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Assessment of Ground Water Dynamics and Potential Zones in Urban Areas: A Case Study of Voi Town, Kenya

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Abstract

Water plays a role in sustaining all the biotic elements. Unfortunately, in the recent times with persistent climate change impacts, parts of the world are facing cases of inadequate water causing stress and increased vulnerability among the people. This is the case with urban areas across the globe as their populations keep increasing with little to no attention paid to urban planning that allows sustainable management of resources amidst rapid development. Urban areas are surrounded by high yielding aquifers that have better water services from groundwater. However, the urban sprawl phenomena have limited attempts in assessing ground water potential in urban areas contributing to urban water scarcity. Therefore, the study aims to look at the problem of urban water scarcity, by analyzing the levels and distribution of groundwater in Voi town using remote sensing and GIS techniques, in order to suggest suitable sites for underground water exploration in regard to the overall urban water supply. From the analysis, the results showed that the area majorly has low to potential zones of groundwater. High potential areas were very few and were mostly on the western side of the area. Very low potential zones were seen on the east and north side of the area.

Keywords

Groundwater, Urban Water, Urban Planning, Remote Sensing, Urban Sprawl

1. Introduction

Nothing is more useful than water: but it will purchase scarcely anything: scarce anything can be had in exchange for it. This is an observation that was made by Adam Smith, a Scottish philosopher, often considered to be the father of economics. This anomaly is in spite of the fact human beings cannot survive and thrive without a reliable supply of water, and it is the only natural resource that has no economic price (Biswas, 2022).

Water plays a role in sustaining all the biotic elements as well as fulfilling the different requirements of the various sectors such as agriculture, industries and domestic purposes (Kuria, 2012). Water is essential for food producing, generating electricity and survival of all ecosystems thus no economic or commercial activity is possible without water. Therefore, water is life and a basic need that every human is entitled to. Unfortunately, in the recent times with persistent climate change impacts, parts of the world are facing cases of inadequate water causing stress and increased vulnerability among the people. This is the case with urban areas across the globe as their populations keep increasing with little to no attention paid to urban planning that allows sustainable management of resources amidst rapid development.

Urban planning is a technical and political process that is focused on the development and design of land use and the built environment, including air, water, and the infrastructure passing into and out of urban areas. An urban area is a place-based characteristic that incorporates elements of population density, social and economic organization, and the transformation of the natural environment into a built environment (Weeks, 2010). Urban sprawl which is described as the unrestricted developments in the urban areas is as a result of little concern for urban planning. The urban sprawl phenomena have limited attempts in assessing ground water potential in urban areas contributing to urban water scarcity. According to the UN, the number of city inhabitants lacking safely managed drinking water has increased by more than 50% since 2000. In bid to solve the problem of urban water scarcity, every possible solution that increases the supply of water from its sources is highly being considered giving room to analyze the future of ground water in sustaining water supply in urban areas.

Urban areas are surrounded by high yielding aquifers that have better water services from groundwater (Foster et al., 2011; Pokrajac & Howard, 2010; Taniguchi, 2009). However, the rapid increase in urban population is affecting the demand and management of groundwater. According to Nationen (2007), between the years 2000-2030 Africa's Urban population will double as World Bank confirms it will take up to 37% of the total African population (World Bank, 2016). There is a growing concern attributed to uncontrolled or mismanaged land use land cover due to poor planning amidst urban sprawl. According to a report given by a hydrogeology journal in Kenya, since 2000, built-up areas in Nairobi have been increasing by 70% declining the groundwater levels at a median rate of 6 m/decade underneath. In addition, rapid urbanization in Nairobi region has contributed to groundwater level declines through modification of aquifer recharge patterns (Oiro et al., 2020; Schaeffer et al., 2013). On the other hand, Mombasa, a city at the coast, is known for lucking sufficient portable water that can be considered safe for drinking and cooking. The city sources water from the neighbouring counties but the water is not enough for the growing population. According to a report done by JICA, Mombasa Island has Pleistocene reef complex sands which have high ground water potential containing unconfined aquifers at shallow depth along most of the coast. In spite of that, the ground water in Mombasa is unexplored due salination and pollution from its ever-increasing population.

Voi, a town in Taita Taveta county has been undergoing land use changes since it existed. Nyongesa et al. (2022) found out that the built-up area increased by 187.98% between 1999 and 2011, 183.40% between 2011 and 2019, and 716.1% between 1999 and 2019. This is an indication of a significant expansion of the city and its surrounding areas. The growth is attributed to population growth, land tenure, transportation and utilities such as water and electricity provision. Additionally, it was established that the bare land is the most common LULC in the area. This is due to the fact that Voi is a semi-desert region with an annual rainfall of 733 mm. As a result, the area is dry for the majority of the year due to climate change and clearing of vegetation to make room for settlement. With this at hand, Voi town is more vulnerable to negative impacts towards its groundwater level and distribution. On that note, an endeavor was made towards studying how these impacts have affected the groundwater levels and distribution in Voi town, and their overall influence on urban water supply.

This paper therefore aims to look at the problem of urban water scarcity, by analyzing the levels and distribution of groundwater in Voi town using remote sensing and GIS techniques, in order to suggest suitable sites for underground water exploration in regard to the overall urban water supply. It is important to first understand the critical role that groundwater plays in the urban water supply. Urban water supply starts from a source of water which includes lakes, rivers, reservoirs and ground water aquifers, and then involves storage, treatment and distribution to users by adequate pump transmissions pipes and canals. As shown in **Figure 1**, groundwater acts as a source in the urban water supply and it therefore needs sustainable management in the waken of increased urban population.

Ground water provides 50% of urban water and probably a higher proportion at times of water stress (Foster & Gogu, 2022). It is also a climate resilient source of water supply because of its large natural storage. The occurrence and movement of groundwater depends on various factors such as; the rate of infiltration, run-off, base flow, and evaporation. These factors are affected by the geological structure of the area, geomorphology, slope, land use and the land cover, and soil type. To study these factors, GIS platforms in conjunction with remote sensors have been proposed since they decrease time spent collecting land-use and environmental information. With remotely sensed images, urban planners can detect current land use, as well as changes to land use for an entire urban area over time. These geospatial technologies are very handy in assessment and analysis of various environmental urban development related issues. Consequentially,

