An Integrated Approach of GIS and Remote Sensing Techniques to Groundwater Exploration in Zamfara, Northwest Nigeria

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Abstract
This study is concerned with the delineation of aquiferous zones for groundwater development across Zamfara State Northwestern, Nigeria. The study employed the integration of multi-criteria decision analysis (MCDA), remote sensing (RS) and geographical information system (GIS) techniques to delineate groundwater potential zones in crystalline basement terrain and sedimentary terrain of the study area and validation of the result with existing borehole/well yield data. The study approach involved integration of nine different thematic layers (geology, rainfall geomorphology, soil, drainage density, lineament density, land use, slope, and drainage proximity) based on weights assignment and normalization with respect to the relative contribution of the different themes to groundwater occurrence using Saaty's analytic hierarchy approach. Following the weigh normalization and ranking, the thematic maps were integrated using ArcGIS 10.4 software to generate the overall groundwater potential map for the study area. The result revealed that the study area can be categorized into four different groundwater potential zones: very high, high, moderate, and low. Great portion of the study area representing about 40 % of the total area, fall within the medium groundwater potential zone which are generally underlain by medium-porphyritic granite, biotite-hornblende granite, and granite gneiss bedrock settings. About 15 % fall under moderate to high groundwater potential zone which are characterized by weathered/fractured quartzite, quartz-schist, amphibolite schist and phyllite bedrock settings. However, areas of low to moderate groundwater potentials constitute only 25% of the total study area and are mostly underlain by migmatite, banded and augen gneiss bedrock settings. Though where there is significant weathered/fractured density including favourable slope shows high to very high within basement rock units which only occur in few localities of the study area. The entire sedimentary terrain of Gundumi formation constitute about 20%, shows high to very high groundwater potentials. Nonetheless, area where it revealed low to moderate potential are zone of high slope and contact with the basement rock units. Subsequent validation with boreholes/well yield data revealed a good correlation with respect to the observed groundwater potential zonation. The validation clearly highlights the efficacy of the integrated MCDA, RS and GIS methods employed in this study, as useful modern approach for proper groundwater resources evaluation, providing quick prospective guides for groundwater exploration and exploitation in both crystalline basement and sedimentary settings.

Key words: Remote sensing, geographical information system, multi-criteria decision analysis, Groundwater exploration, Zamfara State.

INTRODUCTION

In a semi-arid region like Zamfara State in Northwest Nigeria, surface water is not available throughout the year for various purposes. Due to meagre surface water resource, most of the requirements for irrigation, industry and domestic purposes are being met from groundwater. It is therefore essential to ensure the availability of groundwater throughout the year. Consequently, the readily available alternative option to the epileptic pipe-borne water supply from reservoirs and dams is the development of groundwater system in the form of dug wells and boreholes, especially in the crystalline basement terrains, where shallow groundwater systems can be tapped with minimal cost compared to costlier surface water development. Groundwater is a more dynamic renewable natural resource and plays important role in drinking, agricultural and industrial needs as a timely assured source compared with surface water; however, availability with good quality and quantity in appropriate time and space is also important (Rao, 2006; Chowdhury *et al.*, 2009).

Among the many methods available, remote sensing is one of the techniques that can be used for rapid assessment of natural resources; however, it requires validation by field work. With the advances and availability of satellite images, it is possible to indirectly identify the ground conditions through the surface and subsurface features such as topography, land use, drainage, geology, and geomorphology.

Many factors affect the occurrence and movement of groundwater in a region including topography, lithology, geological structures, depth of weathering, extent of fractures, primary porosity, secondary porosity, slope, drainage patterns, landform, land use/land cover, and climate (Mukherjee, 1996; Jaiswal *et al.*, 2003). On-site hydrogeology experiments and geophysics surveys help to explain the process of groundwater recharge and evaluate the spatial–temporal difference in the study region. However, these surveys often focus on a single affecting factor or an indirect site-specific experiment for groundwater recharge, reducing the reliability of the explanation. Recently, remote sensing has been increasingly employed to replace on-site exploration or experiments. Remote sensing not only provides a wide range scale of the space–time distribution of observations, but also saves time and money (Murthy, 2000; Leblanc *et al.,* 2003; Tweed *et al.,* 2007). Sener *et al*., 2005 pointed out that remote sensing can effectively identify the characteristics of the surface of the earth (such as lineaments and geology) and can also be used to examine groundwater recharge.

