International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Groundwater Availability and Suitability Evaluation for Irrigated Agriculture in Mbale District

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ABSTRACT

The purpose of this study was to evaluate the availability and suitability of groundwater in Mbale district basing on potential, quality and vulnerability to support irrigated agriculture. Groundwater potential was assessed using geospatial technique through AHP model. Thematic layers were prepared namely: land use and land cover, slope, soil, rainfall, lineament density, lithology, geomorphology and drainage density. All layers were integrated using the MLC technique. Ranking of each parameter was performed using WOIA. Weights were assigned to each subject class basing on AHP results. The consistency of the outputs was tested by computation of CR and was at a reasonable acceptable level (0.029 < 0.1). Groundwater potential was delineated basing on the values of groundwater potential index. Groundwater quality was determined using IWQI method. Thirty-three water samples were collected. Five chemical parameters were tested in the laboratory: chloride, electrical conductivity, bicarbonate, sodium and SAR to generate the water quality database using Kriging interpolation technique. Computation of IWQI values for each source was made and was used to generate the IWQI map using the weighted summation. DRATIC method was used to delineate vulnerability of groundwater. Layers were generated using the following parameters: depth to groundwater, net recharge, aquifer media, topography, vadose zone impacts, and hydraulic conductivity. The aquifer vulnerability map was prepared by overlaying layers. Three different vulnerability zones were determined according to DRASTIC scores low (<100), medium (100-140) and high (>140). Integration of maps of quality, vulnerability and potential of groundwater was made using an unsupervised MLC classification method. Groundwater potential was in three zones: very good zone was 26.99 km^2 (12.98%), the good zone was 126.22 km^2 (60.71%) and the poor zone was 54.69 km2 (26.31%). The average annual exploitable groundwater reserves are estimated at 0.026 (MCM/km^2) in the zone of “very good”, 0.024 MCM/km^2 in the zone of “good” and 0.018 MCM/km^2 in the zone of “poor”. Groundwater quality was in two use restrictions: High Restriction of 90.90% with the IWQI value from 40 to 55 on the area of 188.98 km^2 of the study area and Severe Restriction of 9.10% with IWQI values from 32 to 40 covering of 18.92 km^2. The study area had a high probability of contamination. Low vulnerability covers an area of 11.23km^2 (5.40%), 77.83km^2 (37.44%) for medium and 118.83km^2 (57.16%) for high. The resulting clustered map was classified into five categories with their respective regions: 17.58% very poor (36.56km^2), 13.84% poor (28.77km^2), 12.69% good (26.39km^2), 31.46% very good (65.39km^2) and 24.43 % excellent (50.78km^2). The sub counties in Mbale district that have inadequate and unsuitable groundwater for irrigated agriculture are Budwale, Wanale, Busano, Bubyangu, Bufumbo and Nyondo since they belong to the zones of very poor and poor. The remaining sub counties

have available and suitable groundwater for irrigated agriculture since they belong to the zones of good, very good and excellent.

CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND

Globally, present rising requirement for water to cater for cultural, societal and economic requirements will be satisfied by surface water or groundwater sources. Equating sources, groundwater stands extensively distributed and comparatively safer (Guppy et al., 2018). Groundwater is a substantial component of global water cycle and it's a vital resource for domestic, agricultural and industrial development water globally. (Frappart & Ramillien 2018). Irrigation requirement for the agricultural sector now sums to in excess of 70% of universal water withdrawals and around 85% of universal resource ingestion and the prediction is that groundwater reserves offer 43% of water consumed for irrigation (Liu et al., 2017). Groundwater is more established in North America and South Asia where accessibility is 57% and 54% respectively of total water for irrigation. In the previous thirty years enormous growth in the creation of irrigation water wells has been done for instance they currently control 19 Mha in China, 39 Mha of irrigated land in India, 17 Mha in the United States of America and massive parts of Pakistan and Bangladesh (Angelakıs, et al., 2020). These have enabled key remunerations for masses of moderate agriculturalists as mitigation to increased temperature and rainfall variation (Munyaradzi, et al., 2022).

The exclusion to this trend is Tropical Africa with merely 1% of land presently benefitting from irrigation by groundwater (Villholth et al., 2017). Prospective accomplishment of groundwater enlargement aimed at irrigated agriculture is more broadly acknowledged, but currently, the composite factor is the estimation of the availability of natural groundwater storage. Due to this, it has now persisted as a superior issue of concentration for legislators and designers (Ringler et al 2020). In Sub-Saharan Africa, there are diverse water benefactions where 40 million hectares of its land are appropriate for irrigation growth. In the past 3 decades, sub-Saharan Africa has observed amplified public and scholar's attention in the use of small-scale irrigation in general and groundwater irrigation in specific (Jambo et al., 2021).

In Uganda, the total internal renewable water resources (IRWR) are projected at 39 km^3/yr and groundwater is about 29km^3/yr (MAAIF, 2020). Though there is this high quantity of IRWR, around 800,000 ha of crops are damaged annually due to climate associated consequences. The damages and losses in the agriculture sector are triggered by rainfall insufficiency and are a threat to agriculture since it's a daily source of livelihood for over 80% of the population. Currently only 1% of renewable fresh water is used for irrigation in Uganda compared to over 70% global average (MoFPED, 2018).

According to the Climate Risk Country Profile report of Uganda by World Bank Group in 2020, the specific climate outlooks of temperature and variable rainfall are on increase in Mbale district and are attributed to climate change. This was confirmed by the survey done by Anna et al in 2021 which revealed that 63% of farmers are affected by drought in Mbale. This has contributed to loss of rural livelihoods and food insecurity (UN, 2015). The Government of Uganda through MAAIF with support from World Bank is implementing the Micro-Scale Irrigation Programme (MAAIF, 2020). However, this program supports only farmers near surface water sources which are inadequate, thereby leaving out 99% of small-scale farmers who have continued to rely on rainfed agriculture (CultivAid, 2021).

Groundwater has proved a reliable and accessible water source for irrigation but in Mbale district water depth and variability in quantity and quality are constraints (Wanyama, 2018). Therefore, there is need to determine the groundwater quantity, quality and vulnerability with the idea of supporting irrigated agriculture.

1.2 Problem statement

According to the survey done by Anna et al in 2021, 63% of farmers are affected by drought in Mbale district. The drought has been manifested by steady rise in temperatures (0.03℃/year), average annual precipitation of 630mm and 560mm in the first and second seasons in the period of 36 years (1980-2015) and less predictableness of commencement of rains (Okiror & Muchunguzi, 2019). This is causing growing difficulties for many crops since agricultural production system is largely rainfed and sensitive to climate change (MAIIF, 2020). This has contributed to loss of rural livelihoods and food insecurity (World Bank, 2020).

To mitigate this situation, the Government of Uganda through MAAIF with support from World Bank is implementing the Micro-Scale Irrigation Programme (MAAIF, 2020). However, this program supports only farmers near surface water sources which are inadequate, thereby leaving out 99% of small-scale farmers who have continued to rely on rainfed agriculture (CultivAid, 2021).

To increase on the availability of water for irrigation, groundwater can be utilized but its quantity and quality are not known (Wanyama, 2018). Thus, this research aimed at assessing the groundwater availability and suitability by considering potential, quality and vulnerability to contamination in Mbale district.

1.3 Objectives

1.3.1 Main objective

To evaluate groundwater availability and suitability for irrigated agriculture in Mbale district.

1.3.2 Specific objectives

The study aimed to;

1. Estimate the groundwater potential in Mbale district
2. Analyze groundwater quality in Mbale district
3. Assess the groundwater vulnerability in Mbale district

1.4 Research Questions

The study was guided by the following questions;

1. What is the groundwater potential in Mbale district?
2. What is the variability of groundwater in Mbale district quality?
3. What is the extent of groundwater vulnerability to contamination in Mbale district?
4.

1.5 Significance of the Study

Groundwater availability and suitability information will be used by government agencies and farmers to promote agriculture in Mbale district as per section 173 of the Uganda Vision 2040 and sections 59 and 140 of the National Development Plan III. This is to contribute to reduction of poverty and hunger which are in line with Sustainable Development Goals 1 and 2 respectively.

1.6 Scope of the study

The study was conducted in Mbale district in Eastern Uganda. It was limited to the determination of groundwater suitability and availability by considering groundwater potential, quality and vulnerability. The period of study was from November 2022 to March 2023. The items outside the study because they would make it have a very large scope are determination of the crops which can grow well in the study area and management of the groundwater quality.

1.7 Conceptual Framework

The conceptual framework for the study is presented in Figure 1-1. It's premised on the fact that groundwater availability and suitability depend on groundwater potential, quality and vulnerability to contamination. These are affected by the independent variables (permanent parameters) and moderating variables (seasonal parameters) as in Figure 1-1.

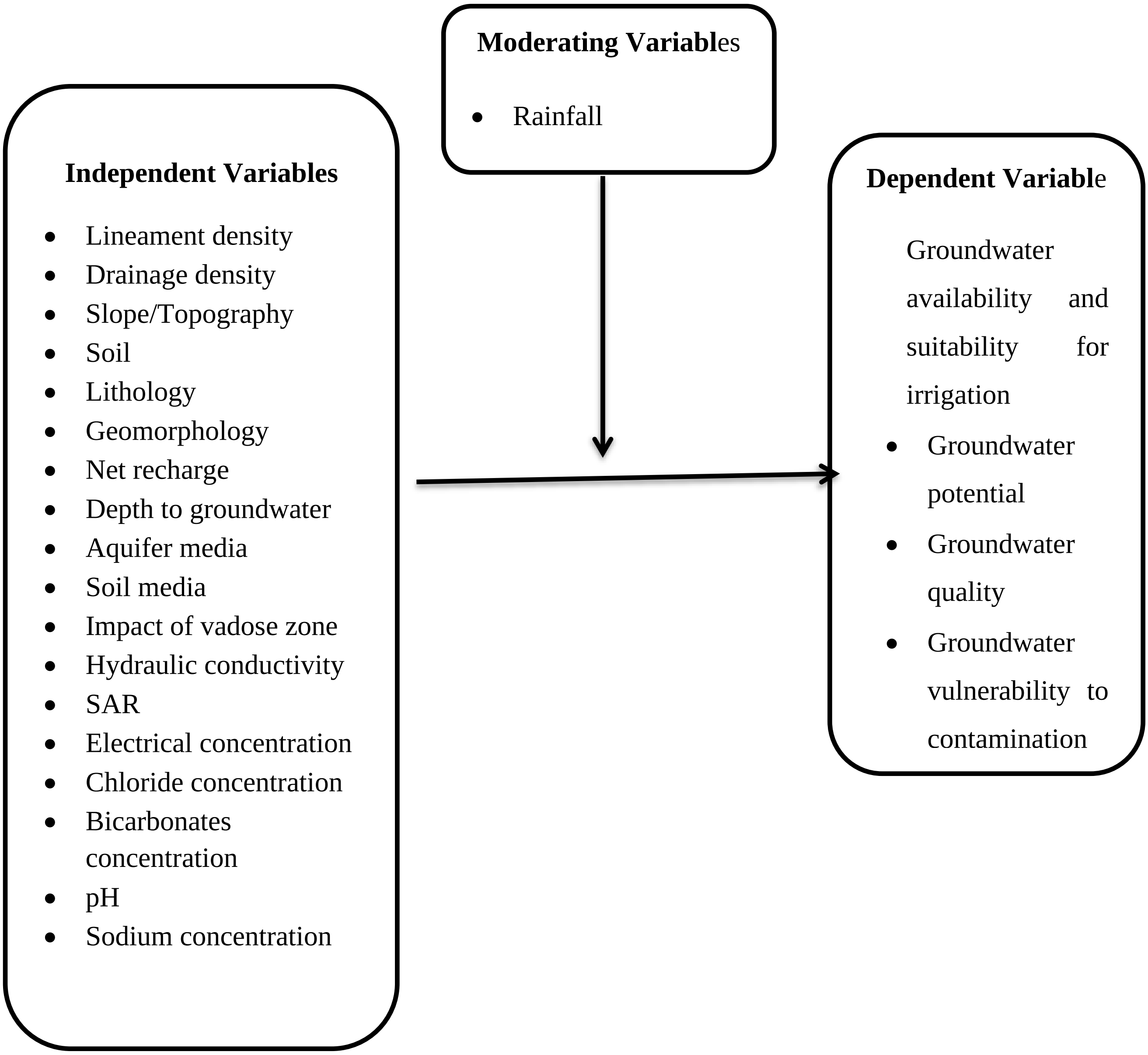

Figure 1- 1: Conceptual Framework for the study

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

Groundwater is a form of water that occupies all the voids in a geological stratum. Aquifer formation in the earth's crust serves as a conduit and reservoir for water (Akinlalu et al., 2017). Climate change, threat of droughts and the risk of surface water pollution due to anthropological activities such as agriculture and industrialization (Çelik et al., 2019) necessitate recognition of other natural water resources. A lesser amount of contamination than surface water and subsurface water is a valuable important reserve. Groundwater can be a crucial source of water in times of surface water shortage (De Stefano & Lopez-Gunn, 2012), especially in climate-changing regions. However, unintended groundwater usage upsets the normal balance of aquifer replenishment. Applying and shaping the efficient use and planning of groundwater are critical to understanding groundwater resources holistically in terms of potential, quality and vulnerability (Mehra et al., 2016). Conventional methods previously used to determine groundwater resources were mainly based on fieldwork. With the advent of remote sensing and geographic information systems (GIS) technology, the assessment of groundwater in each geological unit has become an easy procedure (Ganapuram et al., 2008)

2.2 Groundwater potential

Groundwater potential is clearly described as availability of subsurface water (Jha et al., 2010). Old groundwater investigation methods e.g., drilling, hydrogeology, geology and geophysics are enormously expensive, time intense and need skilled labour (Shishaye et al., 2016). Birth of GIS has delivered time- and budget-effective alternative groundwater potential mapping ways (Nampak et al., 2014). GIS stands as a commendable and valuable tool for managing large amounts of data and is used in decision making for several areas like environmental and hydrology management (Magesh et al., 2012). This is due to the ability to quickly access data obtained through global positioning systems and RS techniques (Zare et al., 2018). Although satellite images cannot directly detect groundwater, surface features prepared as thematic layers from these images serve as a yardstick for estimating groundwater potential (Hammouri et al., 2012). Thematic layers are used as efficiency factors to assess groundwater potential, viz. rainfall, lithology, drainage density, land use and cover, soil, slope, geomorphology and lineament density (Rahmati et al., 2015). The hydrological situations mainly depend on these layers and thus create evidence of existence of groundwater.

2.2.1 Rainfall

The sustainability of present and prospective groundwater extraction depends on groundwater rejuvenation, but the transformation of rainfall into additional amounts is not well understood. This knowledge gap is mainly because of lack of accessibility to persistent observations of variations in groundwater reserves (Taylor et al., 2013). Studies based on observations of pressure measurements and uncommon stable isotope ratios indicate that heavy rainfall events help to replenish groundwater specifically in the tropics (Jasechko and Taylor, 2015) but the role of unsaturated regions in water transport remain uncertain (e.g. permeation and control pathways). Thus, the availability of precipitation is considered to be the main underpinning of recharge (Shekhar et al., 2015). Precipitation has a strong impact on groundwater potential and the effectiveness of Multi-Criteria Decision Analysis (MCDA) (Adiat et al., 2012).

2.2.2 Lithology

Lithology is a vital aspect in forecasting potential of groundwater areas (Ramamoorthy & Rammohan, 2015). The lithological properties regulate the sponginess and seepage of groundwater (Chowdhury et al., 2010). Lithology affects both sponginess and permeability of water-bearing rocks (Ayazi et al., 2010). The higher porosity of the lithological parameter contributes to higher groundwater storage and higher penetrability, which in turn contributes to higher groundwater production.

2.2.3 Drainage density

Drainage density is a reverse function of penetrability (Agarwal et al., 2013) and is considered an important constraint for delineating potential of groundwater. Drainage arrangement of a zone is controlled by type and arrangement of the bedrock, the type of flora, the soil's capability to absorb precipitation, the permeability, and the inclination of the slope (Manap et al., 2013). Areas of low drainage density cause additional seepage and reduced superficial runoff. This detonates that zone with little drainage densities are fit for groundwater uplift (Magesh et al., 2012).

2.2.4 Lineament density

Lineaments are natural surface features such as joints, faults, lamellae or buffer planes that are interpreted directly from satellite images, geophysical maps or aerial photographs (Al-Nahmi et al., 2016). It can also mean defects, fractures and major joints; a lengthy and undeviating geological establishment, linear topography or a straight stream of water (Pradhan, 2010). They reveal a global surface expression of subversive rifting (Pradhan and Youssef, 2010). They stand classified as tributary porosity and are visible in satellite images as tonal differences from other topographic features. They affect the infiltration of surface runoff into the underlying soil layer and are of infinite importance for groundwater storage and movement (Subba Rao et al., 2006). In studies performed by Anifowose and Kolawole (2012), it is clear that the presence of groundwater movements of an area controls yields to a greater extent.

2.2.5 Slope

Slope plays an important role in mapping groundwater potential (Biswas et al., 2012). It determines the surface flow and longitudinal infiltration of water; therefore, it affects groundwater regeneration (Kumar et al., 2014). The penetration is inversely proportional to the slope (Mukhopadhyay et al, 2022). Slope can be considered as a surface measure to determine groundwater status (Al Saud, 2010). In supplementary words, these thematic layers are deliberated as displacing surface flow velocity and vertical filtration (i.e. permeability inversely proportional towards slope) hence influencing the rejuvenation process. (Adiat et al., 2012).

2.2.6 Land use and land cover

Land use land cover (LULC) is one of the important determinants for identifying potential areas for groundwater recharge (Gadrani et al., 2018). Impacts of hydrology like infiltration, surface runoff and transpiration are affected by LULC. Vegetation-covered zones have higher groundwater potential than developed areas, which prevents water penetration into the ground (Adewumi & Akinyelu, 2017). Among land use categories, built-up area has the lowermost weight equated to others but cropland has uppermost weight (Nair & Babu, 2015).

2.2.7 Soil

Soil has a vital influence on the potential of groundwater (Mehra and Singh 2018). Data on the soil types is required as an essential input in hydrologic assessment. Mapping soil usually comprises of delineating soil sorts which have certain features. Soil depth is major aspects in surface and sub-surface overflow generation and infiltration process (Mogaji et al., 2014).

2.2.8 Geomorphology

Geomorphological maps show topographical patterns related to availability of groundwater its prospects. Relief elements were recognized from DEM (Ibrahim-Bathis & Ahmed, 2016). Prediction of groundwater potential is high near the higher streams that correspond to lower sloping topography (Dinesan et al., 2015).

Several publications revealed that some researchers used GIS to localize potential groundwater areas with the incorporation of arithmetical methods for instance Simple Additive Weight (SAW) and Analytical Hierarchy Procedures (AHP) (Yildirim, 2021) and machine learning (Hussein et al., 2020). The amalgamation of GIS technology and remote sensing reduces inaccuracies of hydrogeological data in some respects. Recently, many studies have been applied using index-based models and quantitative methods to assess potential groundwater areas (Gyeltshen et al., 2020). AHP is the most popular and widely used multi-criteria decision analysis (MCDA) technique for zoning groundwater exploration areas (Makonyo & Msabi, 2021). Accordingly, the AHP technique was used for this study to assign the relative importance of each parameter for groundwater zoning. GWPI is a dimensionless measure which supports forecast of the potential of groundwater. The weighted linear matching method is used in the GWPI approximation as in Equation (1) (Shekhar and Pandey,2014):

$$GWPI = \sum_{w=1}^{m} \sum_{i=1}^{n} \left(W_i \times X_j\right) \qquad (1)$$

Wi - the normalized weight of the ith thematic layer, X_j - the rank value of each class relative to the jth class, m - the total number of thematic layer and n - the total number of classes in a thematic class.

2.3 Groundwater vulnerability

Vulnerability means proneness of groundwater to pollutants produced by anthropological activities (Cannon et al., 2013) Assessing inherent vulnerability is similar to assessing the defensive ability of protection layers to the introduction and conveyance of pollutants into groundwater. Vulnerability assessment approaches that use the inherent vulnerability idea include: DRASTIC (depth-to-groundwater, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity), AVI (Aquifer Vulnerability Index), and SINTACS (water table
depth, effective infiltration, unsaturated zone, soil media, aquifer media, hydraulic conductivity and topographic slope) and are able to distinguish degrees of vulnerability at regional scales where different lithologies exist (Oke,2017). These approaches provide a useful tool for assessing and managing groundwater resources to ensure their sustainability. Further research should focus on the development of more comprehensive and accurate models that can handle uncertainty and predict the potential impacts of climate change on groundwater vulnerability

However, DRASTIC model is frequently employed due to its efficacy and simplicity in depicting diverse aquifer configurations (Neshat & Pradhan, 2017). The software possesses a capacity to enable individuals to manage, analyze, and visualize spatial data, rendering it a commendable substitute to other approaches when conducting assessments of groundwater vulnerability (Canora et al. 2022). Furthermore, the DRASTIC model can be readily extrapolated to alternative hydrological catchments given the availability of adequate data and fundamental comprehension of the target region undergoing assessment (Kirlas et al. 2022). Notwithstanding its utility, the DRASTIC method is beset by certain limitations, one of which pertains to its inability to fully integrate pollutant sources and/or the potential impact of future pollution

sources on water contamination (Goyal et al. 2021). Moreover, it precludes the assessment of overarching groundwater susceptible areas (Abiy et al., 2016).
The DRASTIC approach was formulated based on four underlying suppositions, as postulated by Al-Zabet (2002) which are; the contaminant is initiated at the earth surface, the pollutant is introduced into the groundwater through the process of rainfall infiltration, the velocity of the pollutant is commensurate with that of water and the land area under assessment through the utilization of the DRASTIC model is equal to or exceeds 40 hectares.

2.4 Groundwater Quality

Groundwater quality for irrigation is an issue of concern of recent (Ibrahim et al., 2023). Lower or higher chemical fertilization is resulting in groundwater pollution (Nemčić-Jurec & Jazbec 2017). Groundwater quality is a subject to the way of recharging water, precipitation, subsurface and surface water and hydro-geochemical processes in aquifers (Das et al., 2017), land-use land-cover change (Rawat and Singh 2018). Groundwater quality degrades in twofold, first, due to geochemical reactions in the aquifers and soils and, second, time when it is supplied through improper canals/drainages for irrigation. Therefore, it is necessary to perform a regular assessment of irrigation and drinking water quality (Rawat et al., 2018).
Irrigation demands sufficient water supply of usable quality (Gautam et al., 2013). The suitability of groundwater for irrigation depends on the nature of the mineral elements in the water and their impacts on both the soil and plants (Singh et al. 2015). The excess of salts affects plant’s growth by redressing the uptake power of plant due to complex changes arouse out of the osmotic processes (Todd ,1980).
Generally, water quality parameters (major cations as Na^+, Ca^{2+}, Mg^{2+}, K^+) and anions Cl^-, SO_4^{2-} , HCO_3^-,CO_3^{2-}, NO_3^-) and heavy metals are indicators of drinking water use, while Water Quality Indices (WQI) such as sodium adsorption ratio (SAR), sodium percentage (SSP; %Na), residual sodium carbonate (RSC), residual alkalinity (RA), Irrigation Water Quality Index (IWQI), Kelly’s ratio (KR) [or Kelly’s index (KI)], permeability index (PI), chloroalkaline indices (CAI1 and CAI2), potential salinity (PS), magnesium hazard (MH) (or magnesium adsorption ratio; MAR), total dissolved solids (TDS) and total hardness (TH) based on primary water quality parameters are frequently used to determine quality of water for irrigation (Gautam et al. 2015).
To determine groundwater appropriateness for irrigated agriculture is accomplished by utilization of the Irrigation Water Quality Index (IWQI), an index which Meireles and others formulated in 2010. When calculating the Irrigation Water Quality Index (IWQI), the foremost factors taken into account are Electrical Conductivities (EC), Sodium (Na^+), Chloride (Cl^-), Bicarbonate (HCO_3^-), and Sodium Adsorption Ratio (SAR), as these aspects hold significant sway over water quality for the reason of irrigation. This method possesses an important utility and efficiency in evaluating the appropriateness of water quality and disseminating information related to the overall quality of water, as demonstrated by Abbasnia and colleagues in their research conducted in 2018. The application of Geographic Information Systems (GIS) for the purposes of assessment not only facilitates the development of parameter maps that are conducive to intuitive comprehension, but it also heightens the overall rigor, objectivity, and efficiency of the analysis process (Al-Hadithi et al., 2019).

