determine where the elements ended up, how the substances are being taken up in the soil, what form they end up and what is going to happen to them;

3- For a more in depth study of the fate and transport of the contaminate in #2, I would also like to use reactive transport modeling.

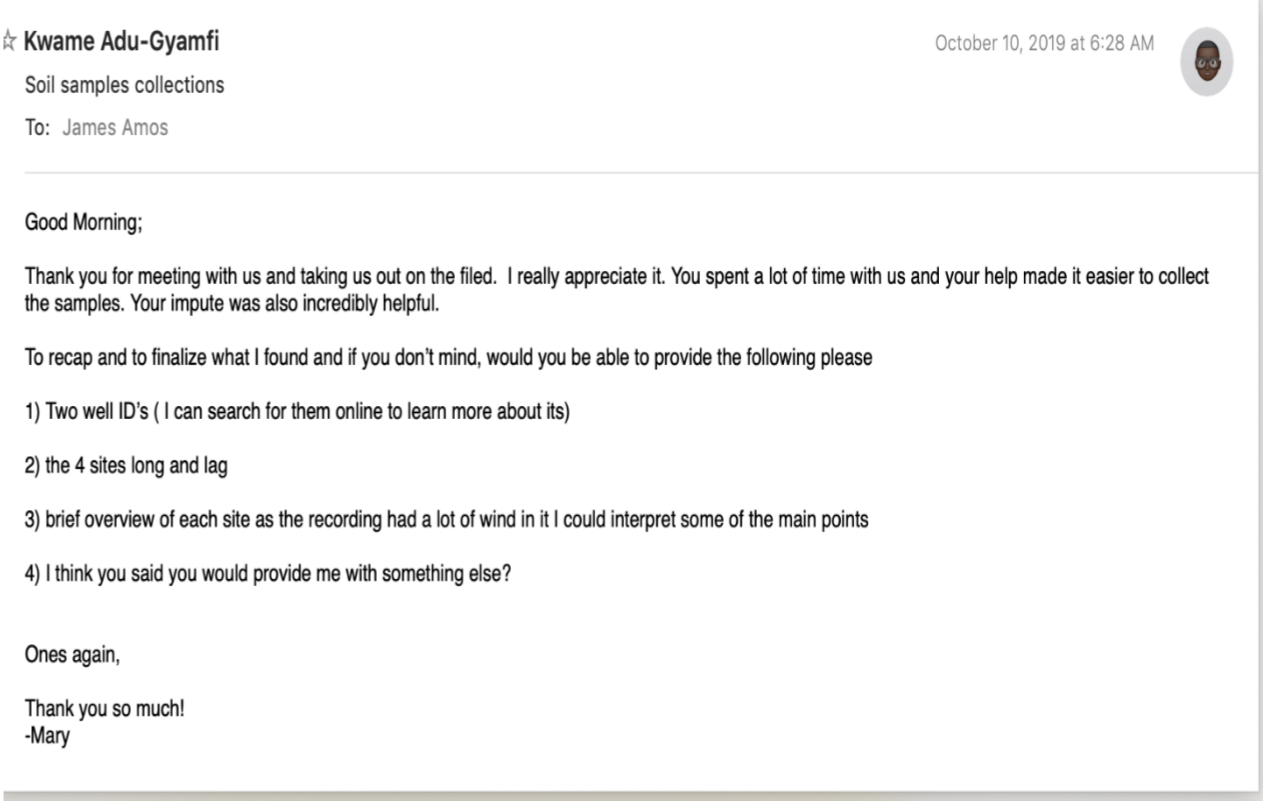
In doing this research, I hope to discover which contaminates are of greater concern in order to develop a mitigation plan for long term, intermediate term and short term.

School will begin first week of September and I would like to come by perhaps before August 20th provided it would be ok to do so to collect some samples from you.

If this would be possible or you have some questions for me, please do not hesitate to contact me at madugyamfi@utep.edu or kwameaj@mac.com

Thank you,

To Terry Gregston
Environmental Protection Specialist-Hazmat
Bureau of Land Management
620 E. Green St
Carlsbad, NM 88220
Office: (575) 234-5958
Cell: (575) 361-2635
Fax: (575) 234-5927



☆ **Kwame Adu-Gyamfi** October 10, 2019 at 6:28 AM

Soil samples collections

To: James Amos

Good Morning;

Thank you for meeting with us and taking us out on the filed. I really appreciate it. You spent a lot of time with us and your help made it easier to collect the samples. Your impute was also incredibly helpful.