Consequently, integration of remote sensing (RS) and geographic information system (GIS) has proven to be efficient, rapid, and cost-effective technique producing valuable data on geology, geomorphology, lineaments, and slope as well as a systematic integration of these data for exploration and delineation of groundwater potentials zones (Prasad *et al*., 2008). Furthermore, such integrated RS-GIS approach enables manipulation of large data base for large areal extent covering, even inaccessible areas (Singh et al. 2013), thus providing a synoptic view of large areas (with associated hydrological information) for rapid and cost-effective assessment of groundwater occurrences.

In recent years, there have been wide applications of RS and GIS in hydrogeological research. Several workers such as (Edet *et al.*, 1997; Murthy, 2000); Obi Reddy *et al.,* 2000; Pratap *et al.*, 2000; Singh and Prakash 2002 and Jaiswal *et al.*, 2003) have used GIS to delineate groundwater potential zone, while Sreedevi *et al.,* (2001) also applied remote sensing techniques in the delineation of groundwater potential zones. Furthermore, many authors such as Krishnamurthy *et al.,* (1996), Murthy (2000), Srivastava and Bhattacharya (2006), Shahid *et al.*, (2000) and Khan and Maharana (2002) have applied both remote sensing techniques and GIS applications in groundwater exploration, delineation of groundwater potential zones as well as identification of artificial recharge sites. In addition, El-kadi *et al.*, (1994), Novaline *et al.*, (1999), Shahid *et al.*, (2000), Boutt *et al.*, (2001), Saraf *et al.*, (2004) Rokade *et al.*, (2007) and Gumma and Pavelic (2013) have carried out groundwater modelling using GIS. In addition, GIS has also been considered for multi-criteria analysis in resource evaluation, for example Saraf *et al.*, (2004) and Rao and Jugran 2003 have used GIS technology for processing and interpretation of groundwater quality data.

In the crystalline basement terrain of Zamfara-Northwest Nigeria which constitutes almost 90 percent of the entire study area, groundwater occurrences are largely limited to shallow weathered overburden units and degree of fracturing of the bedrocks.

These serve as the main sources of freshwater supply for domestic and industrial purposes, especially in the rural and sub-urban areas with no public/municipal water supply. In addition, it should be noted that since early 1990s, most of the major cities and urban centers are increasingly relying on groundwater system too, due to the failing public/municipal pipe borne-water supply systems.

This situation had resulted in a significant increase of indiscriminate exploitation of groundwater resources and random sitting of dug wells and boreholes leading to attendant high failure rate. Consequently, to forestall possible negative impacts of indiscriminate exploitation in terms of lowering of water level and groundwater quality deterioration, it is, therefore, necessary to have a proper understanding of the hydrogeological condition and groundwater potentiality in such basement terrain.

Therefore, the present study employed Analytic Hierarchy Approach (AHP) coupled with Multi Criteria Decision Analysis (MCDA), GIS, and RS techniques to integrate hydrogeological, geomorphologic as well as climatic data in respect of groundwater resources evaluation of the geological terrain of Zamfara. The intent is to delineate the groundwater potential zones of the study area and to develop a prospective guide map for groundwater exploration/exploitation to ensure optimum and sustainable management of this vital resource.

Study Area

This research covers the entire Zamfara State with total area coverage of 39,762Km^2, within NW Nigeria (Figure 1), with Latitude 7˚18′13.709″E to 10˚49′4.152″N and Longitude: 5^{0}1′27.638″E to 13^{0}10′45.537″N, (Figure 1).

Temperatures are generally extreme, with average daily minimum of 18°C, during cool months of January and December and in the hottest months of April to June, an average maximum of 38°C and minimum of 24°C. Throughout the year average maximum temperature is 36°C and average daily minimum is 21°C (Nigeria Meteorological Agency, 2020).

