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Mapping Groundwater Potential Zones for Irrigation against Climate Change Using Geographic Information System and Remote Sensing in the Wenchi Municipality in the Bono Region of Ghana

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Dedication

This thesis is dedicated to my parents, whose unwavering support, love, and guidance have been my constant source of strength and inspiration. I also dedicate this work to all the farmers in rural areas who, through their tireless efforts, feed the world and sustain us all. Their resilience and dedication are the backbone of food security, and their contributions are truly invaluable.

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Abstract

Groundwater resources account for nearly half of all irrigation used in agricultural practices to sustain global food production. The impact of climate change on water resources essential for sustainable agriculture has increased the demand for groundwater, especially in arid and semi-arid regions, such as Ghana. Nonetheless, in the transitional zones of the country, groundwater has not been adequately used for small-scale agricultural production. Therefore, this study employed a GIS-based Multi-Criteria Decision Making (MCDM) analysis in the Wenchi municipality to estimate the potential groundwater zones for irrigation as a climate change adaptation strategy. Eight factors (Geology, Soil type, land use, Topographic Wetness Index (TWI), slope, lineament density, rainfall, and drainage density) were integrated into the analysis to determine the groundwater potential zones. Normalized weights were assigned to the factors, based on their characteristics and contribution to groundwater recharge through literature and groundwater expert consultations. The weights were later combined, using the Weighted Linear Combination technique in the ArcGIS Pro environment to create a map for the groundwater potential zones. The groundwater potential zones were classified into four, according to their potentiality to groundwater. The classes included low, 27.9% (318.1Km^2), moderate 37.9% (432.8Km^2), Good 34.1% (389.6Km^2), and excellent 1.5% (0.1Km^2). To assess the potential benefits of these zones for local populations, the output was analyzed relative to the area's population density, revealing high impact potential. The map showing the spatial distribution of the groundwater potential zones of the municipality will be useful to stakeholders, especially the water research institute at the Council for Scientific and Industrial Research (CSIR) in their groundwater for irrigation inventory projects and at the same time serve as reference material for future groundwater research studies. This study demonstrates the importance of Remote Sensing and GIS techniques in mapping groundwater potential zones at different scales and levels. It suggests that similar methods could be applied in other developing regions.

Riassunto (Abstract in Italian)

Le risorse idriche sotterranee rappresentano quasi la metà di tutta l'acqua utilizzata per l'irrigazione nelle pratiche agricole, sostenendo così la produzione alimentare globale. L'impatto del cambiamento climatico sulle risorse idriche, fondamentali per un'agricoltura sostenibile, ha aumentato la domanda di acque sotterranee, specialmente nelle regioni aride e semi-aride, come il Ghana. Tuttavia, nelle zone di transizione del Paese, le acque sotterranee non sono state adeguatamente sfruttate per la produzione agricola su piccola scala. Pertanto, questo studio ha utilizzato un'analisi di Decisione Multicriteriale (MCDM) basata su GIS nel comune di Wenchi per stimare le potenziali zone di acque sotterranee per l'irrigazione come strategia di adattamento al cambiamento climatico. Otto fattori (geologia, tipo di suolo, uso del suolo, indice di umidità topografica (TWI), pendenza, densità delle lineazioni, precipitazioni e densità di drenaggio) sono stati integrati nell'analisi per determinare le potenziali zone di acque sotterranee. Pesi normalizzati sono stati assegnati ai fattori, in base alle loro caratteristiche e al loro contributo alla ricarica delle acque sotterranee, attraverso la letteratura e consultazioni con esperti di risorse idriche sotterranee. I pesi sono stati successivamente combinati utilizzando la tecnica Weighted Linear Combination nell'ambiente ArcGIS Pro per creare una mappa delle potenziali zone di acque sotterranee. Le zone di potenziale delle acque sotterranee sono state classificate in quattro categorie, secondo il loro potenziale di accesso alle acque sotterranee: basso 27,9% (318,1 km²), moderato 37,9% (432,8 km²), buono 34,1% (389,6 km²) ed eccellente 1,5% (0,1 km²). Per valutare i potenziali benefici di queste zone per le popolazioni locali, i risultati sono stati analizzati in relazione alla densità della popolazione dell'area, rivelando un alto potenziale d'impatto. La mappa che mostra la distribuzione spaziale delle potenziali zone di acque sotterranee del comune sarà utile per le parti interessate, in particolare per l'Istituto di Ricerca sulle Acque del Consiglio per la Ricerca Scientifica e Industriale (CSIR) nei loro progetti di inventario delle acque sotterranee per l'irrigazione e servirà anche come materiale di riferimento per futuri studi di ricerca sulle acque sotterranee. Questo studio dimostra l'importanza delle tecniche di Telerilevamento e GIS nella mappatura delle potenziali zone di acque sotterranee a diverse scale e livelli, suggerendo che metodi simili potrebbero essere applicati in altre regioni in via di sviluppo.

List of Abbreviations

GIS	Geographic Information System
RS	Remote Sensing
MCDM	Multi-Criteria Decision Making
AHP	Analytic Hierarchy Process
GWPZs	Groundwater Potential Zones
WLC	Weighted Linear Combination
SRTM-DEM	Shuttle Radar Topography Mission – Digital Elevation Model
TWI	Topographic Wetness Index
NOAA	National Oceanic and Atmospheric Administration
USGS	United States Geological Survey
GSS	Ghana Statistical Service
IDW	Inverse Distance Weighted
CI	Consistency Index
CR	Consistency Ratio

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CHAPTER ONE

INTRODUCTION

1.0 Research Background

Water is an important resource for the survival of our planet. Although it covers 70% of the world, freshwater makes up only 2.5 percent. Merely 30% of the 2.5% is accessible for use, with the remaining 70% being encased in glaciers and ice caps (Das & Pal, 2019). Water scarcity has recently been an issue in many countries due to rapid population growth, industrialization, urbanization, and resource mismanagement (Anteneh et al., 2022). The agricultural sector is the major consumer of water worldwide, which uses 90% of water globally and 70% in arid and semi-arid countries and regions (Sekyere, 2022). The demand for water for irrigation will rapidly increase to fulfill the need for food production, which is anticipated to double between 1995 and 2025 as population and household income rise (Abdul-Ganiyu et al., 2016). In response, water demand for irrigation in developing countries is anticipated to rise by 14%, and irrigation fields will grow by 45 million hectares to nearly 300 million hectares by 2030 (Abdul-Ganiyu et al., 2016).

A significant part of sub-Saharan Africa is categorized as having arid or semi-arid climates. Finding water for agriculture, livestock agriculture, and domestic use in these places is quite difficult, especially during the dry season. The low amounts of precipitation and high temperatures in these places are the leading causes, resulting in water scarcity and shortages, and eventually, famine and drought (Incoom et al., 2022). In Africa, poor and rural farmers are expected to experience adverse effects from climate change, which may threaten socio-economic growth and food security if proper steps are not taken. Compared to Central Africa, West Africa has been recognized to have more severe droughts. The Sahel region of West Africa had an abrupt reduction in yearly rainfall, and it is unclear whether this trend has reversed recently. Therefore, different stakeholders in sub-Saharan Africa (SSA) are very concerned about how to help farmers increase their capacity for adaptation to the effects of climate change on agriculture (Bedeke, 2023).

Ghana's economy depends heavily on agriculture, which employs more than 50% of the workforce on a formal or informal basis and accounts for 25% of GDP and export revenues (Arndt et al., 2015). For the past 25 years, agriculture has regularly increased by more than 5% every year. However, due to its reliance on rainfed production and susceptibility to drought, the nation remains a significant net importer of agricultural food goods despite its constant expansion (Limantol et al., 2016). An important factor in determining agricultural output is climate. Warm and dry weather frequently has a detrimental impact on soil moisture and nutrients, affecting crop yield. As a result of expected increases in temperature, decreases in rainfall, and changes in the frequency and intensity of weather events, climate change modeling projections show that the nation is extremely vulnerable to climatic variability and change. There is ample evidence in Ghana that temperatures have been rising in all ecological zones while rainfall amounts and patterns have generally been declining and becoming more irregular (Adjei & Kyerematen, 2018; Antwi-Agyei et al., 2018; Arndt et al., 2015; Baffour-Ata et al., 2023; Incoom et al., 2022; Linderhof et al., 2022). The yields of maize and other cereal crops were predicted to decrease by 7% based on baseline climatic readings during the previous 20 years. If the trend continues unabated without implementing and utilizing adaptive measures, the agriculture sector and the economy will be seriously affected. Therefore, additional water sources for agricultural cultivation must be considered to reduce the effects of climate change and improve food security (Adjei & Kyerematen, 2018).

Groundwater is better protected against droughts and climate change/variability than rainfall and surface water. The use of groundwater for agriculture in SSA lags far behind than other parts of the world, such as China and India, even though it has many benefits (Adam & Appiah-Adjei, 2019). For example, groundwater has transformed the agricultural sectors of Bangladesh and Vietnam, turning these once import-dependent economies into global leaders in the export of rice, coffee, and pepper. Similarly, around 40% of India's agricultural output, the country's third-largest producer of grains, comes from groundwater-irrigated areas, adding roughly 9% to the country's GDP. Although most countries find groundwater irrigation beneficial, sub-Saharan Africa is lagging in this "green revolution" and uses groundwater in just 5.8% of its total irrigable area despite its abundance (Adam & Appiah-Adjei, 2019).

Adopting small-scale groundwater irrigation treatments for crop cultivation can significantly increase agricultural production and food security (Forkuor et al., 2013). The internally renewable groundwater supplies in SSA, however, are only about 1500 km^2 per year, according to FAO estimations (Giordano, 2006). This compares positively to data for China and India, two nations whose agricultural economies have undergone a total transformation due to the use of groundwater (Giordano, 2006). Studies reveal that SSA has groundwater availability per person that is about three and six times greater than that of China and India, respectively (Forkuor et al., 2013). Adaptation measures are modifications to ecological, social, or economic systems in response to present or anticipated climatic stimuli and their effects or repercussions. Therefore, farmers need to adapt their practices in response to climatic changes because of their crucial role in agricultural production.

These disparities highlight the untapped potential of groundwater as a critical resource for climate adaptation in agriculture. Identifying and utilizing potential groundwater zones can mitigate the adverse effects of climate change, enhance food security, and promote sustainable agricultural practices. This study focuses on the Wenchi Municipality in Ghana, where surface water sources like the Subinja irrigation scheme are insufficient to meet irrigation demands due to climate-induced variability. Employing advanced geospatial techniques, this research aims to address the gap in identifying potential groundwater zones for irrigation, contributing to effective climate adaptation strategies.

1.1 Problem Statement

Water is an essential natural resource considered sacred and necessary for human survival (Anteneh et al., 2022). It is a crucial supply of life nutrients for daily living, which has been the case since the beginning of human community development. While this resource is widely dispersed across nature, its amount and quality differ depending on the location (Alimi et al., 2022). Climate risk management is prioritized in food security, nutrition, water resources, and energy. The analysis of the agricultural sector's susceptibility to climate change, the promotion of initiatives to increase agroecosystems' resilience, and the creation and dissemination of technology for adaptation are the key goals of every nation, especially developing countries. One way to respond to the effects of climate change is the ability of people, communities, and governments to manage the impacts and exploit opportunities from changed conditions (Siabi et al., 2022).

Several management techniques are described in the literature for crop production systems in Ghana that help smallholder farmers adjust to climate change and variability, such as rainwater harvesting for irrigation (Asante, 2013; Opare, 2012). One technique that is of utmost importance is groundwater irrigation (Gumma & Pavelic, 2013). Groundwater is defined as the water in the microscopic pores of rocks, soil, and sediment that are located beneath the surface of the Earth. It fills the voids left by silt grains and the fissures in rock formations (Adam & Appiah-Adjei, 2019). Surface water irrigation is the most dominant irrigation system in the Wenchi Municipality, and it is known for its intense agricultural production. This irrigation scheme called the Subinja irrigation scheme, is the sprinkler type of irrigation that takes its water source from the Subin River. It is the primary water source in the municipality during the dry season (Abdul-Ganiyu et al., 2016). However, this irrigation type is not enough to counter the effects of climate change on food production in the area. What makes the matter so pressing is that the surface water level in the study area is also heavily affected by climate change, making it inadequate as the only water source for irrigation in the area.

Furthermore, conducting in situ groundwater measurements without prior identification of potential zones can be both costly and time-intensive. This study aims to provide practical recommendations for target areas likely to yield groundwater, assisting in efficient in situ assessments by the Water Research Institute under the Council for Scientific and Industrial Research (CSIR). Again, several works have been done on how farmers in the Brong Ahafo region are adapting to the effects of climate change, their perception of the whole climate change problem, rainwater irrigation as well as the performance of the irrigation systems constructed in the region, and many others (Forkuor et al., 2013; Abdoulaye et al., 2017; Kyereh et al., 2015; Taylor, 2015; Abdul-Ganiyu et al., 2016). However, little attention has been paid to delineating potential groundwater zones for more sustainable irrigation practices using geospatial techniques. This research is relevant due to the limited research on groundwater as a climate change adaptation strategy, especially at the local level in the country. Research at the regional level is relevant because it is at this level that impacts can be felt due to their lack of financial, material, and human resources. It is worth noting that this research is the first groundwater potential research in the study area and the entire region. The study aimed to conduct a multi-criteria analysis in the Wenchi municipality to map the potential groundwater zones for irrigation as a climate change adaptation strategy. More specifically, the study`s key objective was to map out potential zones for groundwater using Multi-Criteria Decision-Making Analysis and Analytical Hierarchical Process (MCDA-AHP) in the GIS environment.

Addressing this research objective is relevant theoretically and practically for the following reasons. Theoretically, this study would contribute to the scarce research on groundwater in this research stream. Thus, it will offer thought-provoking knowledge to the literature on potential groundwater zones for efficient and effective sustainable irrigation in emerging economies like Ghana. This research also provides a sustainable water source for irrigation is needed for effective climate change adaptation and to ensure continuous food production in the municipality, Ghana, Africa, and the world. Therefore, the findings from this research would offer valuable insights into the potential zones for groundwater, which can ensure real-time accessibility to groundwater for effective crop and agricultural production and, in turn, guarantee food security. The collaboration with the Water Research Institute within the Council for Scientific and Industrial Research (CSIR) in Ghana necessitated the successful completion of this research through the provision of relevant data and relevant expert advice.

1.2 Research Objectives

The main objective of this study was to map the potential groundwater zones in the Wenchi municipality using a Multi-Criteria Decision Analysis-Analytic Hierarchical Process (MCDA-AHP) in the GIS environment.

Specific objectives to accomplish the main objective

- To identify and examine factors contributing to groundwater availability in the Wenchi Municipality
- To assign relative weights to the factors and calculate their contributions to groundwater potential using the APH method.
- To compare the groundwater potential zones with the population density of the areas to assess their potential benefits to the people

1.3 Profile of the Study Area

The Wenchi municipality is located in the Bono region of Ghana. Within the region is the Wenchi Municipal District. It is situated in the forest-savannah transition zone of Ghana, with a total area of about 1142km². There is a bimodal rainfall distribution in the area, with an annual total of about 1300 mm and a depth ranging from 0.47 to 0.60mm. April marks the beginning of the rainy season, which lasts until November, with an absence of rain in August. A lengthy dry season lasts from November to April after the rainy season. The Municipality has high temperatures, with an average of 24.5ºC. The municipality lies within latitudes 7º 30' and 8º 05' North and longitudes 2º 15' West and 1º 55' East. The minimum temperature is 21.2ºC, with an average maximum temperature of 30.9ºC. The dominant geological types in the municipality include the Birimian Supergroup, the Erburnean Plutonic Suite, Mesozoic, and the Voltaian supergroup, Kwaho-Morago Group. The dominant soil types of the area consist of Acrosols, Gleysols, Leptisols, and Lixisols. Agriculture is the main economic activity. Maize, yam, tomatoes, cassava, cocoyam, and plantains are the principal crops farmed. Most of the local farmers are smallholders.

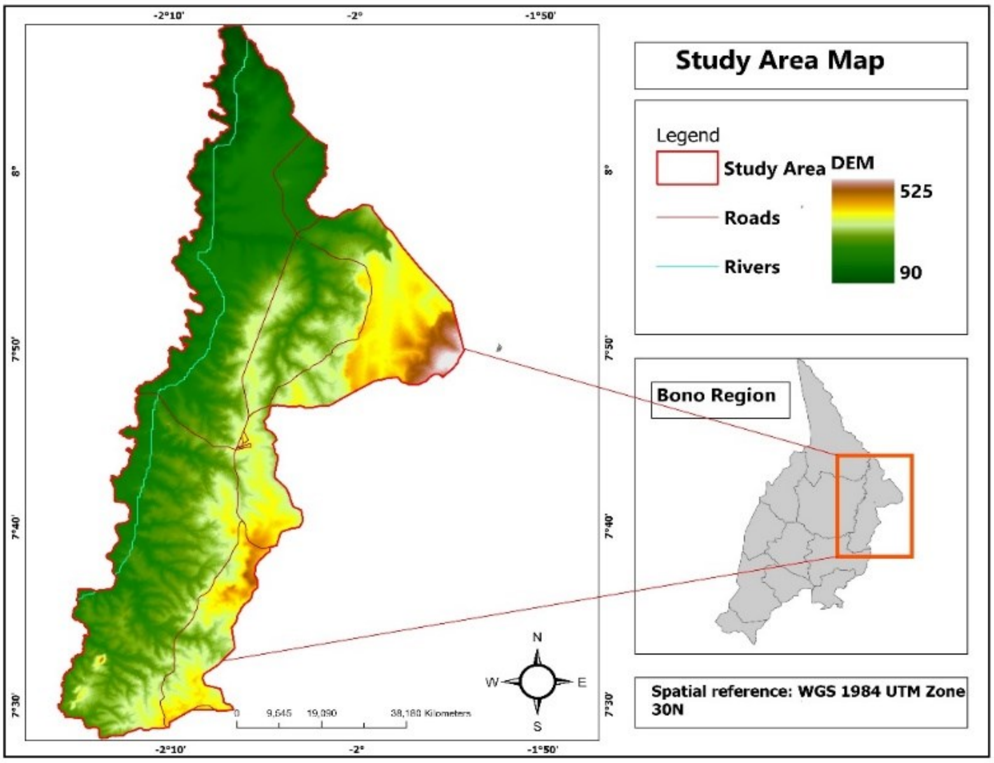

Figure 1: Profile of the Wenchi Municipality

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

All nations now deal with surface water and groundwater issues, particularly in semi-arid areas. These issues include water pollution, shifting groundwater levels, a lack of rainfall, decreased agricultural output, and variables related to climate change (Priyan, 2021). In the West African Sub-region, of which Ghana is a part, irrigation farming is particularly one important strategy for maximizing agricultural potential and improving food security and local income levels (Namara et al., 2014). Therefore, this chapter intends to review articles and bring insight into the irrigation systems in Ghana, farmers' perception of climate change, irrigation as a climate change adaptation strategy by the farmers in Ghana, GIS, and Remote Sensing for groundwater potential mapping, Multi-Criteria Decision-Making (MCDM) for Groundwater Potential Mapping, and Analytical Hierarchy Process (AHP) in Groundwater Studies.