To recap and to finalize what I found and if you don't mind, would you be able to provide the following please

1) Two well ID's (I can search for them online to learn more about its)

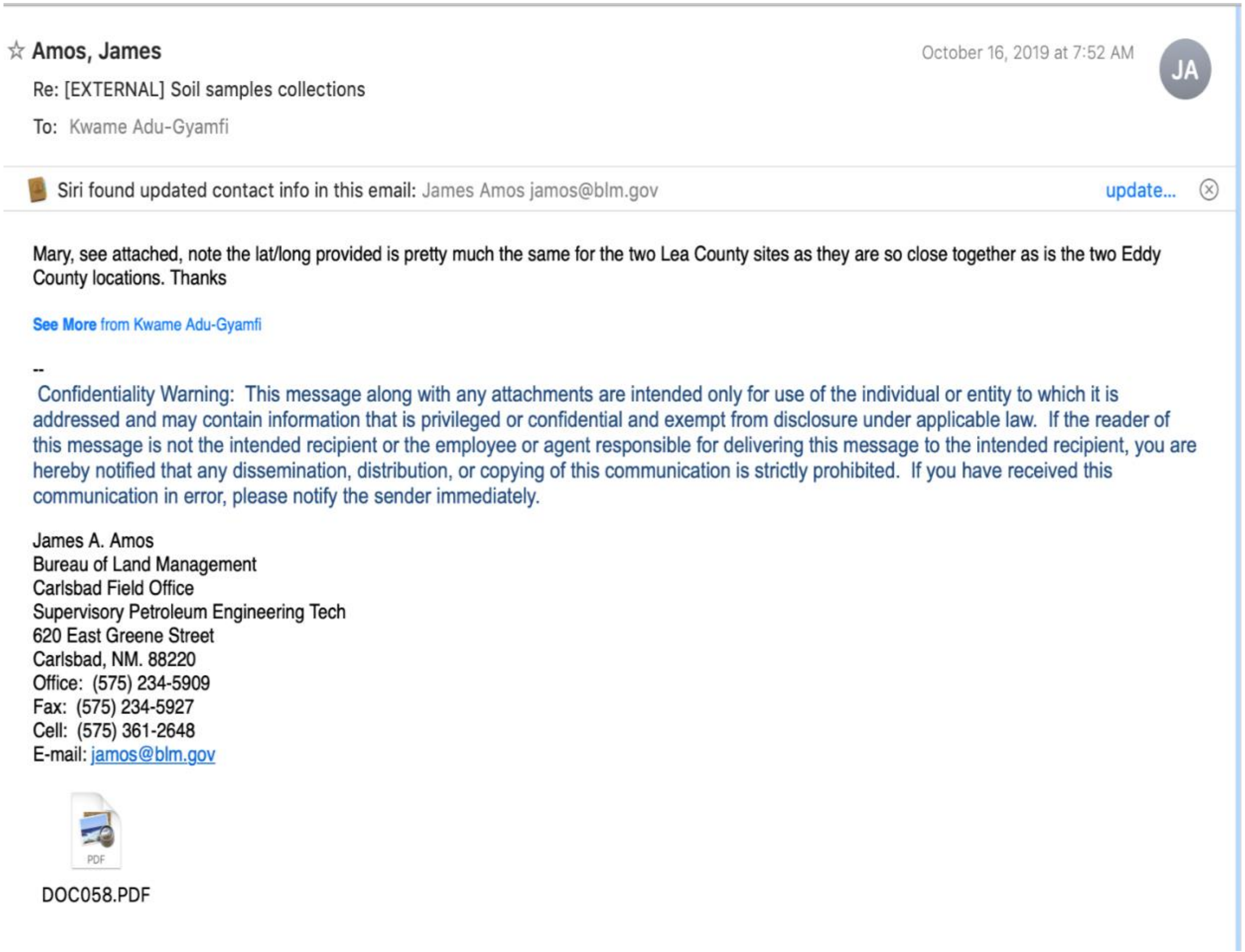
2) the 4 sites long and lag

3) brief overview of each site as the recording had a lot of wind in it I could interpret some of the main points

4) I think you said you would provide me with something else?