Rainfall is generally low; the average annual rainfall ranges from 600 to 1000mm across the entire State. Much of the rain, falls between the months of May to September, while the rainless months are October to April. Evaporation is high, ranging from 80mm in July to 210mm in April to May (Nigeria Meteorological Agency, 2020).

A monthly average evapo-transpiration range of about 140mm represent 30 of monthly average precipitation into the catchment (Nigeria Meteorological Agency, 2020).

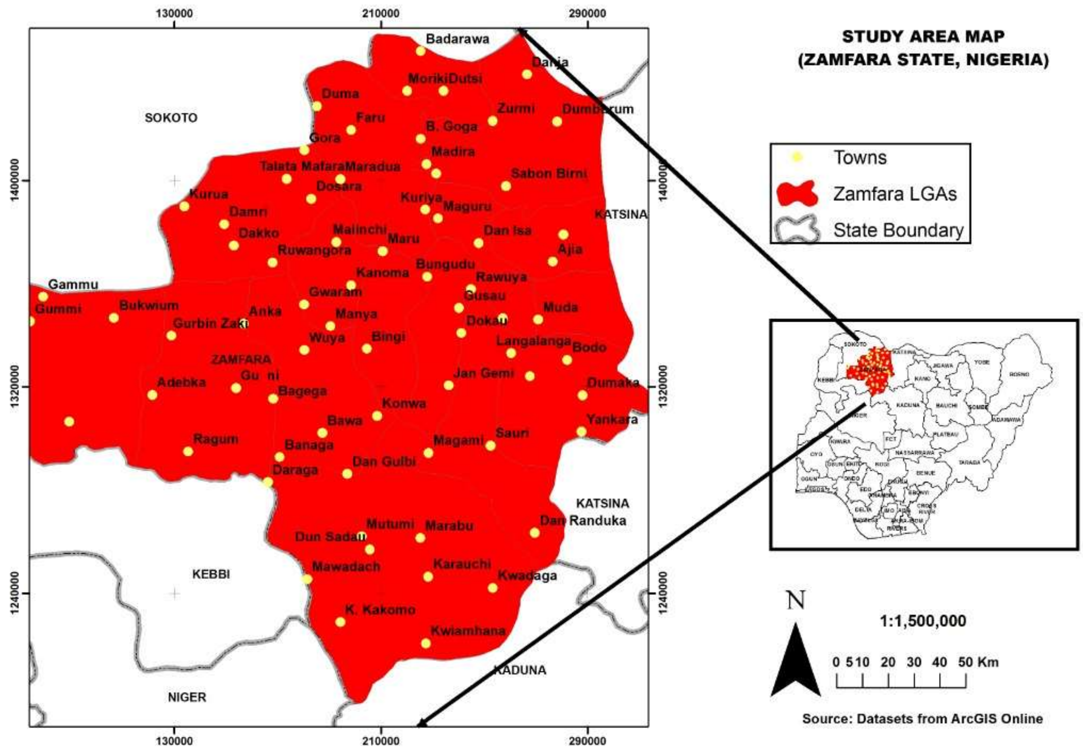

Figure 1: Map of the Study Area

Local Geological Setting of the Study Area

About 80% of the State is underlain by a variety of crystalline rocks of the basement complex of northwestern Nigeria described by McCurry (1976) to be composed largely of gneiss, schist, migmatite, granite and granodiorite (Figure 2). The structural features commonly exhibited by the basement rocks include foliation, lineation, folds, rock-rock contacts, faults, and joints. The rest of the state is occupied by the oldest sediments of the Sokoto (Iullemmeden) basin described by Oteze (1976) and Kogbe (1976). Groundwater in the basement rocks of the state can mainly be sourced from fractures and joints commonly (Yaya *et al*, 2001) and in the intergranular pores of fine to coarse (white or light grey) sand or gravel Oteze (1976) in the sedimentary areas.