2.1 Review of Concepts

2.1.1 Irrigation Systems in Ghana

Water is a vital natural resource for life on Earth and the growth of ecosystems. Over 90% of all wasteful water usage and over 70% of all water withdrawals worldwide are attributed to irrigation. Since water is a valuable resource in agriculture, the effectiveness of farming depends on every drop of water that is available for irrigation. Increased irrigated agriculture, industrialization, urbanization, and population growth have all led to water scarcity and consequent value. Water resources for agriculture will be overused or misused in semi-arid regions in the future due to various factors. Still, agriculture is the main user of surface and groundwater. After surface water sources are exhausted, groundwater will continue to be the primary source of freshwater for many significant agricultural production areas (Siebert et al., 2010). The aquifers holding groundwater are the main drought protectors for food productivity and human needs. The best water sources for long-term and efficient adaptation to the effects of climate change have been proposed to be groundwater resources.

The resource is not only the most extensive freshwater reservoir on earth. It is also deeply and profoundly buried, providing significant protection from the constant high temperatures and high rates of evaporation (Fynn et al., 2023). Irrigation canals rarely match the dependability and flexibility of groundwater availability in many concentrations of intensive agriculture (Siebert et al., 2010). A typical example is the Quanat system, a Persian invention from approximately 3000 years ago that allowed it to extract groundwater from alluvial fans and bring it to the earth's surface for human use (Kwoyiga & Stefan, 2018). Groundwater has been more crucial for irrigation over the previous 50 years. In many nations worldwide, intensive groundwater use has made it possible for a "vibrant wealth-creating" agricultural groundwater economy to emerge, overshadowing the previous belief that salinity and waterlogging posed a threat to irrigated agriculture (Bouarfa & Kuper, 2012). Numerous countries, including Pakistan, India, and the United States of America, have proved their ability to use groundwater for irrigation with notable achievements (Fynn et al., 2023).

However, agriculture accounts for more than 35% of the GDP in the West African sub-region and employs more than 65% of the labor force. Nonetheless, the agricultural sector's current economic contribution to the region's growth has been observed to be far less than anticipated. This is due to the sub-region's potential for much higher agricultural production than the acreage that is now being used. Furthermore, most of the subregion, including Ghana, practices rain-fed agriculture primarily for subsistence. Because of this, the practice is highly dependent on the regularity and consistency of the rain, which has been quite inconsistent lately (Fynn et al., 2023). Due to the sub-region's reliance on rain, farming is only possible during the rainy season, which is unimodal in most locations. Consequently, there is a protracted period of little to no agricultural activity throughout the year.

Water is present in most places on Earth, but it is not always easily accessible, particularly potable water, which is needed for long-term development, food production, and sanitation (Apogba et al., 2024). In Ghana, agriculture has a major socioeconomic role. Approximately 40% of the GDP, roughly 60% of the labor force, and 40% of the foreign exchange earned through exports are accounted for by this industry. Despite being an essential part of the nation's economy, the agricultural structure is vulnerable since it depends on rainfed farming during the roughly six-month rainy season (Awuni et al., 2011). Less than 2% of Ghana's entire cultivable area is irrigated, despite the country's remarkable economic potential and the emphasis on irrigation development in several programmes. Furthermore, even in this limited area, experts are unsure about the precise locations and purposes of Ghana's many irrigation infrastructure types (Asante, 2013). The twenty-two (22) public irrigation schemes overseen by the Ghana Irrigation Development

Authority (GIDA) and the Irrigation Company of Upper Regions (ICOUR), as well as the numerous small reservoir schemes administered by Water Users Associations (WUAs), are unable to reach their full potential due to infrastructure challenges (Namara et al., 2011).

The location, development, and administration of informal irrigation schemes, which comprise the remaining two-thirds of the country's total irrigated land, are poorly understood (Baldwin & Stwalley, 2022). Ghana has sufficient water resources to support intensification through irrigation. Its irrigation potential is estimated to be between 0.36 and 1.9 million hectares or little more than 33,000 hectares under irrigated crops (Mul et al., 1985). Ghana's expansion of irrigation has been justified as a means of achieving three goals: (1) food security, (2) a decrease in poverty, and (3) employment in rural areas (Kansanga et al., 2019). Even while irrigation has a lot of potential and has been prioritized in recent plans, the amount of potentially irrigable areas currently under irrigation is small. Furthermore, current irrigation plans typically have poor productivity and performance, especially those that were created by the government (Adongo et al., 2015).

Farmers are at risk from droughts and other unseasonal weather events. In these circumstances, irrigation expansion ensures year-round agricultural production, which offers the prospect of increased food security and rural-area development. The bulk of irrigation projects in Ghana use surface water, drawing from reservoirs, lakes, and rivers. Only four of the twenty-two irrigation plans use groundwater (Baldwin & Stwalley, 2022). These irrigation projects include the Vea irrigation project in the Volta area, the Tono irrigation project in the upper east, the Sandema irrigation project, and the Keta irrigation project on Ghana's eastern coast (Antwi, 2013). The use of groundwater resources all year round, for massive irrigation, has recently gained popularity nationwide. This is because agriculture, which is mostly rain-fed, accounts for more than 40% of the nation's gross domestic output. All around the nation, particularly in the dry season, groundwater is currently being utilized on a trial basis to irrigate vegetables (Banoeng-Yakubo et al., 2009).

In Sub-Saharan Africa, groundwater development for uses like irrigation received less funding. Since Ghana gained its independence, the government has prioritized formal irrigation by developing its surface water resources (Kyei-Baffour & Ofori, 2006). Not enough consideration has been given to groundwater irrigation, especially in the transition zones of the country where the Wenchi municipality is located. It is worth noting that groundwater is currently one of the main means of subsistence in the Volta region's coastal zones, especially for those with access to power. However, there are many challenges in fully realizing the economic potential of groundwater, such as the lack of clear policy support, the high cost of energy required to withdraw water, and the lack of economical drilling technology (Namara et al., 2011).

2.1.2 Perception of Farmers about Climate Change and Irrigation in Ghana

Sustainable agriculture is ingrained in the human-climate link, particularly in views regarding climate change, its rates, and its effects on the soils, crops, and animals that make up the complete agroecosystem (Kemausuor et al., 2011). Understanding and being aware of climate change and variability is essential to encourage the adoption of policies that might work well in certain socioeconomic contexts (Adeboa & Anang, 2024). The ability of farmers to recognise and respond positively to changes in the environment and climate is essential for the acceptance and successful use of new technologies, new farming methods, and ecosystem adaptation (Ndamani & Watanabe, 2015). A major obstacle to long-term sustainable agriculture in most developing nations, including Ghana, is the absence of an adequate understanding of climate change and its effects on agricultural output. "Perception" is the process through which information or environmental stimuli are taken in and converted into psychological awareness (Kudadze et al., 2019).

People's perceptions of climate change are multifaceted and encompass a variety of psychological concepts, such as knowledge, attitudes, beliefs, and concerns regarding the nature and extent of climate change. To develop policies and programs targeted at fostering successful adaptation in the agricultural sector, a deeper comprehension of farmers' perceptions of climate change, ongoing adaptation initiatives, and the factors affecting the decision to adjust farming techniques is required. Farmers must have comprehensive views of the current climate and potential future trends to properly adapt to climate change. This is because they make choices based on their environment, and discrepancies between their perceived and actual surroundings may exist. A person's perspective is influenced by their characteristics, their experiences, the information they have been given, and their physical and cultural environment (Whitmarsh & Capstick, 2018). The perceptions and adaptive abilities of the impacted community to deal with the risks and repercussions of climate change play a major role in the adaptation process (Abdoulaye et al., 2017). It also affects smallholder farmers' decisions and the pace at which they implement cutting-edge technologies to reduce the negative effects of climate change and variability (Alhassan, 2019).

A study by Limantol et al. (2016) in the Vea catchment area in the Upper East Region of Ghana indicates that most of the farmers perceived that there has been a change in the temperature (increase) and rainfall (decrease) patterns in the past 30 years. However, only 21% of the 365 respondents are adapting to the problem through the combination of rainfed and irrigation. Again, Alhassan (2019) revealed in a study in the arid region of Ghana that the farmers perceive that the lack of rain over the previous ten years has made it difficult for them to obtain water for irrigation, and most of their dugouts have dried up and cannot supply them with water for irrigation until the rainy season starts. According to research by Kudadze et al. (2019), farmers in the Northern region perceive irrigation as an effective strategy against climate change. According to these farmers, the ability of farmers to irrigate their farms is not influenced by their educational level. However, for effective irrigation, informal education on irrigation needs to be conducted. Amadou et al. (2015) compared the perceptions of the farmers in four communities in the Upper East region of Ghana on climate change and variability with historical data in the region. 71% of the respondents from the 186 households interviewed agreed that there has been an increase in temperatures, which matches the local climatological evidence. Also, according to the authors, 95% of the farmers perceived that there has been a reduction in rainfall with shortening periods. Even though the climatological evidence showed no evidence of reduction due to high internal annual variation, there was an agreement on the shifting rainfall onset from April to June, accompanied by an increasing dry spell. Another comparison was done by Asare-Nuamah & Botchway (2019) in the Adansi North of Ghana. Their study revealed the need for the intensification of climate education, mass awareness, and capacity development programs since there was no significant relationship between farmers' perceptions of climate change and the climatological evidence in the district. Moreover, Ndamani & Watanabe (2015) revealed in their study in Lawra that over 80% of the farmers perceived the existence of climate change and ranked irrigation and drought-resistant crops as the most effective adaptation strategies. Also, the rice farmers at the Ketu North in the Volta region of Ghana perceive a decrease in rainfall and an increase in temperature patterns, thereby affecting their farming activities. However, irrigation is one of the adaptation strategies used by farmers (Jacob & Marcus, 2018). According to Jacob & Marcus (2018), the farmers also pointed out some adaptation challenges, including a lack of education on climate change and adaptation options and inadequate surface water for irrigation.

2.1.3 Irrigation as a Climate Change Adaptation Strategy by the farmers in Ghana

For the population that directly depends on agriculture to maintain their livelihoods, there is a need for the agricultural sector to adapt to the negative consequences of climate change (Asfaw et al., 2016). The term "climate change adaptation" describes actions taken to lessen the effects of Climate Change. It refers to the various actions, plans, procedures, and laws that mitigate the consequences on people, the environment, and the economy by adapting to actual or projected changes in the climate (Berkhout et al., 2008). It implies the capacity to react and modify in ways that cause minimal harm and are advantageous to the environment in response to actual or anticipated impacts of Climate Change circumstances (Adeboa & Anang, 2024).

Several factors, including climate change, disease and pest invasions, post-harvest losses, market shocks, and a lack of cash or credit, severely restrict agricultural productivity and the lives of smallholder farmers throughout Africa (Limantol et al., 2016). These farmers rely only on agriculture for their livelihoods, and because of limited resources and a delayed response to environmental changes, they are frequently susceptible to unanticipated shock events that cause crop failure and food and/or income instability (Derbile, 2010). Recent studies imply that even slight temperature rises will negatively impact smallholder farmers' ability to produce primary cereal crops like wheat, rice, and maize, and climate change would make their situation substantially worse. To enable farming in dry regions to mitigate the effects of drought in semi-arid areas, irrigation as an artificial delivery of water to crops is a sure solution. Even in areas with an average annual total of sufficient seasonal rainfall, the amount may be unevenly distributed and varies from year to year. Irrigation can support consistent agricultural output in situations where conventional rain-fed farming is a high-risk endeavor (Abdul-Ganiyu et al., 2016).

Information on the potential of groundwater resources is scarce throughout sub-Saharan Africa (SSA) in general and Ghana in particular (Paria et al., 2021). The scant data currently available, based on information from aquifers, presents a dismal picture of groundwater resources. The potential for using groundwater for agriculture is not fully reflected in the nation's water and irrigation policy, as groundwater is mostly connected with household usage due to its perceived low availability. The agricultural sector in Ghana is dominated by approximately 2.74 million small-scale farmers, with an average farm size of 1.2 hectares and little use of advanced technologies. Approximately 80% of domestic production is produced by small farmers (Asante, 2013). In many places in Ghana, however, farmers use shallow groundwater to grow horticulture crops, despite official statistics and priority. Farmers have shown that groundwater resources are heavily patronized when they have access to information about their availability for irrigation. For example, in the Keta Basin, extractions allow groundwater extracted from an open sandy aquifer throughout the year to irrigate various crops (Fynn et al., 2023).

The development of groundwater infrastructure in the Upper East Region of Ghana, the most populated of the three impoverished Northern areas, relies on the relative abundance of human labor during the extended dry season, employing basic technology (Awuni et al., 2011). Similarly, widespread irrigation practices utilizing Indigenous pump technologies and shallow wells exist in the Upper East Region. Smallholder farmers in southern Ghana and other regions of the country use this method to grow vegetables all year round for urban markets, enabling them to support their families (Fynn et al., 2023). Moreover, research by Kudadze et al. (2019) revealed that 97.5% of the farmers in the Northern region of Ghana take their source of irrigation water from the Golinga and Botanga, which are surface water sources. On the other hand, the remaining 2.5% of the farmers make use of groundwater (wells). Investing in irrigation infrastructure is crucial for decreasing poverty because it can increase agricultural productivity by lowering the risks associated with unpredictable and variable rainfall. In irrigated agriculture, the amount of water supplied is artificially increased through water control technology, which enables the drainage of excess water (Dinye & Ayitio, 2013).

2.1.4 Geographic Information System (GIS) and Remote Sensing (RS) for Groundwater Potential Mapping

Groundwater is not readily accessible, unlike surface water. Groundwater exploration is necessary to locate areas with groundwater potential. Geophysical investigations in the past, which called for expensive instruments for evaluation, were frequently required for groundwater exploration (Apogba et al., 2024). However, groundwater resources in recent years can be accessed, monitored, and conserved more easily because of geospatial technology, which includes manipulating data covering huge, inaccessible places (Dar et al., 2010). Applied geomorphology relies heavily on the mapping and extraction of surface structures, which has been effectively accomplished for decades thanks to the application of geospatial technology (Bishop et al., 2012). Visual interpretation of aerial photographs has proven to be quite efficient in extensive studies such as landform detection, feature distribution analysis, and land cover research. Its benefits for surveying are well-established (Casagli et al., 2017). Airborne photographs offer a significant source of data due to their great spatial resolution, especially in detecting tiny landforms that range in size from metres to decametres. Newer datasets, on the other hand, such as digital elevation models (DEMs) and high-resolution satellite images, have gained immense popularity because of their many benefits (such as multi-spectral characteristics, high level of detail, and increasing worldwide coverage) (Migoń et al., 2013).

For many different applications in water resources, integrating RS and GIS has shown to be a helpful technique. They are considered very essential for groundwater studies, especially the ones considered more complicated (Al-Ruzouq et al., 2019). The prediction of groundwater potential in an area is a spatial issue. Data from several sources is needed for their application. Several parameters of hydrogeologic importance that can be derived from these data can be used to predict groundwater potential spatially (Abijith et al., 2020). Given that the Analytical Hierarchical Process requires the integration of remotely sensed and DEM-derived data to detect landforms of varying sizes, this integration has been thoroughly and successfully tested for several years. They also provide excellent versatility in combining spatial data with a range of sophisticated statistical, mathematical, and decision-making methods, including random forest (Rahmati et al., 2018), Boolean logic (Machiwal & Singh, 2015), catastrophe (Singh et al., 2018), fuzzy logic (Dashtpagerdi et al., 2013), frequency ratio models (Razandi et al., 2015; Naghibi & Pourghasemi, 2015), Analytical Hierarchy Model (Ifediegwu, 2022; Priya et al., 2022).

Numerous studies have used GIS and RS to define groundwater potential zones. Abebrese et al. (2022) used GIS and RS to map groundwater potential zones in the Bole District in the Savannah region of Ghana. Their study combined six thematic factors, soil, geology, geomorphology, drainage density, slope, and land use land cover, using ArcGIS and Erdas Imagine software. Osiakwan et al. (2022), used GIS to delineate groundwater potential zones in the Central region of Ghana. This study used RS data such as Landsat 8 images with 30m resolution, DEM, and other conventional geological and soil data for groundwater mapping. They also used statistical methods to generate the area's overburdened thickness, borehole yields, transmissivity, depth to water, water quality index, and rainfall maps. However, the factors used for the analysis were all generated in the ArcGIS environment. Again, Alimi et al. (2022) assessed groundwater potential in the Kaduna state in Northern Nigeria, using GIS and RS techniques. This study used GIS software to scan and digitize the conventional maps to produce geology and soil maps. The author used RS data in the form of SRTM DEM datasets for the analysis in the GIS environment to produce drainage density, slope, and elevation maps, which they later used for groundwater potential mapping. This study also used Landsat 8 OLI/TIRS datasets, which are remote sensing data for the generation of land use and land cover maps, as well as Normalized Difference Vegetation Index (NDVI) maps. Overall, this study considered ten factors including NDVI, geology, elevation, drainage density, rainfall, slope, fault density, distance to fault, Land use, land cover, and rainfall. These factors were all generated using GIS. Moreover, a study by Danso & Ma (2023) applied geospatial techniques to delineate groundwater potential zones in the Komenda-Edina-Eguafo-Abrem (KEEA) Municipal, a coastal municipality in the Central region of Ghana. This study considered eight factors, namely, lineament density, slope, topographic wetness index (TWI), drainage density, land use/land cover (LULC), NDVI, geology, and soil type for the groundwater potential mapping. The data used for this study were in raster and vector formats, analyzed in the GIS environment. For example, the authors created the drainage density map from the stream order map using the line density tool in ArcGIS.

Andualem & Demeke (2019) assessed groundwater potential in the Guna Tana landscape of the upper Blue Nile basin in Ethiopia, using GIS and RS. The authors considered seven factors (geomorphology, slope, drainage density, lineament density, land use land cover, soils, and geology) for groundwater potential mapping. All the datasets of the factors in this study, comprising remotely sensed and conventional data, were analyzed in the ArcGIS environment. Again, the final output comprising the groundwater potential zones was generated using the weighted overlay analysis tool in the GIS environment. Ponnusamy et al. (2022) produced a final groundwater potential map using GIS and RS techniques (overlay analysis) by integrating eight factors (geology, geomorphology, Land use and land cover type, lineament density, drainage density, type of soil, and slope gradient) in the GIS environment after employing the AHP technique and the Boolean logical model. A study was conducted by Singh et al. (2018) to assess the accuracy of GIS-based MCDM approaches for mapping groundwater potential zones. The study compared the GIS-based MCDM approach with the catastrophe technique. The result indicated an 82% accuracy of the GIS-based MCDM approach compared to a 73% accuracy for the catastrophe. The authors, therefore, concluded that despite the successes of both approaches, the GIS-based MCDM approach is superior. Adiat et al. (2012) also analyzed the accuracy of the GIS-based elementary MCDA as a spatial prediction tool, and the prediction map produced was found to be 81.25% accurate. This revealed the coherency of the approach. Similar studies have also been successfully conducted by numerous scholars and in different contexts (Ali et al., 2015; Abijith et al., 2020; Adam & Appiah-Adjei, 2019; Al-Ruzouq et al., 2019; Ibrahim-Bathis & Ahmed, 2016; Razandi et al., 2015).