Ones again,

Thank you so much!
-Mary



Amos, James

October 16, 2019 at 7:52 AM

Re: [EXTERNAL] Soil samples collections

To: Kwame Adu-Gyamfi

Siri found updated contact info in this email: James Amos jamos@blm.gov

Mary, see attached, note the lat/long provided is pretty much the same for the two Lea County sites as they are so close together as is the two Eddy County locations. Thanks

See More from Kwame Adu-Gyamfi

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Confidentiality Warning: This message along with any attachments are intended only for use of the individual or entity to which it is addressed and may contain information that is privileged or confidential and exempt from disclosure under applicable law. If the reader of this message is not the intended recipient or the employee or agent responsible for delivering this message to the intended recipient, you are hereby notified that any dissemination, distribution, or copying of this communication is strictly prohibited. If you have received this communication in error, please notify the sender immediately.

James A. Amos
Bureau of Land Management
Carlsbad Field Office
Supervisory Petroleum Engineering Tech
620 East Greene Street
Carlsbad, NM. 88220
Office: (575) 234-5909
Fax: (575) 234-5927
Cell: (575) 361-2648
E-mail: jamos@blm.gov

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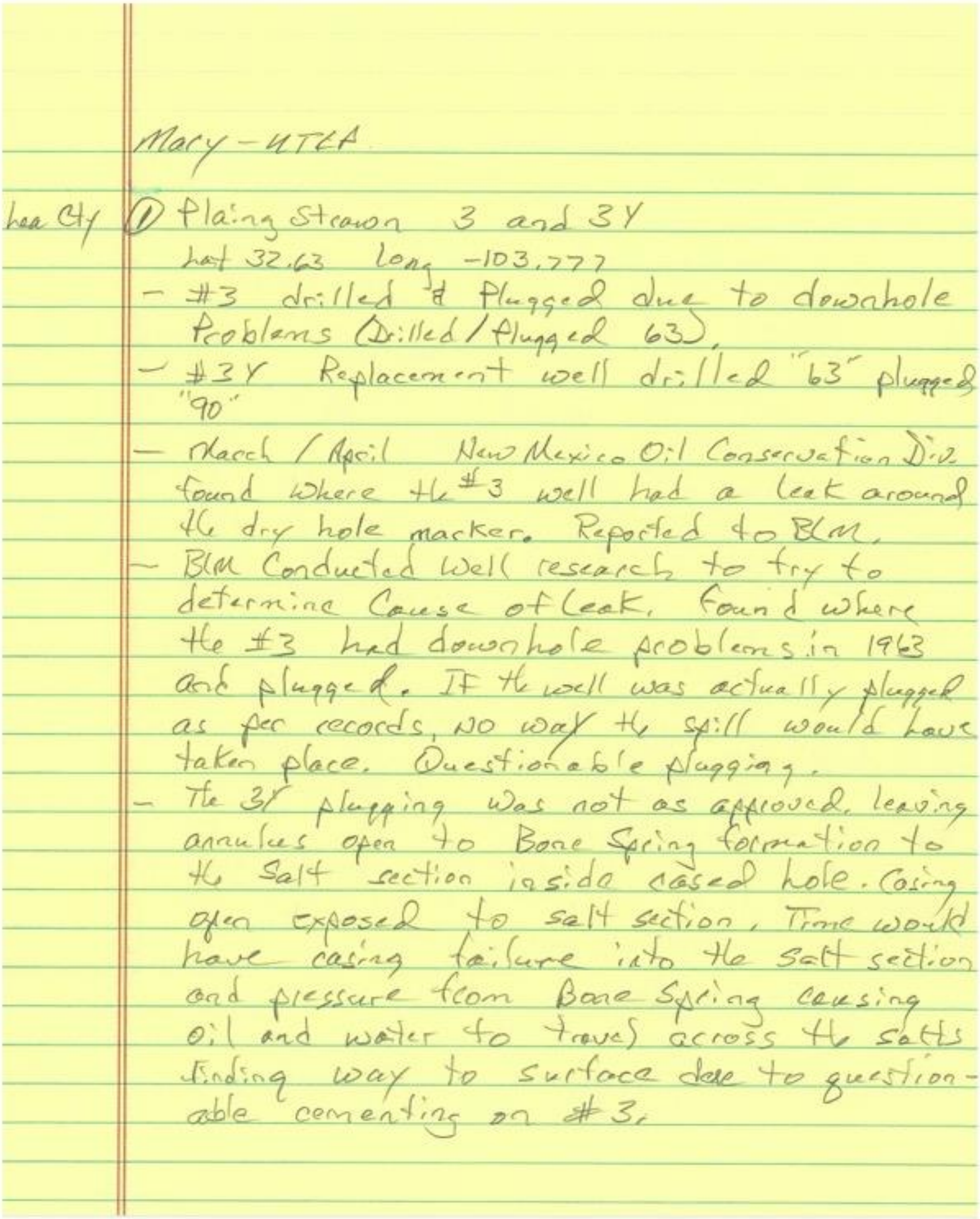
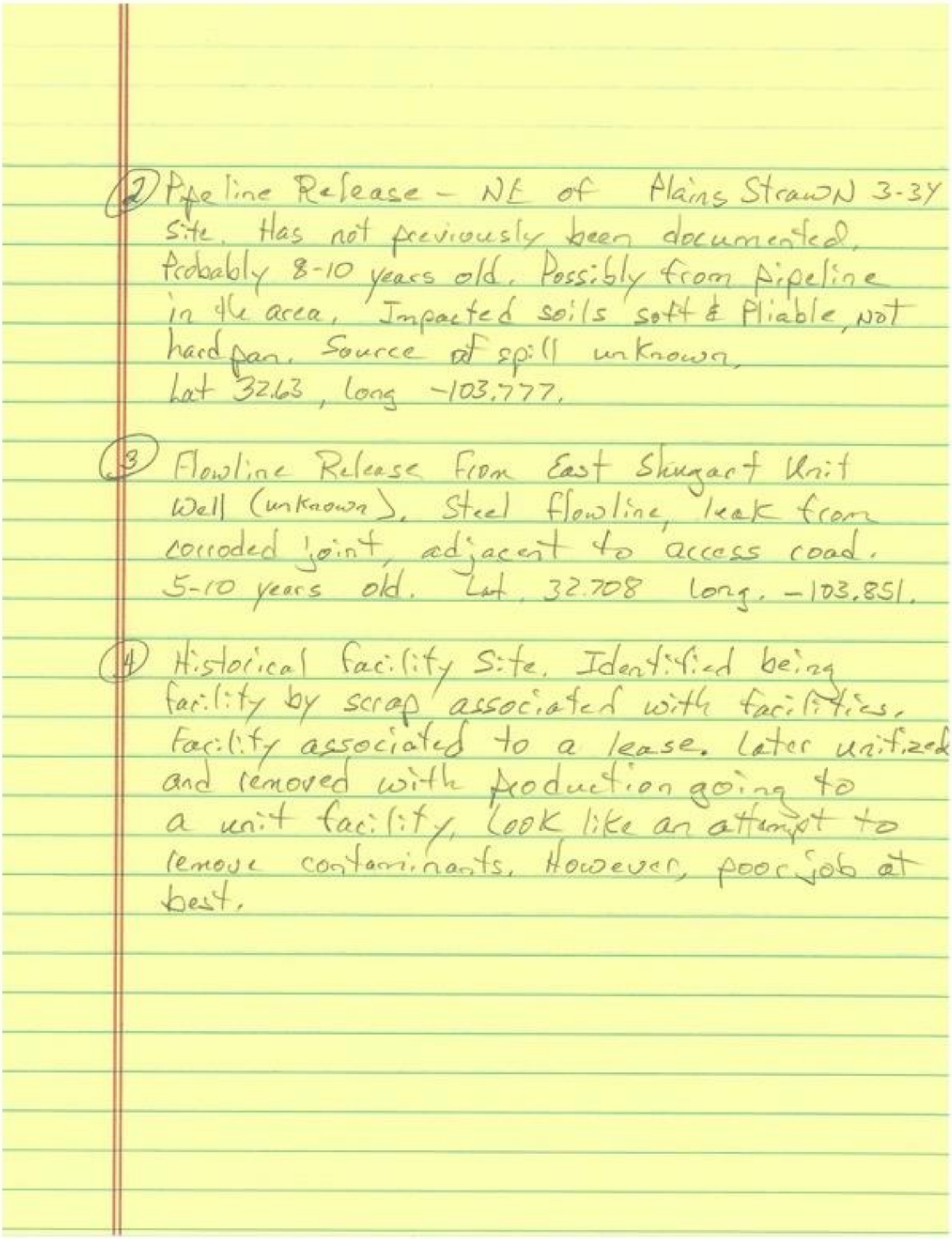
B. Site Location Data