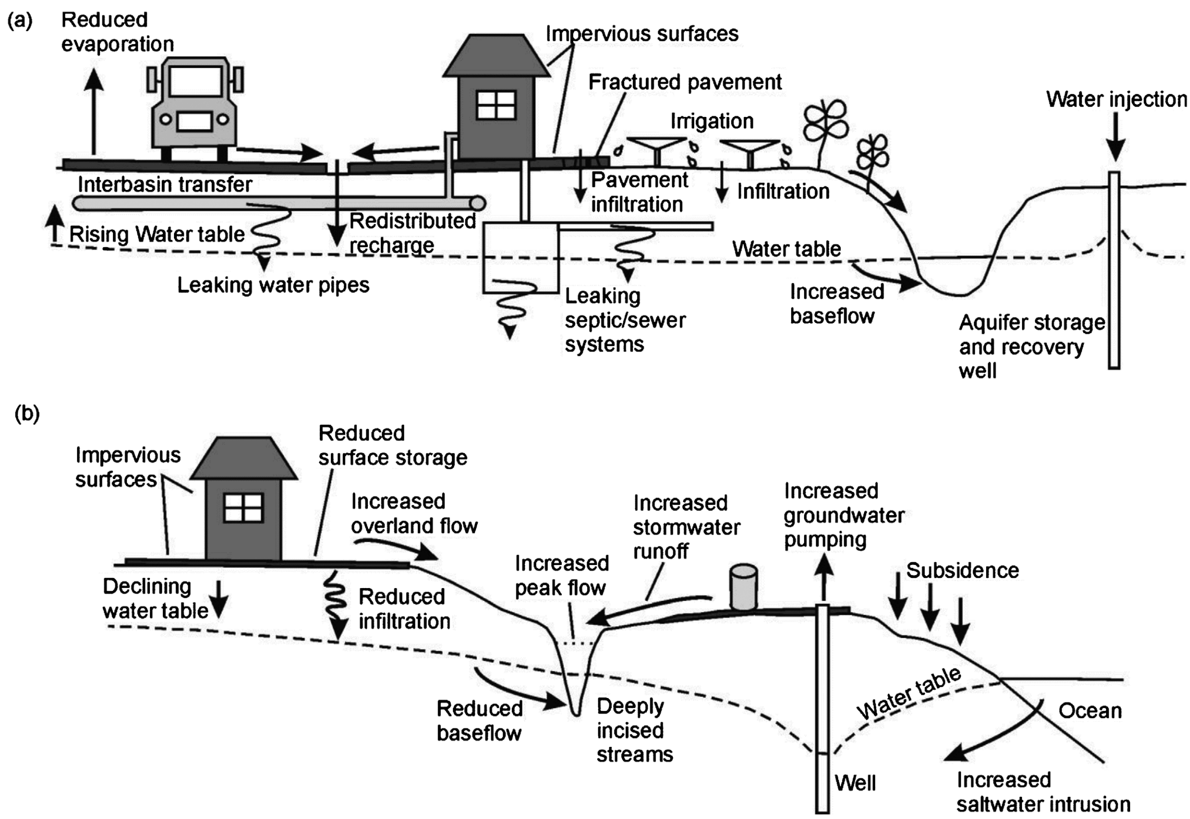

Figure 1. Urban development and groundwater potential.

GIS and Remote Sensing is a more convenient way to determine groundwater potential areas as it utilizes satellite imageries, digital elevation models, conventional maps and field generated data to analyze and generate thematic maps of the Land Use Land Cover, slope, lineament density, drainage network and density, groundwater level, geomorphology, geology, soil, and rainfall distribution. The sequential arrangements of the above layers are then subjected to analytical hierarchy process analysis, whereby weights of the above layers are assigned depending on how they are influenced by the ground water and potential areas that are then determined by the analysis.

2. Description of Study Area

Voi is a historical town in Taita Taveta County that became a township in 1932. It is located at a latitude 3˚23'45.78"S and longitude 38˚33'21.92"E, at an elevation of 600 m as shown in Figure 2. The town covers an area of approximately 55.31 km^2. Infrastructure such as the Kenya-Uganda railway, Standard-gauge railway (SGR): airstrips, the Voi-Tanzania highway, and the Mombasa-Nairobi highway account for the town's rapid growth. The town is close to ranching plains, national parks, and mining operations. Voi, as a commercial and tourist center, has drawn a large population from the surrounding areas, and it has the highest population growth rate among the towns in Taita Taveta County.

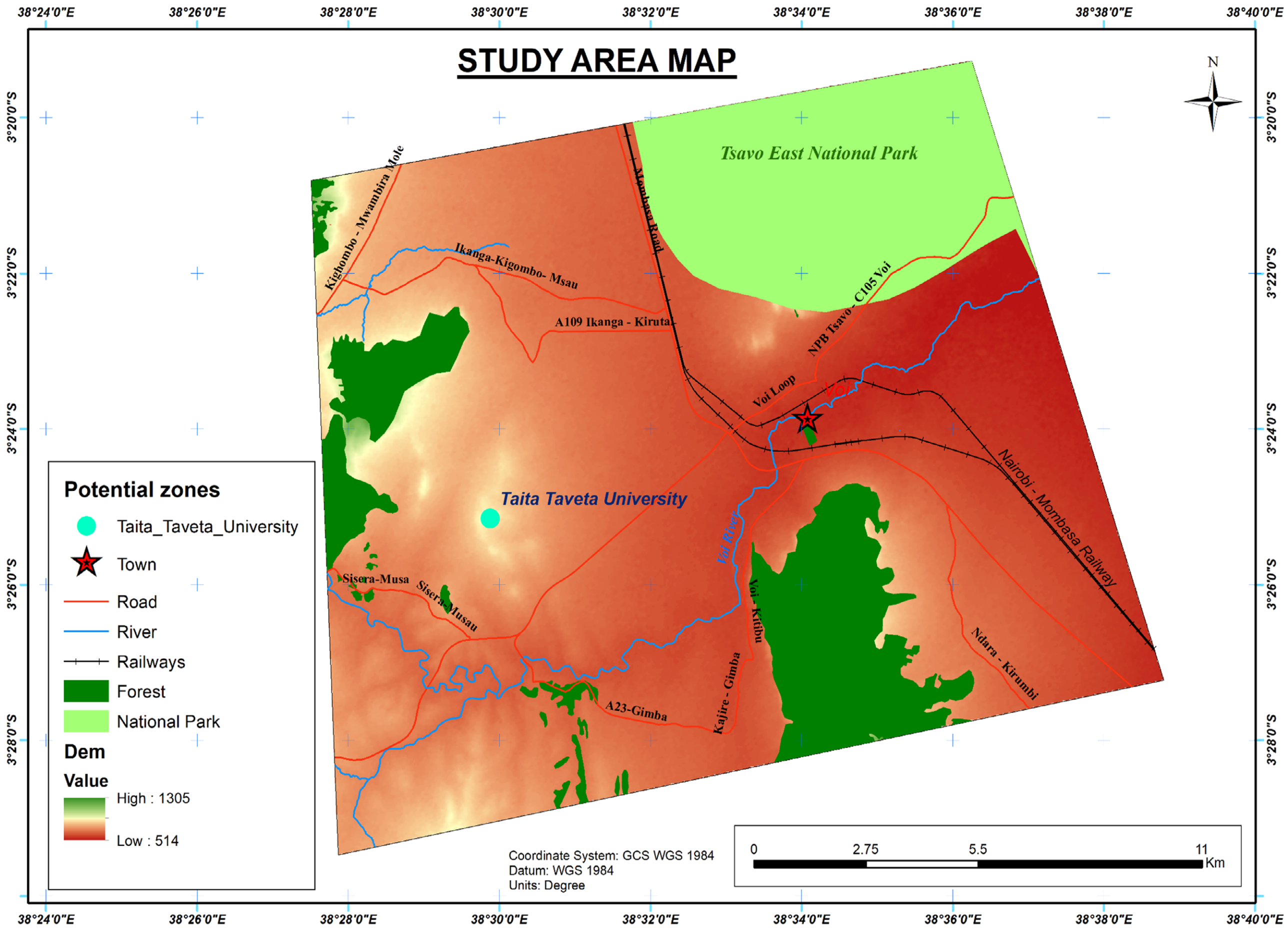

Figure 2. Study area.

3. Materials and Method

3.1. Datasets

Different datasets were utilized to prepare the thematic layers of the study area. Table 1 show the various datasets used in this work and their associated sources.

3.2. Methodology

The methodology applied in general study for groundwater potential areas utilizes the Geographical Information System (GIS) and Remote sensing technologies. In order to prepare the map showing potential zones in Voi town, five stages were applied; Source Data Collection, Image Processing, Building Database, Data Processing and Data Integration as outlined in Figure 3.

3.2.1. Source Data Collection

Sentinel 2 MSI image acquired on 25 January 2023 was collected together with the soil, geology and geomorphology data. Additionally, Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) and Shuttle Radar Topography Mission (SRTM) were acquired for estimating rainfall, slope and drainage density.

Table 1. Data sources.