Traditionally, drilling, geophysical, geological, and hydrological approaches have been the mainstays of groundwater exploration; however, these methods are costly and time-consuming. These survey techniques also don't consider the various variables that govern the flow and occurrence of groundwater (Rahman et al., 2022). Groundwater modeling is now thought to be a beneficial technique for managing groundwater resources. To guarantee a sustainable environment, it is crucial to select an efficient MCDM approach for defining groundwater potential zones and suggested management strategies at both the local and national levels (Mitra & Roy, 2023). Many methods, including logistic regression (Lee & Lee, 2015; Chen et al., 2018), multi-criteria decision analysis, frequency ratio (Razandi et al., 2015; Ozdemir, 2011), weights of evidence (Boughariou et al., 2021), decision trees (Duan et al., 2016), certainty factor, Shannon's entropy (Forootan & Seyedi, 2021), artificial neural network model, and machine learning techniques (random forest, maximum entropy, etc.) (Raju et al., 2019) are used by researchers worldwide to evaluate groundwater potential zones. Before turning into more complex and expensive surveying techniques, groundwater research can be effectively conducted using powerful tools like remote sensing and GIS that can be utilised to swiftly and inexpensively assess groundwater resources (Moodley, 2021). Groundwater potential zone development can be influenced by a variety of factors, including geology, soil type, drainage density, lineament density, slope, land use land cover (LULC), and rainfall (Mallick et al., 2015; Osiakwan et al., 2022).

2.1.5 Multi-Criteria Decision-Making (MCDM) for Groundwater Potential Mapping

We make a lot of judgments in our daily lives based on various factors and thus, it is possible to make decisions by assigning weights to numerous criteria, all of which are obtained from expert groups. Therefore, determining the structure of the problem and assessing multiple criteria are crucial (Aruldoss et al., 2013). Organising and resolving decision-making issues, and incorporating several criteria is known as multicriteria decision-making (Adiat et al., 2012). Decision-makers in many domains must handle issues methodically, accurately, and consistently according to their preferences. Since every problem necessitates a different conclusion, MCDM is very helpful. It handles complicated issues based on decision-makers' approaches to finding solutions. To enable decision-makers to understand the subject at hand, MCDM breaks down problems explicitly into smaller components (Azhar et al., 2021). Because of these advantages, MCDM is widely employed in a variety of sectors, including management, economics, medicine, the environment, energy, and many others, including groundwater. The primary goals of MCDM are to improve effectiveness, quality, rationality, and explicitness in decision-making (Briscilla & Sundarrajan, 2024).

There are various ways to view the solution to a problem. The first is that the best alternative among a range of options could be selected (where "best" is defined as "the most preferred alternative" by the decision maker). Putting the options into distinct preference groups or selecting a small number of more suitable choices is a way to conceptualize the process of solving a problem. Another way is to find all "efficient" or "non-dominated" options to be applied as an extreme interpretation (Aruldoss et al., 2013). MCDM techniques have been used in a variety of contexts to identify the optimum course of action when selecting an option. The two subcategories of MCDM techniques are Multi-Attribute Decision Making (MADM) and Multi-Objective Decision Making (MODC). For the MADM, decision makers choose, categorize, rank, or prioritize a limited set of options before determining the best options. Pairwise comparison, outranking, and distance-based are the three primary methods used in MADM (Kuru & Terzi, 2018).

The most widely used MCDM methods include AHP, which deals with complex problems that require considering multiple criteria and alternatives simultaneously. Applied in this method is the pairwise comparison matrix (Gyani et al., 2022). It primarily entails evaluating and contrasting the significance of multiple factors using a fundamental scale. The Analytical Network Process (ANP) and Analytical Hierarchy Process (AHP) are frequently used in pairwise comparisons (Liu, 2022). However, outranking techniques, on the other hand, provide several options and determine whether one is more dominant than the others. These methods work especially well when there is ambiguous or insufficient information (Alvarez et al., 2021). The Distance-based methods calculate the solution from the ideal point; the solution that is closest to this point is deemed optimal. Another MCDM method is the Fuzzy Analytic Hierarchy Process, where the decision-maker examines outranking relationships between many choices using concordance and discordance indices and then uses crisp data to select the optimal option (Liu et al., 2020). The grey theory is also another MCDM method. This theory looks at interactional analysis when the decision-making process is not clear. In this case, there are a lot of distinct and insufficient input data points. Many decision-making issues in recent years have successfully employed the Grey Theory (Javanmardi et al., 2020).

Multi-Criteria Decision Making (MCDM) is crucial in the interaction between analysts and decision-makers. Scientists and academics have used MCDM extensively to propose improved techniques for determining if groundwater potential zones are accurate (Kodihal and Akhtar, 2024). Because of the growing complexity and multiplicity of planning groundwater problems, the single objective optimization/analysis is no longer a common technique. All the environmental, geological, hydrological, and topographical obstacles to groundwater recharge are thought to be addressed using MCDM as an evaluation framework. Decision-makers can better focus on the factors and choose the optimal option based on priority with the aid of MCDM (Rane et al., 2023). A critical step in the MCDM process is weight assignment. In MCDM, assigning weights to the selected criteria/factors is challenging but fascinating. Both qualitative and quantitative data regarding the requirements are present in the weights (Thakkar, 2021). These weighting techniques fall into two categories: indirect approaches, such as weight generated through theories and mathematical models, and direct criterion weighting techniques, including scaling, ranking weight, and point allocation procedures (Ezell et al., 2021).

The process of integrating and transforming geographic data and value to produce an overall assessment for selecting the best sites for different functions is known as multi-criteria decision analysis (MCDA) and GIS (Kuru & Terzi, 2018). There is increasing interest in linking GIS technology to MCDA procedures due to its capacity to manage, process, upgrade, and store vast volumes of intricate geo-referenced data from multiple sources at multi-spatial, multitemporal, and multi-scale levels, offering a digital database for long-term monitoring and a time-efficient analysis. Weights are used to indicate the relative relevance of the criteria, and each criterion's performance for the land use under consideration is expressed as a suitability class or score (Gyani et al., 2022). Weights can be allocated scientifically or subjectively utilising a basic component analysis of yield-determining factors or expert opinion in a pairwise comparison technique.

2.1.6 Analytical Hierarchy Process (AHP) in Groundwater Studies

Decision Makers mostly struggle to decide what will help them achieve their objectives. To overcome this challenge, Thomas L. Saaty, a mathematics professor at the University of Pittsburgh, created the Analytic Hierarchy Process (AHP) technique. AHP was developed as a practical method to improve judgment in a range of circumstances, from personal contemporary difficulties to international conflicts (Saaty, 2005). It is a method of assigning weights to compare specific alternatives or criteria, and it symbolises a fundamental idea of subjective evaluation. AHP offers a flexible framework for prioritization, ranking, and decision-making that enables the hierarchy model to be managed and developed under the circumstances (Mitra & Roy, 2023).

The AHP method has been observed to be applied in geographical studies, specifically in assessing natural hazards (Morales & de Vries, 2021), mapping the susceptibility to landslides (Thomas et al., 2021), analysing flood risks (Njoku et al., 2018; Adjei-Darko, 2017), and assessing earthquake vulnerability. It has also been observed to be applied in site suitability analysis for city expansion (Ullah & Mansourian, 2016), agricultural land-use suitability identification (Akinci et al., 2013; Owusu et al., 2017; Pramanik, 2016), evaluating the quality of the eco-environment and making decisions regarding natural resources and environmental issues (Gu et al., 2022; Jiskani et al., 2021). It is one of the most popular tools for Multiple-Criterion Decision-Making (Vaidya and Kumar, 2006). According to Vargas & Katz (1990), the Analytic Hierarchy Process (AHP) is a theory of measurement for handling quantifiable and/or intangible criteria based on its rich applications in decision theory, conflict resolution, and brain modeling. It operates under the tenet that people's experience and knowledge are just as valuable when making decisions as the data they utilize (Sipahi & Timor, 2010). Its distinctive benefit is its adaptability to many methodologies, including fuzzy logic, linear programming, and quality function deployment. This makes it possible for the user to benefit from each integrated way and, as a result, better accomplish the intended goal.

AHP gives decision-makers the option of translating their subjective assessments into objective metrics. It has long been a preferred decision-making tool for study in various domains, including engineering, food, business, ecology, health, government, and many more because of its mathematical flexibility and simplicity (Vaidya & Kumar, 2006). This approach works well when making decisions in a situation where multiple factors impact the outcome (Sipahi & Timor, 2010). This methodological procedure of decision-making entails building an eigenvalue pairwise comparison matrix and applying the expertise of experts to establish the rank and weights (Saranya & Saravanan, 2020). This method is more suitable than the direct weight assignment method since the consistency of the results can be confirmed by computing the consistency ratio (Echogdali et al., 2022). Hierarchic design and evaluation are the two main components of using the AHP for decision applications. The first component implies that experience and subject-matter expertise are necessary for designing hierarchies. The identical problem would typically be organised into two distinct hierarchies by two decision-makers. Therefore, hierarchy is not exclusive.

However, even if two people create the same hierarchy, their preferences could lead to different decisions. Nonetheless, a team can collaborate to decide regarding the hierarchy (design) as well as the judgments and their synthesis (evaluation). The second component is evaluation. This is based on the paired comparison. The comparison of items within a hierarchy level is based on their respective contributions or importance to a particular criterion, which is the level immediately above the elements under comparison (Echogdali et al., 2022). However, according to Razandi et a. (2015), the process involves (1) defining the unstructured problem and objectives, (2) identifying the detailed criteria/factors and alternatives, (3) creating comparison matrices through pairwise comparisons, and calculating the consistency index of the matrices, by utilizing the eigenvalue technique to ascertain the relative weights of the decision factors. (4) The overall weights are obtained for the weight overlay analysis from which the potential groundwater map is generated. These stages need to be done with the consultation of existing literature and experts who know the study under consideration and the study area (Singh et al., 2018).

It is also worth noting that each researcher has a unique way of emphasizing the significance of the factors based on the characteristics of the context under study. For instance, a study by Andualem & Demeke (2019) on demarcating groundwater potential zones in the Upper Blue Nile basin In Ethiopia placed geology as the most significant factor and land cover as the least in their pairwise comparison matrix.

Also, Al-Ruzouq et al., (2019), in their research on mapping groundwater potential zones in the North UAE made precipitation the most significant factor and slope the least significant. Abijith et al. (2020), on their groundwater potential mapping in India, made Geomorphology the most significant factor and rainfall the least. The authors established that even though India receives a substantial amount of annual rainfall with an average of 1100 mm, their spatial distribution is uneven resulting in the lack of normal rainfall in some regions even during monsoon which causes water scarcity

At the heart of the AHP process is the pairwise comparison matrix. This matrix is done by considering two factors at a time. The two factors are scored based on their relative influence on groundwater occurrence (Adiat et al., 2012). It is possible to create pairwise comparison matrices by contrasting the top-level items with those at the middle and bottom levels. In pairwise comparisons, the weighting of the factors is subsequently assessed using the fundamental scale of importance. An extension of the AHP process is the ANP process. The network structure of ANP enables decision-makers to make choices in challenging circumstances. The decision criteria and options in ANP are not dependent on each other, unlike in AHP (Saaty, 2005). The top-level and low-level elements must interact and depend on one another to solve some real-world issues. In this instance, ANP promotes relational reliance among the elements, making it more effective than AHP. However, implementing ANP necessitates lengthy brainstorming sessions and a high level of knowledge among those involved. Another disadvantage of ANP is its complexity, which requires the usage of extra software like Expert Choice, Super Decisions, and Decision Lens (Sipahi & Timor, 2010).

2.2 Theoretical Framework

2.2.1 A framework of impact on sustainable water (irrigation) systems

The conceptual framework embedded in this research is the Social Ecological System framework. Scholars have developed many models and frameworks to depict the complex and intertwined aspects of water issues. These include the Social-ecological systems Framework (SESF) (Godden & Ison, 2019), the management and transition framework (Pahl-Wostl et al., 2010), the ecohydrology, socio-hydrology, and economic and hydrologic models. These models and frameworks aim to integrate socioeconomic, ecological, and physical factors into agricultural water management (Partelow, 2018). Elinor Ostrom created the Social-Ecological System Framework (SESF), which is arguably the most popular and frequently mentioned framework (Sarami-Foroushani et al., 2024). Among the various frameworks, the Socio-Economic Systems Framework (SESF) is the most comprehensive conceptual framework for diagnosing interactions and results in a wide range of empirical contexts, including systems for producing food, aquaculture, conservation on land, management of rangelands and watersheds, marine conservation, management of marine ecosystems, coastal development, irrigation systems, energy systems, and pollution control. Beyond just identifying social actors, SESF aims to incorporate both human and non-human actors into dynamic networking systems (e.g., humans, other species, institutions, infrastructural structures, concepts, and documents).

Understanding the function of integrated social-ecological systems has advanced significantly over the past few decades, with a focus on the significance of inhabitants' active engagement, knowledge, and aspirations. It also places underground water resource systems within a socio-ecological framework and obtains input to enhance the system (Sarami-Foroushani et al., 2024). Despite its popularity, the theory's applicability to empirical analysis was questioned. Therefore, Hale et al., (2015) developed iSAW (Integrating Structure, Actors, and Water), a practice-based model that illustrates the dynamic interplay between natural and human (social) components. According to the iSAW, two components operate in structured environments, and the three primary components of the structure (natural, built, and social) link the outputs of the water system, which are quality and quantity, and the human actors (individual and organizational) who operate in them across various temporal and spatial scales. This concept states that irrigation systems, as constructed elements and infrastructure, mediate the qualities and quantities of the water system as well as the consequences of the water for human well-being and other structural elements.

To facilitate knowledge sharing for water management planning and decision-making within this framework, scholars have used a variety of platforms and techniques, including participatory GIS, co-engineering, multi-stage fuzzy-stochastic programming, multi-level and multi-objective water allocation models, multi-criteria decision-making methods, SWOT (strengths, weaknesses, opportunities, and challenges), and/or PESTLE (political, economic, social, technological, legal, and environmental) analyses. One potential method that has garnered a lot of attention for weighing choices against several criteria for water resource management decisions is multiple criteria analysis (MCA).

A substantial amount of research has confirmed that MCA, a useful instrument for managing water resources, makes decision-making more rigorous, transparent, audible, and structured (Abe & Ersado, 2022; Adiat et al., 2012; Agarwal & Garg, 2016; Anteneh et al., 2022; Emami & Shahamat, 2022; Karimi et al., 2019; Li & Chen, 2020; Owusu et al., 2017; Singh et al., 2018). AHP was chosen for this study because it can break down large, complicated, unstructured challenges in water management into smaller, more manageable evaluations without losing sight of or complicating the decision-making process.

CHAPTER THREE

METHODOLOGY

3.0 Research Timeline

The project spanned eleven months, primarily during the second semester of the final year, from February 2024 to the final presentation on December 11, 2024. However, the initial steps such as identifying the research topic and consulting with the supervisor occurred before the second semester. The research proposal outlining the study's scope, including the problem, objectives, questions, and methodology, was drafted in February and approved in the first month. Since this research did not involve collecting primary data through a survey, secondary data sources were reviewed in March 2024 to confirm their availability before the analysis phase. Additionally, experts were consulted for validation and input on the factors used in the multicriteria analysis after all data had been gathered and during the final stages of analysis.

3.1 Research Method

This study utilized a quantitative research method, facilitating the integration of geospatial and mathematical computations. Geospatial data were treated as quantitative due to their reliance on coordinates that can be calculated and analyzed mathematically, despite containing some descriptive elements. Using remote sensing data at various spatial, spectral, radiometric, and temporal resolutions enables the collection of precise, cost-effective, automated, near-real-time information, even in remote locations across the globe (Sarwar et al., 2021).

3.2 Data Sources and Collection

The central objective of this research was to delineate potential groundwater zones through the application of Multi-Criteria Decision-Making Making combined with the Analytical Hierarchical Process (MCDM-AHP) within a Geographic Information System (GIS) environment. Data for this analysis was gathered from various sources and included both raster and vector formats. Land use data for 2022 of sentinel-2A with 10m spatial resolution was acquired from the United States Geological Survey (USGS). The rainfall data of Ghana was downloaded from the National Oceanic and Atmospheric Administration (NOAA) and provided in Excel format. The dataset also included the elevation of the meteorological stations, with the station located within the study area at an elevation of 340 meters. Soil data were sourced from the Food and Agricultural Organization (FAO) Digital Soil Map of the World. Geological information for the study area was obtained from the Ghana Geological Survey Authority. The Shuttle Radar Topographic Mission Digital Elevation Model (SRTM-DEM) data, used to analyze slope, Topographic Wetness Index (TWI) lineament density, and drainage density within the municipality, were acquired from the United States Geological Survey (USGS) at a 30-meter spatial resolution.

Digital Elevation Models (DEMs) have proven to be valuable tools for assessing the topography of a given area (Prasad et al., 2020). DEM is often recorded in raster format and obtained by the Shuttle Radar Topography Mission (SRTM) or ASTER sensors (Mousavi et al., 2017; Rahmati et al., 2018). Digital elevation data are typically used to extract topographic data (Thanh et al., 2022). Population density data for Ghana for the year 2022 was sourced from the Ghana Statistical Service (GSS). Additionally, shapefiles for the study area, including tarred roads, cities, and rivers within the region, were acquired from the Diva GIS website. The table below summarizes the data, including their sources and formats.

Table 1: *Data, format, and source*

No.	Data	Format	Source
1.	Topography (DEM)	TIFF	USGS
2	Geology	Shapefile	Ghana Geological Survey Authority
3	Rainfall	Excel	NOAA
4	Land use	Shapefile	ESRI land cover map
5	Soil Type	Shapefile	FAO digital soil map
6	Population Density	TIFF	GSS
7	Study area, roads, rivers	Shapefile	Diva GIS

3.3 Methodological Framework

In pursuit of the study's objectives, a Multi-Criteria Decision-Making (MCDM) analysis was conducted using QGIS 3.34.4 and ArcGIS Pro. All datasets were projected to the WGS 1984 UTM Zone 30N coordinate system, aligning with the study area to facilitate uniform data extraction and operation execution. Based on extensive literature and groundwater expert consultations, eight factors were selected for delineating potential groundwater zones (Abijith et al., 2020; Thanh et al., 2022; Ali et al., 2021; Ali et al., 2015; Sarwar et al., 2021; Danso & Ma, 2023; Abebrese et al., 2022). The factors included Geology, soil type, Land use, TWI, slope, lineament density, rainfall, and drainage density. These factors were reclassified and weighed according to their significance in contributing to groundwater potential, providing a comprehensive basis for identifying high-potential zones within the study area.

Topographic features impacting groundwater potential zones, namely Slope, Topographic Wetness Index (TWI), Lineament Density, and Drainage Density were derived from the Digital Elevation Model (DEM) within the GIS environment. These features were processed and refined through necessary preprocessing steps to achieve accurate outputs. The geology, soil type, and land use data were pre-generated datasets obtained from external sources. The land use data was extracted from a land use data tile covering Ghana, while soil type and geology data were specifically derived from Ghana's national geology and soil type datasets. The extractions were done using the intersection tool within the GIS environment for precise alignment with the study area.

Rainfall data, initially in Excel format, was converted from .xlsx to .csv format to enable its use within the GIS environment. Point features representing seventeen rainfall stations across Ghana, including Wenchi municipality, were loaded into GIS. Data processing and Inverse Distance Weighted (IDW) interpolation were applied to transform the point features into polygons within ArcGIS Pro.

All data underwent projection alignment and resampling to improve resolution, particularly for rainfall data. Each factor was reclassified to assign numerical values to replace the individual nominal classes. These reclassified factors were then combined into a single evaluation index using a multicriteria analysis method, the Weighted Linear Combination (WLC). The Analytic Hierarchy Process (AHP) technique incorporating the pairwise comparison matrix was used to correctly assign weights to each factor. **Figure 2** below presents the methodological workflow of the study.