Mary – UTEA

Lea Cty ① Plains Strawn 3 and 3Y
Lat 32.63 long -103.777

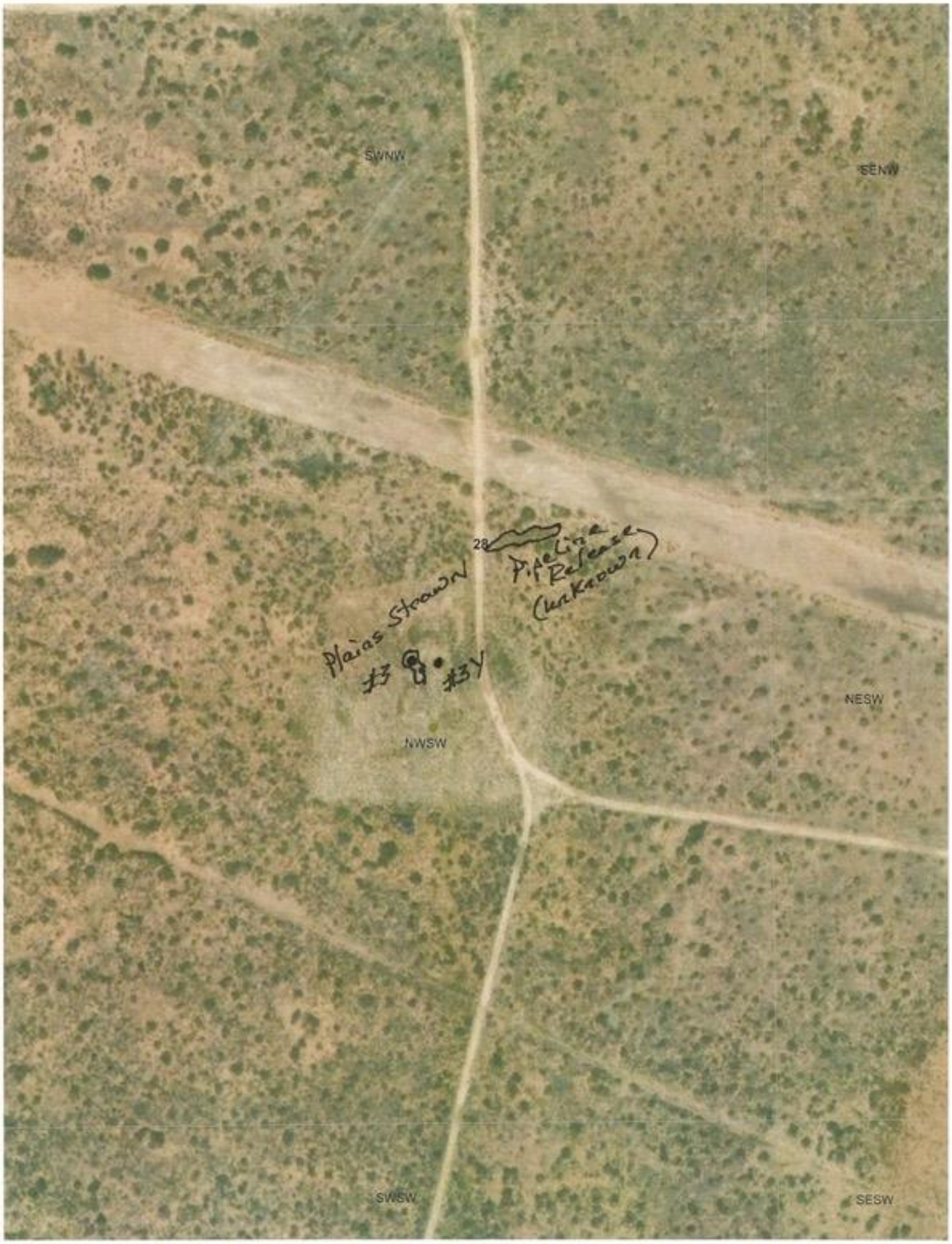
- #3 drilled & Plugged due to downhole Problems (Drilled / Plugged 63).
- #3Y Replacement well drilled "63" plugged "90"
- March / April New Mexico Oil Conservation Div found where the #3 well had a leak around the dry hole marker. Reported to BLM.
- BLM Conducted Well research to try to determine Cause of leak. Found where the #3 had downhole problems in 1963 and plugged. If the well was actually plugged as per records, NO way the spill would have taken place. Questionable plugging.
- The 3Y plugging was not as approved, leaving annulus open to Bone Spring formation to the Salt section inside cased hole. Casing open exposed to salt section, Time would have casing failure into the salt section and pressure from Bone Spring causing oil and water to travel across the salts finding way to surface due to questionable cementing on #3.