2.5 Summary of the Literature

The literature review focused on the assessment of groundwater potential for irrigation from different regions of the world. The studies revealed that groundwater is considered an important source of water for irrigation in areas where surface water is erratic or scarce. The review also highlighted the importance of accurate groundwater mapping and modelling for effective utilization of the resource. Overall, the literature review provided valuable insights into the potential of groundwater for irrigation and underscored the need for proper management of these resources.

The literature review also covers various studies that have been conducted to assess groundwater quality for irrigation. These studies have identified various sources of contamination including agricultural practices, stormwater runoff, sewage disposal systems and industrial activities. Overall, the literature review on groundwater quality for irrigation highlights the importance of understanding the factors that impact groundwater quality. It also emphasized the need for regular monitoring and management of groundwater resources using several indices methods to ensure their suitability for irrigation use purposes.

Groundwater vulnerability for irrigation is a complex issue that is influenced by various factors including geology, hydrology, land use and climate change. Literature review reveals that vulnerability assessments for groundwater for irrigation relies on the use of inherent vulnerability ideas. Overall, the literature suggests continued research and monitoring of groundwater for irrigation is necessary to develop sustainable management strategies and ensure the protection of groundwater resources.

2.6 Research Gap

Several studies done in Uganda (Megersa and Abdulahi, 2015; Haile and Asfaw, 2015; Kadigi et al., 2012; Fermont and Benson, 2011; Van Averbeke et al., 2011; Ngigi ,2009; Machethe et al., 2004) denote that in Uganda, agriculture is mostly rain-nurtured, is progressively more shaken by climate change and unpredictability demonstrated in unreliable rain configurations, lengthy dry periods, and inundations. As a consequence, farm-level productivity is extremely below the achievable prospective for most crops. In regard with these situations, irrigation is vital in helping farmers against climate change and performs an essential part in evolutions from subsistence to commercial agriculture by guaranteeing perennial production and farm jobs. However, Wanyama and colleagues in 2017 proposed that studies should be conducted to harmonize information on the irrigation potential in the areas of Uganda because numerous sources estimate unlike data and the procedures used do not give inclusive statistics to influence planning for irrigated agriculture. Also Wanyama (2018) indicated that Mbale district had groundwater irrigation potential but the quantity and quality are not known. So the purpose of the study was to address the gap of groundwater quantity and quality so that availability and suitability can be known for proper planning of irrigated agriculture in Mbale district.

CHAPTER THREE: RESEARCH METHODOLOGY

3.0 Research Design

The study was both empirical and quantitative in nature. It involved evaluating groundwater availability and suitability in Mbale district through groundwater potential, quality and vulnerability assessment.

4.1 Research Instruments

The research instruments used in the study to achieve the objectives are detailed in Table 3-1.

Table 3- 1: Research instruments used in the study

No	Research Instrument	Objective	Outcome
1.	Document Review	To address objectives 1, 2 and 3 of the study	Proper data and methodology for the study were discovered

2.	Simple Random Sampling	To address objective 2 of the study	Sample size of boreholes to provide water samples for determination of quality for irrigation was acquired
3.	Laboratory experiments	To address objective 2 of the study	Existing water quality for irrigated agriculture was analyzed
4.	Online Surveying (Downloading of maps)	To address objectives 1 and 3 of the study	Raster and vector maps which were used as raw data for the study were obtained
5.	ArcGIS	To address objectives 1, 2 and 3 of the study	Analyzed data for groundwater potential, quality and vulnerability to contamination and created availability and suitability map for irrigated agriculture using MLC method.

3.3 Study area

The study was carried out in Mbale district, eastern Uganda. It lies at the geographical coordinates of 00º57'N 34º20'E. It neighbors Mbale City on the north, Manafwa and Bududa districts on eastern side, Butaleja district on the west and Tororo district on the south. The map of Mbale district is shown in Figure 3-1. The district has 15 sub counties as shown in Figure 3-2.

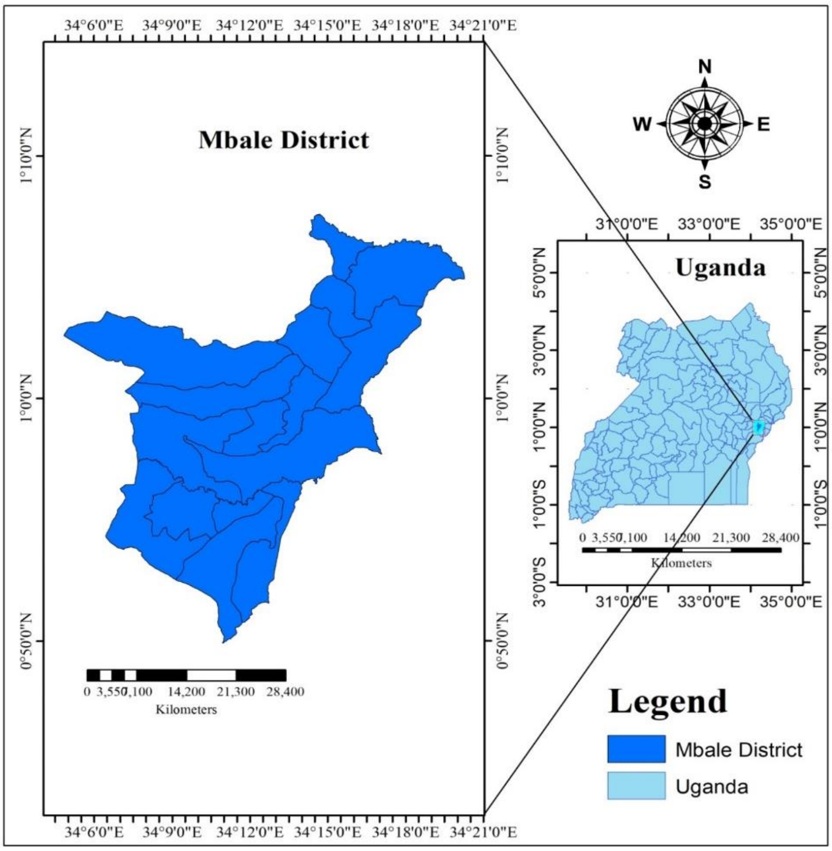

Figure 3- 1: Map of Mbale district

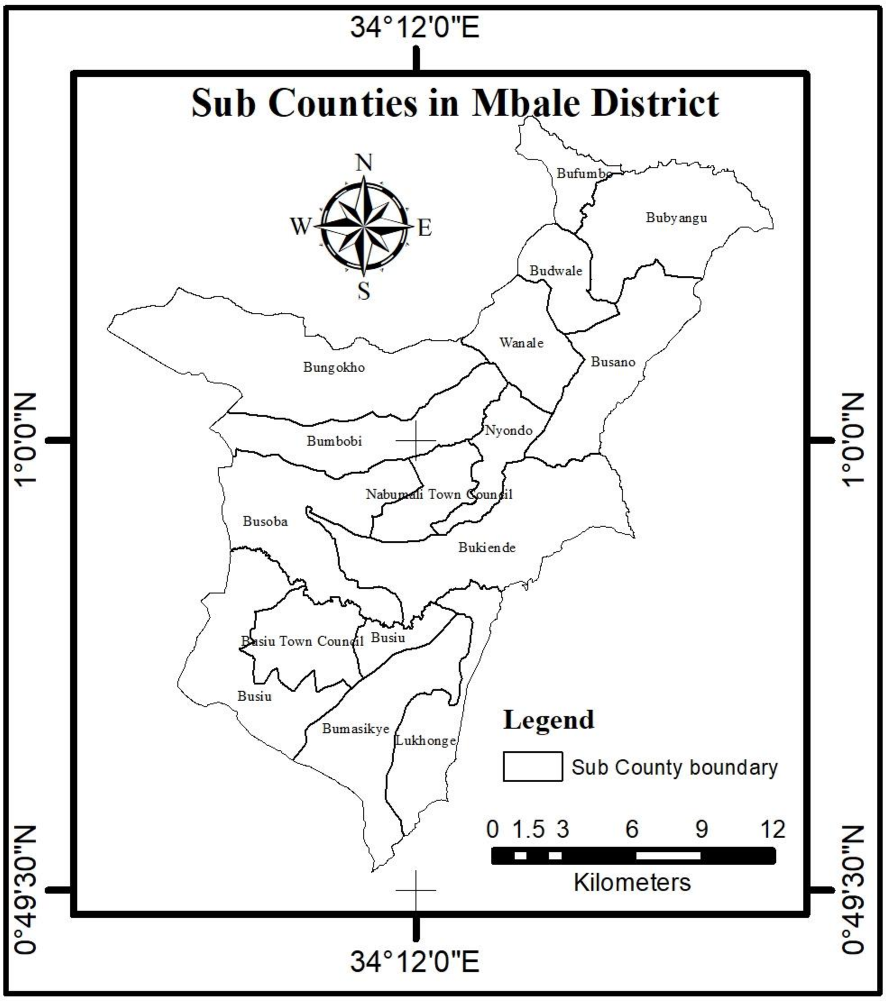

Figure 3- 2: Map of Mbale district showing Sub Counties

3.4 Groundwater potential

Groundwater potential was modeled using AHP based weighted overlay index method because of the following reasons: simplicity and easiness to use, outcomes are very easy to comprehend, results are fare well in real world scenarios based on multiple criteria, checks the results for consistency hence preventing errors and it's a solution for personal bias in decision making. It consisted of three key phases. The first phase was preparation of the thematic layers that were appropriate to potential of groundwater. The second phase involved processing of the thematic layers to guarantee even WGS1984 projection and resolution, allocating scores, and weightages. The third and final phase was to determine the ground water potential index (GWPI) by integration of all thematic layers along with indices using the spatial analysis tool in GIS software.

3.4.1 Selection of thematic layers impelling groundwater potential

To identify potential groundwater areas, eight thematic layers were used viz: lineament density, drainage density, geomorphology, lithology, land use land cover, slope, soil, and rainfall are effective factors. The hydrological conditions largely depend on thematic layers and thus affect availability of groundwater. The thematic layers provide a dependable basis for effectively predicting zones of groundwater potential.

3.4.2 Rainfall

Average annual rainfall data of Mbale district in a period of 30 years (i.e., 1991 – 2021) was extracted from the Climate Research Unit.

3.4.3 Lithology

The lithology layer was extracted from the US Geological Survey raster map at 1:5,000,000). Groundwater potential can largely be measured by the existence lithology features.

3.4.4 Drainage density

Drainage was taken directly from DEM ASTER (28 x28 m) of Uganda. Drainage density means proportion of total flow length to size of grid extent under consideration (Mogaji et al., 2014). Therefore, a grid (with a cell extent totaling to 10 km^2) was designed over the study area and the drainage density index was computed using ArcGIS through Equation (2).

$$DD = \sum \frac{Di}{A} (km^{-1}) \quad (2)$$

Where: Di (km) - totality of the lengths of watercourses while A is the grid area (km^2). Calculated values per grid were plotted midpoint of grid. The coordinates at the center of per grid were then used to construct the drainage density map with the help Kernel density procedure as in Figure 3-6. Drainage density has a negative correlation with groundwater prospect. If drainage density high the probability of groundwater potential is low (Melese & Belay, 2021).

3.4.5 Lineament density

Lineaments were extracted from Uganda's DEM ASTER (28x28 m). Calculation of the lineament density was based the on-grid technique. The lineament density is clearly defined as the ratio of the total length of all recorded lineaments to the area under consideration (Edet et al., 1998). This is shown in Equation 3:

$$Ld = \sum_{i=1}^{i=n} \frac{Li}{A} (km^{-1}) \quad (3)$$

Li is the overall length of all lines (km) and A - grid extent (km^2). Lineament density is comparative to the area of groundwater replenishment. The rationale for the flow examination is to advance knowledge of affiliation between superficial water infiltration and fault systems, by regulating infiltration and water movement.

3.4.6 Slope

The slope map of the area was generated from Uganda's ASTER DEM image using ArcGIS 10.2 software. The water volume accessible during refilling and roughness of the topography of watershed are determined from the slope of that basin. Large flow volumes and lower seepage are associated with areas of high vertical angle. So, slope is one of the main factors that disturb the flow and infiltration rate. Weight per slope type was assigned basing on groundwater potential.

3.4.7 Land use and land cover

Land cover land use (LULC) is an important factor which enhances presence and availability of groundwater (Selvam et al., 2016). The LULC layer was obtained from 2021 30m resolution of Landsat 8. Categorization happened to organize and determine LULC categories. The proportion of groundwater replenishment in irrigated farming increase significantly in all cases (Sheikh et al., 2017).

3.4.8 Geomorphology

Geomorphology is well-thought-out as the great needed feature for considering the existence, prospect, and flow of groundwater resources. The geomorphological development of a hard rock terrain is mainly organized by tectonic events and denudational practices (Bera et al., 2020). The geomorphology map was extracted from the year 2022 Geomorphology Map at scale of 1:100000

3.4.9 Soil

Soil types in the district play an important part during groundwater rejuvenation and retention capacity. Accordingly, it's a vital factor during delineation of potential groundwater areas (Rehman et al., 2019). The soil map was extracted from the year 1967 Soil Map at scale of 1:250000

3.4.10 Formation of weight for prospecting parameters of groundwater using Analytical Hierarchical Process

Analytical Hierarchical Process **(**AHP) model is Multicriteria decision-making (MCDM) tool that offers answers for complex decision-creating problems, and was first presented by (Saaty, 1980). AHP is an extensively acknowledged model for assigning normalized weight to each layer of groundwater prospecting factor. The concluding weight of each thematic layer was generated from the principal Eigenvalue of the generated matrix. The consistency of the yield was governed by the computed consistency index (CI) and consistency ratio (CR) values (Equation 4&5).

$$CR = \frac{CI}{RI} \quad \text{----------} \quad (4)$$

Where: CR is consistency ratio, RI is random consistency index whose values depend on the order of the matrix (Table 3-1), and CI is consistency index which can also be computed using the following formula

$$CI = \frac{\lambda_{\max} - n}{n-1} \quad \text{\_\_\_\_\_\_} \quad (5)$$

Where λ_{max} is the principal Eigen value of the matrix and n indicates the quantity of groundwater prospecting factors. The value of

CR must be <0.1.

The acclimatizing features were likened to one another by pairwise comparison matrix. The inverse ranking method was used to assign a normalized weight for each thematic layer. The potential of groundwater is represented by the rating of 1–9 (Table 3-2), where 1, 2, 3, 4, and 5 for very low, low, medium, high, and very high (Jhariya et al., 2017).

Table 3- 2: Saaty's ratio index for different values of N

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.89	1.12	1.24	1.32	1.41	1.45	1.49

Table 3- 3: Saaty's 1-9 scale of relative importance

Scale	Significance
1	Equal significance
2	Weak
3	Moderate significance
4	Moderate plus
5	Strong plus
6	Strong significance

7	Very strong significance
8	Very very strong significance
9	Extreme significance

3.4.11 Groundwater Potential Index

The groundwater recharge potential map was produced by bearing in mind the comparative significance of numerous thematic layers and their conforming classes. GWPI, a dimensionless quantitative approach was used to delineate groundwater potential zone (Razandi et al., 2017). Considering all the themes of and features in an integrated layer, the groundwater potential index is computed as Equation 6: -

$$GWPI = Lt_w Lt_{wf} + Ld_w Ld_{wf} + Dd_w Dd_{wf} + SwSw_f + Rf_w Rf_{wf} + Ge_w Ge_f + LULC_w LULC_f + So_w So_f \text{ ----- } (6)$$

Where: Lt - lithology, Ld - lineament density, Dd - drainage density, S - slope, Rf - rainfall, Ge is Geormophology, LULC is Land use landcover and So is slope. Subscripts 'W' and 'Wf' designate normalized weight of a layer obtained through AHP and the normalized weight of the discrete features of a layer respectively. The GWPI was computed per grid and then plotted in midpoint the grids. The groundwater potential index map was established using the weighted overlay technique and geostatistical analysis was performed. The GWPI values were classified using a quantum classifier. Quantum classification approach, per class contained the similar quantity of features grouped into their respective classes.

3.5 Groundwater quality

The study was done by means of the GIS and IWQI method which (Meireles et al., 2010) formulated to evaluate the groundwater quality and decide suitability for irrigation use in Mbale district. The IWQI model assessed groundwater quality using the following parameters: Electrical Conductivities (EC), Sodium (Na^+), Bicarbonate (HCO_3^-), Chloride (Cl^-), Potassium (K^+), and Magnesium (Mg^{2+}), parameters, that imitate water toxicity, sodicity hazards, and soil salinity to plants. The data was obtained by simple random sampling of functional deep well water sources (boreholes). Simple random sampling was used since each borehole had an equal chance of being selected and an unbiased sample was obtained (Noor, et al., 2022).

3.5.1 Sampling and testing

The district has 163 functional deep boreholes. The final sample size was 33 boreholes determined from Equations 7-11 and the distribution of the sample size is presented in Table 3-4 and Figure 3-11. Each sample was collected from a clean one-liter plastic bottle and water quality testing was done by the Ministry of Water and Environment Mbale regional Laboratory. The results are attached in Appendix 1

Table 3- 4: Mbale district functional borehole distribution

S/N	Sub County	Number of boreholes (X)	$(X-\mu)^2$
1	Bubyangu	0	118.09169
2	Budwale	0	118.09169
3	Wanale	0	118.09169
4	Bukhiende	22	123.94369

5	Bufumbo	1	97.357689
6	Bumbobi	10	0.751689
7	Nabumali Town Council	10	0.751689
8	Busoba	18	50.879689
9	Bumasikye	24	172.47569
10	Busano	2	78.623689
11	Bungokho	26	229.00769
12	Lukhonge	19	66.145689
13	Busiu Town Council	7	14.953689
14	Busiu	23	147.20969
15	Nyondo	1	97.357689
	Total	**163**	**1433.7333**

Mean, $\mu = \frac{\sum X}{n} = \frac{163}{15} = 10.866667$ -- (7)

Standard deviation, $\delta = \sqrt{\frac{(X-\mu)^2}{n}} = \sqrt{\frac{1433.7333}{15}} = 9.777$ --------------------------------------(8)

Sample size, $n_s = \frac{N}{\left[1+N(e)^2\right]}$ (Singh, 2014) -- (9)

Where $e = 0.10$ is precision at 95% confidence level, $N = 163$ number of functional boreholes in Mbale district.

$n_s = \frac{163}{\left[1+163(0.1)^2\right]} = 61.9772 \approx 62$ samples

Sixty- two samples are many due to time constraint, loss of accuracy and costly which would make the study difficult (Simarjeet, 2017).

According to Smith et al., 2019 the proportion sample n_0 is estimated where the sample is large and there is no replacement (Equation 10),

$n_0 = \frac{Z^2\delta^2}{e^2}$ --- (10)

Sampling error, $e = \frac{Z\delta}{\sqrt{n}} = \frac{1.96x9.777}{\sqrt{62}} = 2.433 \approx 3$

$n_0 = \frac{Z^2\delta^2}{e^2} = \frac{1.96^2 x 9.777^2}{3^2} \approx 41 samples$

Using the finite population correction Equation 11

$n = \frac{n_0 N}{n_0 + (N-1))} = \frac{(41x163))}{41+(163-1)} = 33 samples$ -- (11)

Using random sampling technique, the following number of boreholes will be sampled in each sub county.

Table 3- 5: Sample size of the boreholes

S/N	Sub County	Number of boreholes	Sample size
1	Bubyangu	0	0
2	Budwale	0	0
3	Wanale	0	0
4	Bukhiende	22	4
5	Bufumbo	1	1
6	Bumbobi	10	2
7	Nabumali Town Council	10	2
8	Busoba	18	3
9	Bumasikye	24	5
10	Busano	2	1
11	Bungokho	26	5
12	Lukhonge	19	3
13	Busiu Town Council	7	2
14	Busiu	23	4
15	Nyondo	1	1
Total		**163**	**33**

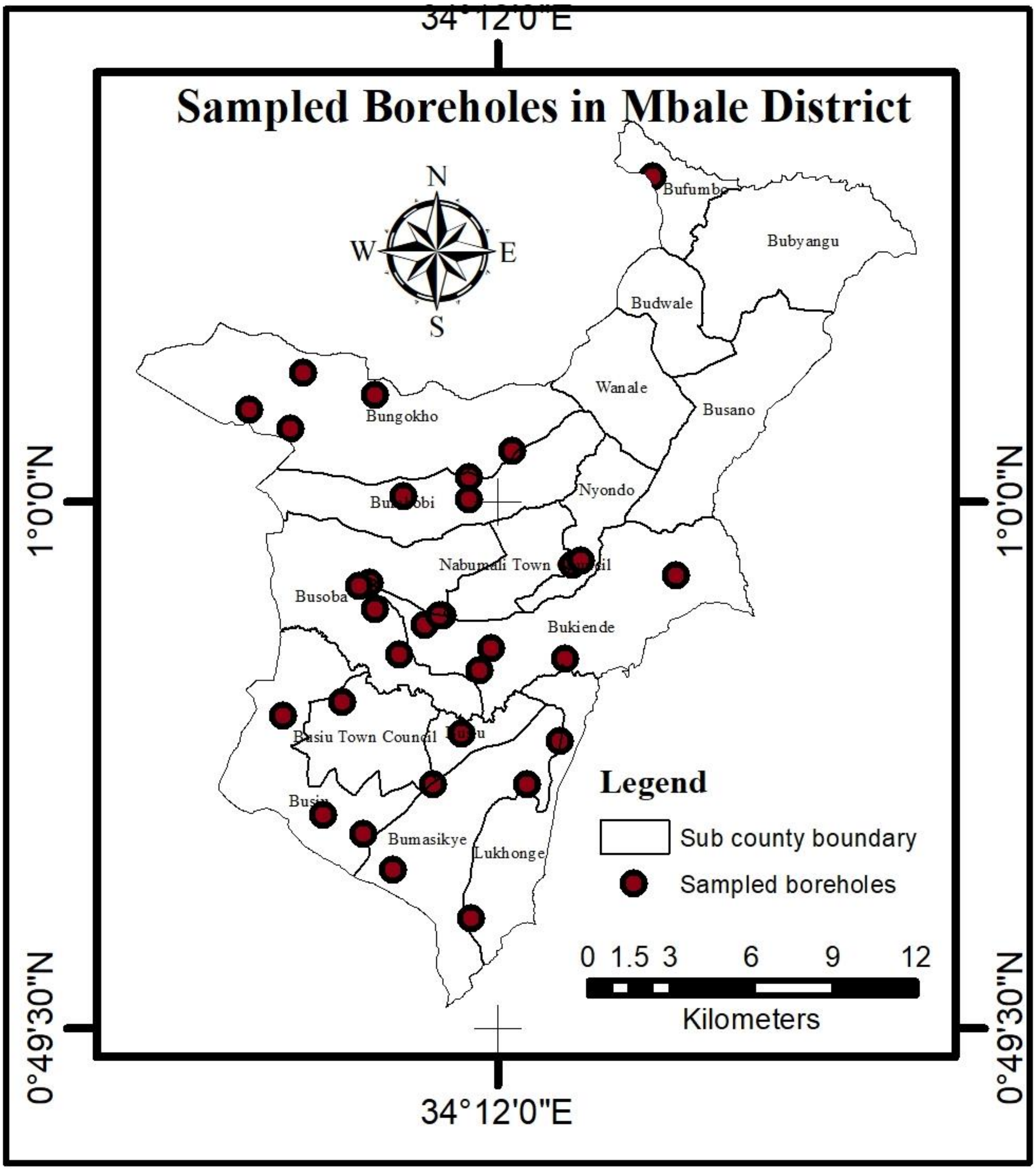

Figure 3- 3: Sampled boreholes in Mbale district

Calculation of the Irrigation Water Quality Index (IWQI)

The EC, Na+, Cl-, HCO3-and SAR parameters suggested by (Meireles et al., 2010) were used to calculate the IWQI. SAR was calculated as the ratio of sodium absorption using the Equation 12:

$$SAR = \frac{Na^+}{\sqrt{0.5\left(Ca^{2+} + Mg^{2+}\right)}} \quad \text{---} \quad (12)$$

First, the values of cumulative weights (wi) suggested by (Meirales et al., 2010) must be well defined according to their relative importance for IWQ. These are normalized values and their sum is one, as shown in Table 3-5.