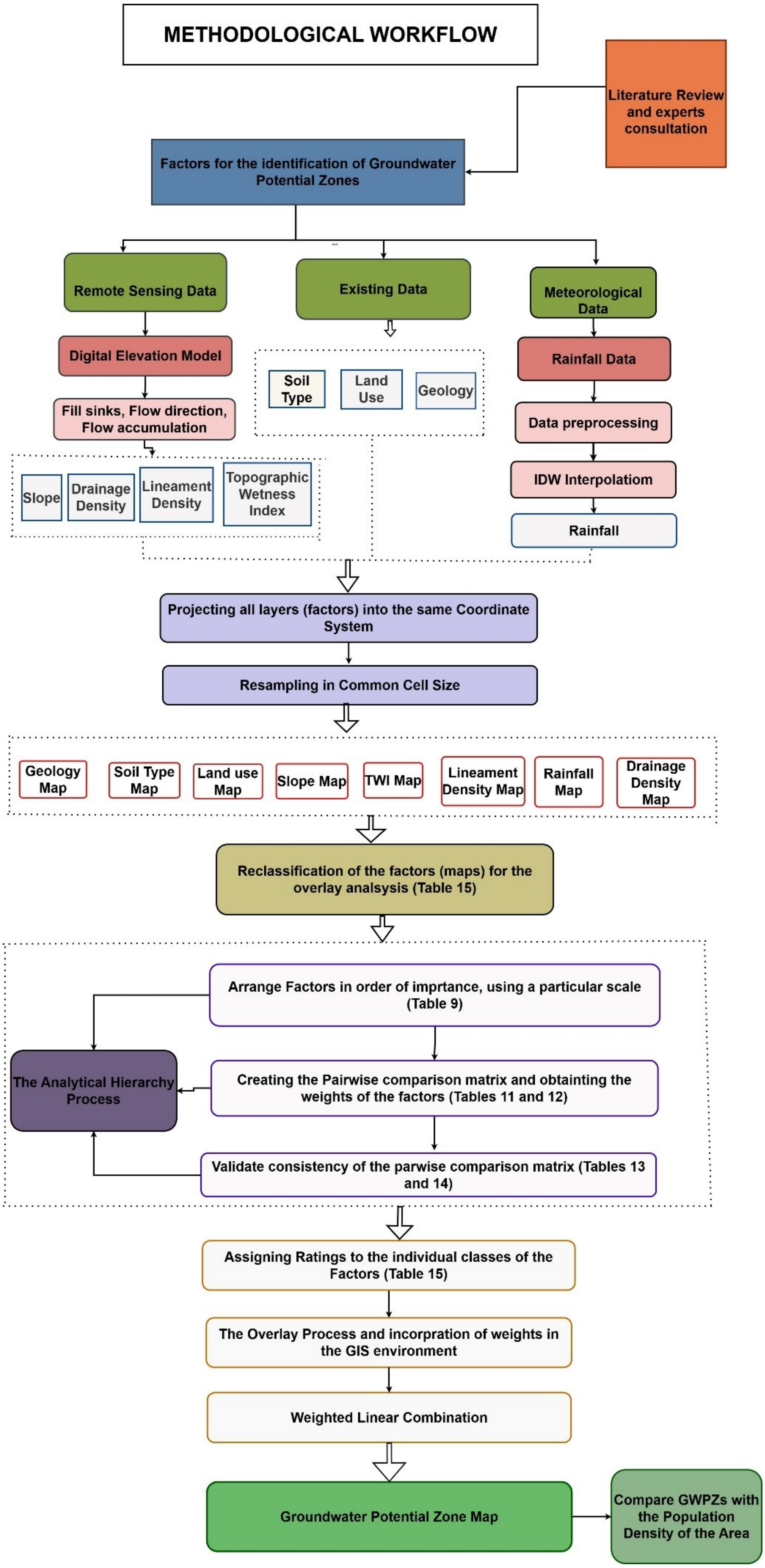

***Figure 2**: Methodological workflow (Authors construct)*

3.4 The Multi-Criteria Decision-Making Analytical Hierarchical Process (MCDM-AHP)

The Multi-Criteria Decision-Making Analytical Hierarchy Process (MCDM-AHP) model evaluates complex problems by considering multiple related factors. In this approach, MCDM-AHP assigns weights to each variable, reflecting its relative importance in the decision-making process. This weighting is based on pairwise comparisons of factors, allowing for a structured evaluation that prioritizes certain elements according to their impact on the outcome. The MCDM-AHP model is widely used in groundwater potential zoning and similar studies to systematically assess the influence of diverse factors (Saha, 2017). In the MCDM-AHP model, variables are evaluated on a scale of 1 to 9, considering their relative impact on each other. This enables hydrogeologists in the Groundwater Potential (GWP) field to effectively identify and prioritize factors affecting groundwater resources. A key advantage of the MCDM-AHP model is its efficiency in delivering results with minimal errors.

Additionally, the model's flexibility in adjusting factor weights makes it adaptable to various needs and contexts. However, a limitation of the model is its subjectivity, as the assigned weights depend on expert judgment. This reliance on expert opinion can introduce bias, which may affect the accuracy of the results. Nonetheless, the structured framework of MCDM-AHP remains valuable for studies requiring nuanced decision-making across multiple variables. (Singh et al., 2018). GIS technologies are commonly integrated with the MCDM-AHP model for effective Groundwater Potential (GWP) zone modeling.

In this process, the Analytic Hierarchy Process (AHP) typically involves four main steps according to Andualem & Demeke, (2019). 1) Establish the factors related to GWP and create the necessary hierarchy. A total of eight factors were identified for the Groundwater Potential zoning (slope, rainfall, Drainage Density, Lineament Density, Land use, soil type, geology, and TWI). These factors were identified based on literature and groundwater expert consultation. The factors were arranged in order of importance from most to least significant. This was done through the consultation of several groundwater experts, including those in academia and those in the field. 2) Organizing the factors in a hierarchical structure. After several consultations with groundwater experts, the factors were arranged as Geology, Soil type, Land use, TWI, Slope, Lineament Density, Rainfall, and Drainage Density. 3) Comparing the criteria in pairs on a scale (usually 1 to 9) to assess their relative importance. This generates a matrix used to calculate the weight for each criterion based on its impact on the objective. For this study, a pairwise comparison matrix was created in Excel to assign weights to the factors. Again, the factors were paired against each other, and weights were assigned to the most important. This is shown in **Table 11** below. 4) Validate the constancy of the pairwise comparisons. To ensure the accuracy of the arrangement of the factors and the weights assigned to them the principal eigenvalue was computed, using the eigenvector technique. A consistency ratio is calculated to ensure logical coherence in expert judgments The Consistency Index and Consistency Ratio were calculated using the equation below.

Consistency Index =(λmax-n)/(n-1) where n is the number of factors used in the analysis and λmax is the principal eigenvalue of the matrix.

Consistency Ratio =CI/RCI where CI is the consistency ratio calculated above and RCI is the Random Consistency Index which can be found in the standard table provided by (Saaty & Katz, 1990). The consistency ratio should be kept below 10% for the weights assigned to the factors to be considered reliable. If the ratio exceeds 10%, the experts will need to revisit and adjust the factor weightings. The groundwater experts prioritized the factors, assigned the weights, and developed the pairwise comparison matrix, with most of these tasks carried out by experts from the Council of Scientific and Industrial Research in Kumasi.

3.5 Groundwater Expert Consultation

3.5.1 Profile of the Groundwater Experts

The consultation with groundwater experts was crucial to ensure that the factors included in the analysis and the weights assigned in the Pairwise Comparison Matrix accurately reflected the characteristics of the study area. To achieve this, four experts from both academia and the field were consulted. These experts collectively determined which factors should be included and which were less relevant. The first expert consulted was a professor from the Civil Engineering Department and the Deputy Director of the Regional Water and Environmental Sanitation Centre Kumasi (RWESCK) at Kwame Nkrumah University of Science and Technology. This professor specializes in hydrogeology, groundwater irrigation, and its impact on rural livelihoods and agricultural water management, particularly in the rural areas of Ghana.

The second expert, who played a key role in selecting the factors, is a research scientist at the Water Research Institute of the Council for Scientific and Industrial Research (CSIR) in Accra, Ghana. He is also a part-time lecturer in the Department of Meteorology and Climate Science at Kwame Nkrumah University of Science and Technology.

The third expert is a post-doctoral researcher at the Kwame Nkrumah University of Science and Technology, specializing in climate change and land use in Ghana.

The final groundwater expert, who provided significant and consistent contributions throughout the study, is a research scientist at the Water Research Institute of CSIR. Specializing in hydrogeology and machine learning applications, this expert has led numerous groundwater projects in the study area and played a crucial role, particularly during the development of the pairwise comparison matrix.

3.5.2 Expert Meeting Arrangements

Upon referral to these experts, an email was sent to request their participation in the process. Once they agreed to assist with the research, an invitation detailing the purpose of the meeting and suggesting potential times was sent. A consensus on a suitable meeting time was reached, and Zoom meetings were scheduled to finalize the factors. These discussions took place during the proposal writing phase. In total, three meetings were held with all four experts at different times. During the first meeting, the experts were provided with a brief introduction to the research's objectives and a proposed list of factors to be included. Following this, they shared their opinions on both the overall objectives and the factors involved. The experts suggested that they be given additional time to conduct further research to confirm their decisions. During the second meeting, all the experts presented their views on each of the proposed factors, highlighting those they considered most significant. They also shared their recommendations on how the analysis could be conducted more effectively. Additionally, they proposed scheduling another meeting during the process of conducting the pairwise comparison matrix.

In the final meeting, the factors were organized based on their significance, and the corresponding weights were assigned through open discussion, with each expert justifying their suggested weight. The experts demonstrated a high level of dedication and support throughout this stage of the research. The fourth expert played a crucial role, especially during the pairwise comparison matrix process, thanks to his in-depth knowledge of the study area.

All the experts contributed constructively based on their areas of expertise, making the process invaluable in ensuring the accuracy of the factors selected for analysis. They also provided valuable recommendations, such as pointing out that the initially generated geology data was incorrect and directing me to a more accurate source. This collaborative effort ensured the reliability of the factors and data used in the research.

3.6 Data Analysis

A preliminary analysis was conducted on each of the factors identified for mapping the groundwater potential zones in the Wenchi municipality. Eight factors including Geology, soil type, land use, Slope, TWI, Lineament Density, Rainfall, and Drainage Density, were analyzed for groundwater potential zoning. This gave insight into the characteristics of the factors and how they contribute to the mapping of the groundwater zones as well as the pairwise comparison matrix. In the sections below is a detailed analysis of the eight factors, a pairwise comparison matrix, and the generation of the groundwater potential zones.

3.7 Description of the Factors

Multiple factors, both natural and human-related, influence and regulate groundwater potential zones. Natural factors such as geology, lineament density, slope, Topographic Wetness Index (TWI), rainfall, soil type, and drainage density play a key role in groundwater occurrence. In contrast, human activities significantly affect land use, which is considered a human-related factor. Furthermore, such anthropogenic changes can notably impact groundwater quality. Consequently, it is essential to examine the combined factors used in the generation of the final Groundwater Potential map. This section first outlines the factors and their relationship to groundwater recharge. The study examines the key factors that significantly influence groundwater in the study area, including geology, soil type, land use, Topographic Wetness Index (TWI), slope, lineament density, rainfall, and drainage density. Groundwater occurrence and movement are primarily governed by the underlying geology, landforms, soil characteristics, lineament density, and drainage features, while recharge is primarily influenced by precipitation, land use/land cover types, and the rate of infiltration (Ifediegwu, 2022). Examining the factors governing groundwater flow, storage, and occurrence is useful in groundwater potentiality modelling.

3.7.1 Geology

Understanding a region's geology improves understanding of the texture, structure, porosity, and permeability of Earth's materials. It provides insights into whether a particular area can absorb and retain water (Al-Ruzouq et al., 2019). The importance of geology for groundwater recharge has been repeatedly confirmed (Danso & Ma, 2023; Ifediegwu, 2022). Geology fully impacts the penetration and percolation of groundwater (Ponnusamy et al., 2022). It is, therefore, an essential factor to consider when evaluating groundwater potential. High permeability and porosity of the geologic units improve groundwater storage and yields. Geological zones characterized by alluvium and limestone are generally favorable for groundwater. Additionally, the nature and intensity of runoff vary depending on the geomorphological layers of the land. For example, sand, which absorbs water more rapidly than asphalt or concrete pavements, results in significantly higher runoff in urban areas, where these materials dominate, compared to sandy regions (Al-Ruzouq et al., 2019).

The Birimian Supergroup predominantly covers the Precambrian basement in the study area. Most of the rocks within the Birimian Supergroup consist of volcanic and metavolcanic materials, which form belts extending from southwest to northeast, interspersed with low-grade metamorphosed and folded sediments. During the Eburnean orogeny, large granitoid masses were intruded into the highly foliated rocks (Tay, 2021). These rocks are extensively deformed, exhibiting complex folding and faulting because of tectonic stress. Due to their pronounced folding, foliation, and jointing, along with intense weathering along fractures and other weak zones, such as bedding and cleavage planes, these rocks facilitate the formation and accumulation of groundwater (Tay, 2021).

The Eburnean Plutonic Suite consists of crystalline rocks, including granites, diorites, granodiorites, tonalites, and gabbros. These rocks facilitate secondary permeability for groundwater through processes such as fracturing and faulting. The Mesozoic rocks in the area are primarily composed of sandstones. Their granular texture and relatively high porosity promote primary permeability, while secondary permeability also occurs in regions affected by dissolution and fracturing, particularly where tectonic activity has occurred.

The Voltaian Supergroup and Kwahu-'Morago Group consist of sedimentary rocks, including sandstones, conglomerates, mudstones, and siltstones. Sandstones within the Kwahu-Morago Group exhibit high primary permeability due to their granular texture and relatively high porosity. Well-sorted, clean sandstones feature substantial interconnected pore spaces that enhance fluid flow. Secondary permeability, resulting from fracturing, jointing, and other structural features, further improves fluid flow pathways. In contrast, mudstones display both low primary and secondary permeability due to their fine grain composition and compactness. Siltstones exhibit moderate primary permeability, which is lower than that of sandstones but higher than that of mudstones. Their fine grain size results in moderate porosity and permeability, but like mudstones, they have limited secondary permeability and only happen when they are extensively fractured. The conglomerates can exhibit high primary permeability due to their coarse-grained nature and the presence of interconnected pore spaces between the larger clasts. Secondary permeability can be further enhanced if the matrix or the clasts are fractured, providing additional pathways for fluid flow. Due to their high permeability, the sandstone and conglomerate rock types within the Kwahu-Morago Group are likely to serve as good aquifers. They can store and transmit significant quantities of groundwater. Meanwhile, mudstones and siltstones act as confining layers, impacting the groundwater's vertical and lateral flow. They can create perched aquifers or contribute to the confinement of deeper aquifers. Due to its substantial influence on groundwater potential, experts ranked geology as the most significant factor in the multicriteria decision analysis for groundwater potential mapping. The geology of the study area was extracted from the geology map of Ghana. The process involved intersecting the study area shapefile with the Ghana geology shapefile. A specific symbology was applied to enhance the clarity of individual geological components, thereby facilitating the identification of their distinct characteristics within the study area.

The dominant geologic type in the study area is the Birimian Supergroup, which covers an area of 510.9 km², accounting for 44.6% of the total area. It is followed by the Voltaian Supergroup, and Kwahu-'Morago Group covering 428km² (37.4% of the study area). Eburnean Plutonic Suite also covers 120.5km² (10.5% of the study area), and the Mesozoic covers 85.1km² (7.4%). A summary of the geological types and their corresponding area is presented in (**Table 2)** below. **Figure 3** shows the map of the geologic types of the study area.

Table 2: *Geology types and their area*

Geological types	**Area (km²)**	**Percentage**
Birimian Supergroup	510.9	44.7
Eburnean Plutonic Suite	120.5	10.5
Mesozoic	85.1	7.4
Voltaian Supergroup, Kwahu-'Morago Group	428	37.4
Total	**1142**	**100**

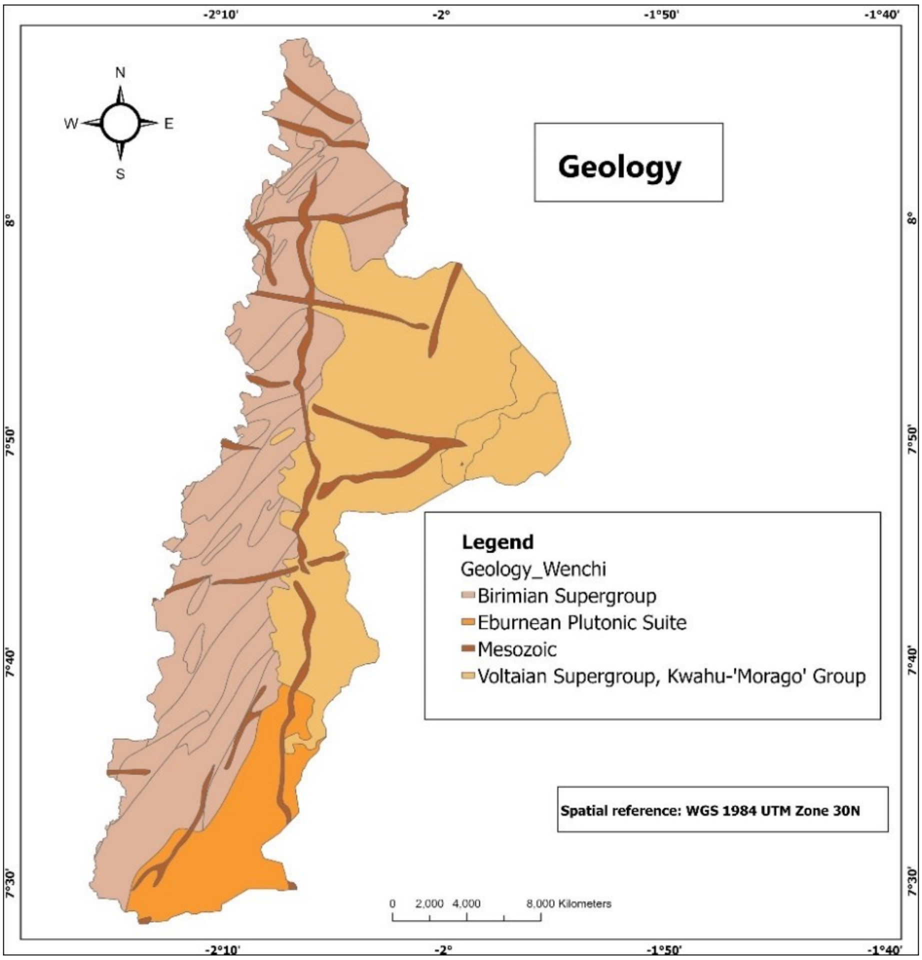

Figure 3: *The geology of the area*

3.7.2 Soil Type

Soil type, determined by the processes of pore saturation or desaturation, influences the rate of water infiltration into the ground. The porosity of different soil types dictates the volume of water that can permeate the ground. Soil types with a coarser grain matrix, such as lithosols, typically exhibit greater groundwater potential compared to fine-grained soils (Ifediegwu, 2022).