Data	Source	Spatial Resolution (m)	Purpose
Sentinel 2 (MSI)	Copernicus Open Access Hub	10 m	To perform LULC classification
SRTM DEM	Earth Explorer	30 m	Obtaining slope, lineaments and drainage density
Soil	ISRIC		Obtaining soil maps
Geomorphology	RCMRD		To produce geomorphology maps
Geology	USGS		To produce a geology map
Rainfall-CHIRPS	USGS FEWS NET DATA Portal	5 Km	To give rainfall estimates

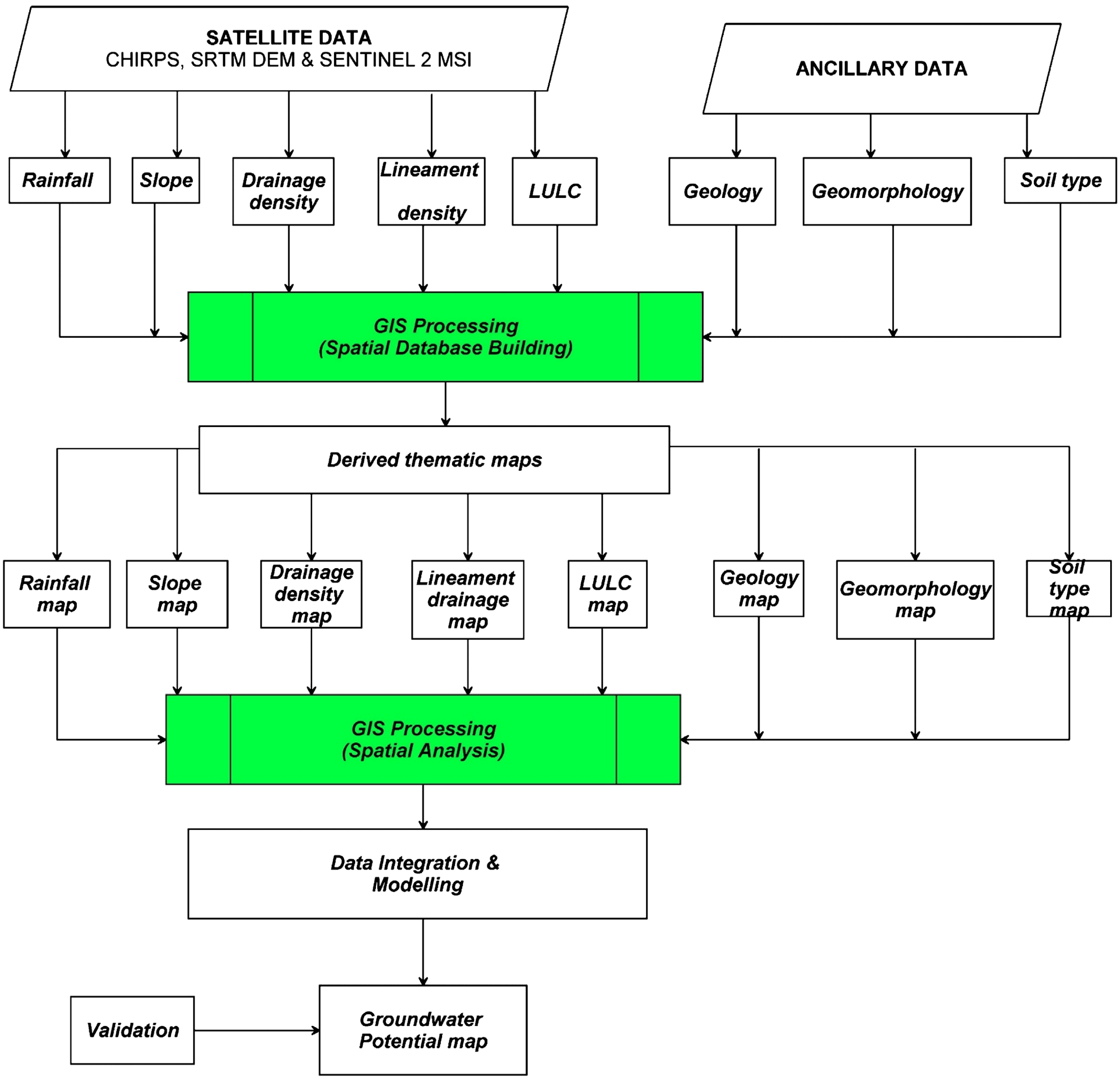

Figure 3. Methodology flowchart.

3.2.2. Satellite Data Analysis

The main task in this stage was to do an analysis and interpretation of satellite and ancillary data in order to produce basic maps. The Sentinel 2 image was pre-processed and later classified using the maximum likelihood classification to obtain the land use land cover of the study area. The image was classified into five classes namely: Built-up, Cropland, Grassland, Bareland and Forest land. The lineaments were identified visually from which their density was obtained. The slope map, drainage networks and density were derived from SRTM DEM. The SRTM DEM was processed in the ArcGIS Spatial Analyst environment. The slope tool was applied in acquiring the slope map of the area. The hydrology tools were used to obtain the watershed of the area. The drainage properties of the watershed were analyzed to determine the drainage density. CHIRPS is a quasi-global rainfall dataset that is obtained by combining data from real-time observing meteorological stations with infra-red data to estimate precipitation (Funk et al., 2015). To obtain the annual rainfall estimates for each of the study years, the data was processed. The processes consisted of projections, resizing and computation of cell statistics to obtain cell information.

3.2.3. Spatial Database Building

All the appropriate data were assembled into a GIS database. The spatial data was properly registered to make sure the spatial component overlaps correctly. Other processes included: transformation and conversion between raster to vector and interpolation. This stage produced derived layers such as rainfall, lineaments density, slope steepness, soil type, land use, geomorphology, geology and drainage density.

3.2.4. Spatial Data Analysis

This stage included various analysis such as polygon classification and weight calculation. Polygons in each of the thematic layers were categorized depending on the recharge characteristics and suitable weightages were assigned.

3.2.5. Data Integration

The final stage involved combining all thematic layers using the modified DRASTIC model. The model considers the intrinsic characteristics of an aquifer, in hand with anthropogenic activities on the earth surface (Garewal et al., 2019). The formula of the groundwater potentiality model (GP) is shown below.

$$GP = Rf + Ge + Ld + Lu + G + Ss + Dd + St \quad (1)$$

where

Rf: *annual rainfall*, *Ge*: *Geology*, *Ld*: *lineament density*, *Lu*: *land use*, *G*: *geomorphology*, *Ss*: *soil steepness*, *Dd*: *drainage density & St*: *soil type.*

The output was reclassified into five groups: very high, high, moderate, low and very low using the Quantile classification method.

4. Results

4.1. Geology

Geology depicts the litho-units and formations that are present in an area. It provides an insight into the sequential arrangement of rock formations below the earth surface. Identification of the litho helps to determine the infiltration capacity, permeability and its ability to discharge and store water. Geologically, the study area is majorly covered with Precambrian rocks as shown in Figure 4.

4.2. Land Use Land Cover

Land use land cover of an area indicates utilization of the land for various purposes. It includes infrastructure such as road networks and settlements, vegetation, bare land, forest and surface water bodies. The occurrence of water depends on the surface features and these act as a mediator in the process of infiltration, runoff and evapotranspiration. The land use in Voi town was classified in 5 classes as shown in Figure 5. Built-up area covered an area of approx. 39. 50 km^2, cropland 127.41 km^2, forest 29.48 km^2, grassland 66.91 km^2 and bareland 32.71 km^2.