Table 3- 6: Weights for IWQI parameters (Meirales et al., 2010)

Parameter	Weight (wi)
EC	0.211
Na^{2+}	0.204
$HCO3^{-}$	0.202
Cl^{-}	0.194
SAR	0.189
Total	**1**

According to Ayers and Westcot (1994), the Qi value is evaluated in the second step as in Table 3-6. This means a dimensionless number, with a higher value representing better water quality. The Qi value was calculated using Equation 13:

$$Q_i = q_{i\max} - \left[\frac{\left[\left(x_{ij} - x_{\inf} \right) * q_{iamp} \right]}{x_{amp}} \right] \text{--- (13)}$$

Where: q_{imax} is the maximum value of qi for the class, x_{ij} is the observed value of the chemical parameters, x_{inf} is the minimum limit of the class to which each parameter belongs; q_{iamp} is the layer amplitude; and x_{amp} is the upper bound of the last layer of each parameter. Finally, the irrigation water quality index (IWQI) is calculated according to the following Equation 14:

$$IWQI = \sum_{i=1}^{n} Qi * wi \text{ --- (14)}$$

Where IWQI is a dimensionless index of irrigation water quality in the range from 0 to 100; Qi is a measure of the quality of the parameter, (i^{th}) a number from (0 to 100) as a function of its concentration; and wi is the normalized weight of the ith parameter. (Meireles et al., 2010) divided the IWQI values for the suitability of irrigation water into five dimensionless parameter categories based on the proposed groundwater quality index determined by the existing groundwater quality index as shown in Table 3-7. The classes were determined based on the problems of salinity risk, reduced water infiltration and toxicity to plants, as suggested by (Bernardo, 1995).

Table 3- 7: Limiting values of Qi calculations (Ayers and Westcot, 1994)

HCO_3^{-1} (mg/l)	Cl^- (mg/l)	Na^+ (mg/l)	SAR $(mg/l)^{1/2}$	EC (µS/cm)	Q_i
$1 \leq HCO3 < 1.5$	$1 \leq Cl < 4$	$2 \leq Na < 3$	$2 \leq SAR < 3$	$200 \leq EC < 750$	85-100
$1.5 \leq HCO3 < 4.5$	$4 \leq Cl < 7$	$3 \leq Na < 6$	$3 \leq SAR < 6$	$750 \leq EC < 1500$	60-85
$4.5 \leq HCO3 < 8.5$	$7 \leq Cl < 10$	$6 \leq Na < 9$	$6 \leq SAR < 12$	$1500 \leq EC < 3000$	35-60
$HCO3 < 1$ or $HCO3 \geq 8.5$	$1 < Cl \geq 10$	$Na < 2$ or $Na \geq 9$	$2 \leq SAR \geq 12$	$EC < 200$ or $EC \geq 3000$	0-35

Table 3- 8: Irrigation Water Quality Characteristics (Meireles et al.,2010)

Recommendation		**Water use restrictions**	**IWQI**
Plant	**Soil**		
No poisonous quality possibility for most plants	May be utilized for the lion's share of soils with moo likelihood of causing saltiness and sodicity issues. Filtering prescribed inside water system hones, but for in soils with greatly low permeability"	No restriction (NR)	85-100
Circumvent salt sensitive plants"	Prescribed for utilize in watered soils with light surface or direct porousness. Salt filtering suggested. Soil sodicity in overwhelming surface soils may happen, being prescribed to maintain a strategic distance from its utilize in soils with tall clay	Low restriction (LR)	70- 85
Plants with modest resistance to salts may be grown"	May be utilized in soils with direct to tall penetrability values, direct filtering of salts recommended.	Moderate restriction (MR)	55- 70
d In order to effectively irrigate plants with moderate to high salt tolerance, it is recommended that special salinity control practices be employed in conjunction with the use of water with low levels of sodium (Na), chloride (Cl), and bicarbonate (HCO_3) values"	This product can be utilized in soil types exhibiting high permeability levels, which are devoid of compact strata. The implementation of a high frequency irrigation regime is recommended for water sources with electrical conductivity (EC) exceeding 2000µS/cm and sodium adsorption ratio (SAR) surpassing 7.0.	High restriction (HR)	40 -55
Plants exhibiting high levels of saline tolerance are suitable for sustenance in water sources except for those with exceedingly low concentrati	It is recommended to refrain from employing it for the purpose of irrigation during regular circumstances. This particular item may be utilized sporadically in exceptional circumstances. When water exhibits low levels of salt and high values of Sodium Adsorption Ratio (SAR), the application of gypsum is necessary. In the context of high salinity water, it is imperative that soils possess a high degree of permeabilit	Severe restriction (SR)	0-40

ons of Na^+, Cl^-, and HCO_3^-.	y in order to prevent salt accumulation. Additionally, it is recommended to apply copious amounts of water to offset any potential issues stemming from excessive salt accumulation.		

3.5.2 Groundwater Quality GIS Database Generation and Analysis

The outcomes garnered from the examination of chemicals in the samples were imported into the Geographic Information System (GIS) platform with the aid of Microsoft Excel, which facilitated the generation of a comprehensive water quality database for the district. Subsequently, a spatial distribution map was produced with the utilization of the weighted sum tool.

3.6 Groundwater vulnerability modelling

The study utilized the DRASTIC model as introduced by Aller and colleagues (1987) to examine the susceptibility of groundwater to potential contamination. The DRASTIC model comprises seven (7) parameters, namely Depth to Groundwater, Recharge, Aquifer Media, Soil Media, Topography, Impact of Vadose Zone Media, and Hydraulic Conductivity of the Aquifer, as represented by the acronym. Such parameters have been assessed in order to arrive at a comprehensive understanding of groundwater vulnerability. In the process of assessing the DRASTIC index (DVI), each parameter was allocated a numerical rating ranging from 1 (representing the lowest pollution potential) to 10 (representing the highest pollution potential). This rating was subject to the specific value of the parameter found at the location under consideration, as indicated in Table 3-9. Each parameter was assigned a weighting factor, which ranged from 1 to 5, in accordance with their relative influence in impacting the pollution potential, as depicted in Table 3-8. The process of calculating the DVI entails the multiplication of each parameter weight by the site rating, followed by the summation of these values as represented in Equation 15.

$$DVI = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \quad (15)$$

Where, Dr = Rating for the depth to water table , Dw = Weight assigned to the depth to water table, Rr = Rating for aquifer recharge , Rw = Weight for aquifer recharge , Ar = Rating assigned to aquifer media , Aw = Weight assigned to aquifer media, Sr = Rating for the soil media, Sw = Weight for the soil media, Tr = Rating for topography (slope), Tw = Weight assigned to topography, Ir = Rating assigned to impact of vadose zone, Iw = Weight assigned to impact of vadose zone, Cr = Rating for rates of hydraulic conductivity, Cw = Weight given to hydraulic conductivity.

The higher the DRASTIC index value, the greater the groundwater pollution potential and aquifer vulnerability. The Drastic index was classified into three classes:

Table 3-9: Relative weights given to the DRASTIC parameters (Aller et al., 1987)

Parameter	Drastic Weight (typical)
Depth (D)	5
Recharge (R)	4
Aquifer media (A)	3
Soil media (s)	2

Topography (T)	1
Impact of vadose zone media (I)	5
Hydraulic Conductivity of the aquifer (C)	3

The parameters employed in the DRASTIC methodology were derived from various sources, including the topographical data obtained from the Uganda Digital Elevation Model (DEM), the Climatic Research Unit (CRU), the United States Geological Survey (USGS), as well as results of hydrogeological field surveys at the district level, which included water level measurements. In order to input the collected data into Arcview 10.6 GIS and avail the benefits of versatile data storage, manipulation, and analysis capabilities at varying scales and formats, a database was established as per Voudouris (2009). Upon entry into the database, it became plausible to formalize all information into data layers that conformed to the WGS 1984 coordinate system. These layers were subsequently calibrated in order to generate thematic maps. The process of constructing the aquifer vulnerability map involved the utilization of a Weighted Sums overlay method to overlap various layers. Based on the DRASTIC scoring system, three distinct levels of vulnerability were identified: low (scores below 100), medium (scores ranging from 100 to 140) and high (scores exceeding 140).

Table 3-10: DRASTIC weighting Factors (Aller et al., 1987)

Parameters	Range	Rating	Description	Relative weighting
Depth to water (D) (feet)	0-5 5-15 15-30 30-50 50-75 75-100 >100	10 9 7 5 3 2 1	The term "water table" is commonly used to refer to the vertical level of the water surface within an unconfined aquifer. Lower water table levels are associated with an increased likelihood of contamination, while deeper water table levels correspond to a reduced probability for the occurrence of contamination. The determination of the depth to the uppermost part of a confined aquifer is achieved through the utilization of the "depth to water" concept.	5
Net recharge (R) (in)	0-2 2-4 4-7 7-10 >10	1 3 6 8 9	This statement denotes the quantity of water that infiltrates the land surface per unit area and eventually percolates into the water table. Recharged water has the potential to facilitate the vertical transportation of a contaminant towards the water table and horizontal migration within an aquifer.	4
Aquifer	Massive shale	2	The degree of permeability and attenuation capacity of an aquifer is directly proportional to its	

media (A)	Metamorphic/igneous Weathered met./igneous Bedded sandstone, Limestone, Shale sequences Massive sandstone Massive limestone Sand and gravel Basalt Karst limestone	3 4 6 6 6 8 9 10	grain size and the presence of fractures or openings within its structure. Thus, the potential for pollution increases as the permeability level rises, due to a reduced capacity for attenuation.	3
Soil media (S)	Soil thin or absent Gravel Sand Peat Shrinking and/or aggregated clay Sandy loam Loam Silty loam Clay loam Muck Non-shrinking and non-aggregated clay	10 10 9 8 7 4 5 4 3 2 1	The term "zone of aeration" describes the uppermost layer of the vadose zone, which is subject to significant biological activity and weathering. The soil's properties exhibit a pronounced influence on the magnitude of infiltration recharge that can transpire into the subsurface.	2
Topography (T) (slope %)	0-2 2-6 6-12 12-18 >18	10 9 5 3 1	The term "slope" pertains to the incline or decline of the terrain elevation. Assisting a pollutant in remaining on the surface within a specific location for an extended period of time enables its gradual infiltration into that area.	1

Impact of vadose zone (I)	Silt/clay Shale Limestone Sandstone Bedded limestone, Sandstone, shale Sand and gravel with significant silt and clay Metamorphic/igneous sand and gravel Basalt Karst limestone	1 3 6 6 6 6 4 8 9 10	The term is denoted as material situated in the unsaturated zone. The confining layers situated above an aquifer are utilized in a confined aquifer, as the medium that bears the greatest influence. Such a zone is known to be considerably restrictive.	5
Hydraulic conductivity (C) (GPD/ft2)	1-100 100-300 300-700 700-1,000 1000-2,000 >2,000	1 2 4 6 8 10	The notion of aquifer transmissivity pertains to the capacity of an underground layer of permeable rock or sediment to facilitate water movement, whereby the rate of groundwater flow is governed by a specific hydraulic gradient. The substance contained in the subterranean water system.	3

3.7 Integration groundwater potential, quality, and vulnerability raster maps

The variance and covariance of class signatures were measured through the employment of MLC, which simultaneously assigned individual cells to their corresponding signed classes within the signature file. The maps depicting the quality, potential, and vulnerability of groundwater were obtained through raster analysis and subsequently utilized as input in the generation of Iso (Iterative Self-Organizing) cluster signatures via the MLC algorithm. The present algorithm operates under an unsupervised classification method, wherein a user-defined count of one-dimensional categories are created for cells within the multidimensional realm of a multi-band raster.

Henceforth, the iterative procedure for assessing the identified class mean values proceeds until definite user specified quantities of iterations are input, or until more than two percent of the cells exhibit variation. "The transition from one cluster to another can be observed in relation to the updated mean within the range of repetitions." The Machine Learning Classifier (MLC) calculates the probability of a cell being a member of a specified class for each class. The underlying logic of this weight and probability approach is predicated upon the Bayesian selection framework. The determination of the probability values for each cell and class is executed by means of the computation of the means and covariance matrix of each class, which are stored in the signature file. The Iso raster map output was categorized into five distinct classifications that corresponded to the degree of suitability and accessibility of groundwater for the purpose of irrigated agriculture.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Groundwater potential

4.1.1 Results of thematic layers

4.1.1.1 Rainfall

The map of the rainfall for the district was classified into five classes as shown in Figure 4-1 in units of cm/year. The minimum and maximum rainfall was 390 and 1128 mm/year respectively. The uppermost score was assigned to the southern areas getting the highest rainfall, whereas the rainfall magnitude decreased towards the northern side of the district and the assigned rating also decreased towards the north.

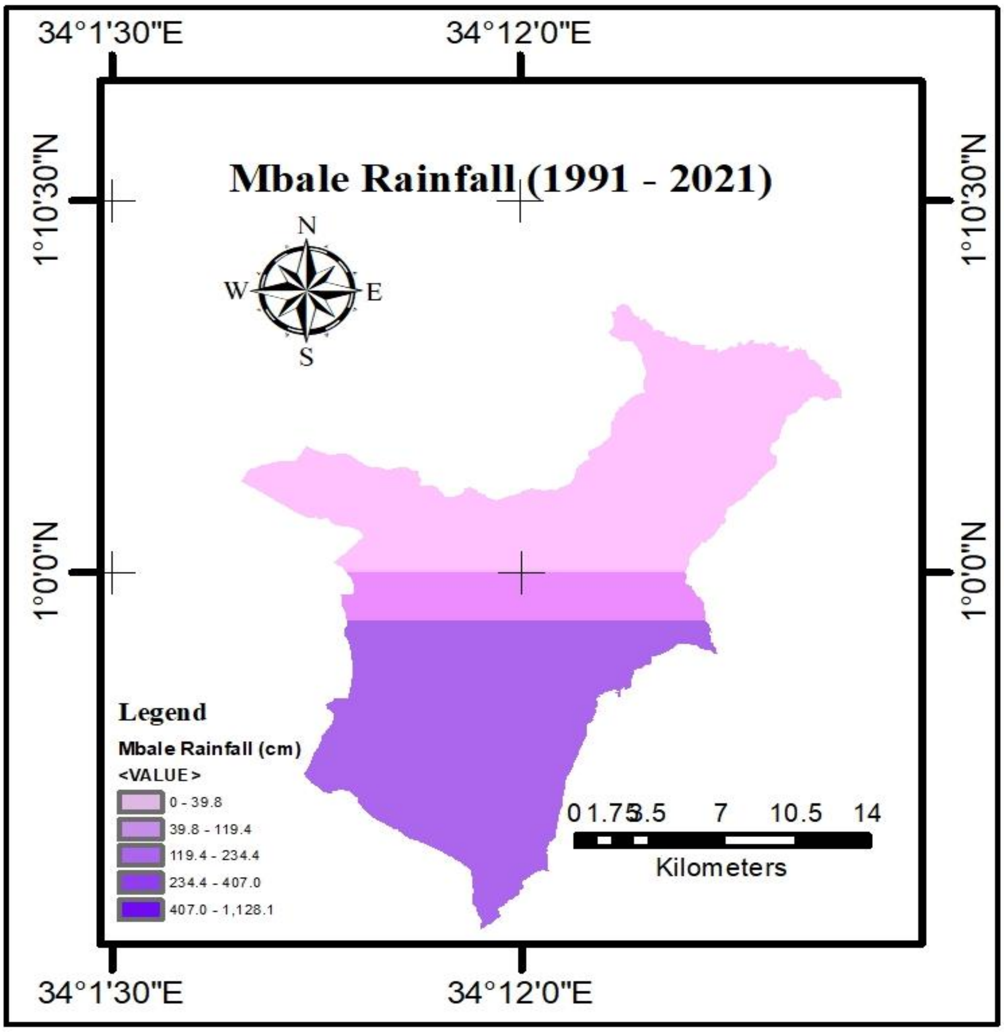

Figure 4- 1: Rainfall pattern map

4.1.1.2 Lithology

The lithological features of the of Mbale district are made up of alluvium; intrusive rocks, mixed sedimentary rocks, siliceous sedimentary rocks and consolidated sedimentary rocks (Figure 4-2 and Table

3-1). Mixed sedimentary rocks, siliciclastic sedimentary rocks and intrusive rocks are solid and firm in nature and are not important in relations to penetrability and sponginess. The lithological weights are assigned basing on minerals, variability, fractures, and weather conditions.

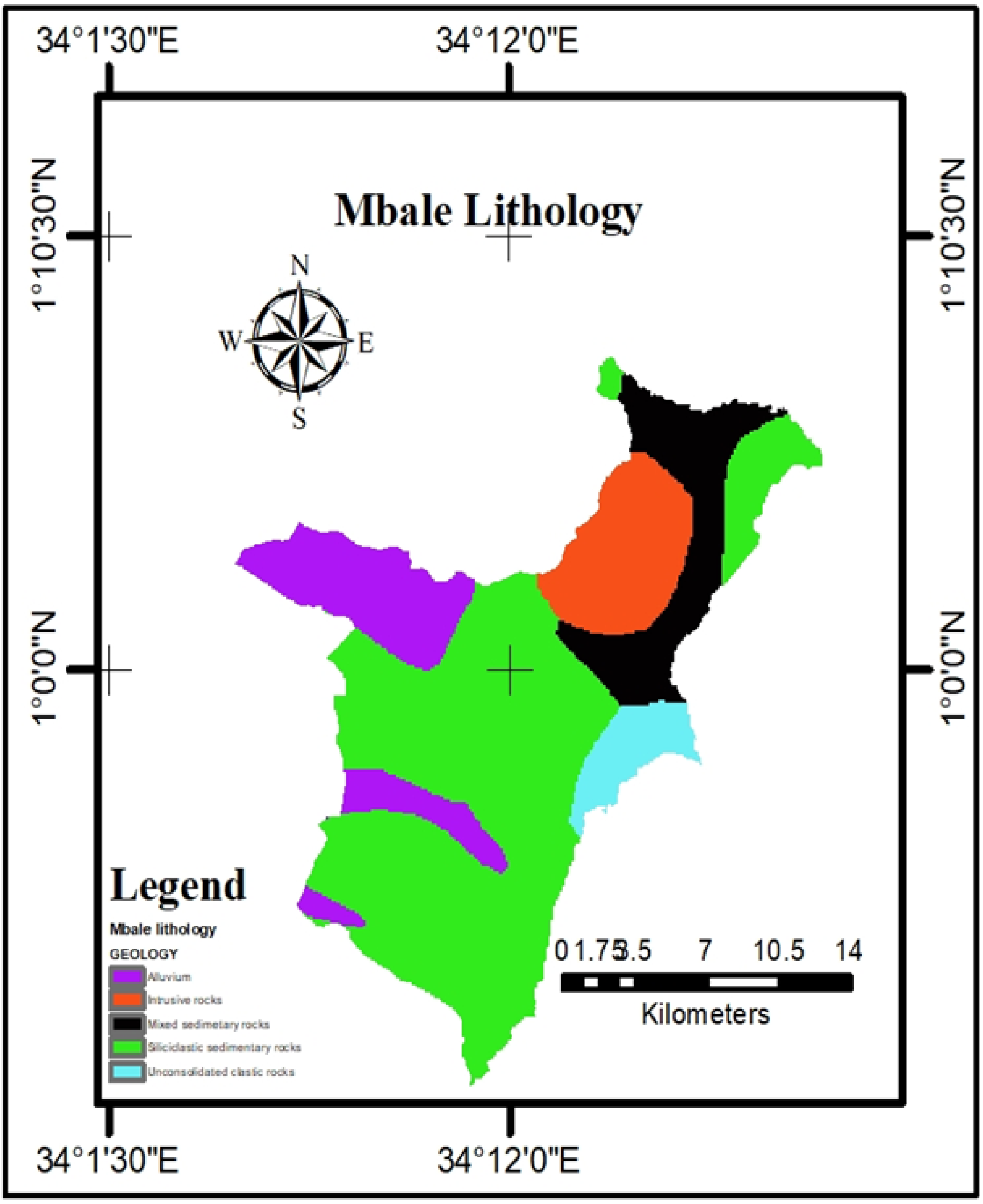

Figure 4- 2: Lithology map

4.1.1.3 Drainage density

In Mbale district, the dominant ranges are 0-0.484 and 0.968 - 1,450km^{-1} as in Figure 4-3.