The study area is covered by four primary soil types: lixisols, gleysols, leptosols, and acrisols. Lixisols are the most prevalent soil type in the region. The texture of lixisols varies depending on the underlying parent material, ranging from sandy loam to silty clay. Typically, the upper soil profile is characterized by a higher clay content, with coarser material becoming more dominant at greater depth. Like lixisols, acrisols can be found across a variety of parent materials but are predominantly located on older land surfaces with gently undulating topography, such as the bases of scarps. The subsoil of these soils generally contains a higher clay content than the topsoil. While silty and clay loams are intermittently present, sandy loams make up the majority of the Acrisols. In the B horizon, which is rich in clay, acrisols in the area typically exhibit low to moderate permeability, affecting both the rate of groundwater recharge and the movement of water through the soil profile. Despite their limited permeability, Acrisols can retain substantial amounts of water, particularly in the clay-rich subsoil (P.C. et al., 2021). Leptosols typically develop as shallow soils on upland or mid-slope areas. They are commonly found in gently undulating regions, such as the high plains of the Precambrian basement, the rim of the Voltaian sedimentary basin, or the Akwapim-Togo Range. These soils are generally composed of loamy sand and sandy loam, with occasionally gravelly appearances. The permanent or seasonal water saturation capacity of Gleysols plays a significant role in groundwater recharge processes. Due to their clay-rich composition and frequent waterlogging, Gleysols typically exhibit low to moderate permeability (Tsbf-ciat et al., 2008). This factor affects the rate at which water infiltrates and replenishes groundwater aquifers. Due to soil type's importance in determining groundwater potential, experts ranked it as the second most significant factor in the multicriteria decision analysis for groundwater potential mapping. The soil type of the study area was extracted from the soil type map of Ghana. The process involved intersecting the study area shapefile with the Ghana soil type shapefile.

The results from the soil type map extracted from the soil map of Ghana show that the area is predominantly made up of Lixisols covering 861km² (75.4% of the area) and Acrisols, 275.5 km² (24.1% of the area). However, gleysols and leptisols also exist to a lesser extent (4.3km² representing 0.4% and 1.2km² representing 0.1% respectively). These soil types differ in terms of their mechanical, chemical, physical, and water-physical characteristics. This may help maintain the availability of groundwater during periods of drought. The most common soil type in the study area is the lixisol which extends from the northern and almost to the southern part of the Wenchi municipality. **Table 3** below summarizes the soil types and the area they cover. The soil type map can also be found in **Figure 4.**

Table 3*: Soil type and their area*

Soil type	**Area (km²)**	**Percentage**
Acrisols	275.5	24.1
Gleysols	4.3	0.4
Leptosols	1.2	0.1
Lixisols	861	75.4
Total	**1142**	**100**

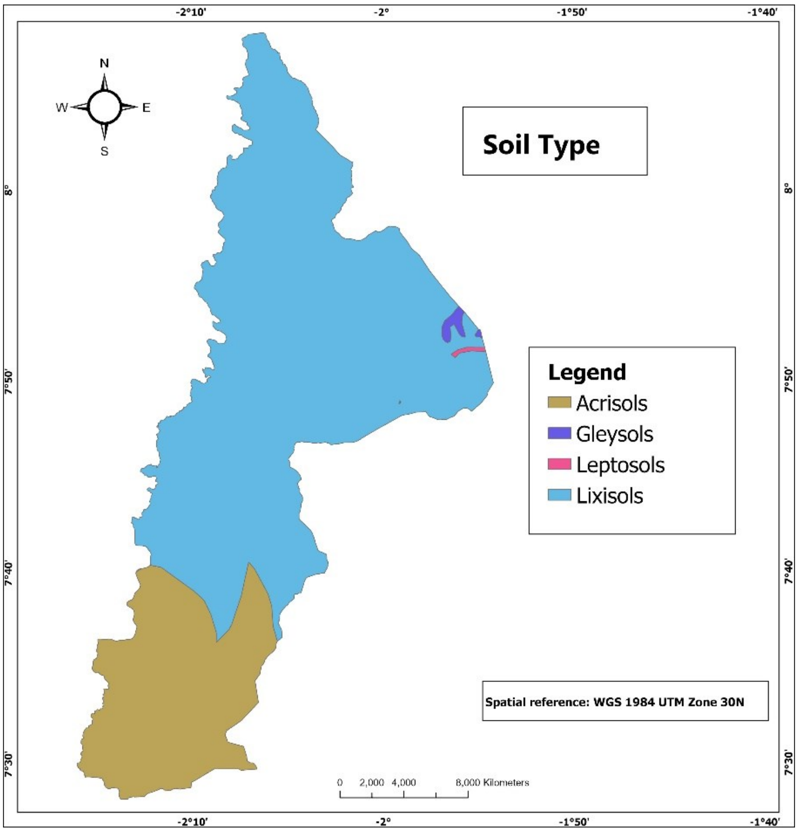

Figure 4: *Soil type of the area*

3.7.3 Land use

The pattern of land use and cover is one of the most crucial factors influencing surface runoff because it affects evapotranspiration, penetration, and condensation, all of which are influenced by soil wetness and vegetation type. Patterns of land use and cover significantly influence groundwater recharge. Human activity has a major impact on the land cover pattern and use (Ponnusamy et al., 2022). It consequently has a major effect on groundwater recharge. Vegetation cover plays a crucial role in minimizing water loss by reducing surface runoff. Studies have shown that soil surfaces with dense vegetation cover exhibit higher infiltration capacity compared to barren areas. Conversely, urbanized regions and settlements may reduce groundwater recharge, as paved surfaces impede water infiltration into the soil (Das & Pal, 2019). On the other hand, surface water provides the greatest opportunity for water infiltration, as most river catchments exhibit efficient hydraulic connectivity with the underlying aquifer system. As a result, surface water percolation is expected to be higher beneath water bodies (Mishra &

Singh, 2019). Due to its importance in determining groundwater potential, experts ranked it as the third most significant factor in the multicriteria decision analysis for groundwater potential mapping.

The land use data for the study area was extracted from a tile representing the land use of Ghana by intersecting the study area shapefile with the land use data tile covering the entire country, utilizing the "Intersect" tool within the Spatial Analyst toolbox. The land use map of the Wenchi municipality reveals that the area is characterized by five distinct land use types: water bodies, dense vegetation, sparse vegetation, built-up areas, and farmlands. The area is predominantly covered by farmland indicating an area of 589.5km² of land (51.6%). It is followed by dense vegetation covering 478.5km² of land (41.9% of the study area). Sparse vegetation and built-up covers only 37.8km² (3.3%) and 36.2km² of the study area (3.2%), respectively. Although a water body is present in the area, its size is minimal, covering only 0.03 km², which is negligible (0%) in comparison to the other land use types. A summary can be found in the (**Table 4**) below. The area contains few built-up zones, reflecting a low level of infrastructure development, such as concrete roads. The green areas are indicative of moist soil conditions and high groundwater potential. This is because tree cover acts as a protective canopy, shielding groundwater from the adverse effects of extreme climatic conditions. **Figure 5** below shows the map of the land use of the area.

Table 4: *Land use types and their area*

Land use type	**Area (km²)**	**Percentage (%)**
Waterbodies	0.03	0.0
Dense Vegetation	478.5	41.9
Sparse vegetation	37.8	3.3
Built-up	36.2	3.2
Farmlands	589.5	51.6
Total	**1142**	**100**

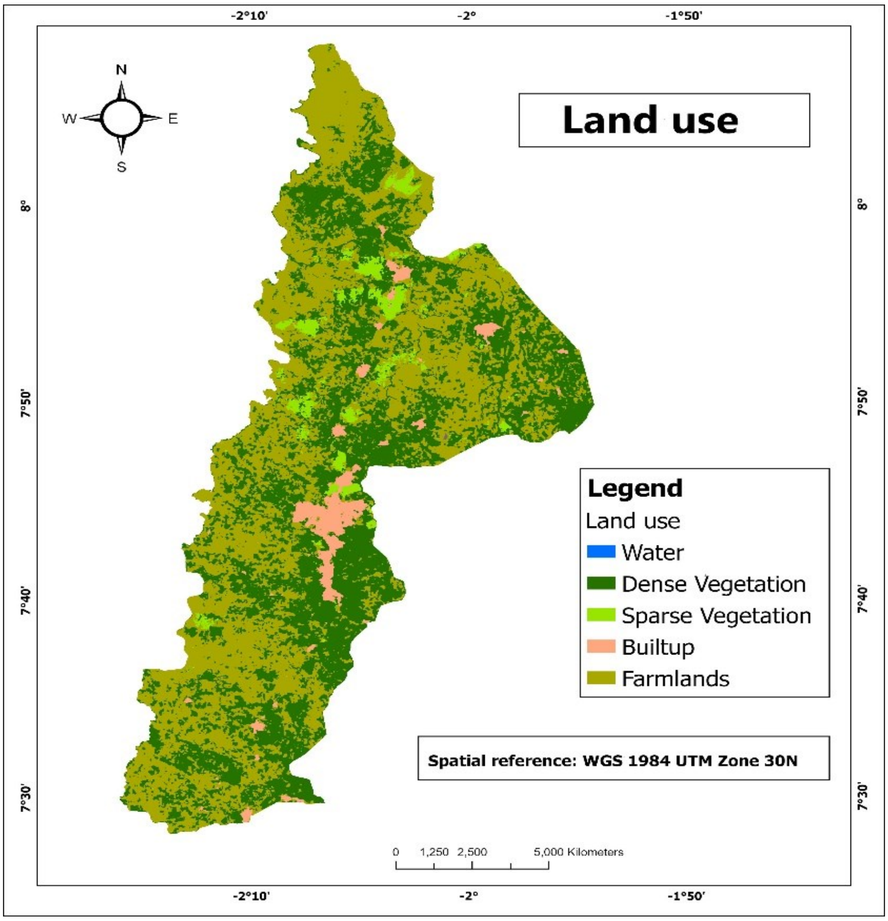

Figure 5: *The land use of the area*

3.7.4 TWI

The Topographic Wetness Index (TWI) is utilized to assess the influence of topography on hydrological processes, such as waterlogging. It quantifies the extent of flow accumulation at a given location within a watershed and reflects the tendency of water to flow downslope under gravity, which accelerates flow accumulation and helps define the wetness conditions of a region (Abdekareem et al., 2022). It is commonly used to characterize the influence of topography on the spatial distribution of water and its effect on soil conditions (Chen et al., 2018). The TWI is a secondary topographic index commonly used to describe how topography influences the location and extent of saturated source zones that contribute to surface runoff (Razandi et al., 2015). It is a popular unitless index mostly applied in Groundwater Potential zone mapping processes (Rahman et al., 2022). This index accounts for both the potential for water to accumulate at a given location within the catchment and the gravitational tendency for that water to flow downslope. It quantifies the extent of water accumulation at a specific pixel within the study area (Rahmati et al., 2018).

The TWI was generated using the DEM within a GIS environment. The process began with the filling of sinks as a preprocessing step. The resulting output from the filled sinks was then used to compute the flow direction, flow accumulation, and slope. Additionally, the raster calculator was employed to calculate the Specific Catchment Area (SCA) using the expression: SCA = (Flow Accumulation * (cell size^2). Finally, the TWI was derived using the formula: TWI = ln (“SCA” / tan(“β”)).” Where β is the slope of the area. In other words, TWI = ln (“SCA” / tan(“slope”).

The TWI values of the study area range from 4 to 23. It was grouped into five classes including 4-7 (very poor wetness), 7.1 - 8.7 (poor wetness), 8.8 - 11 (Good wetness), 12 - 14 (Very Good), and 15-23 (Excellent). Although the area exhibits low wetness, the values are not extremely low, indicating the potential for groundwater accumulation. Based on expert assessments, the TWI of the study area was ranked as the fourth most significant factor in the multicriteria decision analysis for groundwater potential mapping. **Figure 6** below is the TWI map of the area.

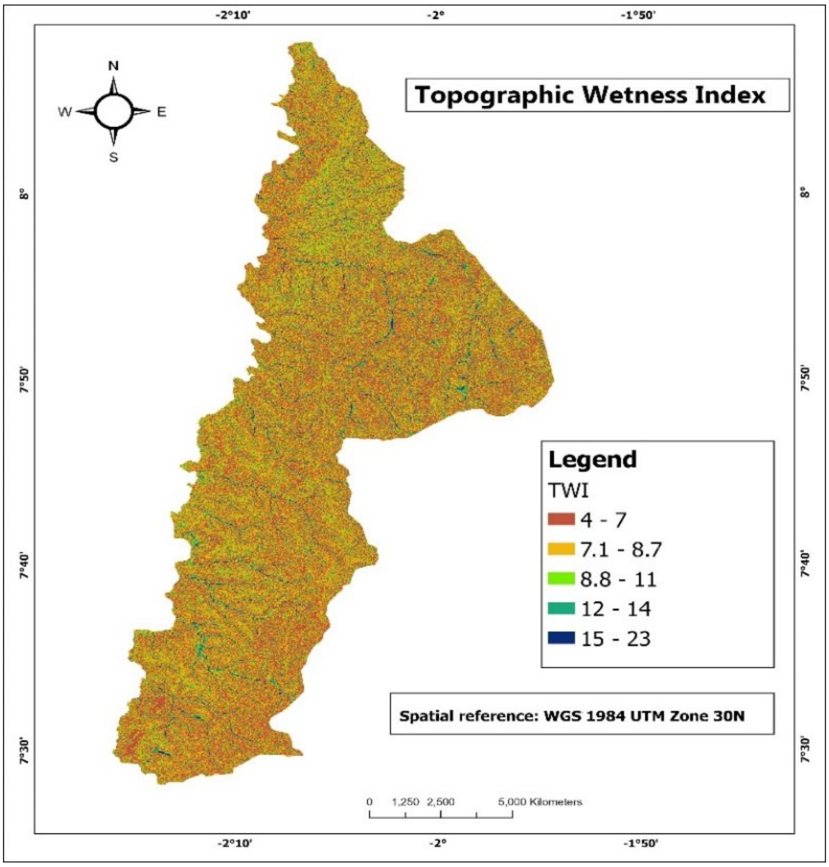

Figure 6: *The Topographic Wetness Index of the area*

3.7.5 Slope

Slope plays a critical role in groundwater recharge as it directly influences surface runoff dynamics. The slope of an area is a key factor in defining its surface morphology, which, in turn, controls the velocity of surface runoff and the extent of erosion activity (Ponnusamy et al., 2022). Both flat and steep slopes can influence groundwater potential, as groundwater tends to follow patterns similar to those of surface water. Research indicates that areas with low slopes have a higher likelihood of retaining groundwater due to reduced surface runoff and greater water infiltration (Das et al., 2022). However, water flowing down steeper slopes tends to move more rapidly, resulting in significantly reduced infiltration rates (Thapa et al., 2018). As a result, areas with gentle slopes provide more time for water to infiltrate the soil. While regions with steep slopes typically have high levels of soil runoff and rapid meteoric water evaporation by directly impacting water or rainfall. Areas with low slopes have negative surface runoff and positive percolation rates. Therefore, the slope degree of an area controls vertical percolation, which is influenced by surface flow velocity and groundwater recharge (Thanh et al., 2022).

The slope of the study area was derived from the DEM using the slope tool within the Spatial Analyst tools in ArcGIS Pro software. This factor provides insights into the degree of gentleness or steepness of the topography across the study area. From the analysis, the identified slope categories range from 0.1º to 34.9º in the study area and are grouped into five classes. 0.1 - 2.2º (flat), 2.3 - 4.1º (gentle), 4.2 - 6.6º (moderately steep), 6.7 - 12.3º (steep), and 12.4 - 34.9º (very steep). The area identified as flat occupies 400.5km² (35.1%), the gentle area occupies 429.5km² (37.6%), the moderately steep sloping areas occupy 242.4 km² (21.2%), steep areas occupy 62.7km², (5.5%) and the very steep slopes occupy 6.9km², which is only 0.6% of the study area. The summary can be found in the (**Table 5**) below. The results indicate that the area is predominantly flat or gently sloped, making it favorable for water percolation and suggesting high groundwater potential zones. Based on expert judgment, the slope of the study area was ranked fifth in terms of significance among the factors influencing groundwater potential. **Figure 7** below shows the slope of the study area.

Table 5: *Slope classes and their area*

Slope length (degrees)	**Area (km²)**	**Percentage**
0.1-2.2	400.5	35.1
2.3-4.1	429.5	37.6
4.2-6.6	242.4	21.2

6.7-12.3	62.7	5.5
12.4-34.9	6.9	0.6
Total	**1142**	**100**

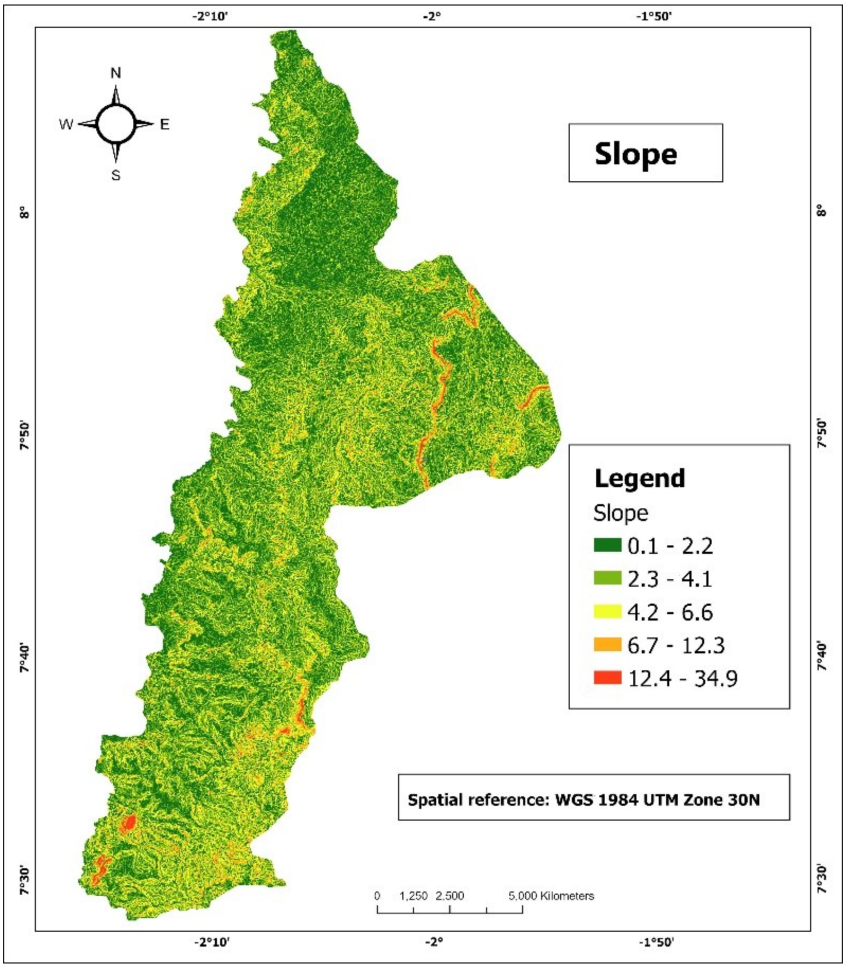

Figure 7: *The slope of the study area*

3.7.6 Lineament Density

The term "lineaments" refers to linear surface features that represent the superficial expression of subsurface structures, such as faults, fractures, dykes, and other geological formations (Ponnusamy et al., 2022). The lineament density of an area is a crucial factor for groundwater potential, as it provides insights into groundwater flow patterns (Gumma & Pavelic, 2013). Lineaments are linear or curvilinear fractures and faults found in hard rock environments, functioning as secondary pathways for the movement of groundwater. Faults are surfaces along which there has been a noticeable displacement of Earth's materials due to a loss of cohesiveness. Faults can be categorized into two types: major faults and lineaments. The primary distinction between them is size, with major faults being larger and lineaments smaller. Both faults and lineaments provide valuable information about an area's permeability and, consequently, its potential to sustain groundwater (Al-Ruzouq et al., 2019). Groundwater development is most promising in areas with higher lineament densities. Areas with greater lineament densities are believed to have significant groundwater potential, as they suggest higher secondary porosity, which enhances groundwater storage and movement (Das et al., 2022). Thus, the presence of faults, along with other favorable variables, indicates a higher likelihood of groundwater occurrence (Alimi et al., 2022).