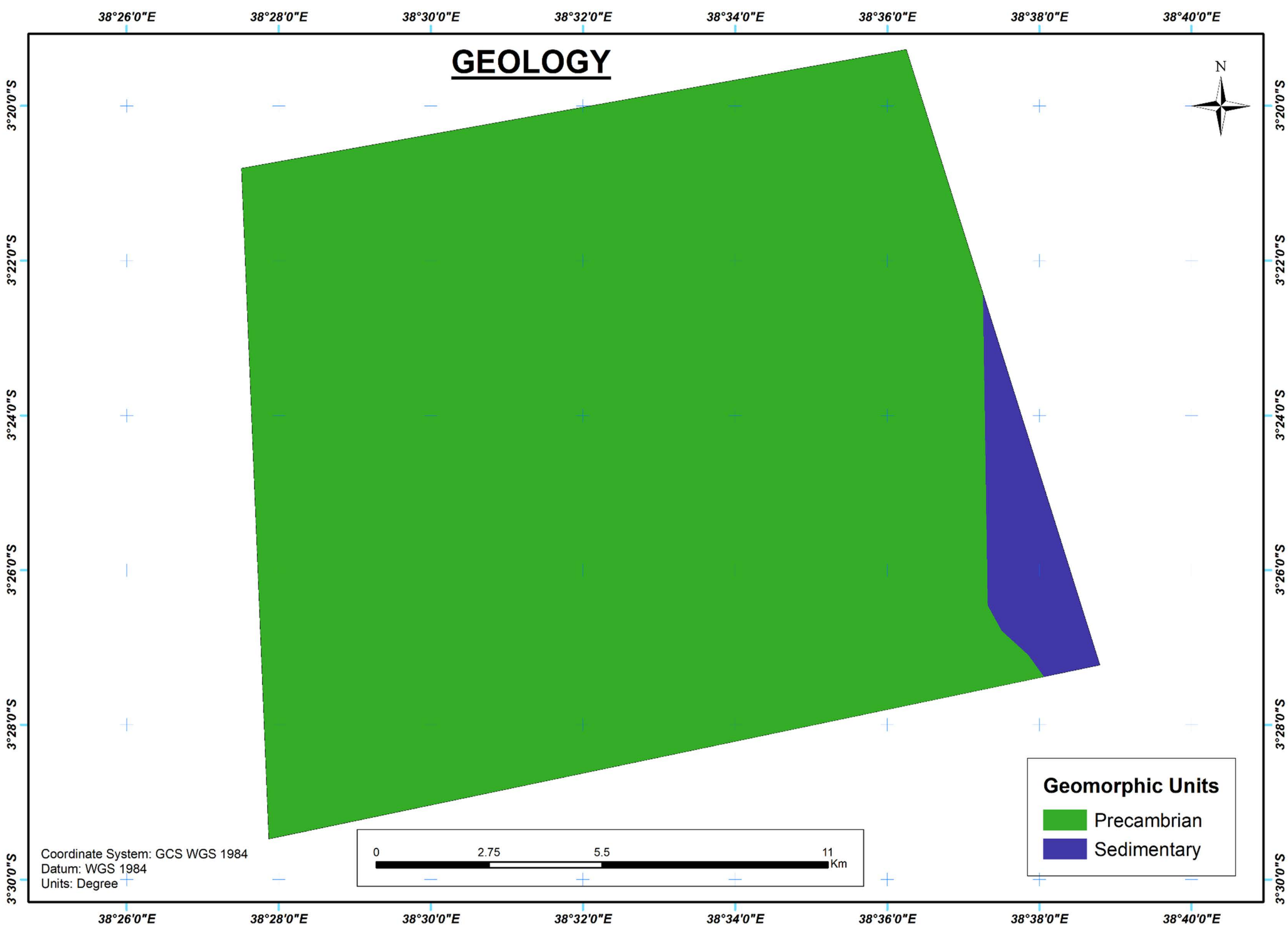

Figure 4. Geology.

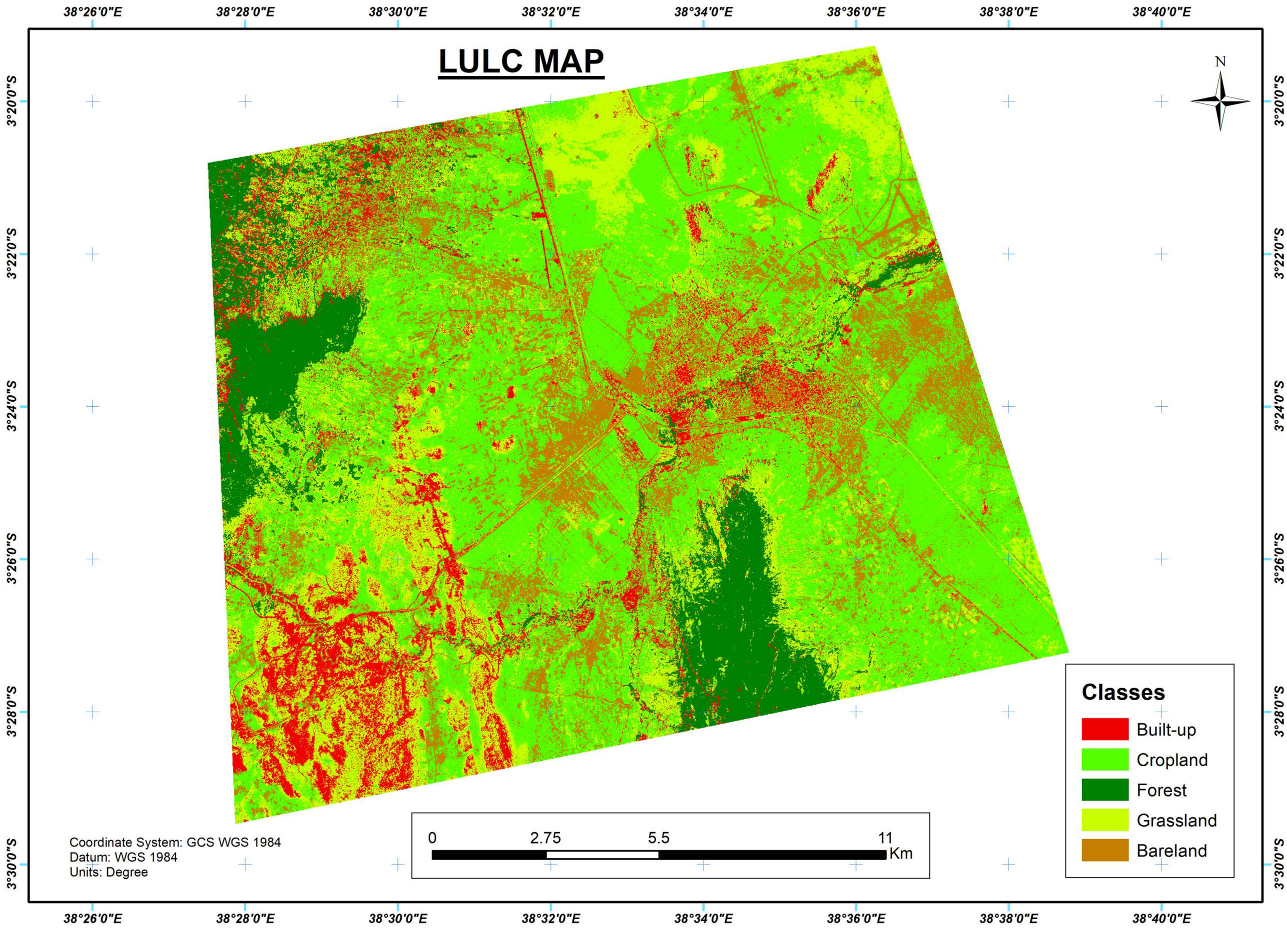

Figure 5. Land use land cover classes.

4.3. Lineaments Density

Lineaments are the linear features that show on the earth surface, which are the traces of subsurface structures. Lineaments are mainly related to faults but can also represent the presence of subsurface structures such as lithological boundaries, boundaries between different land use and drainage lines. Lineaments are also important in the case of a groundwater potential study because they may control the movement and storage of the groundwater. High percentage of lineaments indicates high chance for water prospects. The lineaments of town were obtained as shown in Figure 6. The lineaments density was very high on the western, southern and some parts of the eastern region which was an indication of many faults and sharp change in linear alignment. Water drains through the faults to the permeable rock hence they are suitable sites of groundwater potential.

4.4. Drainage

The drainage network in an urban area reflects the actual surficial condition of the watershed in which the urban area falls in. The drainage network consists of geomorphological features that were formed by the activity of flowing water over