The Gundumi formation consists of clays, sandstones, and pebble beds, thought to be lacustrine and fluviatile in origin (Figure 2). Its maximum thickness is reported to be up to 300m, near the Niger border. The base is marked by conglomeratic beds which are well preserved and exposed by the roadside at Tureta and Ruwan Kalgo (Kogbe, 1976). These basal beds contain rounded quartz cobbles and pebbles and attain a thickness of about 3m. The formation is the oldest sedimentary rocks in the Northern parts of the basin, lies uncomfortably on the Basement Complex. Other exposures of the Formation are found by Rivers Zamfara and Dutsin Dambo, near Bakura. The indication, from borehole sections, is that the basal conglomerates are overlain by beds which are more argillaceous from the bottom to the top (Anderson and Ogilbee, 1973).

From the work of Garba and Schoeneich, 2005, much of the groundwater is in Gundumi Formation of the sedimentary hydrogeological Province and only little or less are present in crystalline hydrogeological province, despite that the latter underlies as much as 80% of Zamfara State.

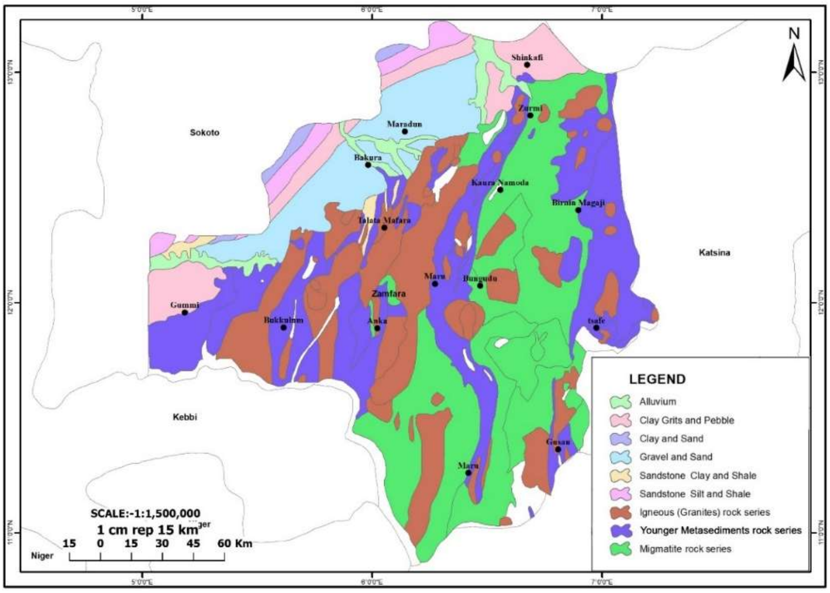

Figure 2: General Geological Map of Zamfara State, (Nigeria Geological Survey Agency, 2006).

MATERIAL AND METHODS

For the study, hydrogeological and relevant data on soils, geological/lithological units, structural features, geomorphologic and climatic conditions of the study area were collated. The overall study concept involved integration of nine thematic layers of conventional geology, soil, drainage and lineament maps, rainfall data as well as remotely sensed data of land-use, slope and geomorphology using both ArcGIS 10.4 and Envi GIS software. All the map themes were presented in UTM Projection Zone 31, Datum WGS84 with 12.5meter resolution.

Preparation of thematic layers

The analogue geological and lineament maps of the study area obtained from Nigeria Geological Survey Agency (NGSA) with scale 1:1,500,000 were georeferenced and digitized in ArcGIS 10.4 software platform. Lineaments are manifestation of linear features that can be identified directly on the rock units or from remote sensing data while lineaments and their intersections play a significant role in the occurrence and movement of groundwater resources in crystalline rocks (Rao 2006; Prasad et al. 2008). The presence of lineaments may act as a conduit for groundwater movement which results in increased secondary porosity and, therefore, can serve as groundwater potential zone (Obi Reddy et al. 2000). Lineament density map was computed in and expressed in terms of length of the lineament per unit area (km/km^2) in the GIS software. In addition, land use/land cover (LULC) plays important role in the occurrence and development of groundwater.

LULC map for the study was extracted from a mosaicked Landsat ETM imagery UTM 32N WGS 1984, of 25th October 2018 series through supervised classification of the false colour composite of bands 4, 3 and 2 to obtain the land use category in Envi software platform. Also soil zone generally has significant role on the amount of infiltrating water and hence influences groundwater recharge. The rate of infiltration largely depends on the grain size and related hydraulic characteristics of the soils. For this study, soil map of the study area was clipped from Soil Unit FAO/UNESCO/ISRIC map of Nigeria.