② Pipeline Release - NE of Plains StrawN 3-34 site. Has not previously been documented. Probably 8-10 years old. Possibly from pipeline in the area. Impacted soils soft & pliable, not hardpan. Source of spill unknown. Lat 32.63, long -103.777.

③ Flowline Release from East Shugart Unit Well (unknown). Steel flowline, leak from corroded joint, adjacent to access road. 5-10 years old. Lat. 32.708 long. -103.851.

④ Historical facility Site. Identified being facility by scrap associated with facilities. Facility associated to a lease. Later unitized and removed with production going to a unit facility. Look like an attempt to remove contaminants. However, poor job at best.


SWNW
SENW
28
Pipeline Release (unknown)
Plains Strawn
#3
#3Y
NESW
NWSW
SWSW
SESW

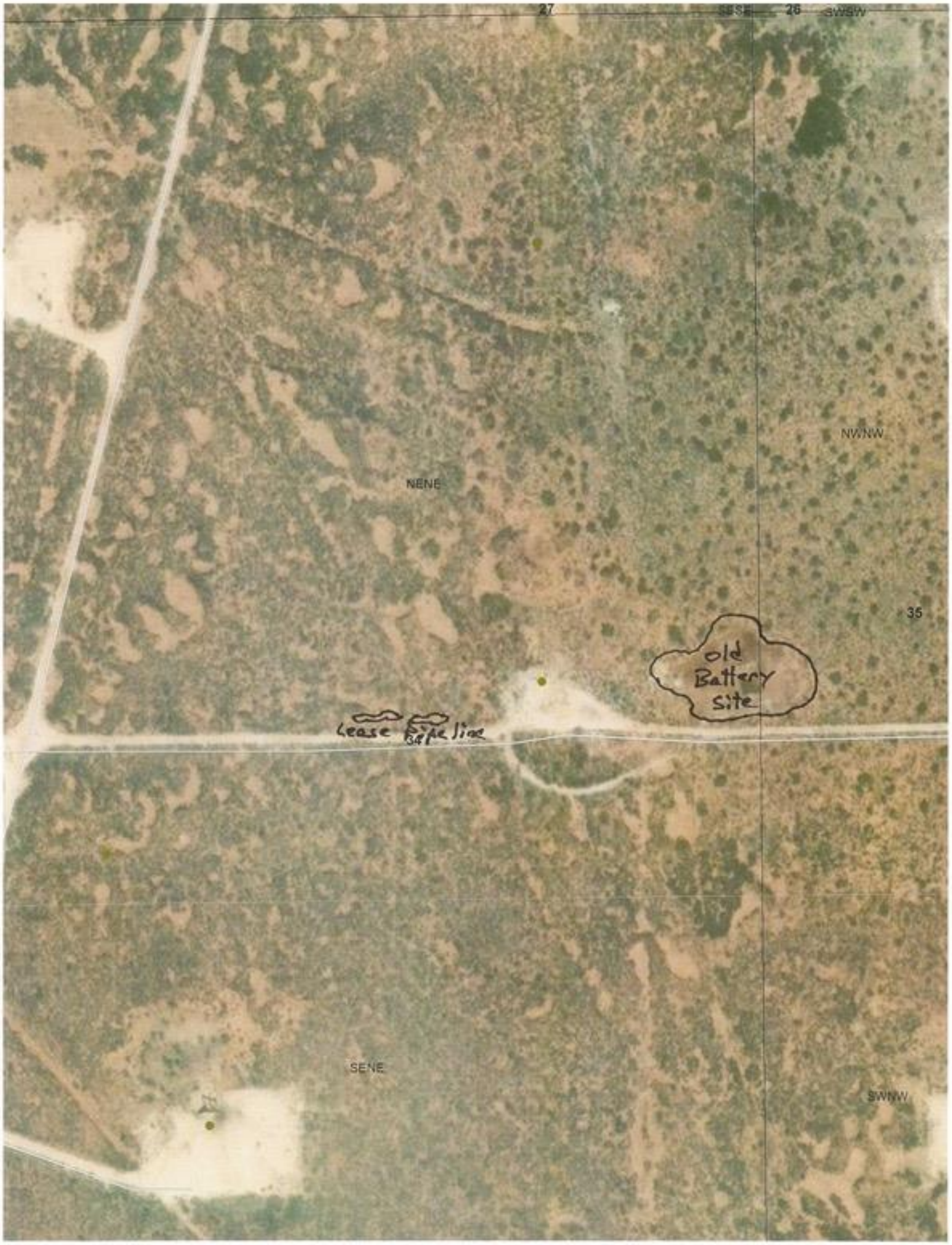
Google Maps

Imagery ©2019 Google, Imagery ©2019 Maxar Technologies, NMRGIS, USDA Farm Service Agency, Map data ©2019 100 ft

Google Maps

Imagery ©2019 Google, Imagery ©2019 Maxar Technologies, NMRGIS, USDA Farm Service Agency, Map data ©2019

100 ft


27
SESE
26
SWSW
NWNW
NENE
35
Old Battery Site
Lease Pipeline
34
SENE
SWNW

C. New Mexico Bureau of Geology and Mineral Resources: Standard Operation Procedure for Paste pH and Conductivity

STANDARD OPERATING PROCEDURE NO. 11

PASTE PH AND PASTE CONDUCTIVITY

REVISION LOG

Revision Number	Description	Date
0.0	Original SOP	10/23/03
11.1	Revision I	10/24/03
11.2	Revisions by PJP	5/19/2004
11.3	JRM	12/12/2004
11v4	Edits by LMK, changes made, sent to J. Hamilton and posted to Granite FTP site on 2/8/05	2/1/05
11v5	Revisions by KMD	1/29/07
11v5	Finalized by LMK ready to send to Jack Hamilton to post on Utah website and to George Robinson for audit	3/21/07
11v6	Editorial by SKA	10/22/08

1.0 PURPOSE AND SCOPE

This Standard Operating Procedure describes the method for determining the paste pH and paste conductivity of rock and soil samples. Paste tests are used to evaluate the geochemical behavior of mine waste materials subject to weathering under field conditions and to estimate the pH and conductivity of the pore water resulting from dissolution of secondary mineral phases on the surfaces of oxidized rock particles.

2.0 RESPONSIBILITIES AND QUALIFICATIONS