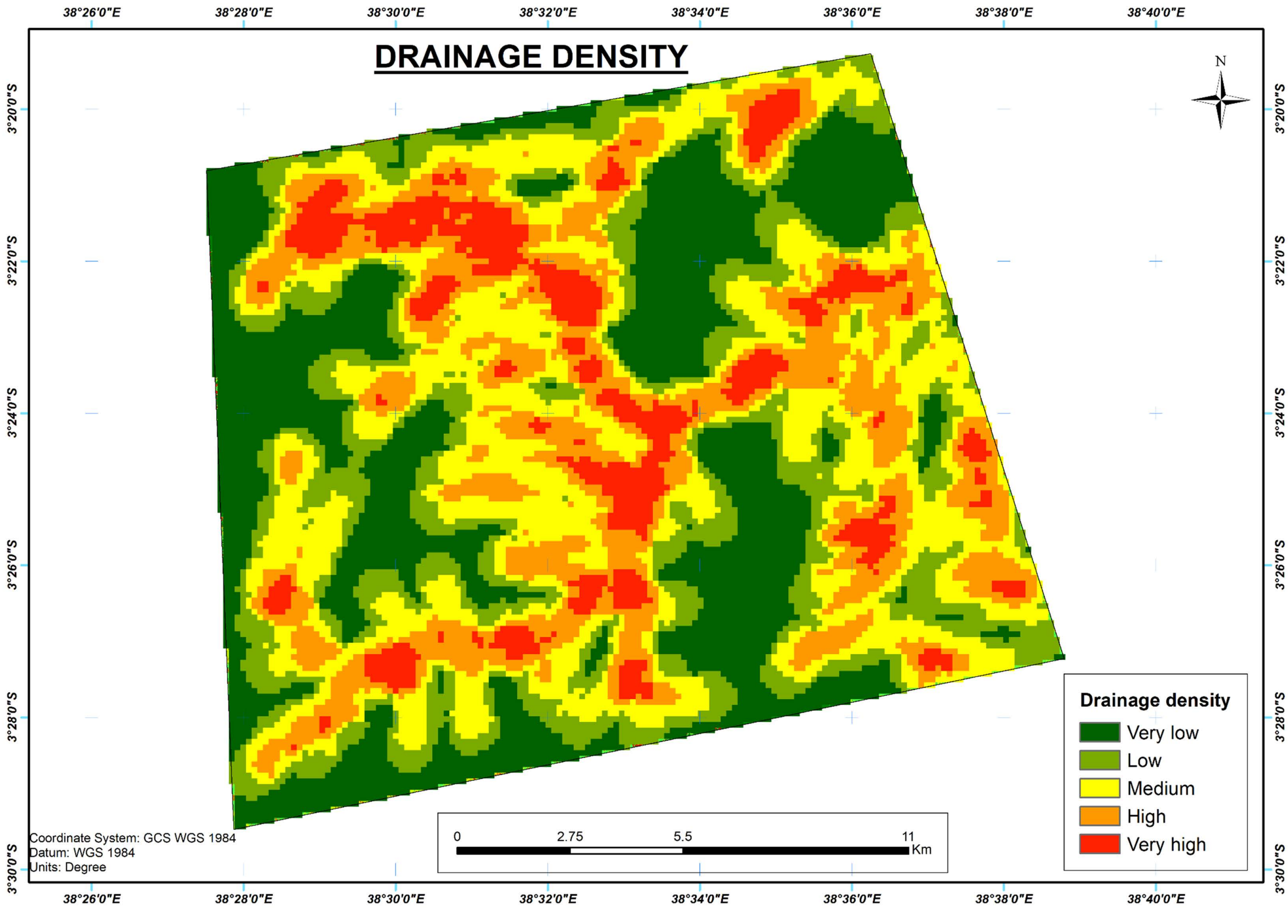

Figure 6. Lineament density.

a terrain. According to the conditions of terrain, it forms different patterns. Drainage density is one of the powerful factors that indicate the runoff and infiltration of a specific region. Drainage density is defined as the total length of the stream to the total drainage area. Low drainage density is an indicator of the presence of highly resistant or highly permeable rocks on the surface. High drainage density indicates more runoff than infiltration. In Figure 7, low drainage density areas were observed on the exterior periphery of the area since these areas are characterized with first order stream. High drainage density areas were seen on the north part towards the central part of the area. This was so because these areas have a high concentration of third and fourth order streams.

4.5. Slope

Slope determines the speed of water runoff. The degree of the slope determines whether the region is capable of holding water by infiltration or if it promotes runoff. When the degree of slope decreases, the possibility of runoff also decreases. The runoff rate increases with an increase in the slope amount. A rapid flow of water prevents infiltration into the soil. An increasing percentage of slope decreases the infiltration capacity of the soil and formation hence promoting run off. As shown in Figure 8, the area is generally steep with the majority of

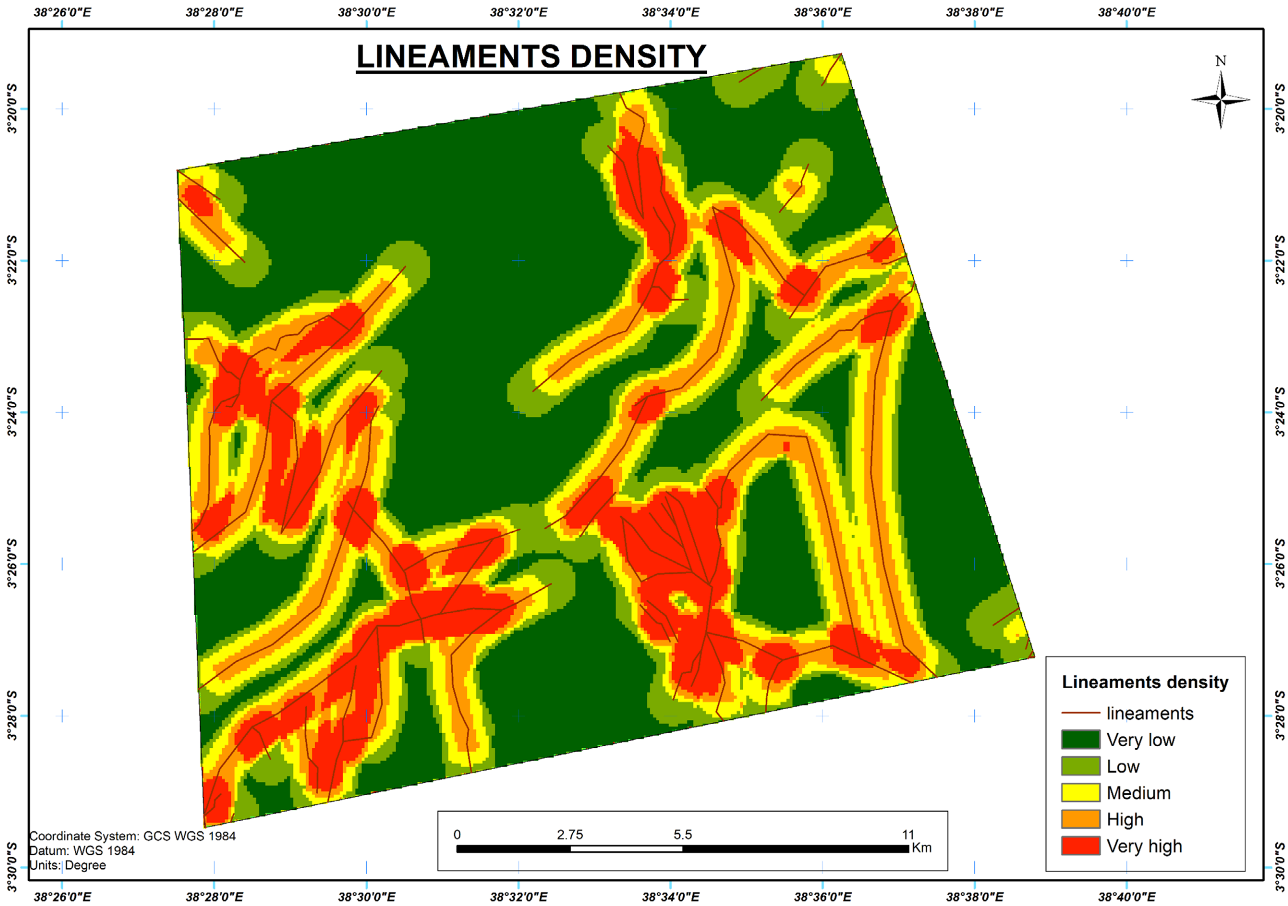

Figure 7. Drainage density.

the region having slope between 65% - 85%. Some areas on the west and south region are very steepy with slopes more than 85%.

4.6. Soil

Soil types are important to determine the groundwater potential of an urban area. Primary infiltration of water into the ground is controlled by the water conducting properties of the soil. Seven soil units comprising Cambisols, Ferrasols, Fluvisols, Luvisols, Lixisols, Leptosols and Vertisols are distributed across the area as shown in Figure 9. Cambisols are medium-textured and have a good structural stability, a high porosity, and good water holding capacity and good internal drainage hence have good infiltration capacity to recharge groundwater. On the other hand, leptosols are found in all climatic zones, particularly in eroded areas and are have low water holding capacity. Ferralsols and Luvisols had the highest coverage while the Vertisols had the lowest coverage. Ferralsols are deeply weathered and they have low water holding capacity and highly permeable.

4.7. Geomorphology

Geomorphology plays an essential role in the groundwater conditions of an area.