Geomorphology reflects various landform and topographical features. Surface water is one of the important geomorphological agents in the development and shaping of landscapes and landforms; thus, hydrogeomorphological studies are of importance in the planning and execution of groundwater exploration. Slope, on the other hand, is an aspect of geomorphologic features which controls the infiltration and recharge of groundwater system: thus, the nature of slope alongside other geomorphic features can give indication of groundwater prospect of an area.

Therefore, Digital Elevation Model (DEM) of the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) of 2010 at 12.5 m resolution were used to generate the geomorphology and slope thematic maps using assigned threshold values (Saraf and Choudhary 1998; Rao and Jugran, 2003; Prasad et al. 2008).

Generally, rainfall represents direct recharge source of groundwater in the study area while the development and exploitation of groundwater is through open dug wells and shallow boreholes. As mentioned earlier, groundwater occurs in the weathered zone under unconfined conditions as well as in the fractured zone. Satellite data of Mean annual rainfall data for 30 years were obtained from several stations and standardized with Nigerian Meteorological Agency (NIMET) stations located in the study area. The data were processed using the Thiessen polygon technique in the ArcGIS software platform to obtain the spatial rainfall pattern of the study area. Thiessen polygons define the individual 'regions of influence' around each of a set of points such that any location within polygon is nearer to that polygon's point than to any other point, and, therefore, has the same value (Heywood et al. 1998). This method is commonly used in the analysis of climatic data when the local observations are not available and so the data from the nearest weather stations are used.

Drainage pattern reflects the characteristic of surface as well as subsurface formation. Drainage map was obtained from DIVAGIS (http://www.diva-gis.org) and subsequently processed to obtain the drainage density map. Drainage density map delineation was followed by the division of study area into micro-watersheds (Singh et al. 2013).

Intersection of micro-watersheds and drainage layer was used for the calculation of drainage density for each of the micro-watershed expressed in terms of the length of channels per unit area (km/km^2) in the ArcGIS software platform. The drainage density values thus obtained were reclassified to prepare a drainage density map of the study area. Furthermore, water bodies are fewer in areal extent in the study area; thus, the buffered areas are considered more suitable zone for groundwater occurrence than areas beyond. Consequently, the drainage map was used to obtain the proximity to water bodies map using the buffering option of ArcGIS software.

After the preparation of all the different thematic maps (including rainfall, slope, drainage density, soil, land use, slope, geology, and lineament thematic maps) with varied attributes, the maps were converted into raster format and then assigned suitable weights in order of their hierarchy in groundwater potentiality using the analytic hierarchy process (AHP) (Saaty 1980, 1992). All the normalized weighted thematic layers were integrated and processed in ArcGIS 10.4 platform to demarcate the potential groundwater zones in the study area. The details of the procedures adopted for this study is summarized graphically as flow-chart in Figure 3 while further details on the AHP and weight assignments are highlighted in the following section.