The lineament density of the study area was derived from the DEM. Four hillshade maps were generated with different azimuth and altitude combinations: Azimuth 314° and altitude 45°, Azimuth 200° and altitude 50°, Azimuth 100° and altitude 60°, and Azimuth 90° and altitude 50°. These hillshade maps were used to manually digitize fault lines through the editor tool, creating polylines that were subsequently used to calculate lineament density. Multiple fault lines, which facilitate water seepage, were identified across the study area. The resulting digitized lineament map, along with borehole locations, is shown in **Figure 8** below. These fault lines allow water percolation, especially in areas where the underlying rock types exhibit low porosity.

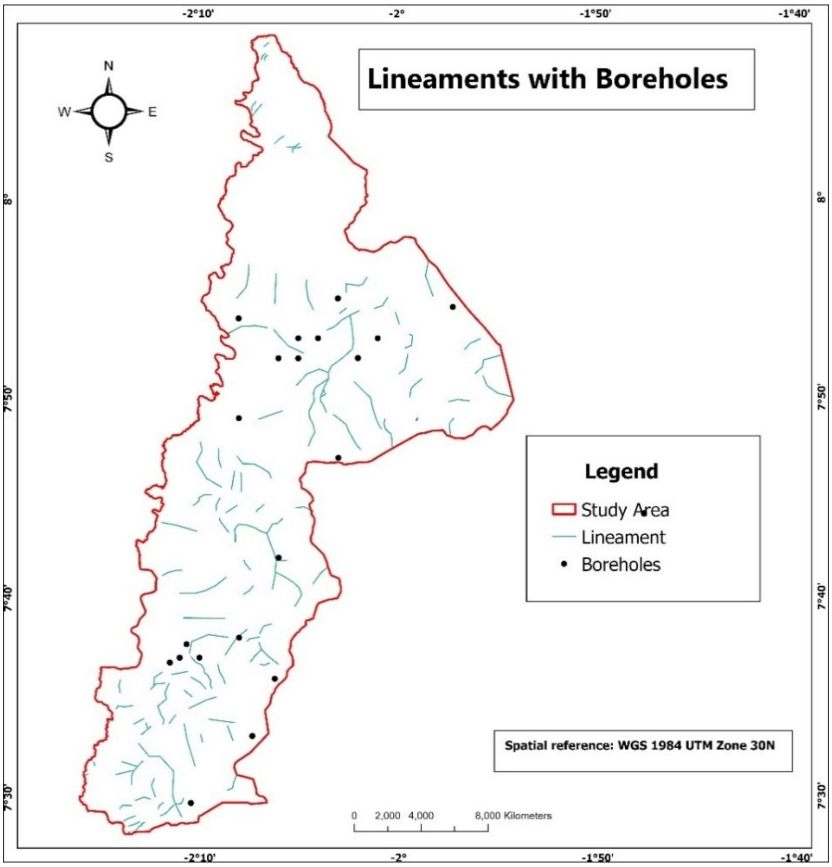

Figure 8: *Lineament map with boreholes of the area*

The Lineament Density categories were grouped into five classes which include 0.1 - 0.2 (very poor), covering 790.5km² (69.2%) of the study area, 0.3 - 0.5 (poor) which covers 105.3km² (9.2%) of the study, 0.6 - 0.7 (Good) covering 111.4km² (9.8%), 0.8 - 1.1 (Very good) covering 115.6km² (10.1%), and 1.2 - 2.4 (Excellent) covering 19.2km² (1.7%). Details can be found in the (**Table 6**) below. Although the area with very high lineament density occupies a relatively small portion of the study area, it is important to note that the fault lines, which contribute to high lineament density, are distributed throughout the region. This suggests that these fault lines facilitate the infiltration of water into the subsurface. The results were compared with existing boreholes in the area (see **Figure 8**) to evaluate the accuracy of the manually digitized lineaments. It was observed that all boreholes were located near the fault lines. According to groundwater experts, lineament density was ranked as the sixth most significant factor in the multicriteria decision-making process for groundwater potential mapping. The lineament density of the study area is presented in **Figure 9** below.

Table 6: *Lineament Density classes and their area*

Classes	**Area km²**	**Percentage**
0.1-0.2	790.5	69.2

0.3-0.5	105.3	9.2
0.6-0.7	111.4	9.8
0.8-1.1	115.6	10.1
1.2-2.4	19.2	1.7
Total	**1142**	**100**

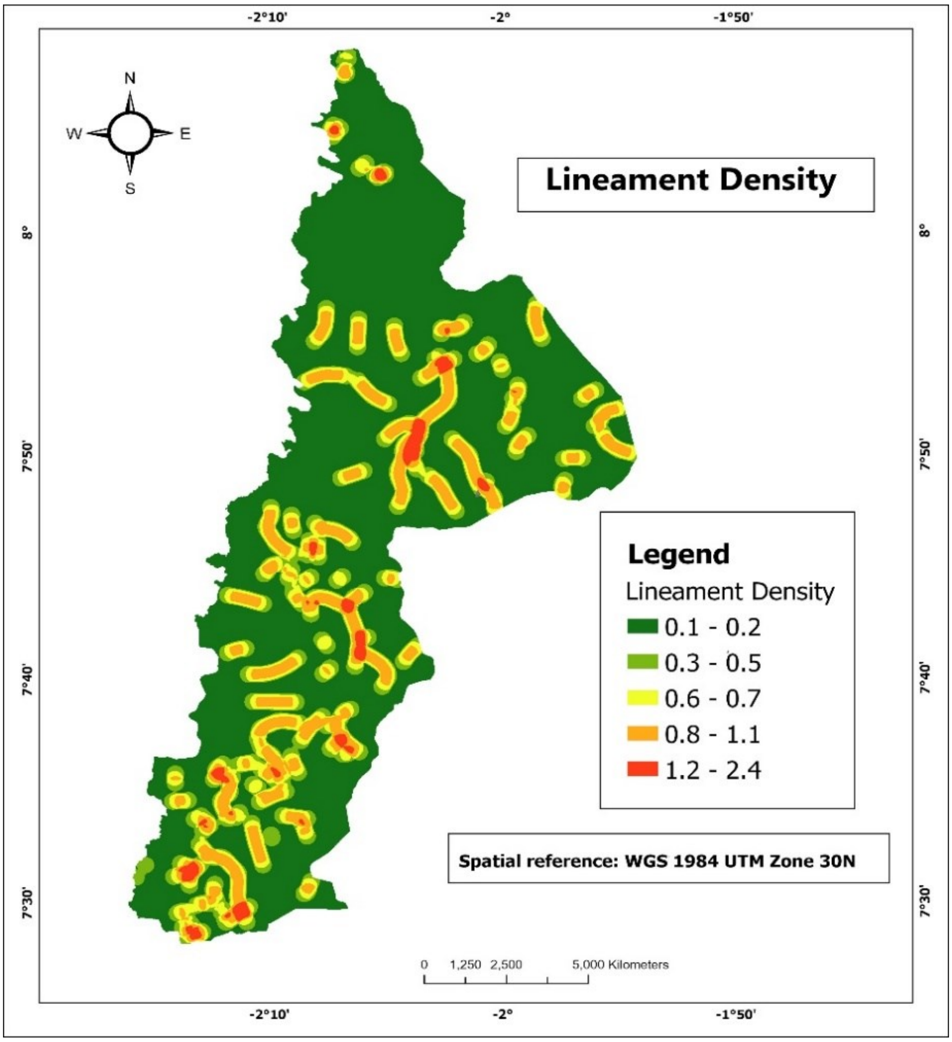

Figure 9: *The Lineament density of the area*

3.7.7 Rainfall

Rainfall is a critical factor as it directly influences the volume of water available for infiltration and enhances the potential for groundwater recharge. The quantity of rainfall determines the extent of aquifer replenishment, with regions experiencing higher rainfall rates being more likely to exhibit greater infiltration and recharge rates (Ponnusamy et al., 2022). Rainfall plays a crucial role in runoff and drainage processes, facilitating the storage of water as groundwater or its movement from surface water into the subsurface. In the absence of adequate precipitation, other controlling factors would have a minimal impact on groundwater availability. Consequently, precipitation serves as the fundamental driver of groundwater potential in any given region (Al-Ruzouq et al., 2019).

Groundwater receives its primary water supply from precipitation. The study area has a single rainfall station, indicating that the region experiences a significant amount of rainfall compared to the northern parts of Ghana. However, analyzing the rainfall data for the region using only one station was insufficient. To address this, rainfall data from 17 stations across the country was obtained and saved in an Excel CSV format. This data was then imported into a GIS environment as point features representing the locations of the 17 rainfall stations. These points were interpolated using the Inverse Distance Weighted (IDW) method to create a polygon feature, with precipitation serving as the Z value in the IDW tool in the spatial analyst toolbox in ArcGIS Pro. Finally, the rainfall data specific to the study area was extracted from the interpolated rainfall map of Ghana.

From the output, the area receives rainfall ranging from 0.47 to 0.60 depth. The rainfall map was grouped into two classes 0.47 - 0.52 (Good), and 0.53 - 0.53 (Very Good). The region is grouped as low rainfall extends from the northernmost to the southern part of the study area, covering 963.2 km² (84.3%) of the total area. Conversely, the southernmost part of the study area is identified as having a significantly higher precipitation depth, representing 178.8km² (15.7%) of the area. See the (**Table 7**) below for more details. Although regions with very high precipitation account for the smallest portion of the study area, the rainfall in these areas serves as a valuable source for groundwater recharge, making it a key factor in the multicriteria decision-making analysis. Groundwater experts ranked rainfall as the seventh most significant factor in the groundwater potential zoning process. **Figure 10** below shows the rainfall map of the study area.

Table 7: *Rainfall classes and their area*

Classes	**Area km²**	**Percentage**
0.47-0.52	963.2	84.3

0.53-0.6	178.8	15.7
Total	**1142**	**100**

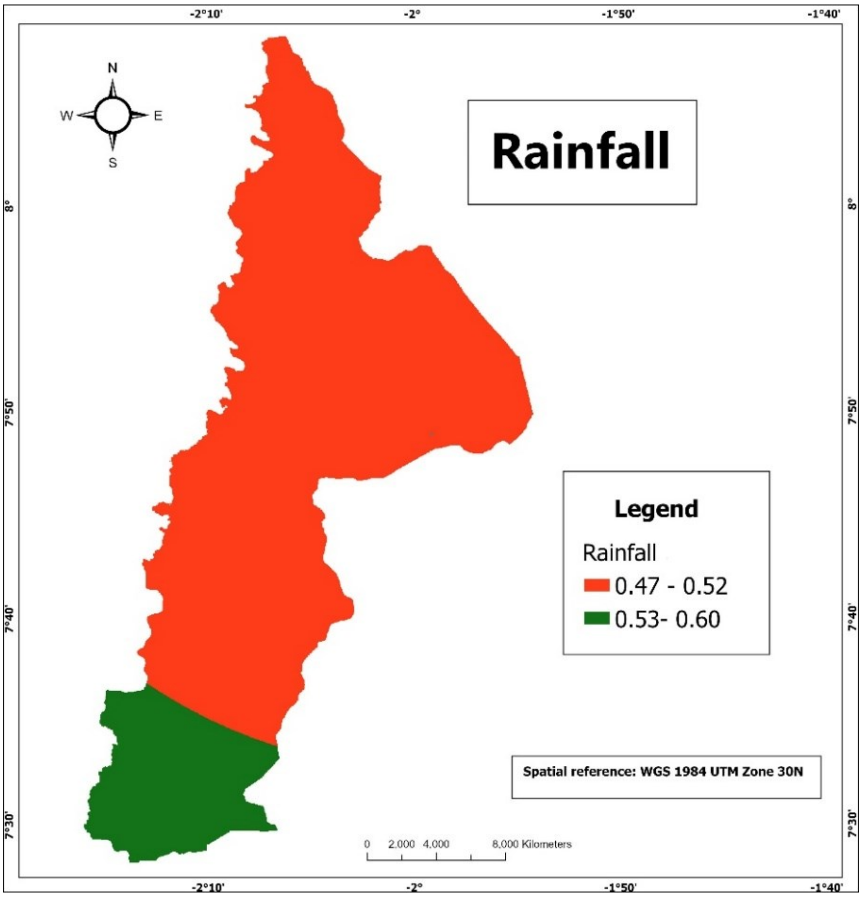

Figure 10: *Rainfall map of the area*

3.7.8 Drainage Density

The characteristics and density of a drainage network have an indirect influence on the permeability of water, similar to the effects of climatic (rainfall) and hydrological factors. As a result, the spatial distribution of runoff and groundwater is shaped by drainage density. Drainage density is defined as the average length of stream channels within a basin, representing the total length of stream channels per unit area (Andualem & Demeke, 2019). Drainage density influences the rate of water flow and its infiltration into the aquifer. In regions with high permeability of the underlying rocks, the drainage density tends to be low. Consequently, areas with low drainage density are more likely to support groundwater production. Several factors, including the characteristics and structure of the rock, land use and land cover patterns, soil permeability, vegetation types, and slope gradient, all contribute to shaping the drainage pattern of an area (Ponnusamy et al., 2022).

The Drainage Density (DD) was derived by first filling the sinks in the DEM. This filled DEM was then utilized to calculate flow direction and flow accumulation. The stream network was extracted using the conditional tool in the Spatial Analyst toolbox. Subsequently, drainage line vectorization was performed with the 'Stream to Feature' tool. The final DD output was generated by using the 'Stream to Feature' output as the input feature. Finally, the line density tool from the Spatial Analyst tools was applied to obtain the final drainage density map

The drainage Density of the study was grouped into five classes, including 0.1 - 0.5 (very good) covering 228.1Km² (20%) of the study area, 0.6 - 0.8 (good) covering 314Km² (27.5%) of the area, 0.9 - 1.1 (moderate) covering 299.6km² (26.2%), 1.2 - 1.4 (poor) covering 213.7Km² (18.7%), and 1.5 - 2.2 (very poor) covering 86.7Km² (7.6%) of the study area. The details are provided in (**Table 8**) below. Based on the output generated, the area exhibits high groundwater potential in terms of drainage density. Specifically, only 26.3% of the area was classified as having poor to very poor drainage density. This suggests the presence of predominantly flat and gently rolling terrain, which facilitates the percolation of water into the subsurface. Groundwater experts ranked drainage density as the eighth most significant factor in the multicriteria decision-making process. The Drainage Density map is shown in **Figure 11** below.

Table 8: *Drainage Density classes and their area*

DD Class	**Area (Km²)**	**Percentage**
0.1-0.5	228.1	20.0
0.6-0.8	314.0	27.5
0.9-1.1	299.6	26.2
1.2-1.4	213.7	18.7
1.5-2.2	86.7	7.6
Total	**1142**	**100**

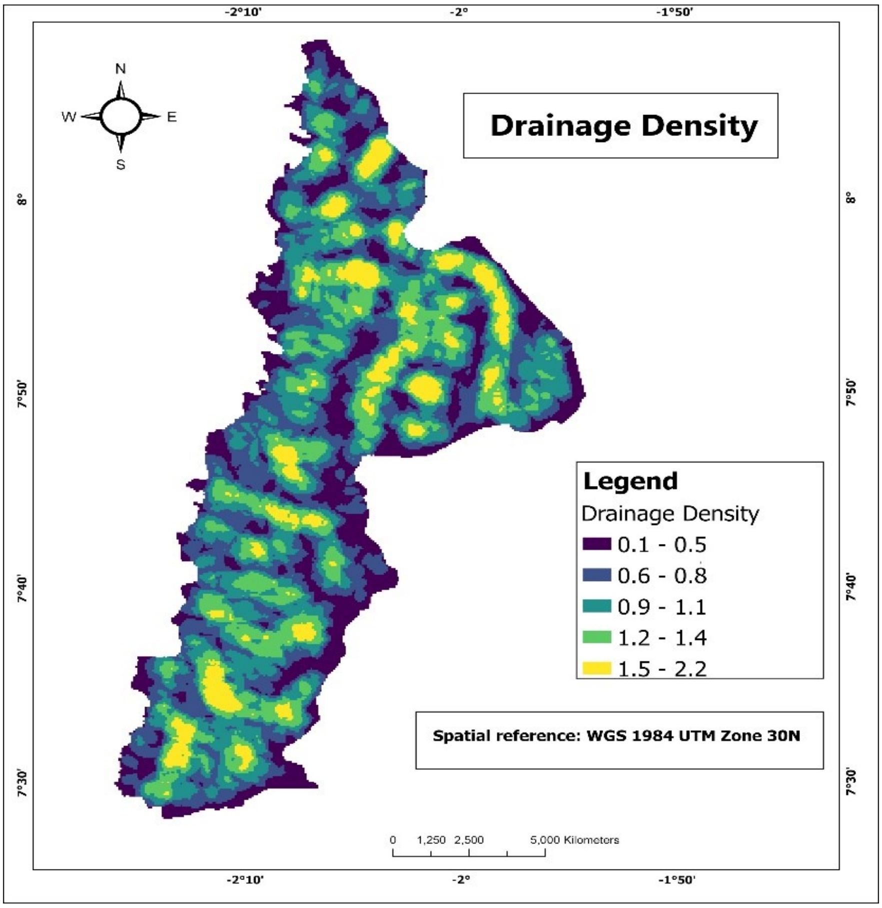

Figure 11: *The Drainage Density of the area*

Due to the inability to overlay the geology and soil type maps in the Weighted Linear Combination (WLC) analysis because they were in vector format, the "Polygon to Raster" tool within the Conversion toolbox was applied to convert these vector maps into raster format. Again, the eight maps were subsequently reclassified using the "Reclassify" tool within the Spatial Analyst toolbox, assigning numerical values to the individual classes of each factor (**Table 15**). These reclassified maps were then incorporated into a Weighted Linear Combination (WLC) analysis, which was used to generate the Groundwater Potential Zones. Following the generation of the groundwater potential zones, the results were compared with the municipality's population density map to evaluate their potential benefits for local communities.

3.8 Pairwise Comparison Matrix

The factors were assigned appropriate weights according to Saaty's AHP scale, reflecting their relative significance in groundwater potential. **Table 9** displays the factors and their corresponding weights, which were determined based on their importance in groundwater existence. **Table 10** explains the meaning and significance of the scale (1-9) used to generate these weights in the pairwise comparison matrix.

The pairwise comparison matrix was constructed by organizing the factors in order of their significance, a process carried out by the experts. For instance, in the pairwise comparison matrix shown in **Table 11**, a value of 1 was assigned when geology was compared with geology (equal importance), indicating that the two factors contribute equally to the objective.