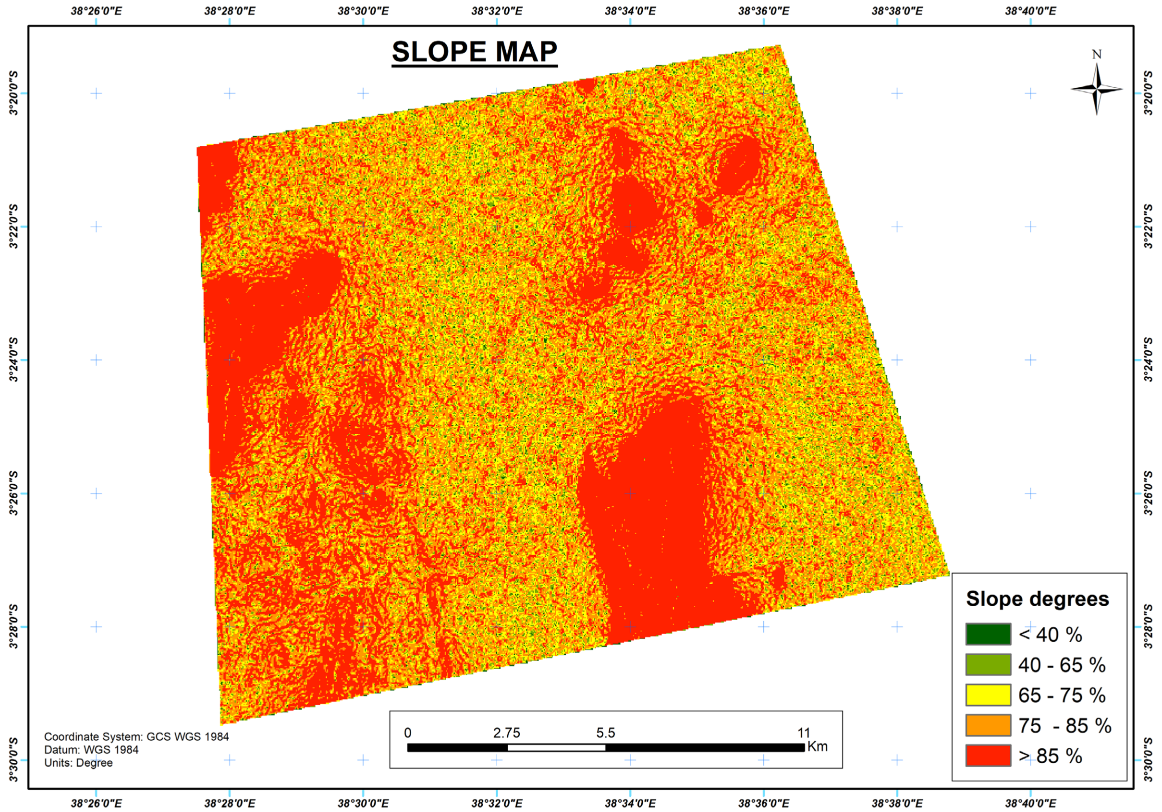

Figure 8. Slope map.

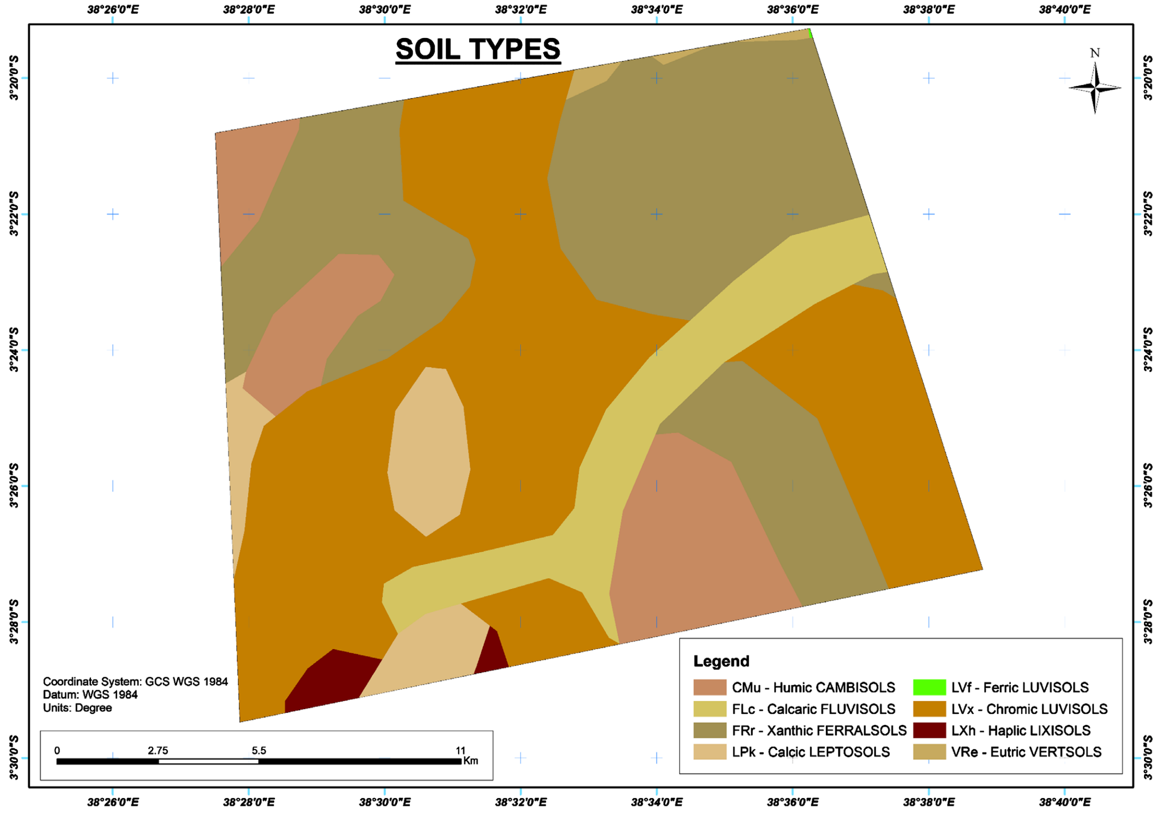

Figure 9. Soil types.

Geomorphological features of a given area controls not only the occurrence but the surficial distribution of a surface water as well as the groundwater conditions. Voi town consist of three geomorphological units as captured in Figure 10 below and they include: Alluvial plains, plains and hills and mountain footridges. The area is majorly covered by the plain.

4.8. Rainfall

An increase in rainfall pattern can directly influence the water table depth. The water level may decline if the rainfall is significantly less. Urban areas are characterized by surface run-off due to developed infrastructures that are more of paved surfaces which sometimes tends to translate to storm-water drains causing havoc in many cities. The annual rainfall in Voi town for ranged between 1228 mm to 1334 mm. Areas on the north west side received high rainfalls while those on the eastern side received low rainfalls as shown in Figure 11.

4.9. Groundwater Potential Zones

Figure 12 illustrates four categories of groundwater potential zones such as very low, low, potential and high potential. The area majorly has low to potential