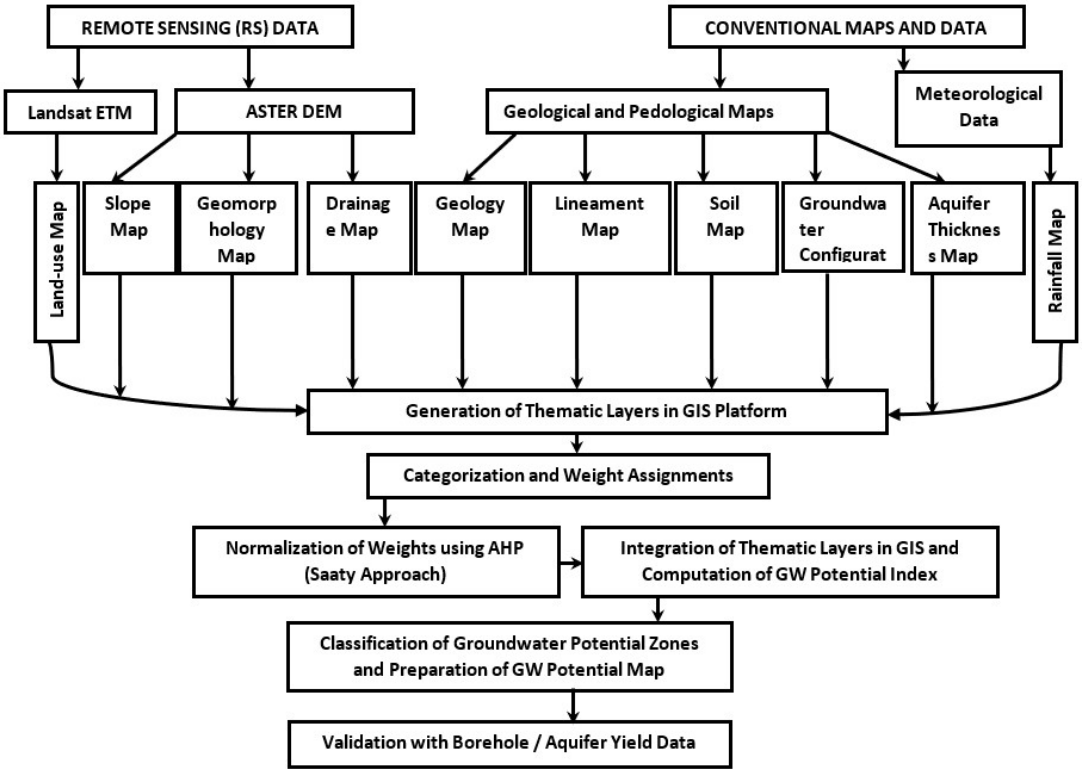

Figure 3: Flowchart for different inputs, outputs, and processes for this study area

Analytical Hierarchy Process, Weights Assignments, and Integration of Thematic Maps

The Analytic Hierarchy Approach (AHP) developed by Saaty (1980, 1986, 1992) was used in this study as a decision aiding method to finalize the weights assigned to different themes and their respective features used in deciphering groundwater potentiality. AHP is a simple mathematical matrix-based technique that allows users to assess the relative weight of multiple criteria in an intuitive manner. It allows efficient group decision-making, where group members can use their experience, values, and knowledge to breakdown a problem into a hierarchy and solve it by AHP steps (Chowdhury *et al.,* 2009). It also incorporates systematic checks on the consistency of judgments, which is one of the strongest points over the other multi-attribute value processes.

The attributes of each of the thematic maps employed in this study were assigned weightage of 1–4, depending on the relative contribution to the occurrence and movement of groundwater. In terms of groundwater potentiality, the weightage factor 1 denotes low/poor, 2 implies moderate, 3 represents good and 4 denotes high groundwater potentiality (Table). The weightage employed is in accordance with the respective importance of the map theme to groundwater occurrence following the approach of Saraf and Choudhary (1998), Rao and Jugran (2003), Prasad *et al*., (2008), Jha *et al.,* (2010), Machiwal *et al.,* (2011), Mukherjee *et al.,* (2012) and Singh *et al.*, (2013). The weights of the individual themes and their associated features were then normalized by the Saaty's AHP and the eigenvector technique was used to reduce the subjectivity associated with the assigned weights (Table 1). Further, the pair-wise comparison matrices of the assigned weights of the different thematic maps were constructed and computed (Table 2) using the Envi software.

Table 1: Saaty's Pairwise Comparison Scale

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two factors contribute equally
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one factor over another
4	Moderate Plus	
5	Strong Importance	Experience and Judgement strongly favour one factor over another
6	Strong Plus	
7	Very strong or Demonstrated Importance	One factor is favoured very strongly over another, its dominance demonstrated in practice
8	Very, very strong	
9	Extreme Importance	One factor has total dominance over the other

***Note**: If factor X is compared to factor Y, and factor X is assigned one of the numbers above (1-9), then factor Y will be assigned the reciprocal value of X (that is, 1 / (value for X).*