The Team Leader and Characterization Team will have the overall responsibility for implementing this SOP. They will be responsible for assigning appropriate staff to implement this SOP and for ensuring that the procedures are followed accurately.

All personnel performing these procedures are required to have the appropriate health and safety training. In addition, all personnel are required to have a complete understanding

VITA

I am Mary Naadanswa Adu-Gyamfi, a Ph.D. Candidate in Environmental Science and Engineering. I hold a Master of Education and Initial Teacher Licensure, which I earned in January 2006, and a Bachelor of Science in Chemistry with a minor in Arts, which I obtained in June 1996. My educational background underscores my commitment to interdisciplinary excellence. With robust skillset encompassing data collection, qualitative and quantitative research analysis, database management, laboratory proficiency, and GIS software expertise, I am a versatile researcher interested in tackling complex challenges in my field.

My academic journey has been further enriched with notable certifications, including a GIS Graduate Certificate, Texas and Massachusetts Teacher Licensure for Chemistry, and the Collaborative Institutional Training Initiative (CITI Program) certificate. Furthermore, I have accumulated a portfolio of publications showcasing my expertise and research contributions. Notably, my work has been featured in journals such as the International Journal of Environmental Monitoring and Protection and the Science Journal of Energy Engineering, reflecting my commitment to advancing knowledge and innovation in environmental science and engineering.

Beyond my published works, my dedication to scholarly contribution is evidenced by ongoing projects that are under review. These include comprehensive reviews on Harkness & PLTL Techniques and a call to scholars for New Mexico's Permian Basin investigations, focusing on spills and leaks in unconventional resources. My diligent research efforts and collaborative spirit have made me make meaningful contributions to my field.

Contact Information: madugyamfi@miners.utep.edu or madugymafin@gmail.com.