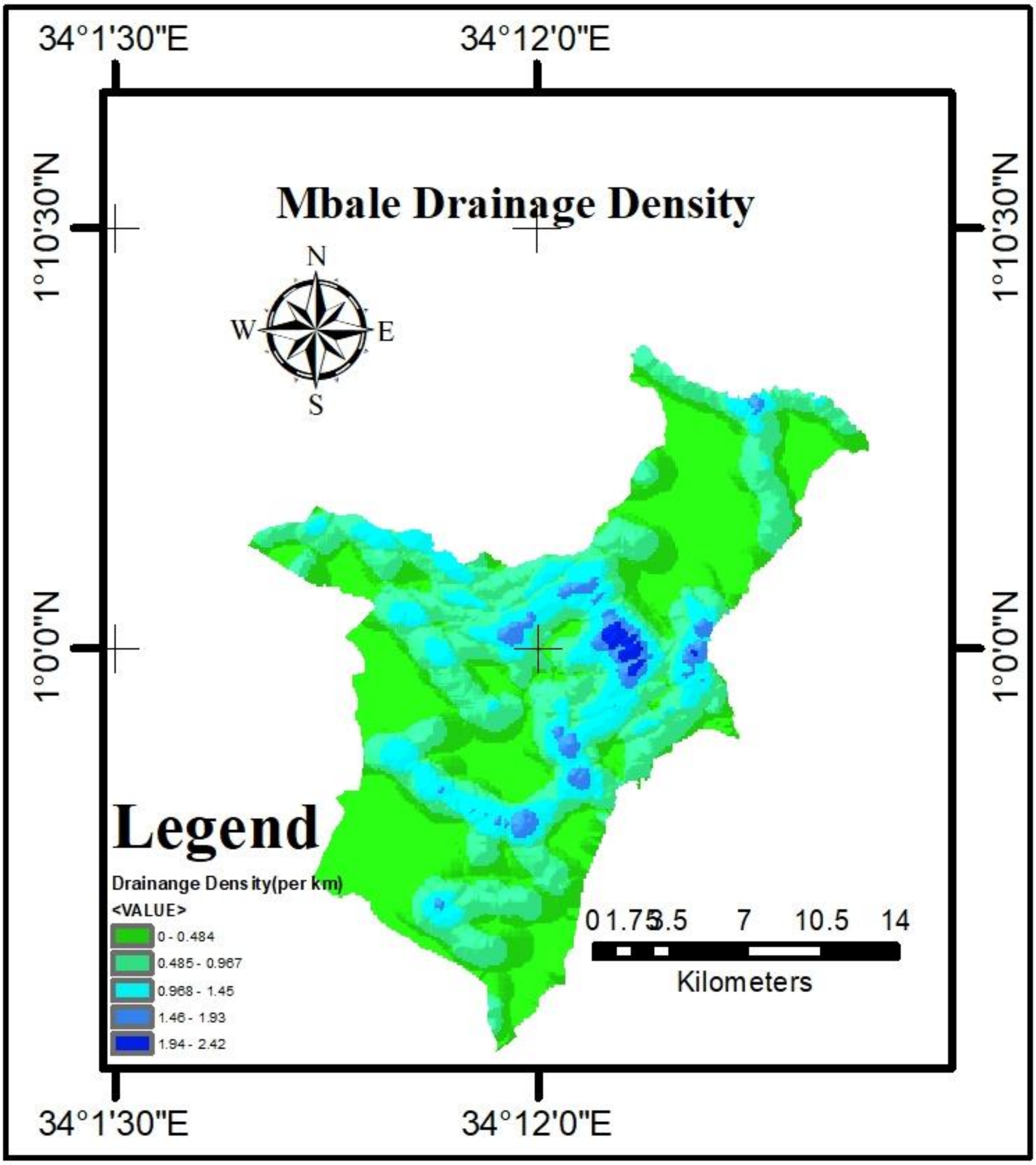

Figure 4- 3: Drainage density map

4.1.1.4 Lineament density

Map of flow density illustrates that central part of the district was considered as excellent and promising groundwater area (Figure 4-4).

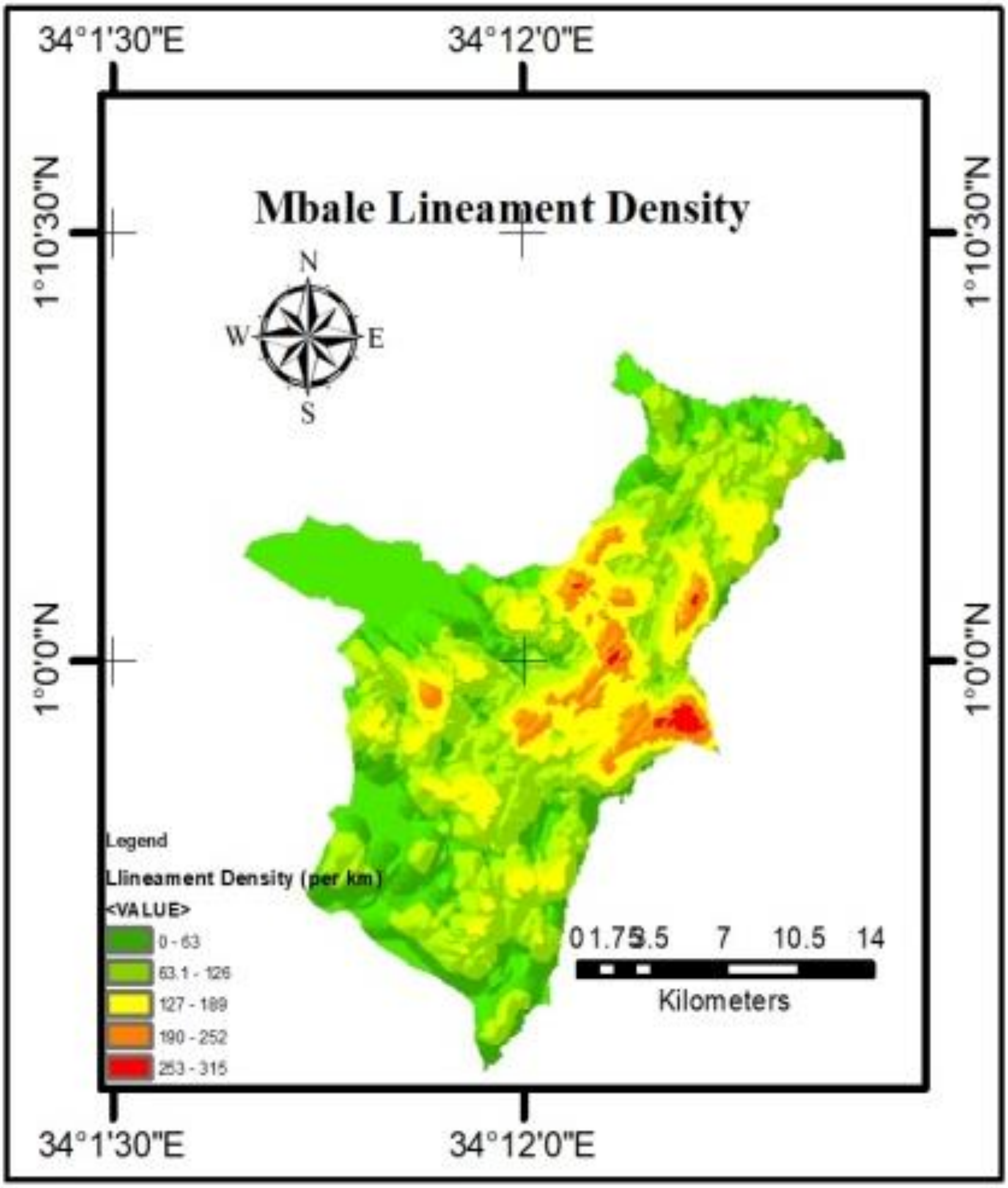

Figure 4- 4: Lineament density map

4.1.1.5 Slope

For the rank assignment effect, slope was classified into 5 classes. The maximum rating was allocated to flat terrain with slope values from 0 to 5.69, and the ratings decrease as the slope value increases. The maximum slope values ranged from 38.9 to 80.6 with the lowest of 0.03 being found in western, central and southern parts, as shown in Figure 4-5.

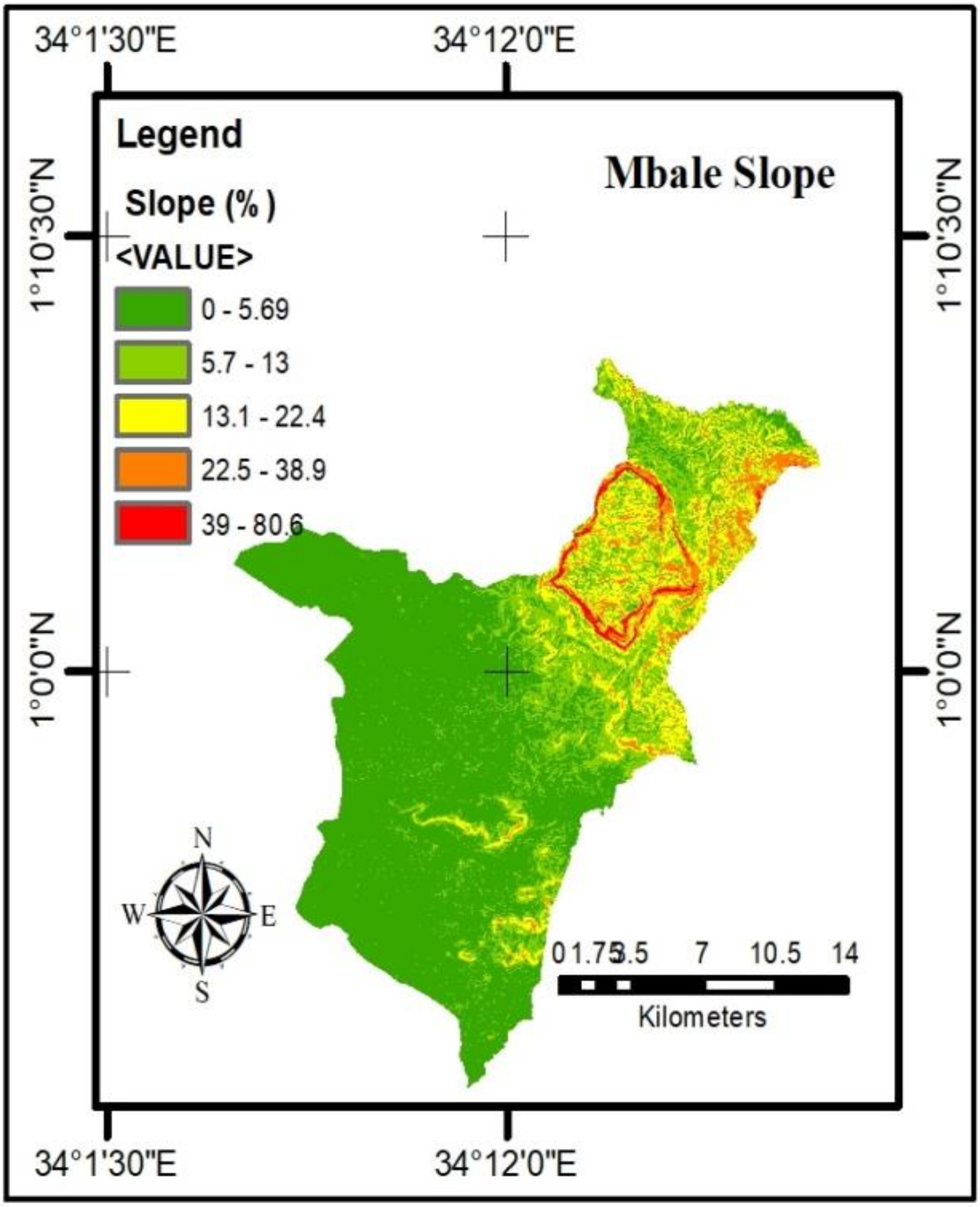

Figure 4- 5: Slope map

4.1.1.6 Land use and land cover

Seven categories of LULCs exist (Figure 4-6) viz.; broadleaved tree plantations, built up areas, bush, commercial farmland, grassland, tropical high forest well stocked, wetland, woodland and subsistence farmland. The main LULC in the district is subsistence agricultural land, followed by grasslands and dense tropical rainforest. Subsistence farmland has been considered the most suitable recovery area since it promotes the filtration of rainwater and irrigation water.

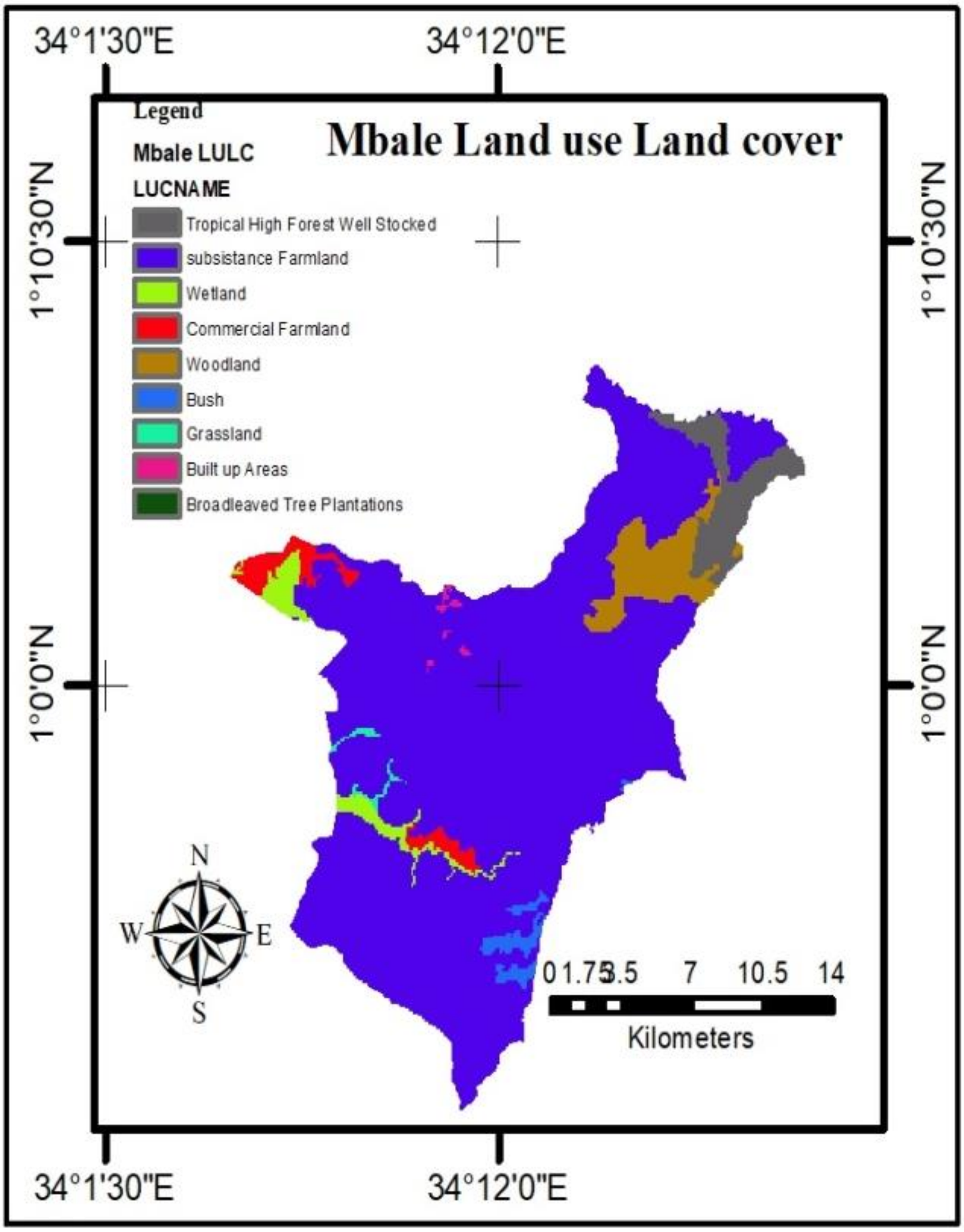

Figure 4- 6: Land use land cover

4.1.1.7 Geomorphology

Mbale district comprises the following geomorphic features: outwash fans, area of infill, pre-Pleistoscene volucanic centre, bevels in eastern upwarp and remnants of lowland surface as in Figure 4-7. The dominant feature is the remnants of lowland surface which occupies south and North West areas of the area. This feature together with areas of infill performs as a prospective recharge basis of groundwater in the research area.

International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

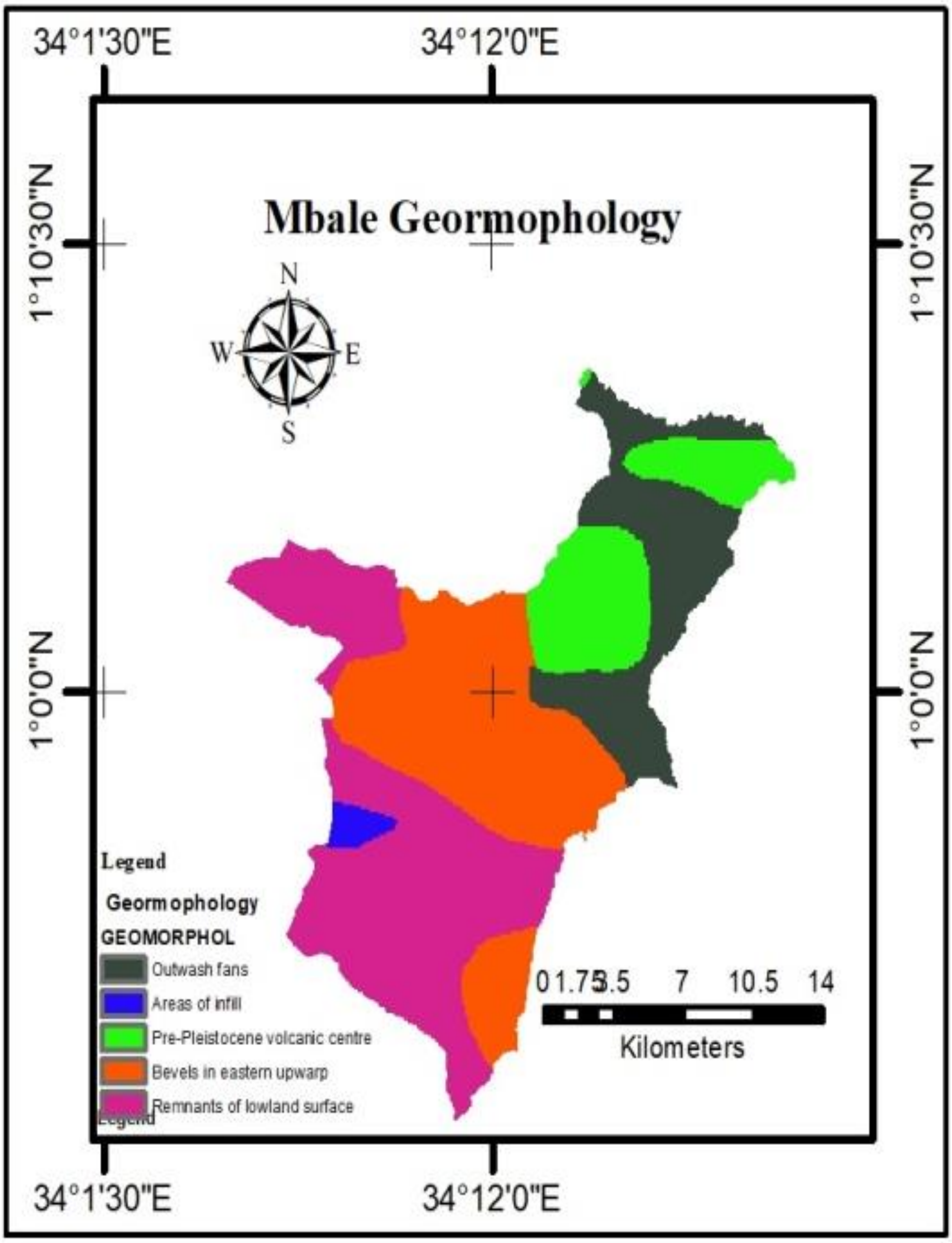

Figure 4- 7: Geomorphology map

4.1.1.8 Soil

The most important soils in the district were Eutric Versisols (VRe), Humic Cambisols (CMu), Haplic Phaeozems (PHh), Albic Plinthosols (PTa), Humic Ferralsols (FRu) and Nitisols haplic (NTh). Every soil division was assigned weights separately while considering soil nature and water retention capability. predominant soils are Albic Plinthosols (PTa) and Humic Cambisols (CMu), as shown in Figure 4-8.

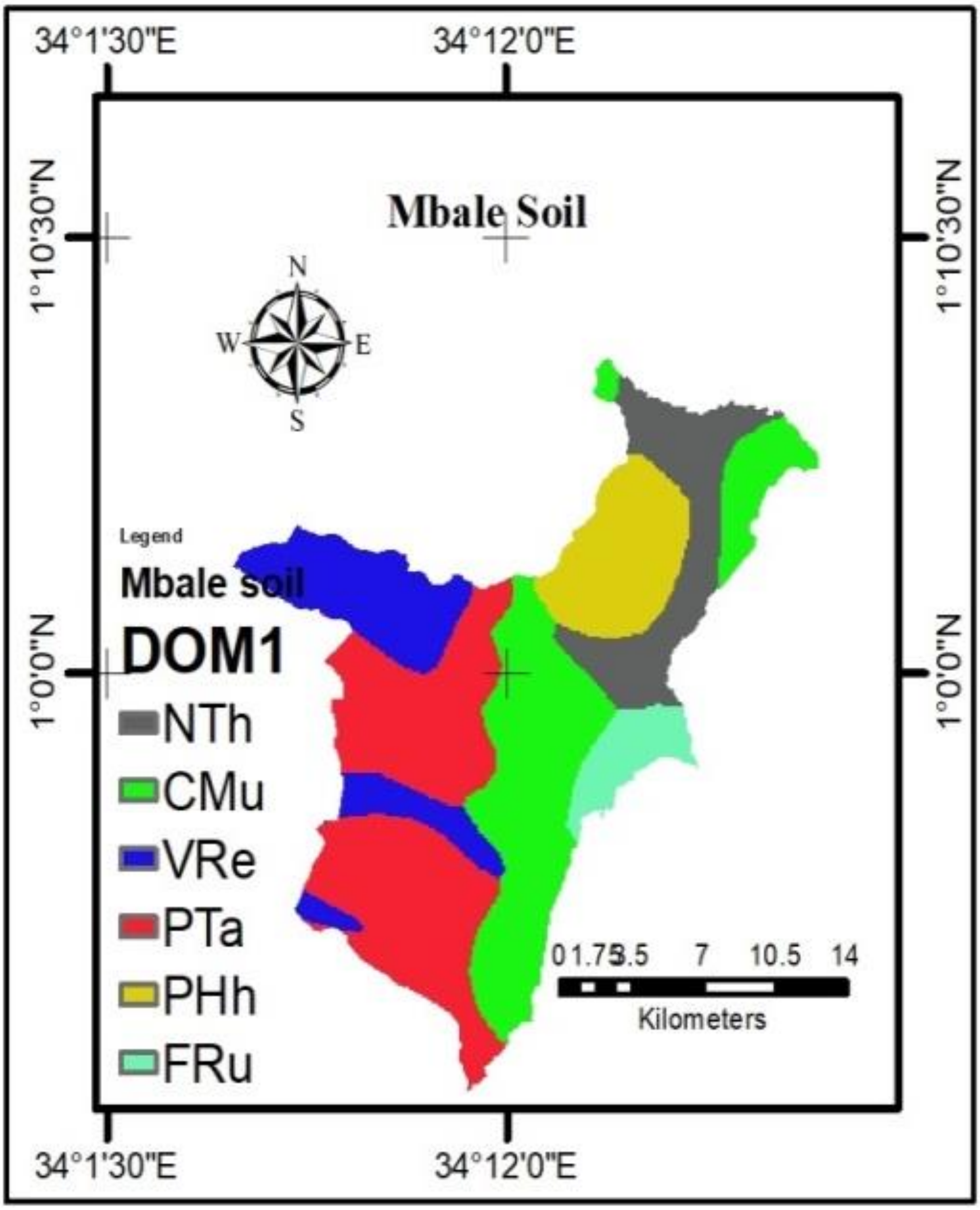

Figure 4- 8: Soil Map

4.1.2 Analytic Hierarchy Process model

The study recognized and classified a total of eight regulatory factors pertaining to groundwater, based on an extensive review of the relevant literature. The present study employs the Analytic Hierarchy Process (AHP) model to explore various factors of interest. To this end, the pairwise comparison matrix, normalized comparison matrix, eigenvalues, and normalized feature weights are computed and presented in Tables 4-1 to 4-4

Table 4- 1: Pairwise comparison matrix of 8 groundwater prospecting factors for AHP model

Thematic layers	LI	GE	LD	DD	RF	SO	SL	LULC
LI	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00
GE	0.50	1.00	2.00	3.00	4.00	5.00	6.00	7.00
LD	0.33	0.50	1.00	2.00	3.00	4.00	5.00	6.00
DD	0.25	0.33	0.50	1.00	2.00	3.00	4.00	5.00
RF	0.20	0.25	0.33	0.50	1.00	2.00	3.00	4.00
SO	0.17	0.20	0.25	0.33	0.50	1.00	2.00	3.00
SL	0.14	0.17	0.20	0.25	0.33	0.50	1.00	2.00
LULC	0.13	0.14	0.17	0.20	0.25	0.33	0.50	1.00
Total	**2.72**	**4.59**	**7.45**	**11.28**	**16.08**	**21.83**	**28.50**	**36.00**

Table 4- 2: Normalized pairwise comparison matrix of 8 groundwater factors for AHP model

Thematic layers	LI	GE	LD	DD	RF	SO	SL	LULC	Total	Weights
LI	0.37	0.44	0.40	0.35	0.31	0.27	0.25	0.22	2.61	0.33
GE	0.18	0.22	0.27	0.27	0.25	0.23	0.21	0.19	1.82	0.23
LD	0.12	0.11	0.13	0.18	0.19	0.18	0.18	0.17	1.25	0.16
DD	0.09	0.07	0.07	0.09	0.12	0.14	0.14	0.14	0.86	0.11
RF	0.07	0.05	0.04	0.04	0.06	0.09	0.11	0.11	0.59	0.07
SO	0.06	0.04	0.03	0.03	0.03	0.05	0.07	0.08	0.40	0.05
SL	0.05	0.04	0.03	0.02	0.02	0.02	0.04	0.06	0.27	0.03
LULC	0.05	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.19	0.02

$$CR = \frac{CI}{RI}$$

CI indicates consistency index, $CI = \frac{\lambda_{\max} - n}{n-1}$

λ_{max}= 8.286 from Table 4-3

n = 8, number of thematic layers

RI = 1.14 from Table 3-1

$$CI = \frac{8.286 - 8}{8-1} = 0.041$$

$$CR = \frac{0.041}{1.14} = 0.029$$

Table 4- 3: Determination of Eigen value

Implying that consistency ratio (CR) = 0.029 < 0.1 and the consistency index (CI) is 0.041. For the model, where the AHP is used, the CR (consistency ratio) is performed. The result was acceptable since the value of CR <0.1 is reasonable.