Table 9: *Arrangements of the factors and their weights*

Factor	Weight
Geology	38
Soil type	19
Land use	16
TWI	11
Slope	6
Lineament Density	5
Rainfall	3
Drainage Density	2

Table 10: *AHP scale and its interpretation*

Intensity	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment strongly favor one activity over another
5	Strong importance	The value is preferable to the other
7	Very strong importance	An activity is strongly favored, and its dominance is demonstrated in practice

9	Extremely important	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8 can be used to express intermediate values		When compromise is needed

Source: (Saaty & Katz, 1990)

The factors were paired against each other and assigned weights based on their significance using a scale of 1 to 9. They were then arranged in a matrix with rows and columns, and each factor was compared to the others. The factor deemed more important was assigned a higher value, while factors of equal importance were assigned a value of one. This process allowed for a clear ranking of the factors based on their relative significance in the analysis. For example, Geology was paired against geology, and a value of **1** was given to it (the ideal was 1/1= 1). Geology was also paired with soil type; the final value was **2**. Geology was assigned the value of **2** and soil type **1** (i.e. 2/1= 2). Lastly, Drainage Density was given a value of **1**, and geology, **9**, making it (1 divided by 9). More details can be found in **Table 11.** These values in the columns were summed up to aid in the determination of the final weights and the consistency level of this pairwise comparison matrix. (Therefore, summing up 1+1/2+1/5+1/6+1/7+1/7+1/8+1/9 = **2.4**). It is important to highlight that the pairwise comparison matrix was developed in collaboration with the groundwater experts, particularly the fourth expert, who has extensive experience and knowledge of the study area. This expert's familiarity with the area's characteristics was instrumental in ensuring that the matrix accurately reflected the local conditions and groundwater dynamics. **Table 11** below shows the pairwise comparison matrix.

Table 11: *Pairwise comparison matrix of the factors*

Criteria	**Geology**	**Soil type**	**Land use**	**TWI**	**Slope**	**LD**	**Rainfall**	**DD**
Geology	1	2	5	6	7	7	8	9
Soil type	1/2	1	2	3	3	4	6	7

Land use	1/5	1/2	1	2	4	5	6	7
TWI	1/6	1/3	1/2	1	1	5	6	5
Slope	1/7	1/3	1/3	1	1	2	2	3
LD	1/7	1/4	1/3	1/5	1/2	1	2	3
Rainfall	1/8	1/6	1/6	1/6	1/2	1/2	1	2
DD	1/9	1/7	1/7	1/5	1/3	1/3	1/2	1
Column total	2.4	4.7	9.5	13.6	17.3	24.8	31.5	37

3.8.1 Determining the final weights for the factors

The relative weights for each of the comparisons were calculated by dividing the individual weights by the total sum of the corresponding column. This method helped normalize the weights, ensuring that the overall sum of each column equaled one, which is essential for consistency in the pairwise comparison process. For example, **1** divided by **2.4** gave **0.42**, (**1/2**) divided by **2.4** gave **0.21,** and the rest can be found in **Table 12**. The final weights for each factor were determined by summing the relative weights in each row. For instance, the final weight for geology was calculated by adding the relative weights in its corresponding row (i.e., 0.42 + 0.42 + 0.53 + 0.46 + 0.40 + 0.30 + 0.25 + 0.24), which resulted in a final weight of **0.38**, or **38%**. These percentage weights were then incorporated into the GIS environment to map the study area's groundwater potential zones. The complete list of the factors and their respective weights can be found in **Table 12** below.

Table 12: *Determining the relative and final weights of the factors*

Criteria	**Geology**	**Soil type**	**Land use**	**TWI**	**Slope**	**LD**	**Rainfall**	**DD**	**Weights**	**(%) weights**
Geology	0.42	0.42	0.53	0.46	0.40	0.30	0.25	0.24	**0.38**	**38**

Soil type	0.21	0.21	0.21	0.21	0.17	0.16	0.19	0.19	**0.19**	**19**
Land use	0.08	0.11	0.11	0.14	0.23	0.20	0.19	0.19	**0.16**	**16**
TWI	0.07	0.07	0.05	0.07	0.06	0.20	0.19	0.14	**0.11**	**11**
Slope	0.06	0.07	0.03	0.07	0.06	0.08	0.06	0.08	**0.06**	**6**
LD	0.06	0.05	0.03	0.01	0.03	0.04	0.06	0.08	**0.05**	**5**
Rainfall	0.05	0.04	0.02	0.01	0.03	0.02	0.03	0.05	**0.03**	**3**
DD	0.05	0.03	0.01	0.01	0.02	0.01	0.02	0.03	**0.02**	**2**
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	**1.00**	**100**

3.8.2 Examining the consistency of the comparison matrix

The Consistency Ratio (CR) must be less than **0.1**, or **10%**, for the comparisons to be deemed acceptable and consistent. This ensures that the judgments made in the pairwise comparison matrix are logically coherent and reliable. The following actions were carried out to determine the CR for the comparison:

i) The weighted sum vector was calculated by multiplying the weight assigned to each factor (geology, soil type, land use, TWI, slope, lineament density, rainfall, and drainage density) by the sum of the relative weight values in the corresponding column of the initial pairwise comparison matrix shown in **Table 12**. The results of each multiplication were summed together. For instance, in the case of the geology row from the pairwise comparison matrix in **Table 11**, **1** was multiplied by the total of the relative weights (**0.38**) for the geology row in Table **12**, **2** was multiplied by **0.19**, and so on. After performing these calculations for each factor, the sums for each row were obtained, resulting in a value of **3.49** for geology. For further details, see **Table 13.**

ii) The consistency vector was calculated by dividing the row total obtained in step i) by the row total of the relative weights in **Table 12**. For example, the value **3.49** from **Table 13** was divided by **0.38** from Table **12**, resulting in a consistency vector value of **9.22**. This consistency vector was then used to calculate the consistency index, as detailed in **Table 14**.

The Consistency Index and Consistency Ratio (a summary can be found in **Table 14**) were calculated using the equation below.

Consistency Index =((λmax-n))/((n-1)), where *n* is the number of factors used in the analysis, and *λmax* is the principal eigenvalue of the matrix.

The λmax (largest eigenvalue) was calculated by dividing the total of the consistency vector (**69.09**) from **Table 13** by the number of factors (**8**), which resulted in **8.64**. Then, **1** was subtracted from the total number of factors (**8**), giving **7**. Therefore, the final equation to get the Consistency Index is CI= (84.64-8)/ (8-1) = **0.09**

The Consistency Ratio = CI/RI, where CI is the Consistency Index calculated above (**0.09**) and RI is the Random Index found in the standard table provided by (Saaty, 1980). The Random Index (RI) used in this calculation is **1.4**, as per Saaty (1980), based on the number of factors in the analysis. Since there are eight factors in this study, the RI value applied was **1.4**. Dividing the Consistency Index (CI) of **0.09** by the Random Index (RI) of **1.4** results in a consistency ratio of **0.06** (**6%**). Since this value is below the 0.1 (10%) threshold, it indicates that the pairwise comparison matrix is consistent. Further details can be found in **Table 14.**

Table 13: *Obtaining the Consistency Vector*

Factor	**Equation**	**Total**	**Consistency vector**
Geology	(1*0.38) +(2*0.19) +(5*0.16) +(6.5*0.11) +(7*0.06) +(7.5*0.05) +(8*0.03) +(9*0.02)	**3.49**	**9.22**
Soil type	(0.5*0.38) +(1*0.19) +(2*0.16) +(3*0.11) +(3*0.06) +(4*0.05) +(6*0.03) +(7*0.02)	**1.74**	**8.95**
Land use	(0.2*0.38) +(0.5*0.19) +(1*0.16) +(2*0.11) +(4*0.06) +(5*0.05) +(6*0.03) +(7*0.02)	**1.38**	**8.86**

TWI	(0.17*0.38) +(0.33*0.19) +(0.5*0.16) +(1*0.11) +(1*0.06) +(5*0.05) +(6*0.03) +(5*0.02)	**0.91**	**8.64**
Slope	(0.14*0.38) +(0.33*0.19) +(0.33*0.16) +(1*0.11) +(1*0.06) +(2*0.05) +(2*0.03) +(3*0.02)	**0.56**	**8.74**
LD	(0.14*0.38) +(0.25*0.19) +(0.33*0.16) +(0.2*0.11) +(0.5*0.06) +(1*0.05) +(2*0.03) +(3*0.02)	**0.38**	**8.23**
Rainfall	(0.13*0.38) +(0.17*0.19) +(0.17*0.16) +(0.17*0.11) +(0.5*0.06) +(0.5*0.05) +(1*0.03) +(2*0.02)	**0.26**	**8.13**
DD	(0.11*0.38) +(0.14*0.19) +(0.14*0.16) +(0.2*0.11) +(0.33*0.06) +(0.33*0.05) +(0.5*0.03) +(1*0.02)	**0.19**	**8.32**
Total			**69.09**

Table 14: *calculation of the consistency Ratio*

Formula	**Results**
λmax **(consistency vector/8)**	8.64
λmax-n	0.64
n-1	7
$\mathbf{CI = (\lambda max - n)/(n - 1)}$	0.09
RI	1.4
$\mathbf{CR} = \boldsymbol{CI/RI}$	**0.06**

3.9 Generation of the Groundwater Potential Zones

For the overlay in the GIS environment, each of the factors was reclassified and converted to a raster format to ensure compatibility. The geology and soil type data, originally in vector format, were rasterized to facilitate their integration with the other layers. The weighted overlay analysis was conducted using the Weighted Overlay tool in the spatial analyst tools, where each factor was assigned, a weight based on the pairwise comparison matrix (see **Tables 9** and **12**), with the cumulative weight for all factors totaling 100%. Additionally, probability ratings (on a probability scale of 1-5) were applied to the individual classes within each factor, enabling a nuanced assessment of groundwater potential zones based on the combined influence of all eight. The ratings were assigned through a literature review (Abebrese et al., 2022; Danso & Ma, 2023) and with the assistance of the expert. **Table 15** presents the probability ratings assigned to each factor, with higher values (five) allocated to factors that contribute significantly to groundwater potential and lower values (one) to those with minimal impact. The geographic extent for the final groundwater potential map was set to match the study area precisely, ensuring alignment and accuracy of spatial data. The groundwater potential map generated thus reflects a weighted combination of the reclassified factors, identifying zones with varying groundwater potential across the study area.

Table 15: *Probability ratings and reclassified values*

Influencing factors	**Classes**	**Reclassified**	**Probability for groundwater storage**	**Ratings**
Geology	Birimian Supergroup	1	Excellent	5
	Eburnean Plutonic Suite	2	Very Good	4
	Mesozoic	3	Poor	2
	Voltaian Supergroup, Kwahu-'Morago' Group	4	Very Good	4
Soil type	Acrisols	1	Poor	2
	Gleysols	2	Low	2
	Leptosols	3	Very Poor	1
	Lixisols	4	Very Good	4

Land use	Water	1	Excellent	5
	Dense Vegetation	2	Very Good	4
	Sparse Vegetation	3	Good	3
	Built-up	4	Very Poor	1
	Farmland	5	Good	3
TWI	4 - 7	1	Very Poor	1
	7.1 - 8.7	2	Poor	2
	8.8 - 11	3	Good	3
	12 - 14	4	Very Good	4
	15 - 23	5	Excellent	5
Slope	0.1 - 2.2	1	Excellent	5
	2.3 - 4.1	2	Excellent	4
	4.2 - 6.6	3	Good	3
	6.7 - 12.3	4	Poor	2
	12.4 - 34.9	5	Very Poor	1
Lineament Density	0.1 - 0.2	1	Very poor	1
	0.3 - 0.5	2	Poor	2
	0.6 - 0.7	3	Good	3
	0.8 - 1.1	4	Very Good	4
	1.2 - 2.4	5	Excellent	5
Rainfall	0.47- 0.52	1	Good	3
	0.53 – 0.60	2	Very Good	4

Drainage Density	0.1 - 0.5	1	Excellent	5
	0.6 - 0.8	2	Very Good	4
	0.9 - 1.1	3	Good	3
	1.2 - 1.4	4	Poor	2
	1.5 - 2.2	5	Very Poor	1

3.9.1 Weighted Linear Combination

The multicriteria decision-making method is frequently employed in research where more than one factor is utilized for selecting several functions to achieve integrated data (Kuru & Terzi, 2018). Employed in this process of achieving the integrated goal is the Weighted Linear Combination (WLC). One distinct method for combining factor values is the WLC technique. The WLC approach is an easy way to combine multi-class thematic factor maps (Saha, 2017). As was done above, the relevance level of each factor determines how much weight it is given. Final weights were allocated to the factors that make up the outcomes. The factor is considered more significant when the score is higher. First, applying the WLC process involves assigning numerical values (ratings) directly to the individual classes of the factors (in **Table 15**). The weights assigned to each factor (**Table 12**) were multiplied by the appropriate rating (**Table 15**) to get the GWPZs. The products across all factors were then added together. Any GIS with overlay capability can apply the methods outlined (Abe & Ersado, 2022). GIS makes it easier to combine the map layers with assessment criteria to determine the composite map layer, which is the final product. The GWPZs were generated using factor layers, which enabled the computation of the cumulative weights of every pixel following the assignment of weights for every factor and subclass. This may be done using the Equation below.

$$\boldsymbol{GWPZs} = (G_w * G_N) + (ST_w * ST_N) + (LU_w * LU_N) + (TWI_w * TWI_N) + (S_w * S_N) + (LD_w * LD_N) + (R_w * R_N) + (DD_w * DD_N),$$

Where GWPZs = Groundwater Potential Zones, G = Geology, ST = Soil Type, LU = Land use, TWI = Topographic Wetness Index, S = Slope, LD = Lineament Density, R = Rainfall, DD = Drainage Density, W = normalized weights of the factors and N = normalized ratings of each class of the reclassified factor. The pictorial explanation of integrated factors as overlay analysis is shown in **Figure 12** below. The output classes were generated using the "unique values" method in the primary symbology, resulting in values of **2, 3, 4,** and **5**. These values were then renamed for easier interpretation: **2** was labeled as **low** groundwater potential, **3** as **moderate** groundwater potential, **4** as **good** groundwater potential, and **5** as **excellent** groundwater potential (refer to **Table 16** for details).

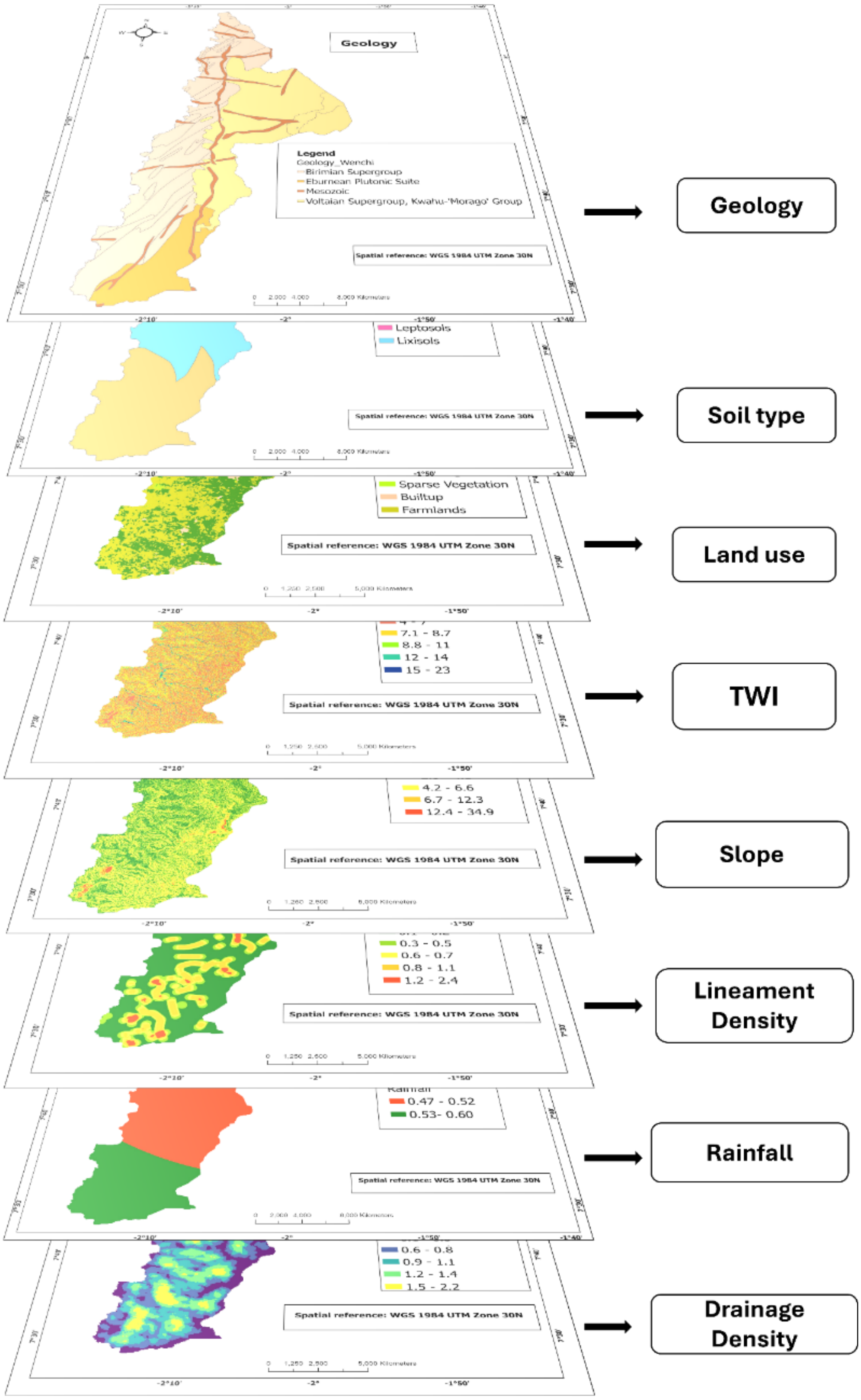

Figure 12: Integration of the factors in GIS

CHAPTER FOUR

RESULTS AND DISCUSSION

4.0 Ground Water Potential Zones

The groundwater potential zones for the study area were determined after integrating the results from the AHP process into the GIS environment using the Weighted Linear Combination technique. The final map was generated using the weighted overlay tool from the Spatial Analyst toolbox in ArcGIS Pro. The pairwise comparison analysis was consistent, yielding a Consistency Ratio (CR) of 6%. The output resulted in four groundwater potential zone classes: low groundwater potential (2), moderate groundwater potential (3), good groundwater potential (4), and excellent groundwater potential (5). The area with moderate groundwater potential is the largest, covering 432.8 km², which accounts for 37.9% of the study area. This zone extends from the northern part, through the center, to the southern part of the area. The next largest zone is good groundwater potential, which spans 389.6 km², or 34.1% of the study area. It appears in small patches throughout the study area but is more concentrated in the southern part. A total of 318.1 km², or 27.9% of the land, was classified as having low groundwater potential, mainly found in the northeastern part of the study area. Only 1.5 km², which represents a negligible 0.1% of the study area, was identified as having excellent groundwater potential. This small area is located in tiny patches in the southern part of the municipality. These results are summarized in **Table 16** and **Figure 13**, with **Figure 14** displaying the map of the groundwater potential zones.