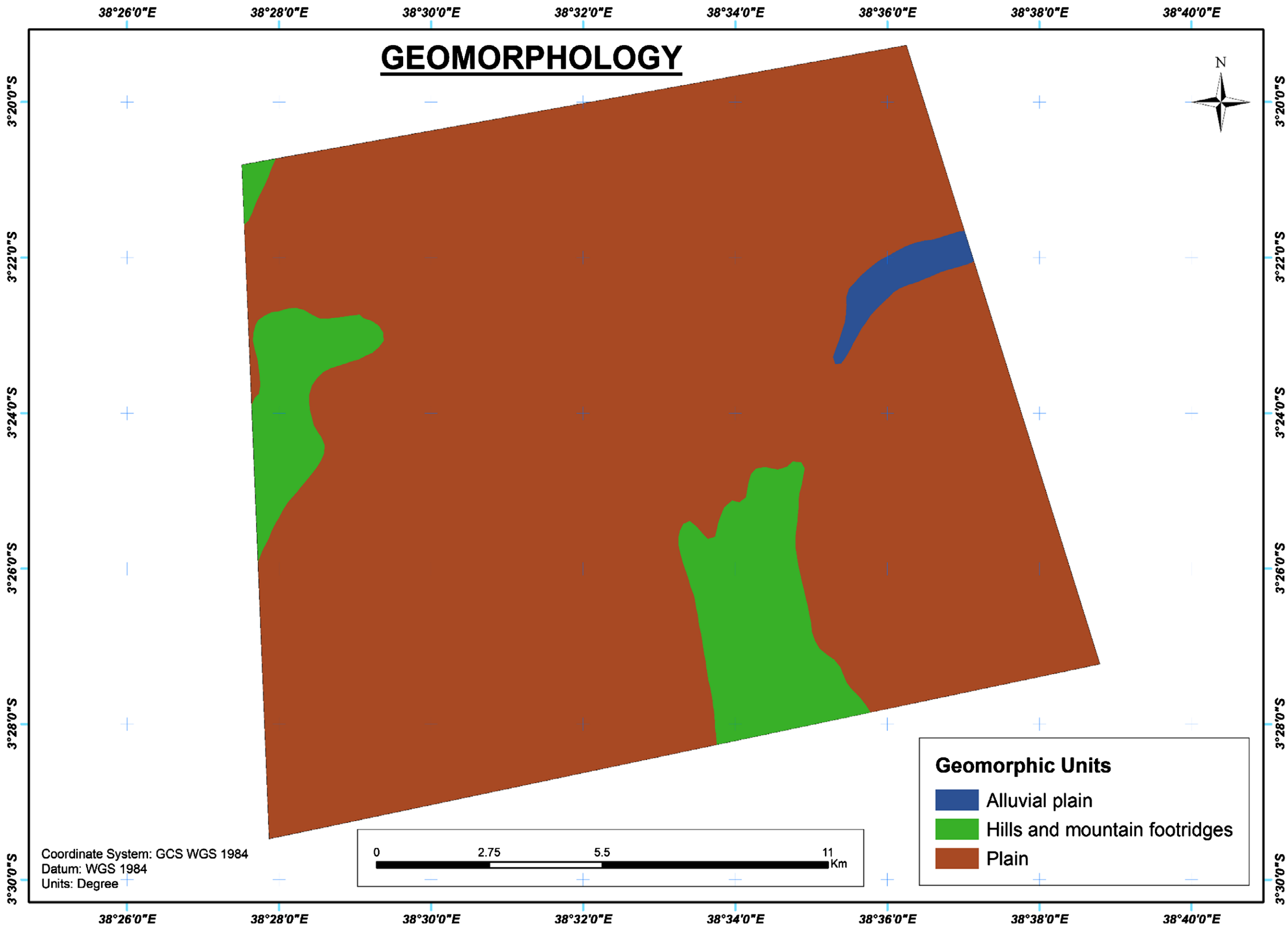

Figure 10. Geomorphology.

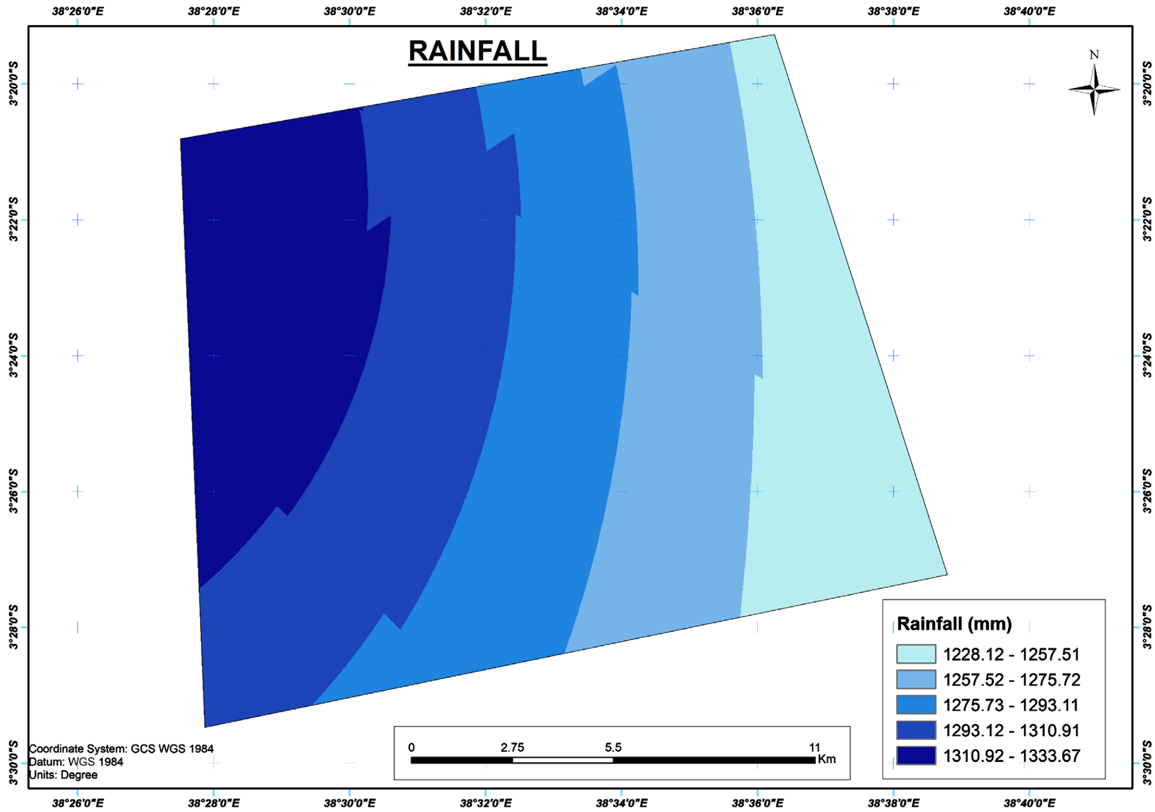

Figure 11. Annual rainfall.

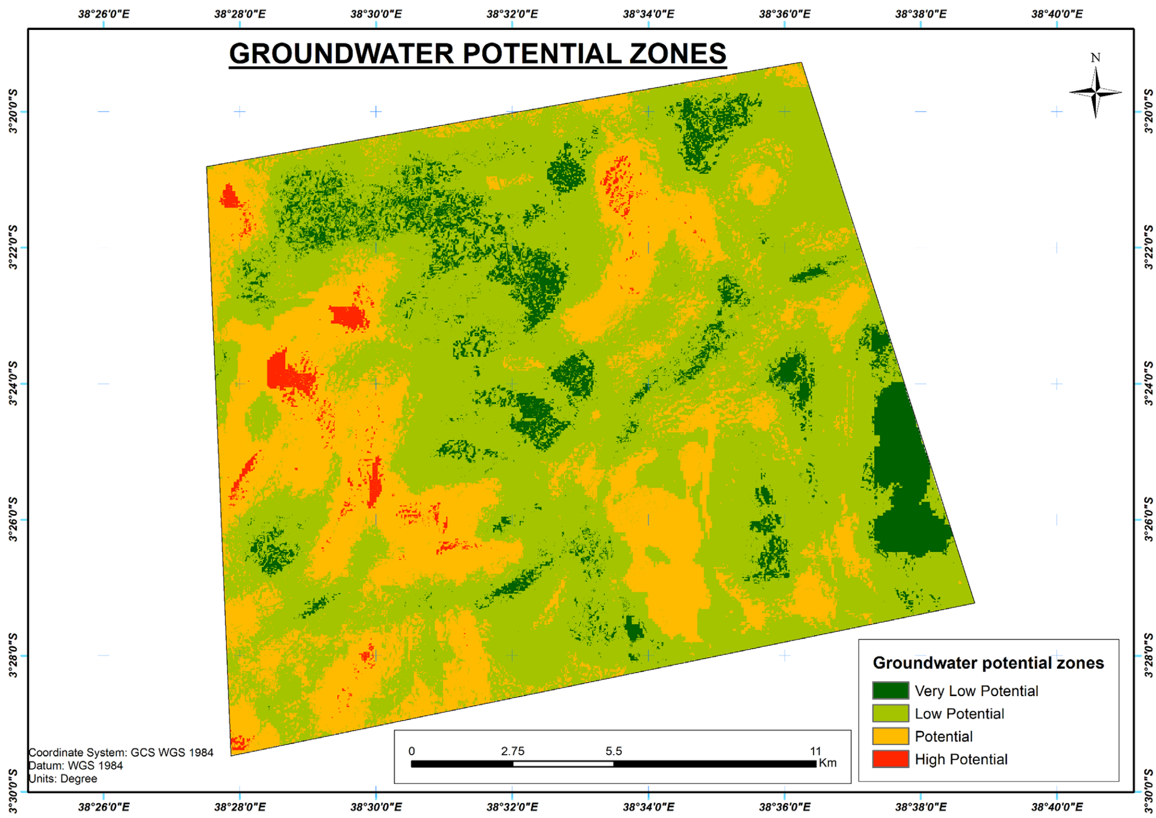

Figure 12. Groundwater potential zones.

zones of groundwater. High potential areas were very few and were mostly on the western side of the area. Very low potential zones were seen on the east and north side of the area.