Table 4- 4: Weight assigning and normalization

Influencing factors	**Feature**	**Assigned rank**	**Groundwater prospect**	**Feature normalized weight**
Lithology	Alluvium	High	4	4/14 = 0.286
	Intrusive rocks	Very low	1	1/14 = 0.071
	Mixed sedimentary rocks	Low	2	2/14 = 0.143
	Siliciclastic sedimentary rocks	Low	2	0.143
	Unconsolidated sedimentary rocks	Very high	5	0.357

Thematic layers	LI	GE	LD	DD	RF	SO	SL	LULC	Weighted sum value	Weights	λ
Weights	0.327	0.227	0.157	0.108	0.073	0.05	0.034	0.024			
LI	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	2.779	0.327	8.504
GE	0.50	1.00	2.00	3.00	4.00	5.00	6.00	7.00	1.943	0.227	8.544
LD	0.33	0.50	1.00	2.00	3.00	4.00	5.00	6.00	1.329	0.157	8.469
DD	0.25	0.33	0.50	1.00	2.00	3.00	4.00	5.00	0.896	0.108	8.321
RF	0.20	0.25	0.33	0.50	1.00	2.00	3.00	4.00	0.599	0.073	8.167
SO	0.17	0.20	0.25	0.33	0.50	1.00	2.00	3.00	0.402	0.050	8.066
SL	0.14	0.17	0.20	0.25	0.33	0.50	1.00	2.00	0.274	0.034	8.064
LULC	0.13	0.14	0.17	0.20	0.25	0.33	0.50	1.00	0.197	0.024	8.152
									Total		66.286
										λ_{max}	8.286

Geormophology	Outwash fans	Moderate	3	0.200
	Area of infill	Very high	5	0.333
	Pre-Pleistocene volcanic centre	Low	2	0.133
	Bevels in eastern upwarp	Very low	1	0.067
	Remnants of lowland surface	High	4	0.267
Lineament Density	0-33	Low	2	0.111
	33-79	Medium	3	0.167
	79-123	High	4	0.222
	123-178	High	4	0.222
	178-315	Very high	5	0.278
Drainage density	0-0.218	Low	2	0.111
	0.218-0.559	Medium	3	0.167
	0.559-0.910	High	4	0.222
	0.910-1.356	High	4	0.222
	1.356-2.418	Very high	5	0.278
Rainfall	0-42.4	Very Low	1	0.091
	42.4-124.2	Low	2	0.091
	124.2-238.5	Low	2	0.182
	238.5-408.1	Moderate	3	0.273
	408.1-1128.1	high	4	0.3636
Soil	NTh	Very high	5	0.263
	CMu	Very low	1	0.053
	VRe	Low	2	0.105
	PTa	High	4	0.211
	PHh	High	4	0.211
	FRu	Moderate	3	0.158
	0-5.69	Very high	5	0.333

Slope	5.7-13	High	4	0.267
	13.1-22.4	Medium	3	0.200
	22.5-38.9	Low	2	0.133
	39-80.6	Very low	1	0.067
Landuse and Land cover	Broadleaved tree plantations	Medium	3	0.115
	Built up areas	Very low	1	0.038
	Bush	medium	3	0115
	Commercial farmland	Low	2	0.077
	Grassland	Medium	3	0.115
	Tropical high forest well stocked	High	4	0.154
	Wetland	Very high	5	0192
	Woodland	medium	3	0.115
	Subsistence Farmland	Low	2	0.077

4.1.3 Groundwater Protentional

The outputs of the thematic layers are in Figures 4-1 to 4-8 and final output groundwater potential zone map is in Figure 4-9. The GWPI value was accepted for classification if an area had excellent groundwater potential (5), very good (4), fair (3), poor (2) and very poor (1). The zone with high potential (very good) occupies 26.99 km^2 (12.98%), the zone with good potential occupies 126.22 km^2 (60.71%) and the other zone with poor potential occupies 54.69 km^2 (26.31%) of Mbale district. The very good and good zones fall areas that are low lying where the slope ranges from 0-13%, land use and land cover of subsistence farming and lithology of weathered sedimentary rocks which facilitate good percolation of water. These areas also receive higher rainfall. The areas of poor zones comprise of slopes>13%, land cover of built-up areas and lithology of intrusive rocks which hinder percolation of water into the ground.

Comparing these results to similar studies conducted in different regions, there are significant variations. Melese and Belay's study in Muga watershed, Abay basin in Ethiopia in 2022 found that about 60% of the area had moderate to very good groundwater potential for irrigation while 39% of the area had poor to no potential. Obuobie and others' study in north-eastern Ghana in 2013 found that only 7% of the area had good potential for irrigation while 25% of the area had moderate potential and 68% had poor potential. Ganapuram and others' in Musi basin in Prriyabrata in 2009 in the semi-arid region of India had similar results to Mbale district with 15% of the area having very good potential, 65% having good potential and 20% ha poor potential. Markos and others conducted a study in 2021 in the Adilo catchment in Ethiopia, which showed that around 13% of the area had very good groundwater potential for irrigation, 56% had good potential and 31 had good potential

In conclusion Mbale district has relatively high percentages of the areas with good and very good groundwater potential for irrigation compared to other regions studied. While the percentage of poor potential is also relatively high, the overall availability of groundwater is promising for irrigation development in the region.

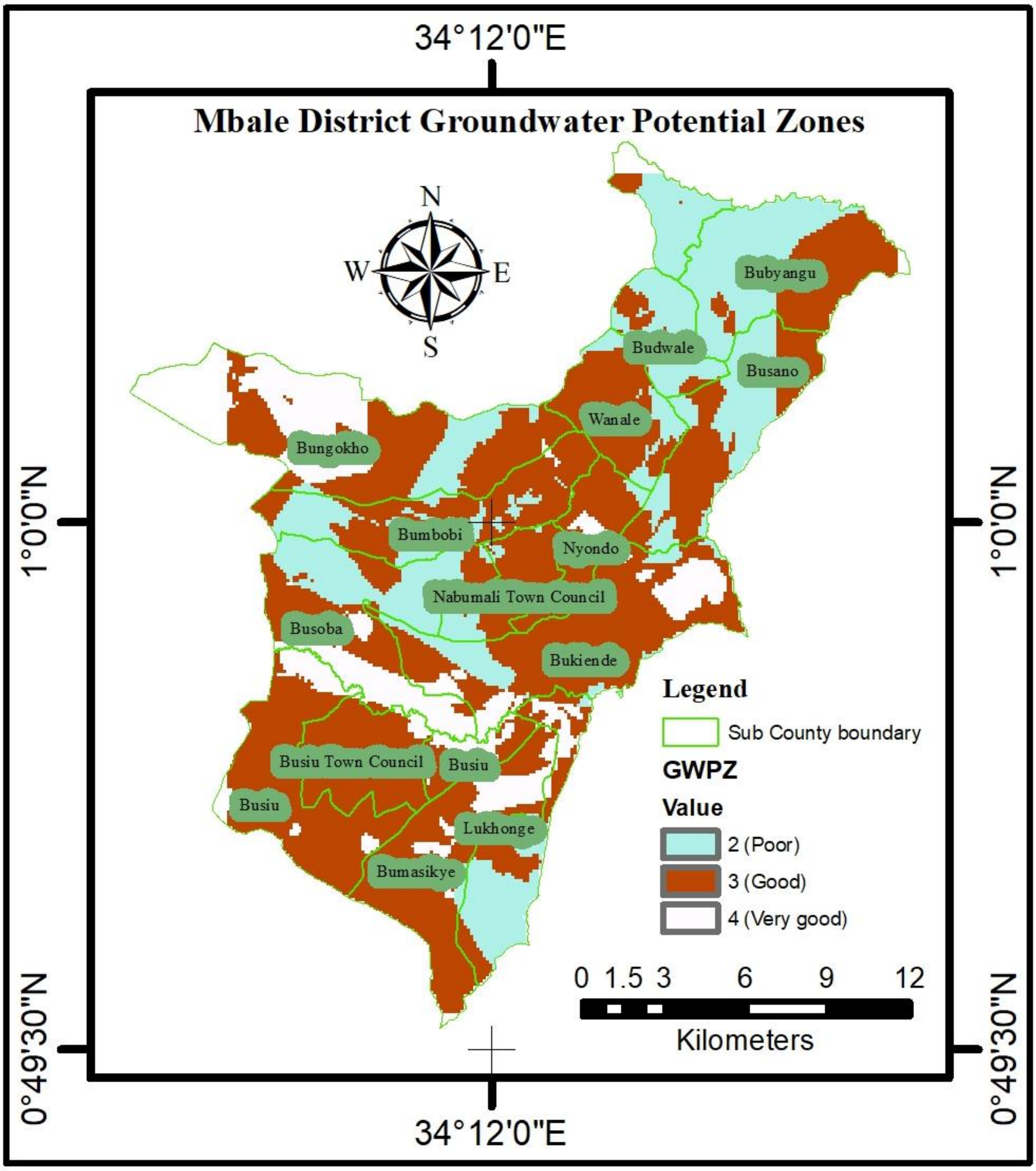

Figure 4- 9: Groundwater Potential Map

4.2 Groundwater quality

4.2.1 Salinity Hazard

The EC of the samples collected in the district was determined and the spatial distribution map is as in Figure 4-10. Overall, there is a difference in EC that arrays from 106.5µmhos/cm to 932µmhos/cm attributed to predominant anthropological activities in the research area. In agreement with Rao and others' (1986), the high EC value was due to reduced osmotic movement of vegetation which inhibits absorption of water and nutrients.

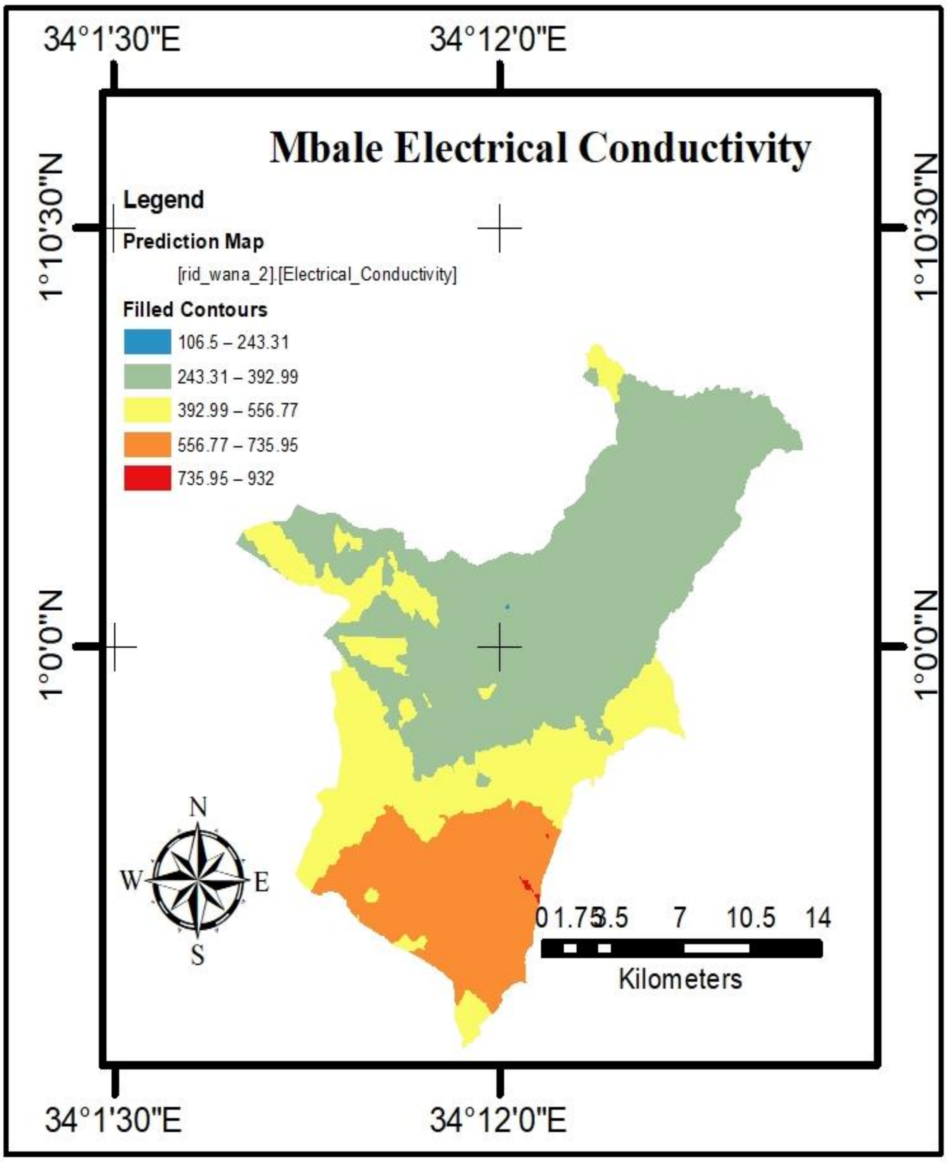

Figure 4- 10: Electrical Conductivity map

4.2.2 Sodium concentration

Sodium concentration ranged from 6.2 - 285mg/L. The sodium concentration spatial distribution map is as in Figure 4-11.

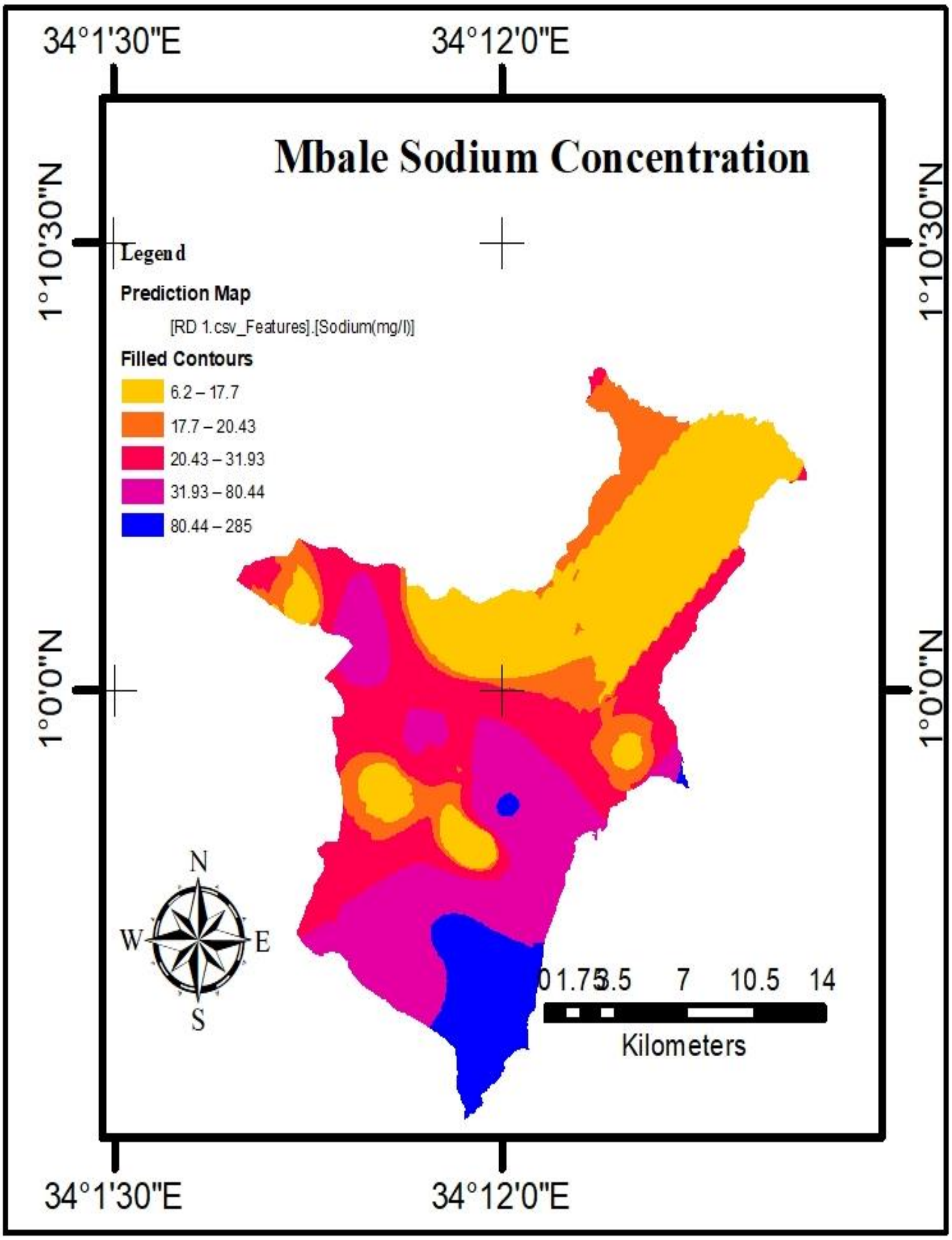

Figure 4- 11: Sodium concentration map

4.2.3 SAR

SAR values ranged from 1.58 mg/L-16.03 mg/ L. These values were used generate the spatial distribution map, as in Figure 4-12. When SAR value is above 18mg/L, groundwater is taken as inappropriate for irrigation (Varol and Davraz, 2015). According to results values of SAR values it's suitable for irrigation purposes.

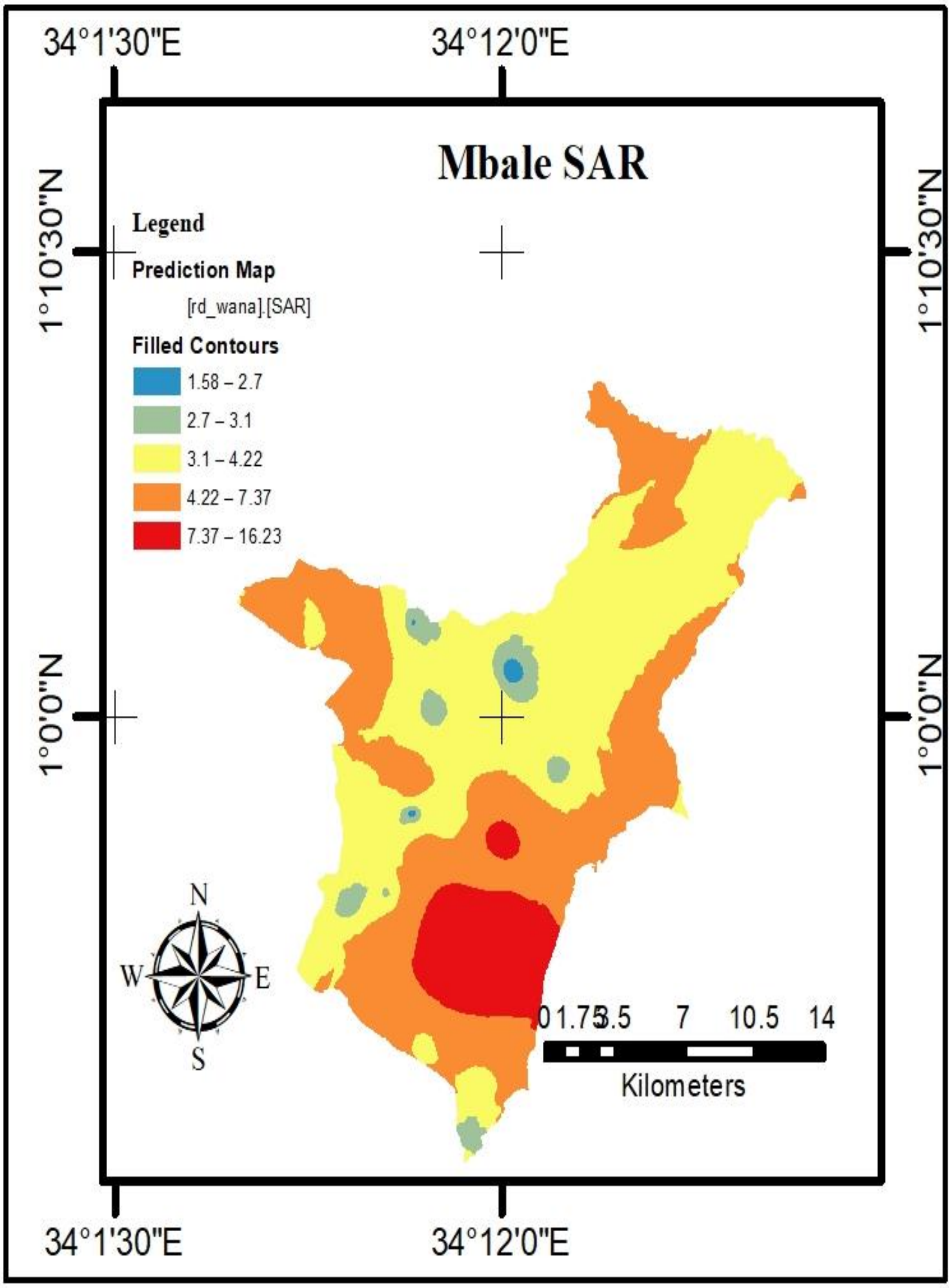

Figure 4- 12: SAR concentration map

4.2.4 Toxicity and Miscellaneous Effects

The chloride concentration is offered as a constraint that determines the exact toxicity of the ions. Chloride values ranged from 6.2 mg/L to 245 mg/L. The spatial distribution of chloride concentration is shown in Figure 4-13. Chloride concentrations were observed to be moderately high. Chloride is needed in minimal quantities by plants, but is toxic to sensitive plants at elevated concentrations, as described by Bauder et al., 2003 in Table 4-5.