Table 16: *GWPZ classes and their area*

GWPZ Classes	Area (Km²)	Percentage
2 (Low)	318.1	27.9

3 (Moderate)	432.8	37.9
4 (Good)	389.6	34.1
5 (Excellent)	1.5	0.1
Total	**1142**	**100**

Figure 13: *Chart of the Groundwater Potential Zones and their area (Km²)*

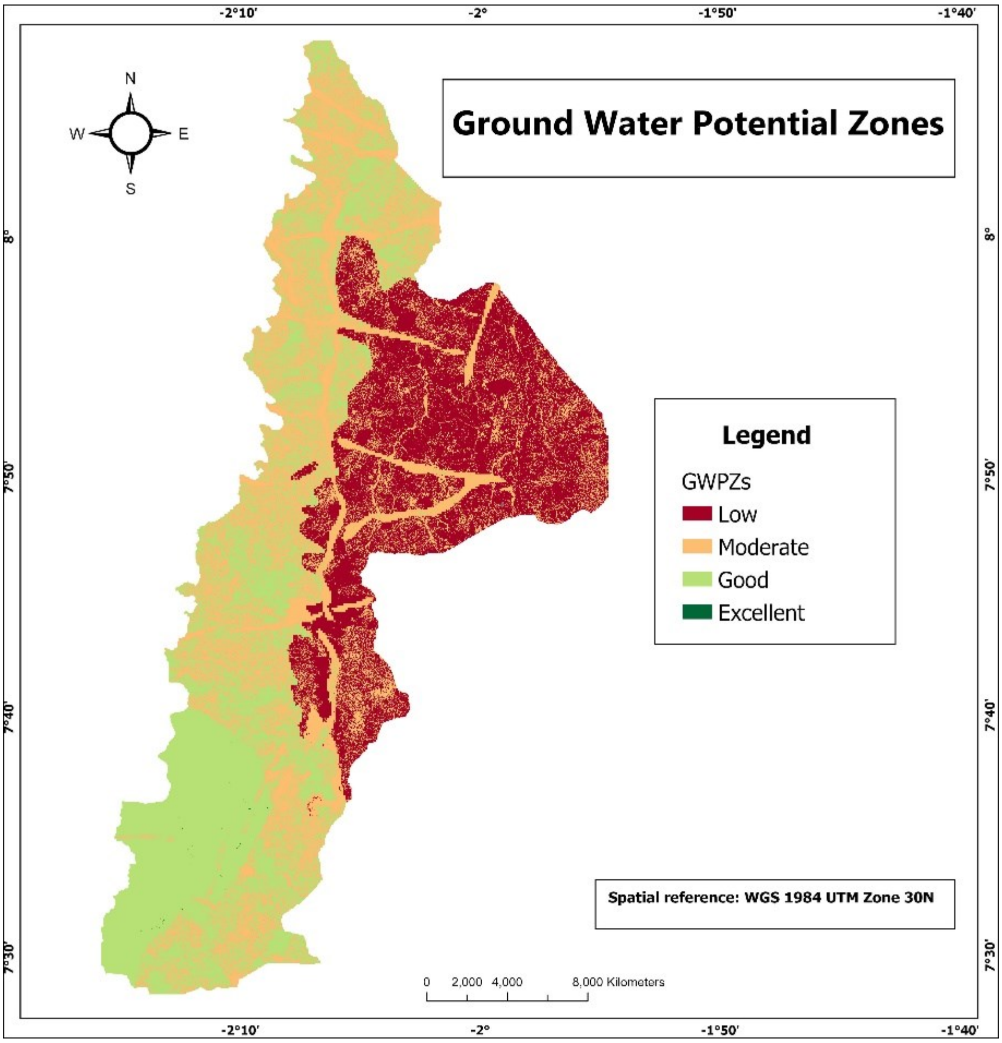

Figure 14: Groundwater Potential Zones

4.1 Population Density

The area's population Density ranges from 7.12 to 13.50. It was grouped into three classes: 7.12 - 7.27 (low), 7.28 - 9.10 (moderate), and 9.11 - 13.50 (High). In comparison to other municipalities, the study area has a relatively low population density, with most of the population concentrated in the central part of the municipality. However, there are also smaller populations scattered in the northern and southern regions. **Figure 15** below illustrates the population density across the study area.

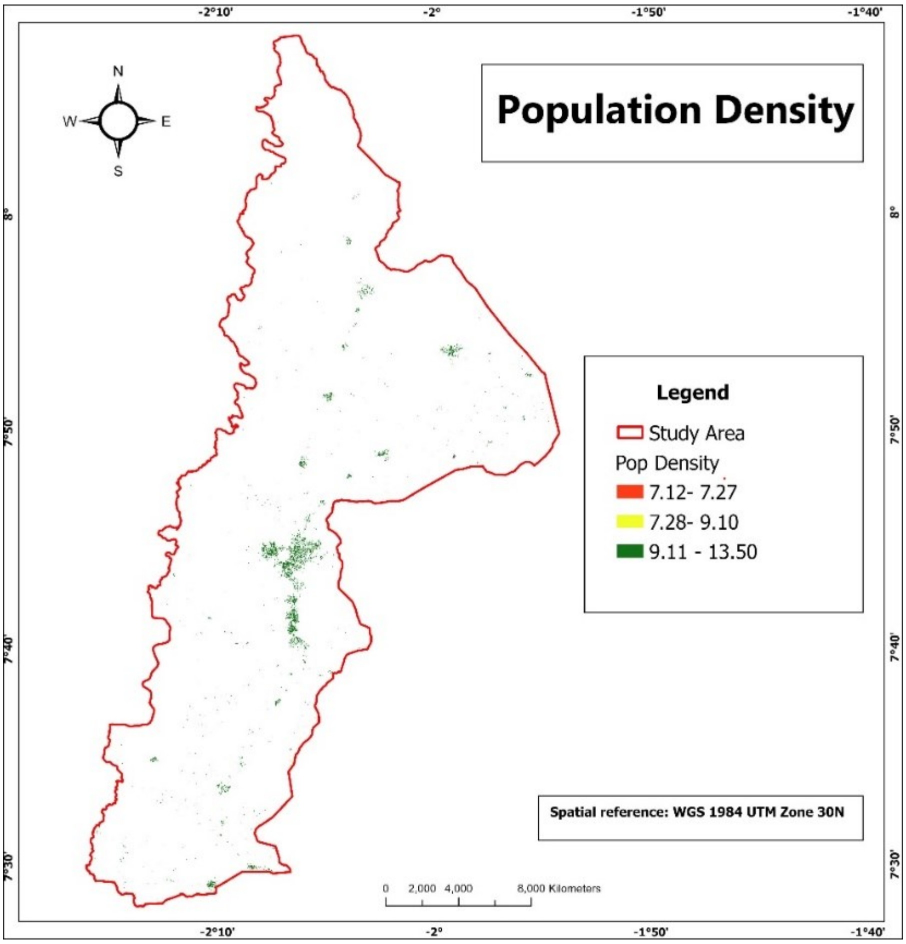

Figure 15: *The Population Density of the area*

4.2 The Comparison of the Groundwater Potential Zones with the Population Density of the Area

The municipality's population density was superimposed onto the GWPZs map to evaluate their potential benefits for the local population. This approach aimed to determine the potential impact on the community should the study be further developed, as well as to assess the viability of groundwater for both domestic and agricultural use. Overlaying population density data onto the GWPZs map revealed that most high-density areas are in zones with low groundwater potential, with only a few situated in zones of moderate to good potential. However, a significant portion of the population in the southern region is near moderate and good groundwater potential zones, indicating that these areas could be beneficial for both domestic and agricultural purposes. **Figure 16** below shows the GWPZs with the municipality's Population Density.

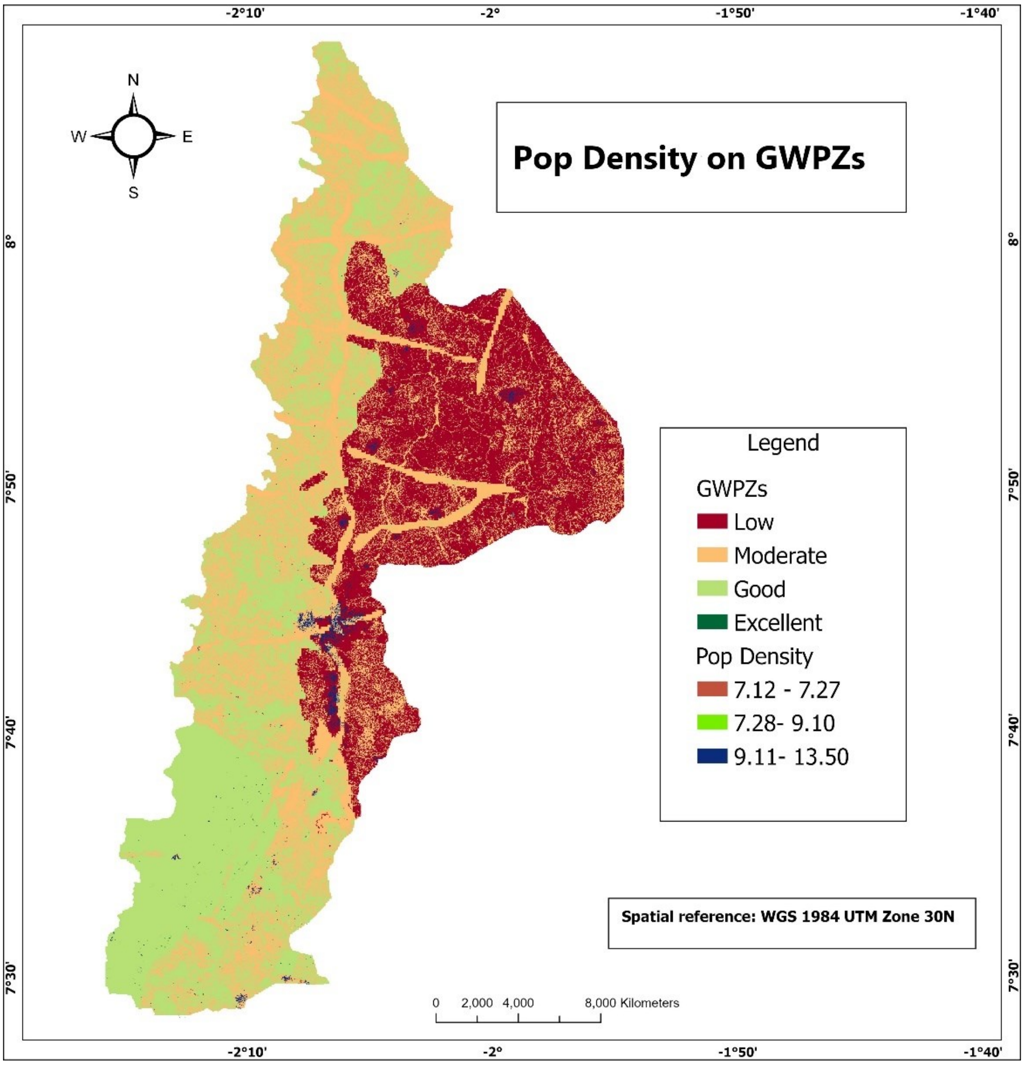

Figure 16: *Population Density on the Groundwater Potential Zones*

4.3 Discussion

This study exclusively employed a quantitative research approach, incorporating various techniques to systematically examine social phenomena through numerical or statistical data. Quantitative research involves measurement and assumes that the subject being studied is quantifiable. Its primary aim is to collect data through measurement, identify patterns and relationships within the data, and evaluate the results of these measurements (Watson, 2014). All quantitative analyses were conducted within the GIS environment, where data is measurable. GIS is widely recognized as a valuable decision-support tool that aids in problem-solving by integrating spatially referenced data (Adiat et al., 2012). The Multicriteria Decision-Making Analysis and Analytical Hierarchy Process (MCA-AHP) for mapping groundwater potential zones in the Wenchi municipality was conducted using GIS and Remote Sensing data, and the analysis was carried out using QGIS and ArcGIS Pro software. These techniques and tools have been extensively applied in various fields for similar spatial analysis and decision-making tasks. Waikar, (2014) asserted that GIS and Remote Sensing (RS) applications are valuable for hydrogeomorphological mapping in water resource management, as well as for multicriteria analysis in resource management. There are various methods available for structuring, designing, and evaluating decision-making processes. One such method, GIS-MCDM, combines geographic data with value judgments or the preferences of decision-makers, ultimately providing crucial information for informed decision-making (Adiat et al., 2012).

For this study, eight factors were considered in delineating the groundwater potential zones: geology, soil type, land use, Topographic Wetness Index (TWI), slope, lineament density, rainfall, and drainage density. Thanh et al. (2022) reaffirms that these factors are crucial for effective groundwater potential mapping. The results from the analysis indicated that the municipality has a high groundwater potential. The study area is primarily covered by moderate to good groundwater potential (28% and 34%, totaling 62%), compared to 38% of poor groundwater potential.

In the AHP analysis, geology, soil type, and land use were identified as the top three significant factors, as they influence the penetration, percolation, and retention of water underground. Strong groundwater production and storage are largely determined by the permeability and porosity of the geologic units in the area (Ifediegwu, 2022). Abebrese et al. (2022) also emphasized that the geological formation of an area plays a crucial role in determining the level of groundwater and its water-bearing capacity. Rahman et al. (2022) noted that settlements and bare lands lead to poor groundwater potential, while forested and vegetated areas enhance groundwater potential. Soil type is a critical factor for groundwater, as the porosity of the soil regulates the movement of water into the underground. According to Ifediegwu (2022), soil type influences the rate at which water enters or is retained in the soil.

The topographical characteristics derived from the DEM, such as slope, TWI, drainage, and lineament densities, are also crucial for groundwater mapping. Among these crucial factors is the slope which is defined as the rate of change in elevation. Steeper gradients often result in increased surface soil erosion and runoff. In contrast, gently sloping surfaces allow water to move more slowly, providing the soil with more time to absorb the water (Ibrahim-Bathis & Ahmed, 2016). The lineament density of the area was included in the analysis because fractures, or lineaments, formed due to geological deformations, enhance the permeability of water underground. These fractures create pathways that allow water to flow more easily through the subsurface, making them an important factor in determining groundwater potential (Abijith et al., 2020). In areas with hard rocks, these lineaments act as secondary conduits for water movement, facilitating the transfer of water into the underground. The fractures in the rock formations provide pathways that allow water to infiltrate and move through the subsurface, enhancing groundwater recharge in such areas (Danso & Ma, 2023). The drainage density is closely linked to permeability, which plays a crucial role in determining how runoff is distributed and the extent to which water infiltrates the soil (Ibrahim-Bathis & Ahmed, 2016). Rainfall, on the other hand, is a key factor in groundwater recharge, as it directly contributes to the replenishment of underground water reserves by infiltrating the soil and replenishing aquifers (Abe & Ersado, 2022). Rainfall was considered the seventh most significant factor in the analysis due to its irregular distribution across the area. The rainfall data was interpolated using the Inverse Distance Weighting (IDW) method. IDW is a widely recognized technique that has proven to be highly effective in estimating rainfall distribution across various locations globally (Worqlul et al., 2019). The Weighted Linear Combination in the GIS environment was used to map out the groundwater potential zones in the Wenchi Municipality. It was a simple and direct method to combine all the factors into a single map. This technique has been widely used by most scholars worldwide and has proven very efficient. For example, Saha (2017) employed the Weighted Linear Combination technique in the GIS environment to generate the groundwater potential map for the Md. Bazar Block of Birbhum District in West Bengal. Singh et al. (2018) also generated a groundwater potential map in the Damodar Canal Command (DCC) located in the upper Damodar River basin, south-central part of West Bengal, India, using the WLC technique. Again, Forkuor et al, (2013) employed the WLC technique to generate the groundwater potential map for the Northern region of Ghana. Lastly, the WLC technique was also successfully used by Abe & Ersado (2022) to generate a groundwater potential map in Lemo Woreda and Hossana town, Ethiopia. Other researchers, including (Ponnusamy et al., 2022) in the Maputaland Plain, South Africa, Wijesinghe et al. (2023) in the Thalawa Division, Sri Lanka, and a lot more.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.0 Conclusion

The primary objective of this study was to map groundwater potential zones to promote the development of the agricultural sector in the Wenchi Municipality against climate change. This was achieved using GIS-based Multi-Criteria Decision Making (MCDM), and the Analytical Hierarchy Process (AHP). The study considered eight factors: Geology, Soil Type, Land Use, Topographic Wetness Index (TWI), Slope, Lineament Density, Rainfall, and Drainage Density. These factors were individually evaluated to determine their contribution to mapping the groundwater potential zones, based on their characteristics and contribution to groundwater recharge. Weights were assigned to each factor and ranked according to their level of significance. This process was conducted with the assistance of groundwater experts and relevant literature.

A pairwise comparison matrix was used to determine the final weights of the factors, obtaining a consistency ratio of 6%, which indicates the reliability of the assigned weights. The weights derived from the pairwise comparison matrix were incorporated into the GIS environment, where the Weighted Linear Combination Technique was applied to generate groundwater potential zones. The findings of this study demonstrate the efficacy of using GIS and remote sensing data to delineate groundwater potential zones in the Wenchi Municipality. The methods employed are efficient in terms of time, labor, and cost, making them applicable to groundwater development projects even in developing countries. The groundwater potential zones generated were grouped into four classes: low, fair, moderate, and excellent. The results indicated that moderate groundwater potential covered 432.8km^2, representing 37.9% of the study area, followed by good groundwater potential, which covers an area of 389.6km^2, representing 34.1 % of the study area. Again, an area of 318.1km^2, representing 27.9% of the land was identified as having a low groundwater potential. Only 1.5km^2 of the area was seen as having an excellent groundwater potential. The study area’s population density was also superimposed onto the groundwater potential zones to assess its potential relevance to the local population. The analysis suggested that, if further developed, the identified zones would benefit the community, as high-density areas were found to be near zones with moderate and good groundwater potential zones. These findings can serve as a foundation for identifying potential groundwater irrigation sites and provide practical recommendations for target areas likely to yield groundwater, assisting in efficient in situ assessments, and offering a viable strategy for adapting to climate change and ensuring food security in both the municipality and the country.

5.1 Recommendations

Agriculture is a critical pillar of the country's economy; however, its vulnerability to the impacts of climate change is increasingly apparent, contributing to food security challenges and a general decline in the quality of life for the rural population of Wenchi Municipality. Policymakers should give further attention to groundwater issues in these rural areas as a means of addressing climate change-related challenges within the agricultural sector. Additionally, it is recommended that public education on the role of groundwater as a climate change adaptation strategy be prioritized prior to its implementation. Such educational efforts are crucial to ensuring community engagement and the long-term sustainability of groundwater initiatives in the municipality.

5.1.1 Future Research Recommendations

This study did not extensively explore the socio-economic aspects of the local population, as no primary data was collected from the residents of Wenchi Municipality. Furthermore, the research focused solely on mapping potential groundwater zones without considering the depth of groundwater, which is crucial for irrigation purposes. As such, future research should incorporate an analysis of the socio-economic factors of the community and conduct a more in-depth evaluation of the feasibility of these zones for irrigation use in the municipality

5.2 Limitations of the Study

The implementation of climate change adaptation strategies using groundwater resources is a costly endeavor, necessitating the full attention of policymakers. This can be particularly challenging when their focus does not prioritize these issues. The research relied significantly on the expertise of groundwater specialists, and locating professionals with comprehensive knowledge of the study area proved both difficult and time-consuming. Additionally, the availability of these experts posed a challenge, potentially extending the duration of the research, as their expertise was essential throughout the analysis process.

5.3 Personal Concluding Thoughts

Improving agricultural livelihoods has always been my aspiration, given my personal experience of living in rural areas and relying on agriculture for subsistence. I have witnessed firsthand the challenges farmers face due to climate change, particularly the ongoing dependence on rainfed agriculture. The introduction of groundwater irrigation in these areas would represent a significant advancement in enhancing these livelihoods. This is because farmers rely on their harvests for both food and income, and prolonged dry spells lead to food shortages, disrupting their ability to farm, sell produce, and meet their nutritional needs. Access to an alternative water source would enable year-round farming, enhance food security, and contribute to poverty reduction. I believe this research can be valuable to the municipality and community leaders when planning groundwater irrigation projects. The identified groundwater potential zones can serve as key indicators for selecting sites for drilling and guiding the implementation of groundwater irrigation initiatives within the municipality, thereby cutting costs and saving time.

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