5. Discussion

Groundwater potential zone is demarcated with the help of the thematic layers and assigned weight and rank. The high potential areas correspond with high percentage of lineaments, rainfall and low drainage density. Potential sites for productive water are usually located around lineaments features because, they are responsible for infiltration of surface runoff into subsurface and also for movement and storage of groundwater. Rainfall determines the amount of water that would be available to percolate into the ground thus high rainfall translates to a large volume of water percolating into the ground. Additionally, the areas consist of plain and include geological formations of Precambrian rocks. This area covers cultivated area, grassland and forest which has a positive impact on groundwater occurrence.

The potential zones had low drainage density values reflecting the relatively permeable surface strata and medium relief, hence more infiltration occurs. Also, this area had high lineament occurrence which significantly controls the permeability of the rock. Therefore, areas with high concentration of lineaments and high lineament density coincided with potential to high potential zones.

The very low and low potential zones were present in areas with low lineaments density, high drainage density and receives low rainfall. The drainage density is an inverse function of permeability, thus the less permeable a rock is, the less the infiltration of rainfall. These areas are covered with settlements, road network industrial areas and open land.

Voi town holds the potential to become water sufficient with a sustainable ground water system especially during this time of climate change impacts making the residents further vulnerable. From the results, Voi holds both potential and high potential zones, has a fast ground water recharge that gives the water good quality unlike that of Mombasa and a well laid land use land cover unlike Nairobi. This begs the question of why is Voi town not utilizing their ground water? The officer from TAVEVO answers this question by confirming that there is a knowledge gap in the field that could give reliable data on where exactly is suitable for setting up boreholes. Just like Voi town, many urban areas in Kenya are yet to utilize the use of GIS and remote sensing tools to fully explore urban water sources and curb the issue of insufficient water in urban homes.

6. Validation

The validation process was based on the borehole spatial distribution data. The ground truthing map was generated to show where the boreholes fell in the study area. The ground truthing was done to validate the results and seven existing boreholes in Voi town were selected that fall under our study area. Of the

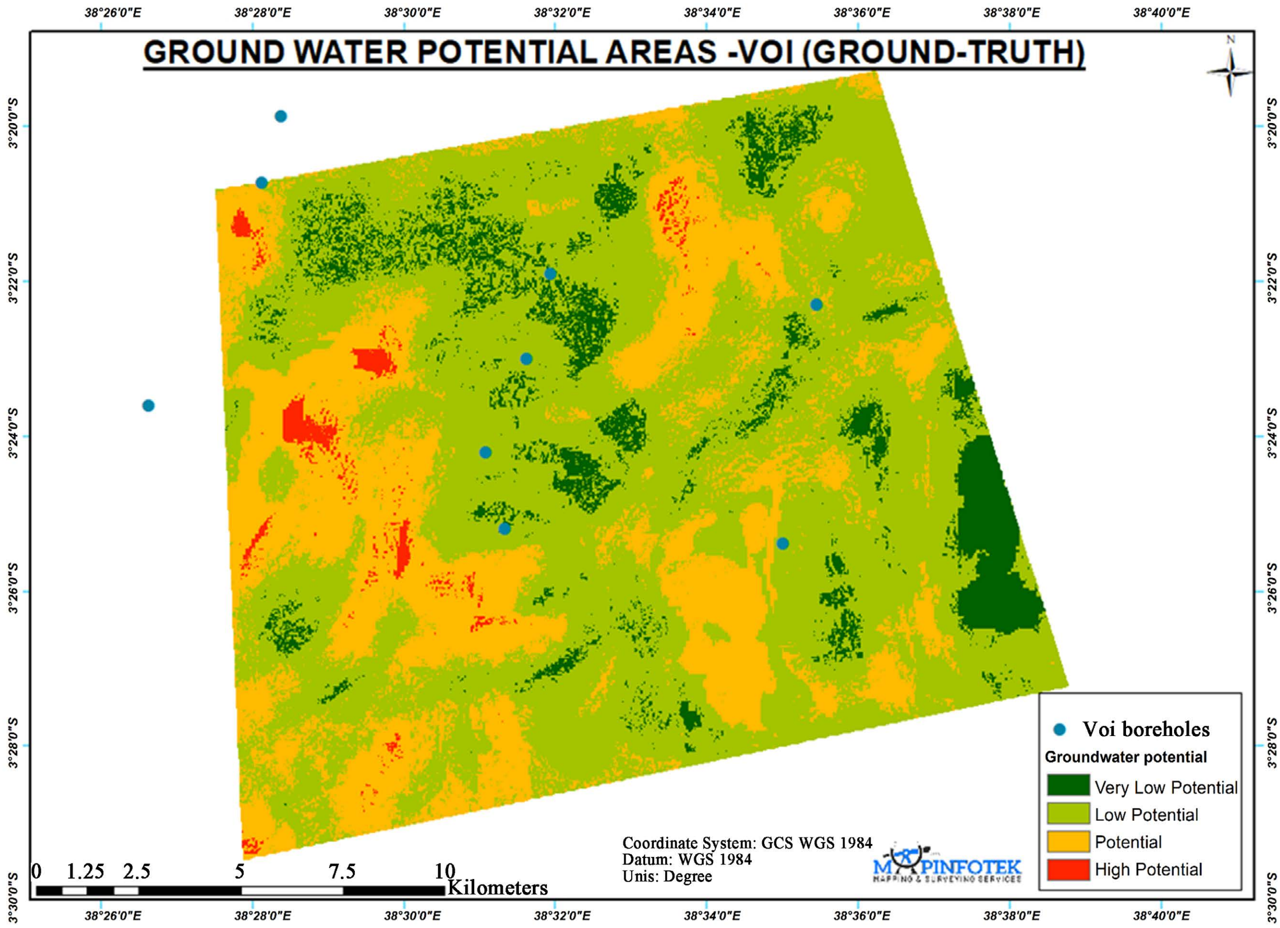

Figure 13. Ground truthing map.

seven, two lie in very low potential area, three lie in low potential area, 2 lie in potential areas and none lie in a high potential area as shown in Figure 13. Given that 7 is the total number of boreholes representing 100%.

Boreholes in potential areas are:

$$\frac{2}{7} * 100 = 28.57\% \tag{2}$$

Therefore, only 28.57% of boreholes in Voi town lie in potential ground water zones.

7. Conclusion

Geographic information systems (GIS) have become a useful and important tool in the field of hydrology to study and manage Earth's water resources. Climate change and greater demands on water resources require a more knowledgeable disposition of arguably one of our most vital resources—water. The rapid growth of urban area has two basic effects on groundwater resources such as: effects on natural recharge of aquifers due to sealing of ground with concrete and pollution of groundwater due to leakage from drainage and, industrial wastage and effluents. The increase in impervious or hard surfaces, including rooftops and pavement, decreases the amount of water that soaks into the ground, or infiltrates. This increases the amount of surface runoff. Pumping water out of the ground faster than it is replenished over the long-term cause similar problems. The volume of groundwater in storage is decreasing in many urban areas/cities all over the world in response to pumping. Groundwater depletion is primarily caused by sustained groundwater pumping. Nations, regions or continents should strive towards urban ground water sustainability which is the development and use of groundwater resources to meet current and future beneficial uses without causing unacceptable environmental or socioeconomic consequences.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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