Table 4- 5: Chloride classification for irrigation water (Bauder et al., 2008)

Chloride (mg/l)	Effect on Crops
Less than 70	Commonly harmless to all plants
70 to140	Sensitive plants show harm
141 to 350	Moderately tolerant plants show harm
Exceeding 350	Can cause severe problems

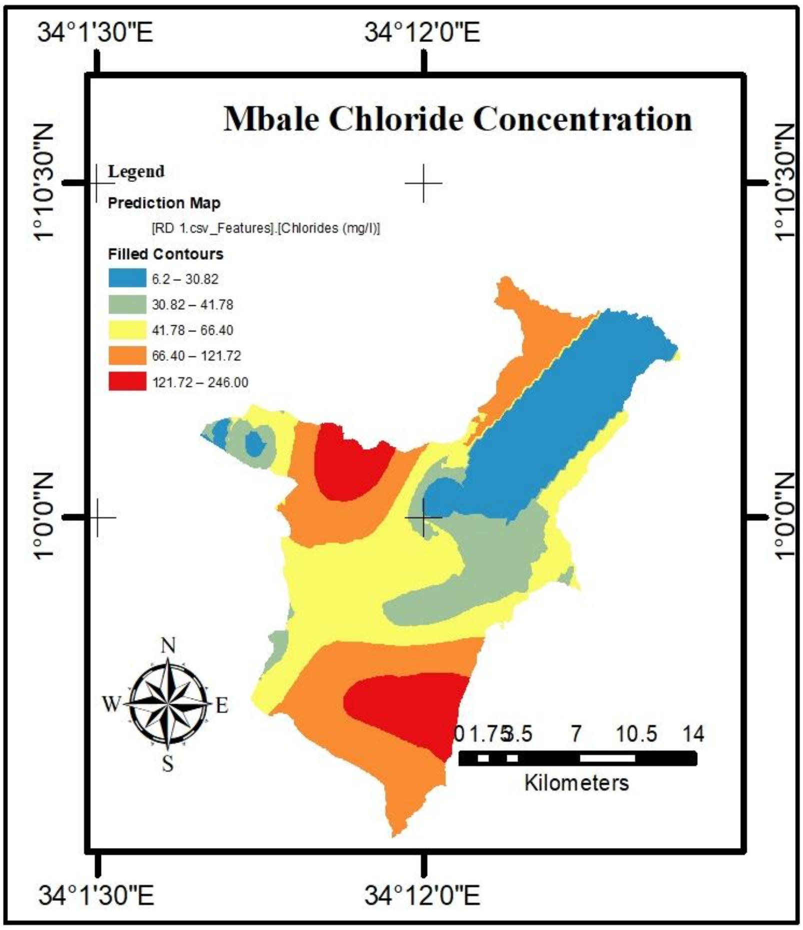

Figure 4- 13: Chloride concentration map

4.2.5 Bicarbonate and pH

The pH parameter was found to have different influence ranges for sensitive crops. The pH value ranged from 5.2 - 7.9 in studied samples, as in Figure 4-14. A plant's ability to absorb nutrients from the soil differs with the pH value (Charmaine and Anitha, 2010). High or low pH values both limit the capability to grip nutrients. If pH is low, the solubility of ammonium and manganese salts rises and concentrations can be destructive to plants. Bicarbonate ion concentrations (HCO_3^-) oscillated from 46.36 mg/L - 722.24 mg/L as in Figure 4-15. Agreeing with (Ayers and Westcot, 1994), concentration of bicarbonate lower than 90 mg/l are deliberated perfect for purposes of irrigation. Therefore, all samples comprising of above 90 mg/L were unsuitable for purposes of irrigation.

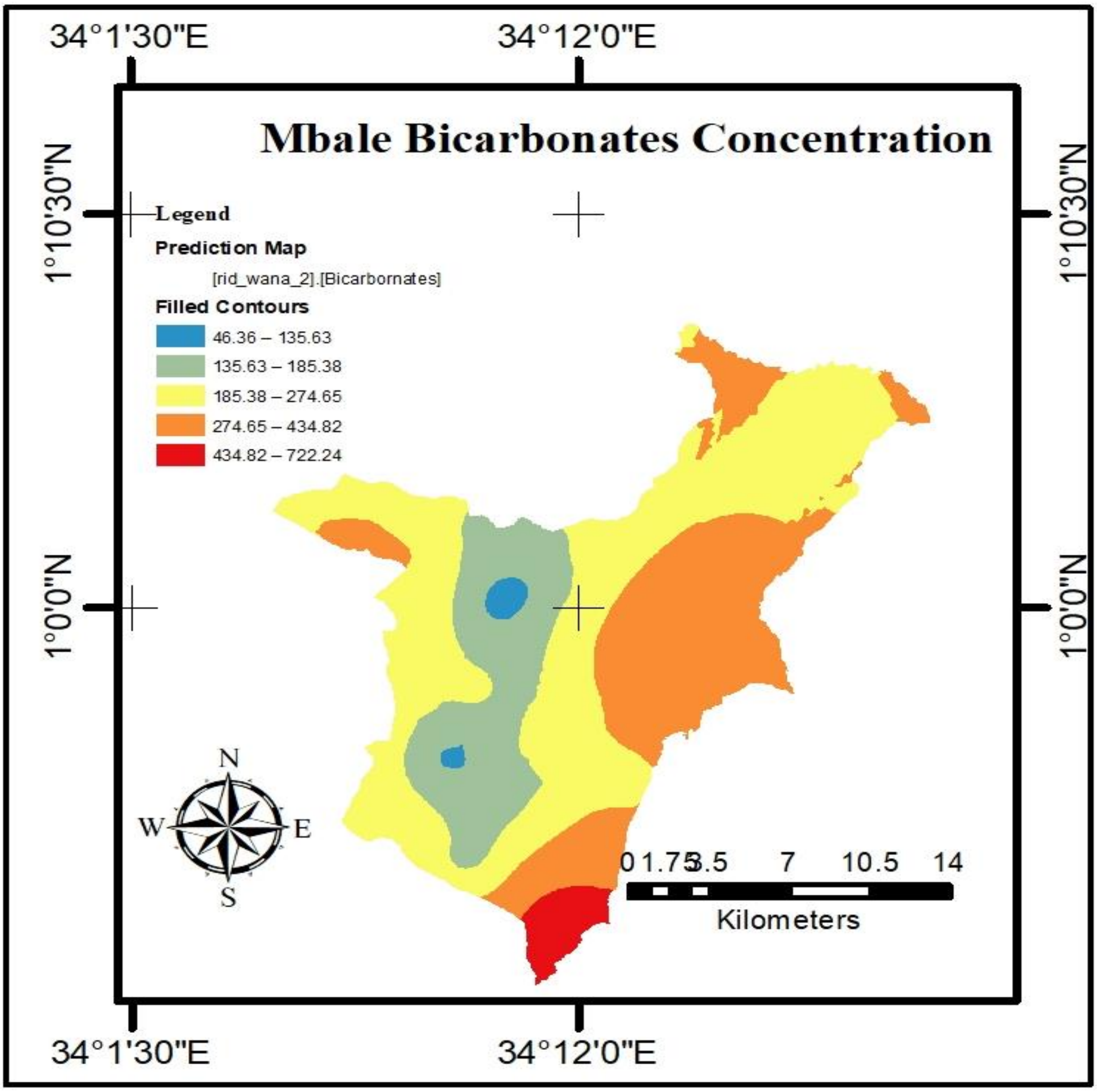

Figure 4- 14: Bicarbonates concentration map

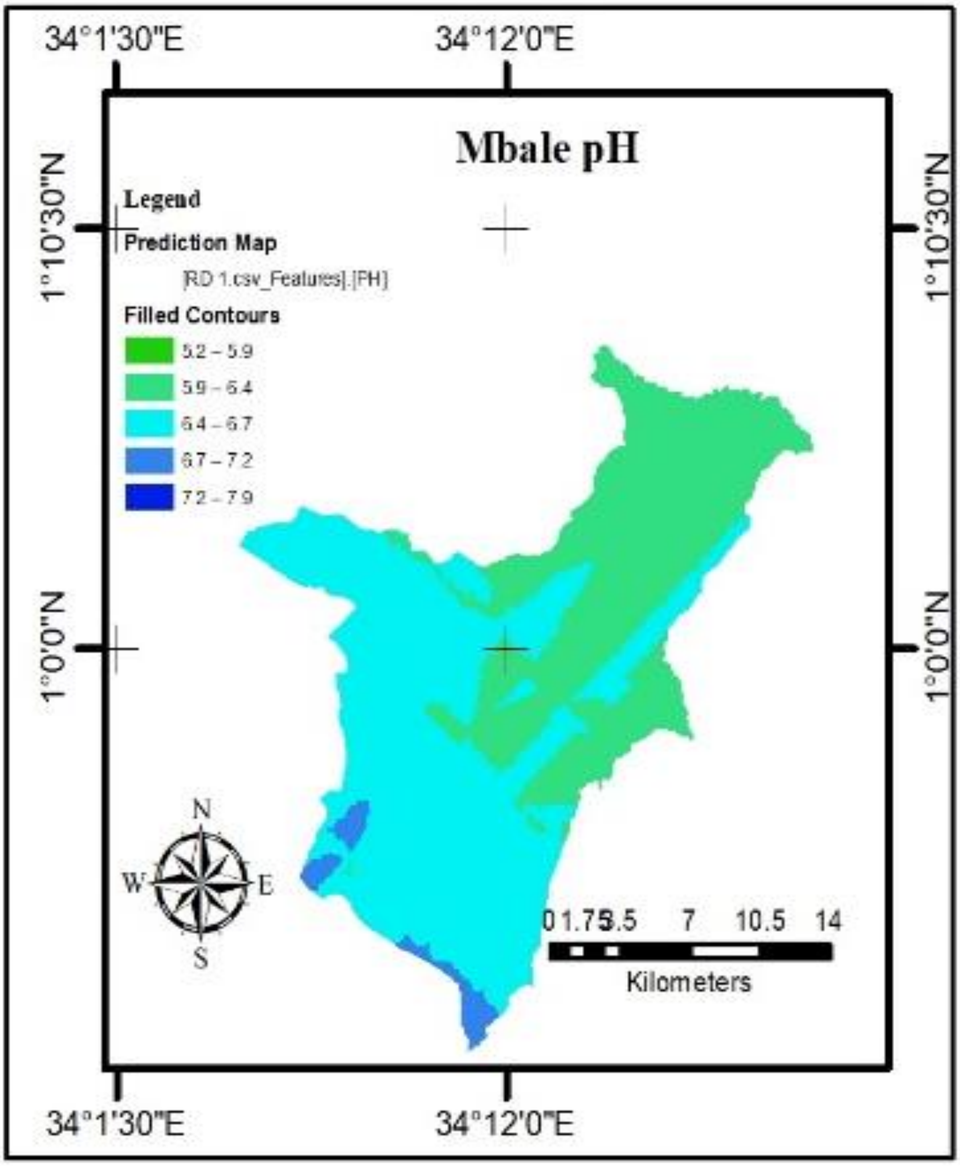

Figure 4- 15: pH map

4.2.6 Irrigation Water Quality Index

SAR, $HCO3^-$, EC, Na+ and Cl^- parameters were used during computation of IWQI. maps of spatial distribution were organized per parameter and integrated. The integration created the IWQI index map after geostatistical analysis (Figure 4-16). The analysis of IWQI map was categorized into two classes that depict water use restrictions and they were High Restriction (40-55) and Severe Restriction (32-40). 90.90% (188.98km^2) of the study area was under high restriction water use and 9.10% (18.92km^2) was under severe restriction water use.

Results from several studies done are similar to the study. For instance, Supriyanto and others' (2022) study in Polinella, India found that the groundwater quality in the area was mostly suitable for irrigation, but there were some limitations due to high levels of salinity and alkalinity in certain areas. The study in Gaza strip found that the groundwater in the area was contaminated with nitrate and other pollutants from agricultural activities and sewage (Gharbia et al., 2021). Likewise, Al-Hadith and others (2019) study in

Baghdad, Iraq found that the groundwater in the area was contaminated with nitrate and other pollutants from agricultural and industrial sources. Eid and

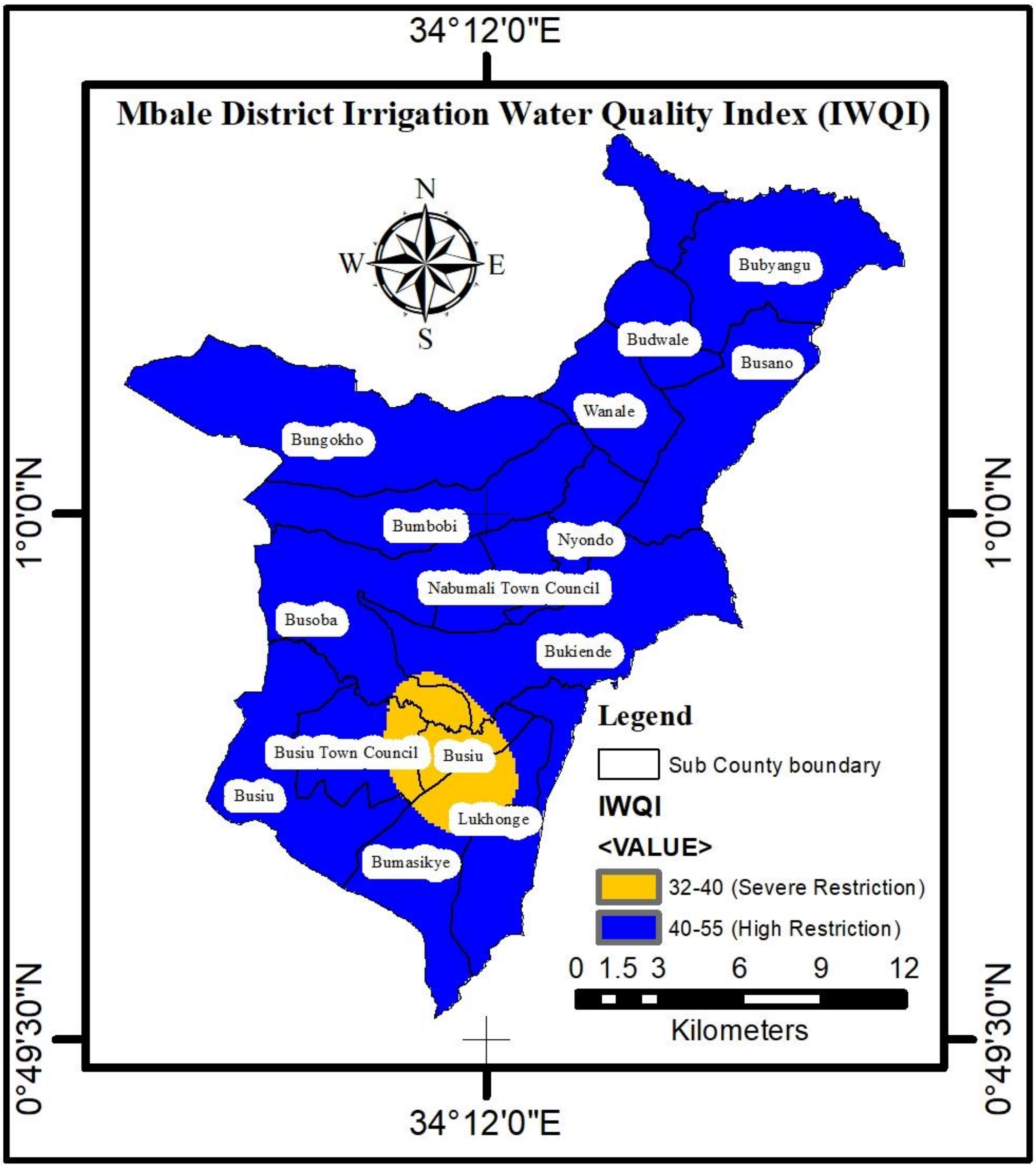

Figure 4- 16: Irrigation Water Quality Index (IWQI) map

others (2023) Souf Valley's study in Algeria found that the groundwater quality in the area was generally poor due to high levels of salinity, but that some improved agricultural practices could still allow for use of the water. Rawat and others' (2018) study in Kanchipuram district, Tamil Nadu, India found that the groundwater quality in the area was generally good for irrigation, but that there were concerns regarding overuse and depletion of resources.

However, it is clear that the groundwater quality for irrigation in Mbale district falls primarily in high restriction use category, indicating limitations on its use for agriculture. This is consistent with other studies globally that have found water resources to be limited or of poor quality for irrigation. It is important to note that water quality deterioration are global concerns, and sustainable management practices are needed to ensure the availability of adequate and safe water resources for future use. Further research and monitoring are necessary to track changes in water quality and develop effective management practices.

4.3 Groundwater Vulnerability

4.3.1 Depth to groundwater

The recorded depths to the groundwater table experienced a variation from 38.45 meters to 70.34 meters, as depicted in Figure 4-17. The depth to groundwater was then categorized and assigned rates g from 1 (minimum influence on vulnerability) to 10 (maximum influence on vulnerability) as in Figure 4-18.

4.3.2 Net recharge

The study demonstrates that the net recharge exhibited variability within the range of 351.98 to 819.76m per annum, as visualized in Figure 4-19. The map depicting net recharge was subsequently classified and allocated values ranging from 1(indicating negligible effect on vulnerability) to 10 (indicating substantial effect on vulnerability), as demonstrated in Figure 4-20.

4.3.3 Aquifer media

Aquifer media refers to either consolidated or unconsolidated geological formations that effectively serve as a medium for water storage, transportation and extraction. The primary aquifer was restricted beneath strata comprised of fresh granite and bedded sandstone, as depicted in

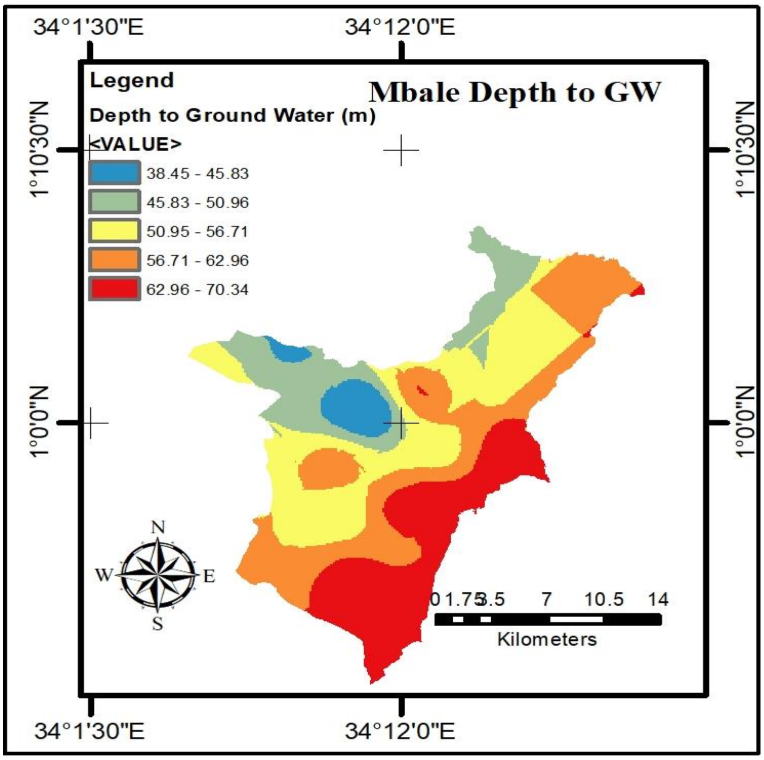

Figure 4- 17: Depth to groundwater map

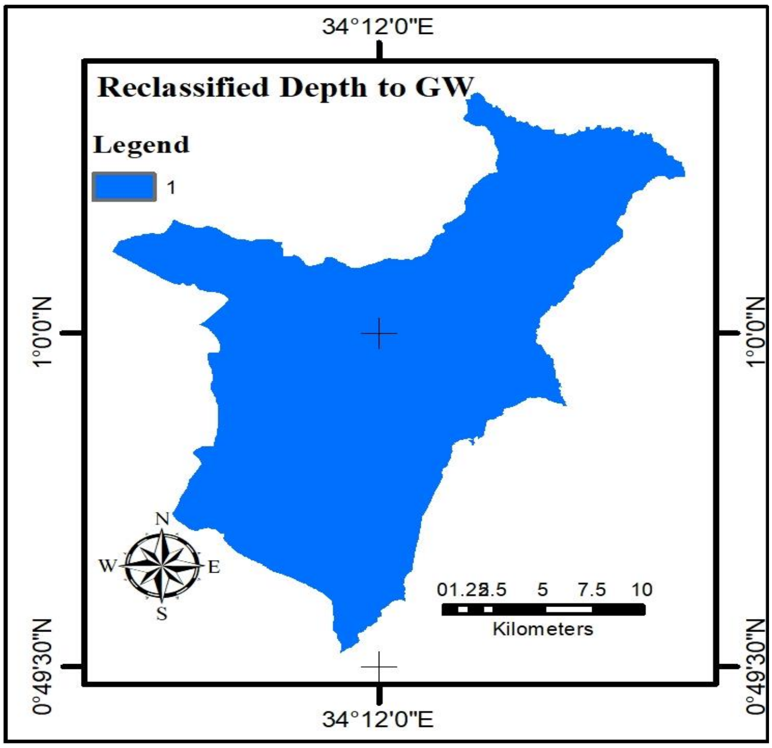

Figure 4- 18: Reclassified depth to groundwater map

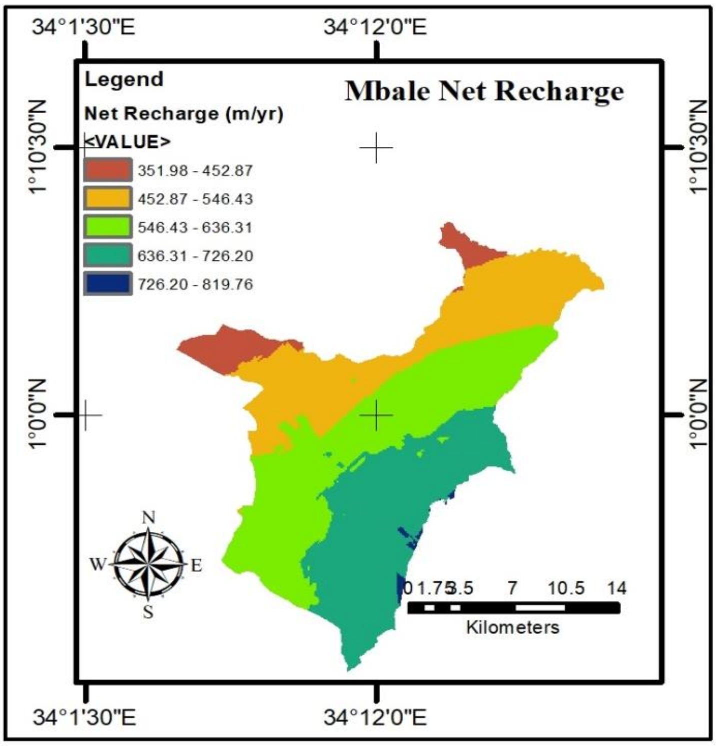

Figure 4- 19: Net recharge map

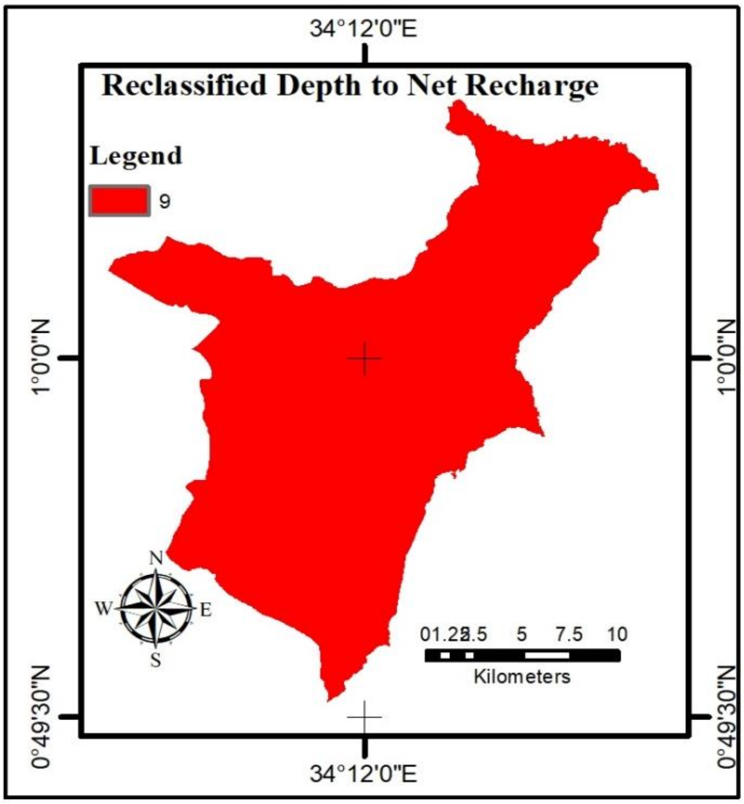

Figure 4- 20: Reclassified net recharge map

Figure 4-21. The Aquifer media map was stratified into varying degrees of impact, ranging from 1 (signifying the least significant effect on vulnerability) to 10 (indicating the most profound effect on vulnerability), as illustrated in Figure 4-22.

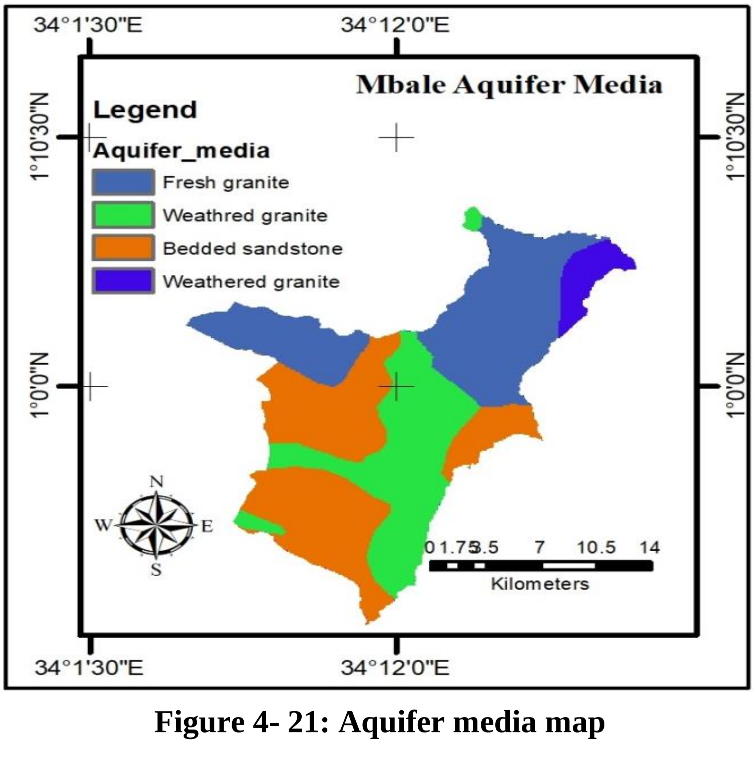

Figure 4- 21: Aquifer media map

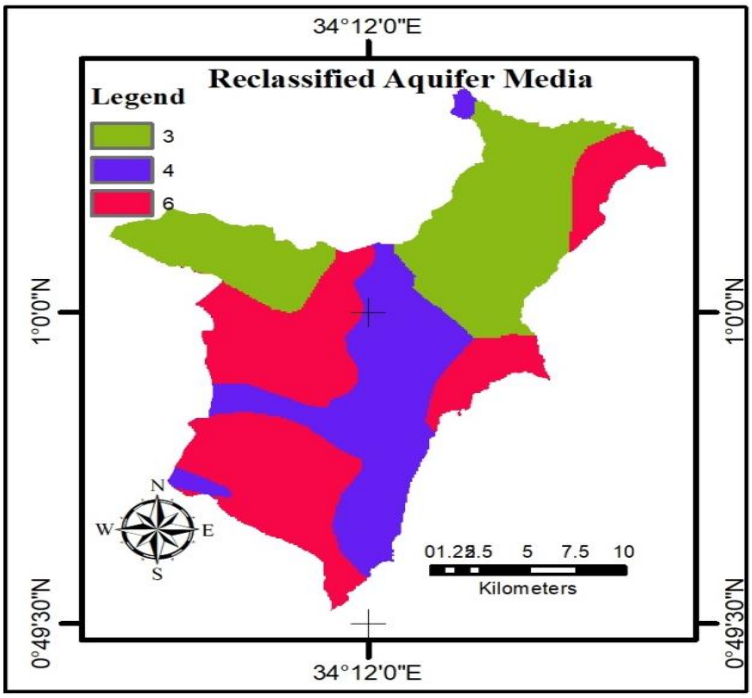

Figure 4- 22: Reclassified Aquifer media map

4.3.4 Soil media

The aquifers are mainly covered with clay gravel and sand, as shown in Figure 4-23. Soil map was then reclassified and scored (Figure 4-24).

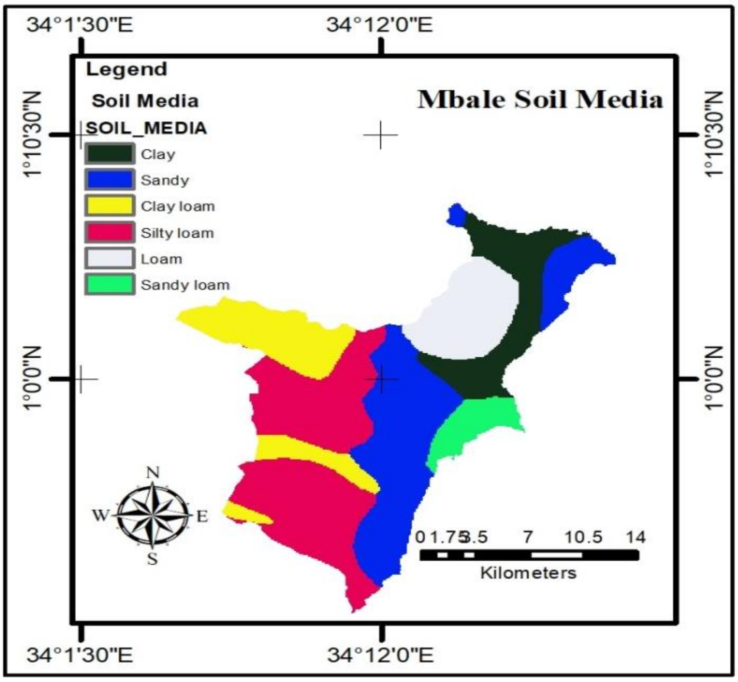

Figure 4- 23: Soil media map

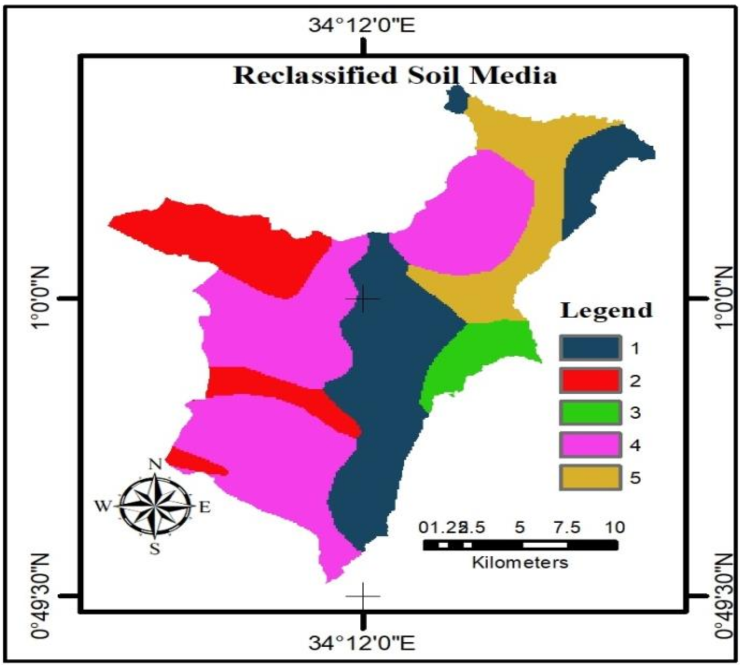

Figure 4- 24: Reclassified soil

4.3.5 Topography

The predominant area has a gentle slope of less than 13%. Northeastern regions are made up of ridges with slopes greater than 22%. The terrain map is shown in Figure 4-25. The topographic map was then categorized and ranked as shown in Figure 4-26.

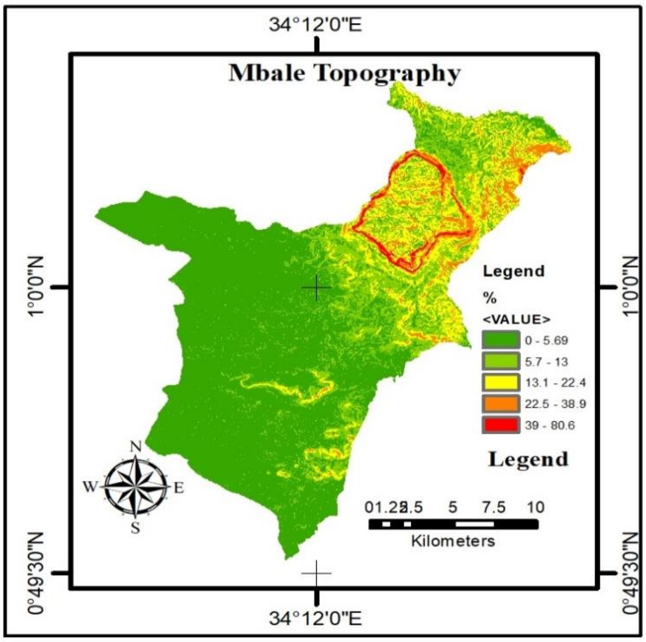

Figure 4- 25: Topography map

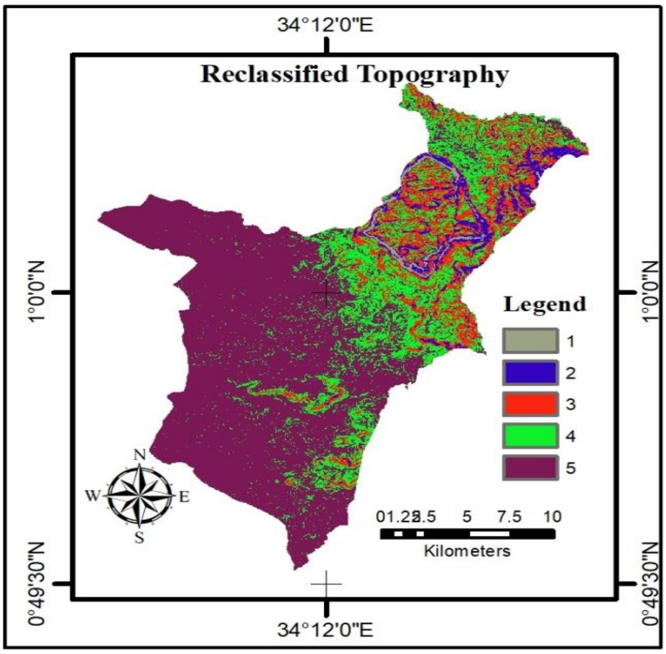

Figure 4- 26: Reclassified Topography map

4.3.6 Impact of Vadose zone

Amalgamated silt, sand and clay characterize the vadose zone. Vadose zone map is in Figure 4-27. Vadose zone map was categorized and assigned ratings from 1 to 10 (Figure 4-28).

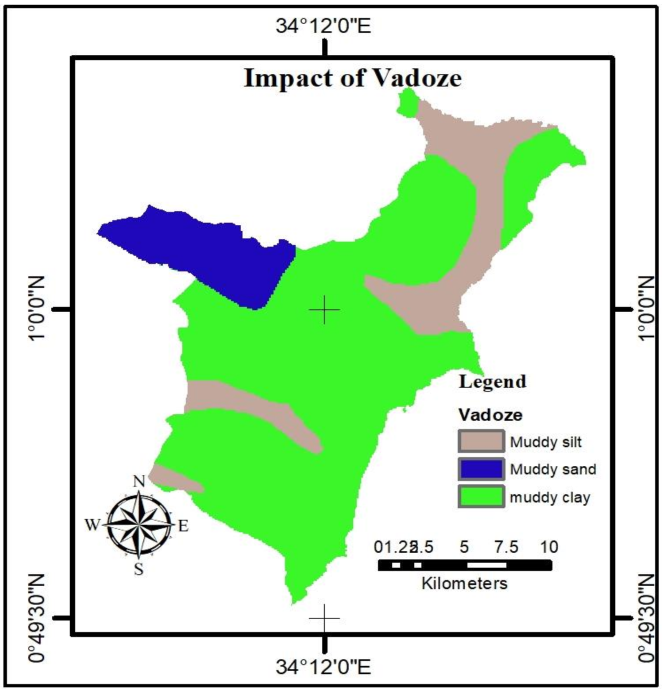

Figure 4- 27: Impact of Vadose Zone map

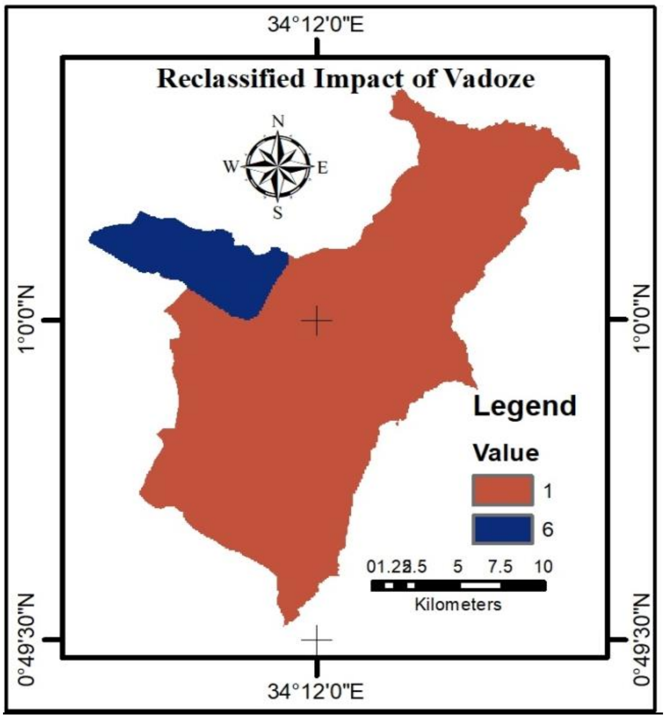

Figure 4- 28: Reclassified impact of Vadose Zone map

4.3.7 The aquifer's hydraulic conductivity

Hydraulic conductivity is substantial since it influences the degree of groundwater flow in the saturated area, thus regulating the degree and outcome of pollutants. Hydraulic conductivity values used originated from the Mbale district pump test data of sampled boreholes Hydraulic conductivity ranged from 13.41-45.29 m/day as in Figure 4-29. Hydraulic conductivity rating distribution is as in Figure 4-30.

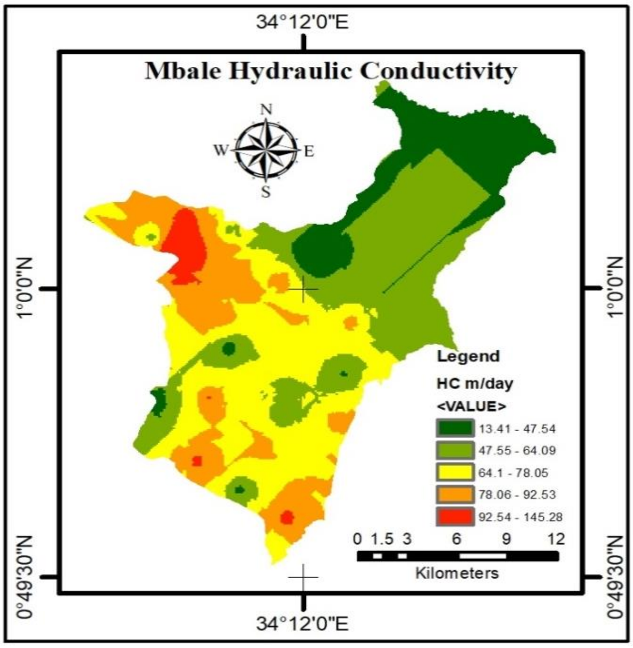

Figure 4- 29: Hydraulic Conductivity map

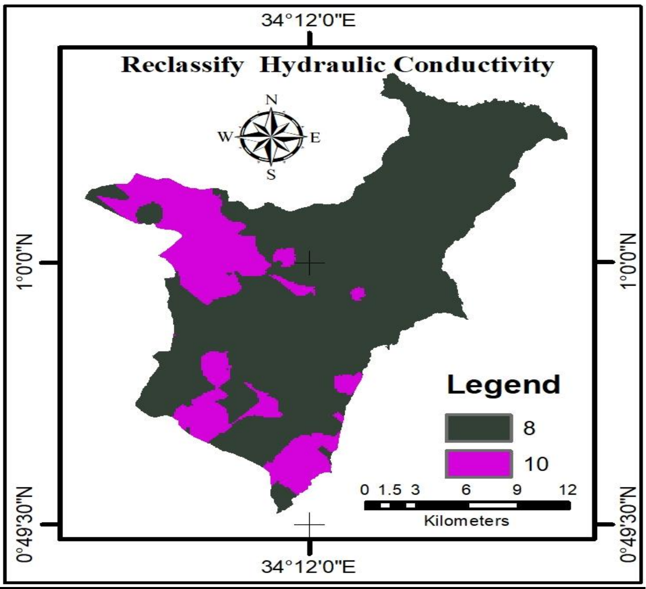

Figure 4- 30: Reclassified Hydraulic Conductivity map

4.3.8 Drastic Vulnerability Index

Scores of DRASTIC varied from 96 to 156, bearing in mind the determined ratings and weightings. The vulnerability was categorized as low (less than 100) occupying an area of, medium (100 to140) and high (greater than 140) in regard to data from hydrogeological surveys (Figure 4-31). 11.23km^2 (5.40%) had low vulnerability, 77.83km^2 (37.44%) had medium vulnerability and 118.83km^2 (57.16%) had high vulnerability.

The groundwater vulnerability results in Mbale district show that the majority of the area (57.16%) has a high vulnerability to contamination which highlights the need for proper management and protection of groundwater resources in the region, particularly related to irrigation practices.

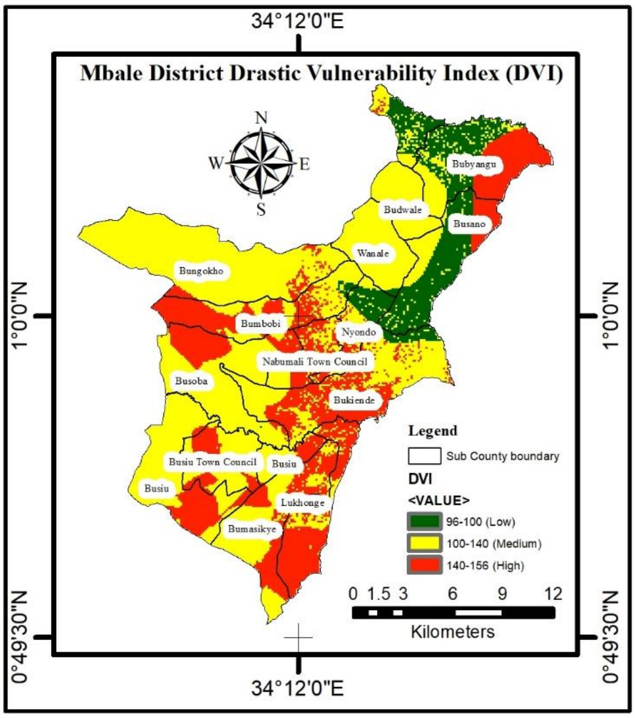

Figure 4- 31: Drastic Vulnerability Index map

Comparing these results with studies done in other regions, Assef and others' (2022) study in Doornfontein area, Johannesburg, South Africa showed a high vulnerability of 60% of the area. Machar and others (2017) found out medium to high vulnerability in two sub districts in Banda Aceh city, Indonesia with 45.5% and 31.8% of the area respectively being vulnerable. Abad and others (2017) found that the Zanjan Plain in Iran had medium, with 28% of the areas being vulnerability. Also, Hamed and others in 2022 in Central Erbil Basin in Iraq found groundwater vulnerability was high, with 45% of the area being vulnerable.

Overall, the results indicate that groundwater vulnerability is a significant issue across different regions, with some areas being more vulnerable than others. In the context of irrigation, it is crucial to consider the impact of agricultural activities on groundwater quality and to use appropriate measures to protect groundwater resources from contamination. The results of these studies suggest a need for better management and protection of groundwater resources to ensure sustainable use for irrigation.

4.4 Groundwater availability and suitability

An unsupervised MLC classification method integrated quality, vulnerability and potential maps of groundwater to form availability and suitability map. The integrated map (Figure 4-32) was categorized to five classes with their corresponding areas: 17.58% very poor (36.56km^2), 13.84% poor (28.77km^2), 12.69% good (26.39 km^2), 31.46% very good (65.39km^2) and 24.43% excellent (50.78km^2).

The sub counties in Mbale district that have inadequate and unsuitable groundwater for irrigated agriculture are Budwale, Wanale, Busano, Bubyangu, Bufumbo and Nyondo since they belong to the zones of very poor and poor. The remaining sub counties have available and suitable groundwater for irrigated agriculture since they belong to the zones of good, very good and excellent.

Comparing this to the studies done in various regions around the world, it appears that the results are somewhat consistent with the findings in Algeria and Iraq where ground water availability and suitability for agriculture are generally good with some areas of lower suitability (Kadri et al., 2022; Al Maliki et al., 2020). However, the results in North China plain indicate challenges with groundwater quality with less than a third of the area suitable for irrigation (Guo et al., 2021).

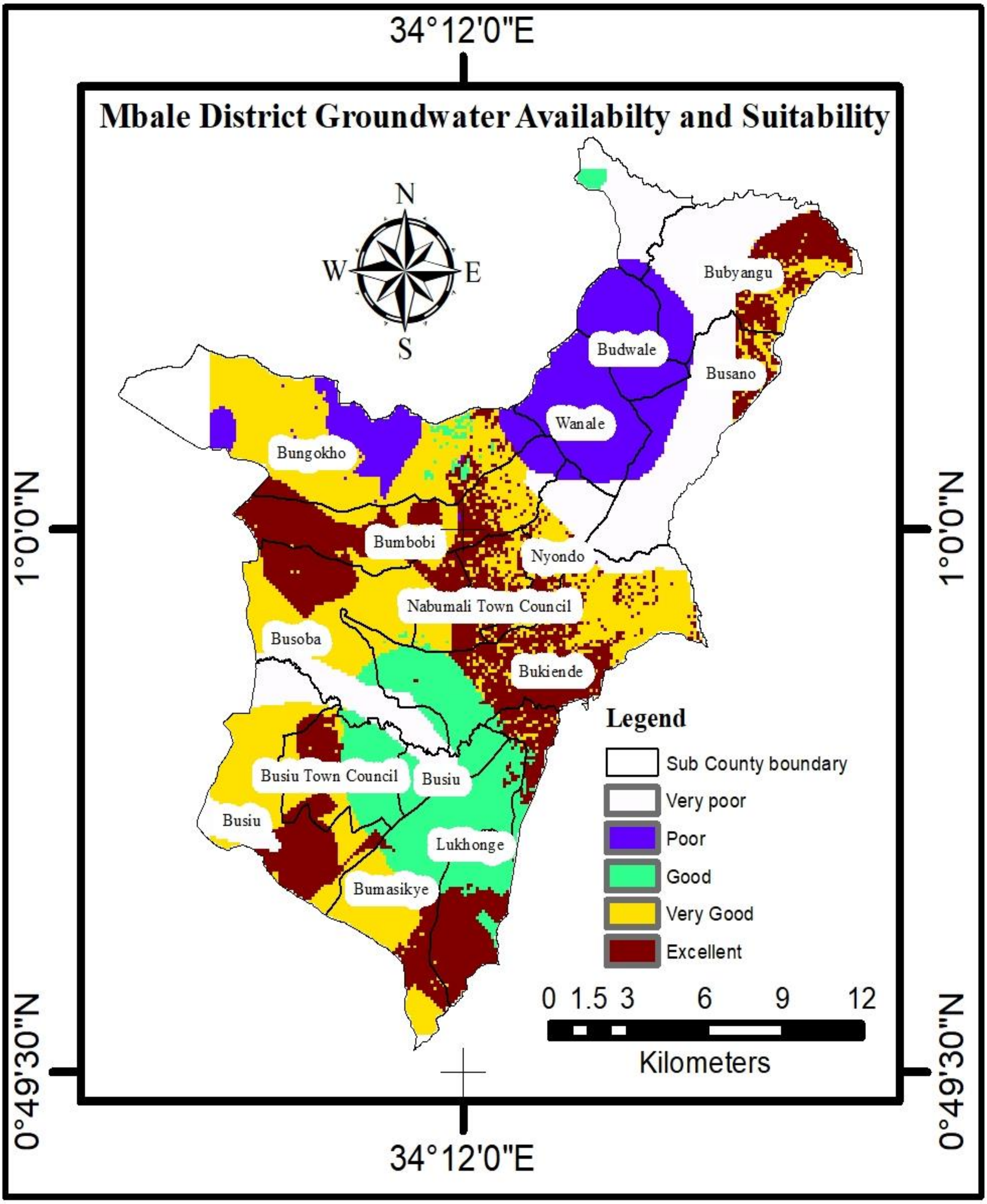

Figure 4- 32: Groundwater Availability and Suitability Map

The study in United Arab Emirates showed relatively low groundwater availability with less than 10% of the area suitable for irrigation (Murad, 2014). Bari's study in 2021 in India showed similar trends as Mbale district with a significant portion (29.03%) having poor groundwater suitability for irrigation.

Overall, while the results in Mbale district are positive compared to other regions, there is still room for improvement in ensuring adequate groundwater availability and suitability for irrigation. Managing groundwater resources, promoting sustainable agriculture practices and investing in infrastructure to enhance irrigated agriculture could help address this challenge.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the results obtained through unsupervised Multivariate Cluster (MLC) classification method, it can be concluded that the groundwater availability and suitability for irrigation purposes in Mbale district is relatively good. Approximately 44% of the groundwater potential is classified as very good or good, while just a quarter is classified as poor. This indicates that there is a potential for irrigation using groundwater in the area.

However, it is important to note that the quality of groundwater has a significant impact on its suitability for irrigation. In this area, approximately 91% of the groundwater falls under the high restriction use category, indicating that it may not be suitable for irrigation without strict management practices. Additionally, the vulnerability of groundwater is medium to high in over 90% of the area, indicating that further monitoring and management of the groundwater resources is necessary to ensure sustainable utilization.

Overall, these results suggest that while groundwater may be a potential source for irrigation in the area, careful consideration of both the groundwater quality and vulnerability is essential before making decisions.

5.2 Recommendations

The following interventions should be implemented to make the study effective:

- Further research and monitoring are necessary to track changes in water quality and develop effective management practices.
- There is need for better management and protection of groundwater resources to ensure sustainable use for irrigation.
- There is need to promote sustainable agricultural practices and invest in infrastructure to enhance irrigated agriculture
- Study should be carried out in Mbale district to determine the crops to be grown in each region

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APPENDICES

Appendix 1 : Irrigation Water Quality Index tables

Lab Identification Code: MBL 23 - 7041									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	246	1	200	100	15	932	99.260	0.211	20.944
Na^+	22.4	4	2	35	35	101.9	27.993	0.204	5.711
HCO_3^-	333.06	4	1	35	35	722.24	18.908	0.202	3.819
Cl^-	46	4	1	35	35	246	28.598	0.194	5.548
SAR	2.81	1	2	100	15	16.234	99.256	0.189	18.759
Total								1	54.781
Lab Identification Code: MBL 23-7042									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	218	1	200	100	15	932	99.710	0.211	21.039
Na^+	20.4	4	2	35	35	101.9	28.680	0.204	5.851
HCO_3^-	335.5	4	1	35	35	722.24	18.790	0.202	3.796
Cl^-	39	4	1	35	35	246	29.593	0.194	5.741
SAR	2.60	1	2	100	15	16.234	99.447	0.189	18.796
Total								1	55.222
Lab Identification Code: MBL 23-7043									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	263	1	200	100	15	932	98.986	0.211	20.886
Na^+	22.4	4	2	35	35	101.9	27.993	0.204	5.711
HCO_3^-	567.3	4	1	35	35	722.24	7.557	0.202	1.526
Cl^-	37	4	1	35	35	246	29.878	0.194	5.796
SAR	2.71	1	2	100	15	16.234	99.348	0.189	18.777
Total								1	52.696

Lab Identification Code: MBL 23-7044									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	592	1	200	100	15	932	93.691	0.211	19.769
Na^+	28.5	4	2	35	35	101.9	25.898	0.204	5.283
HCO_3^-	722.24	4	1	35	35	722.24	0.048	0.202	0.010
Cl^-	75.2	4	1	35	35	246	24.443	0.194	4.742
SAR	2.95	1	2	100	15	16.234	99.122	0.189	18.734
Total								1	48.538

Lab Identification Code: MBL 23-7045									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	106.5	4	200	35	35	932	38.511	0.211	8.126
Na^+	6.2	3	6	60	25	101.9	59.951	0.204	12.230
HCO_3^-	442.86	4	1	35	35	722.24	13.587	0.202	2.745
Cl^-	6.2	2	4	85	25	246	84.776	0.194	16.447
SAR	1.58	4	2	35	35	16.234	35.911	0.189	6.787
Total								1	46.334
Lab Identification Code: MBL 23-7046									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	554	1	200	100	15	932	94.303	0.211	19.898
Na^+	56.1	4	2	35	35	101.9	16.418	0.204	3.349
HCO_3^-	274.5	4	1	35	35	722.24	21.746	0.202	4.393
Cl^-	113.6	4	1	35	35	246	18.980	0.194	3.682
SAR	6.23	3	6	60	25	16.234	59.650	0.189	11.274
Total								1	42.596
Lab Identifier Code: MBL 23-7047									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	271	1	200	100	15	932	98.857	0.211	20.859
Na^+	17.3	4	2	35	35	101.9	29.745	0.204	6.068
HCO_3^-	270.84	4	1	35	35	722.24	21.923	0.202	4.429
Cl^-	51.2	4	1	35	35	246	27.858	0.194	5.404
SAR	2.29	1	2	100	15	16.234	99.735	0.189	18.850
Total								1	55.610

Lab Identifier Code: MBL 23-7048									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	447	1	200	100	15	932	96.025	0.211	20.261
Na^+	28.5	4	2	35	35	101.9	25.898	0.204	5.283
HCO_3^-	192.76	4	1	35	35	722.24	25.707	0.202	5.193
Cl^-	37.8	4	1	35	35	246	29.764	0.194	5.774
SAR	3.30	2	3	85	25	16.234	84.533	0.189	15.977
Total								1	52.488
Lab Identification Code: MBL 23-7049									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	704	1	200	100	15	932	91.888	0.211	19.388
Na^+	25.5	4	2	35	35	101.9	26.928	0.204	5.493
HCO_3^-	69.54	4	1	35	35	722.24	31.679	0.202	6.399
Cl^-	70	4	1	35	35	246	25.183	0.194	4.885
SAR	2.83	1	2	100	15	16.234	99.236	0.189	18.756
Total								1	54.922
Lab Identification Code: MBL 23-7050									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	712	1	200	100	15	932	91.760	0.211	19.361
Na^+	56.1	4	2	35	35	101.9	16.418	0.204	3.349
HCO_3^-	46.36	4	1	35	35	722.24	32.802	0.202	6.626
Cl^-	156	4	1	35	35	246	12.947	0.194	2.512
SAR	5.75	2	60	85	25	16.234	168.549	0.189	31.856
Total								1	63.704
Lab Identifier Code: MBL 23-7051									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	710	1	200	100	15	932	91.792	0.211	19.368
Na^+	71.3	4	2	35	35	101.9	11.197	0.204	2.284
HCO_3^-	71.3	4	1	35	35	722.24	31.593	0.202	6.382
Cl^-	134.6	4	1	35	35	246	15.992	0.194	3.102
SAR	8.34	3	6	60	35	16.234	54.963	0.189	10.388
Total								1	41.525

Lab Identifier Code: MBL 23-7052									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	495	1	200	100	15	932	95.252	0.211	20.098
Na^+	34.6	4	2	35	35	101.9	23.803	0.204	4.856
HCO_3^-	152.5	4	1	35	35	722.24	27.658	0.202	5.587
Cl^-	56.3	4	1	35	35	246	27.132	0.194	5.264
SAR	5.03	2	3	85	25	16.234	81.881	0.189	15.475
Total								1	51.280
Lab Identification Code: MBL 23-7053									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	459	1	200	100	15	932	95.832	0.211	20.220
Na^+	44.8	4	2	35	35	101.9	20.299	0.204	4.141
HCO_3^-	353.8	4	1	35	35	722.24	17.903	0.202	3.616
Cl^-	92	4	1	35	35	246	22.053	0.194	4.278
SAR	7.00	3	6	60	25	16.234	58.459	0.189	11.049
Total								1	43.305
Lab Identification Code: MBL 23-7054									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	290	1	200	100	15	932	98.552	0.211	20.794
Na^+	17.3	4	2	35	35	101.9	29.745	0.204	6.068
HCO_3^-	341.6	4	1	35	35	722.24	18.494	0.202	3.736
Cl^-	17.2	4	1	35	35	246	32.695	0.194	6.343
SAR	3.77	2	3	85	25	16.234	83.813	0.189	15.841
Total								1	52.782
Lab Identifier Code: MBL 23-7055									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	158.1	4	200	35	35	932	36.573	0.211	7.717
Na^+	11.2	4	2	35	35	101.9	31.840	0.204	6.495
HCO_3^-	207.4	4	1	35	35	722.24	24.998	0.202	5.050
Cl^-	16.4	4	1	35	35	246	32.809	0.194	6.365
SAR	2.30	1	2	100	15	16.234	99.724	0.189	18.848
Total								1	44.475
Lab Identifier Code: MBL 23-7056									

Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	566	1	200	100	15	932	94.109	0.211	19.857
Na^+	24.4	4	2	35	35	101.9	27.306	0.204	5.570
HCO_3^-	341.6	4	1	35	35	722.24	18.494	0.202	3.736
Cl^-	22.5	4	1	35	35	246	31.941	0.194	6.197
SAR	2.71	1	2	100	15	16.234	99.341	0.189	18.776
Total								1	54.136
Lab Identification Code: MBL 23-7057									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	188.5	4	200	35	35	932	35.432	0.211	7.476
Na^+	10.2	4	2	35	35	101.9	32.184	0.204	6.565
HCO_3^-	207.4	4	1	35	35	722.24	24.998	0.202	5.050
Cl^-	13.7	4	1	35	35	246	33.193	0.194	6.439
SAR	3.99	2	3	85	25	16.234	83.482	0.189	15.778
Total								1	41.309
Lab Identification Code: MBL 23-7058									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	238	1	200	100	15	932	99.388	0.211	20.971
Na^+	14.3	4	2	35	35	101.9	30.775	0.204	6.278
HCO_3^-	237.9	4	1	35	35	722.24	23.520	0.202	4.751
Cl^-	35	4	1	35	35	246	30.163	0.194	5.852
SAR	2.57	1	2	100	15	16.234	99.477	0.189	18.801
Total								1	56.653
Lab Identification Code: MBL 23-7059									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	515	1	200	100	15	932	94.930	0.211	20.030
Na^+	26.5	4	2	35	35	101.9	26.585	0.204	5.423
HCO_3^-	104.92	4	1	35	35	722.24	29.964	0.202	6.053
Cl^-	65	4	1	35	35	246	25.894	0.194	5.023
SAR	3.68	2	3	85	25	16.234	83.955	0.189	15.868
Total								1	52.397
Lab Identification Code: MBL 23-7060									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI

EC	932	2	750	85	25	932	80.118	0.211	16.905
Na^+	86.6	4	2	35	35	101.9	5.942	0.204	1.212
HCO_3^-	52.46	4	1	35	35	722.24	32.506	0.202	6.566
Cl^-	34.8	4	1	35	35	246	30.191	0.194	5.857
SAR	10.87	3	6	60	35	16.234	49.497	0.189	9.355
Total								1	39.895
Lab Identification Code: MBL 23-7061									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	193	4	200	35	35	932	35.263	0.211	7.440
Na^+	19.4	4	2	35	35	101.9	29.024	0.204	5.921
HCO_3^-	195.2	4	200	35	35	722.24	35.233	0.202	7.117
Cl^-	19.4	4	1	35	35	246	32.382	0.194	6.282
SAR	3.12	2	3	85	25	16.234	84.821	0.189	16.031
Total								1	42.791
Lab Identification Code: MBL 23-7062									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	305	1	200	100	15	932	98.310	0.211	20.743
Na^+	14.3	4	2	35	35	101.9	30.775	0.204	6.278
HCO_3^-	114.68	4	1	35	35	722.24	29.491	0.202	5.957
Cl^-	246	4	1	35	35	246	0.142	0.194	0.028
SAR	2.59	1	2	100	15	16.234	99.455	0.189	18.797
Total								1	51.803
Lab Identification Code: MBL 23-7063									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	820	2	750	85	15	932	83.873	0.211	17.697
Na^+	101.9	4	2	35	35	101.9	0.687	0.204	0.140
HCO_3^-	151.28	4	1	35	35	722.24	27.717	0.202	5.599
Cl^-	172	4	1	35	35	246	10.671	0.194	2.070
SAR	16.23	4	2	35	35	16.234	4.312	0.189	0.815
Total								1	26.321
Lab Identification Code: MBL 23-7064									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	188.9	4	200	35	35	932	35.417	0.211	7.473

Na^+	21.4	4	2	35	35	101.9	28.337	0.204	5.781
HCO_3^-	165.92	4	1	35	35	722.24	27.008	0.202	5.456
Cl^-	43	4	1	35	35	246	29.024	0.194	5.631
SAR	6.02	3	6	60	35	16.234	59.964	0.189	11.333
Total								1	35.673
Lab Identification Code: MBL 23-7065									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	777	2	750	85	25	932	84.276	0.211	17.782
Na^+	33.6	4	2	35	35	101.9	24.146	0.204	4.926
HCO_3^-	139.08	4	1	35	35	722.24	28.309	0.202	5.718
Cl^-	47.7	4	1	35	35	246	28.356	0.194	5.501
SAR	5.66	2	3	85	25	16.234	80.905	0.189	15.291
Total								1	49.218
Lab Identification Code: MBL 23-7066									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	177.7	4	200	35	35	932	35.837	0.211	7.562
Na^+	12.2	4	2	35	35	101.9	31.497	0.204	6.425
HCO_3^-	131.76	4	1	35	35	722.24	28.663	0.202	5.790
Cl^-	102	4	1	35	35	246	20.630	0.194	4.002
SAR	3.51	2	3	85	25	16.234	84.208	0.189	15.915
Total								1	39.694
Lab Identification Code: MBL 23-7067									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	275	1	200	100	15	932	98.793	0.211	20.845
Na^+	25.6	4	2	35	35	101.9	26.894	0.204	5.486
HCO_3^-	176.9	4	1	35	35	722.24	26.476	0.202	5.348
Cl^-	34.3	4	1	35	35	246	30.262	0.194	5.871
SAR	4.61	2	3	85	25	16.234	82.528	0.189	15.598
Total								1	53.148
Lab Identification Code: MBL 23-7068									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	293	1	200	100	15	932	98.503	0.211	20.784
Na^+	18.3	4	2	35	35	101.9	29.401	0.204	5.998

HCO_3^-	176.9	4	1	35	35	722.24	26.476	0.202	5.348
Cl^-	43	4	1	35	35	246	29.024	0.194	5.631
SAR	4.20	2	3	85	25	16.234	83.146	0.189	15.715
Total								1	53.476
Lab Identification Code: MBL 23-7069									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	723	1	700	100	15	932	99.630	0.211	21.022
Na^+	66.1	4	2	35	35	101.9	12.983	0.204	2.649
HCO_3^-	152.5	4	1	35	35	722.24	27.658	0.202	5.587
Cl^-	188	4	1	35	35	246	8.394	0.194	1.628
SAR	7.83	3	3	60	35	16.234	49.591	0.189	9.373
Total								1	40.259
Lab Identification Code: MBL 23-7070									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	820	1	700	100	15	932	98.069	0.211	20.692
Na^+	45.8	4	2	35	35	101.9	19.956	0.204	4.071
HCO_3^-	195.2	4	1	35	35	722.24	25.589	0.202	5.169
Cl^-	107	4	1	35	35	246	19.919	0.194	3.864
SAR	7.75	3	6	60	35	16.234	56.221	0.189	10.626
Total								1	44.423
Lab Identification Code: MBL 23-7071									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	292	1	200	100	15	932	98.519	0.211	20.788
Na^+	15.3	4	2	35	35	101.9	30.432	0.204	6.208
HCO_3^-	318.42	4	1	35	35	722.24	19.618	0.202	3.963
Cl^-	32	4	1	35	35	246	30.589	0.194	5.934
SAR	4.47	2	3	85	25	16.234	82.732	0.189	15.636
Total								1	52.529
Lab Identification Code: MBL 23-7072									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	778	1	700	100	15	932	98.745	0.211	20.835
Na^+	96.8	4	2	35	35	101.9	2.439	0.204	0.497
HCO_3^-	181.78	4	1	35	35	722.24	26.239	0.202	5.300
Cl^-	156	4	1	35	35	246	12.947	0.194	2.512
SAR	12.35	4	2	35	35	16.234	12.678	0.189	2.396

Total								1	31.541
Lab Identification Code: MBL 23-7073									
Chemical parameter	x_{ij}	Class	x_{inf}	q_{imax}	q_{iamp}	x_{amp}	Q_i	W_i	IWQI
EC	283	1	200	100	15	932	98.664	0.211	20.818
Na^+	15.1	4	2	35	35	101.9	30.500	0.204	6.222
HCO_3^-	315.98	4	1	35	35	722.24	19.736	0.202	3.987
Cl^-	31	4	1	35	35	246	30.732	0.194	5.962
SAR	4.82	2	3	85	25	16.234	82.192	0.189	15.534
Total								1	52.523

Appendix 2: SAR table

Lab Identification Code	Calcium (mg/l)	Sodium(mg/l)	Magnesium (mg/l)	SAR
MBL 23-7041	121	22.4	6.5	2.81
MBL 23-7042	117	20.4	6.3	2.60
MBL 23-7043	130	22.4	7.1	2.71
MBL 23-7044	179.3	28.5	7.3	2.95
MBL 23-7045	27.8	6.2	3.1	1.58
MBL 23-7046	155.4	56.1	6.9	6.23
MBL 23-7047	112	17.3	2.5	2.29
MBL 23-7048	146.7	28.5	2.2	3.30
MBL 23-7049	159.2	25.5	3.5	2.83
MBL 23-7050	187.6	56.1	3.0	5.75
MBL 23-7051	143.2	71.3	3.1	8.34
MBL 23-7052	89.6	34.6	5.2	5.03
MBL 23-7053	76.4	44.8	5.5	7.00
MBL 23-7054	37	17.3	5.1	3.77
MBL 23-7055	43.3	11.2	4.2	2.30
MBL 23-7056	156	24.4	5.8	2.71
MBL 23-7057	6.9	10.2	6.2	3.99
MBL 23-7058	56	14.3	6.1	2.57
MBL 23-7059	98.9	26.5	4.9	3.68
MBL 23-7060	122.6	86.6	4.3	10.87
MBL 23-7061	73.6	19.4	3.9	3.12
MBL 23-7062	54	14.3	7.0	2.59
MBL 23-7063	75	101.9	3.8	16.23
MBL 23-7064	20.6	21.4	4.7	6.02
MBL 23-7065	65	33.6	5.5	5.66
MBL 23-7066	17.2	12.2	6.9	3.51
MBL 23-7067	54.5	25.6	7.3	4.61
MBL 23-7068	32.3	18.3	5.6	4.20

MBL 23-7069	136.5	66.1	6.1	7.83
MBL 23-7070	65.2	45.8	4.6	7.75
MBL 23-7071	18	15.3	5.4	4.47
MBL 23-7072	120	96.8	2.8	12.35
MBL 23-7073	15	15.1	4.6	4.82

Appendix 3: Bicarbonates table

Lab Identification Code	Total Alkalinity (mg/l)	Bicarbonates (HCO3) (mg/l)
MBL 23-7041	273	$= \frac{61}{50} x273 = 333.06$
MBL 23-7042	275	335.5
MBL 23-7043	465	567.3
MBL 23-7044	592	722.24
MBL 23-7045	363	442.86
MBL 23-7046	225	274.5
MBL 23-7047	222	270.84
MBL 23-7048	158	192.76
MBL 23-7049	57	69.54
MBL 23-7050	38	46.36
MBL 23-7051	220	268.4
MBL 23-7052	125	152.5
MBL 23-7053	290	353.8
MBL 23-7054	280	341.6
MBL 23-7055	170	207.4
MBL 23-7056	280	341.6
MBL 23-7057	170	207.4
MBL 23-7058	195	237.9
MBL 23-7059	86	104.92
MBL 23-7060	43	52.46
MBL 23-7061	160	195.2
MBL 23-7062	94	114.68
MBL 23-7063	124	151.28
MBL 23-7064	136	165.92
MBL 23-7065	114	139.08
MBL 23-7066	108	131.76
MBL 23-7067	145	176.9
MBL 23-7068	145	176.9
MBL 23-7069	125	152.5
MBL 23-7070	160	195.2
MBL 23-7071	261	318.42

MBL 23-7072	149	181.78
MBL 23-7073	259	315.98

Appendix 4: Photographs during laboratory testing

Testing of pH

Electrical conductivity testing

Mixing of chemicals in fumes cage

Titration during testing of total alkalinity

Appendix 5: Photographs during collection of water samples

Waninda borehole, Bungokho S/County

Mafutu Borehole, Bumbobi S/County

Kitindya borehole, Bukiende S/County

Lambo A lower borehole, Busiu S/County