Table 2 : AHP Pairwise Comparison Matrix

Factor	**Geology**	**Rainfall**	**Lineament**	**Elevation**	**Soil**	**Slope**	**Drainage**	**Depth to Water Bearing**	**Aquifer Thickness**	**Land use**
Geology	1									
Rainfall	0.33	1								
Lineament	0.2	0.33	1							
Elevation	0.2	0.33	0.33	1						
Soil	0.33	0.33	0.33	0.33	1					
Slope	0.33	0.2	0.33	0.33	1	1				
Drainage	0.33	0.2	0.33	0.33	1	1	1			
Depth to Water Bearing	0.2	0.33	0.33	0.33	0.33	0.33	0.33	1		
Aquifer Thickness	0.25	0.33	0.33	0.2	0.33	0.33	0.33	0.33	1	
Land use	0.2	0.33	0.2	0.33	0.33	0.33	0.33	0.33	0.33	1
Sum of Factors Column =	3.38	6.38	11.18	13.85	15.99	17.99	17.99	24.66	28.33	32

***AHP Pairwise Comparison Normalized Matrix.** The normalization process involved dividing each of the record in **AHP Pairwise Comparison Matrix Table (Table 2)** by its corresponding column total.*

Furthermore, each of the thematic maps was then assigned weight in the range of 1–9 according to Saaty's scale of assignment (Table 1), which depicts the relative importance of the respective themes to groundwater availability. The weights assigned to the respective thematic maps as presented in table 3 indicate that geology was ranked the dominant factor with a normalized weight value of 0.26 while proximity to water bodies is the least accounted factor with a normalized weight of 0.0224 for groundwater occurrence in the study area. The summary of the assigned and normalized weights of the features of the different thematic layers alongside with ranking is presented in table 3 and 4. On the final analysis, nine different thematic maps were integrated using ArcGIS 10.0 software to generate the groundwater potential index (GWPI) for the study area. The index was computed by the integration of the total normalized weights of different polygons using equation stated below (equation 1). This technique is associated with the study of locations of geographic phenomena together with their spatial dimension and associated attributes (Prasad *et al.,* 2008).

$$GWPI = (GM_w\ GM_{wi} + GG_wGG_{wi} + LULC_wLULC_{wi} + DD_wDD_{wi} + SL_wSL_{wi} + DD_wDD_{wi} + SL_wSL_{wi} + LD_wLD_{wi} + ST_wST_{wi} + RF_wRF_{wi} + GCwGCwi + AT_wAT_{wi}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (1).$$

Where GG is the geology, GM is geomorphology, LULC is Land-use/land cover, DD is drainage density, SL is slope, LD is lineament density, ST is soil type, and RF is rainfall, GC is groundwater configuration, AT is aquifer thickness w is normalized weight of a theme and *wi* is the normalized weight of individual classes.

Thus, using raster calculator tools in ArcGIS platform, a composite groundwater potential index (GWPI) for the study area was generated based on which the overall groundwater potential map was produced using equation 1. Finally, well/borehole data (for example: yield, depths, and saturated thickness) were collated from existing wells in the study area. These data were used for the purpose of validation of the proposed groundwater potential map, as a useful guide for a quick assessment of groundwater occurrence on regional scale in the study area.

Table 3: Scaled values and weights assigned to different classes for different parameters

S/No	FACTORS	ATTRIBUTE	RANK	PRIORITY VECTOR	WEIGHT (%)
1	AQUIFER DEPTH	0-13.98	1	0.037	3.70%
		13.9-35.75	2		
		35.75-56.27	4		
		56.27-79.27	4		
2	RAINFALL	149.77-161.51	1	0.181	18.10%
		161.07-175.59	2		
		175.59-191.21	3		
		191.21-206.29	4		
3	SLOPE	0-0.35	4	0.068	6.80%
		0.35-0.65	3		
		0.65-1.43	2		
		1.43-4.80	1		
4	TOPOGRAPHY	241-354.7	4	0.113	11.30%
		375.7-434.2	4		
		434.2-526.1	2		
		526.1-754	1		
5	DRAINAGE DENSITY	0-4.57	5	0.067	6.70%
		4.57-11.44	4		
		11.44-18.93	2		
		18.93-38.92	1		
6	SOIL	Loamy Sand	2	0.07	7%
		Sand	4		
		Sandy Clay Loam	1		
		Sandy Loam	3		
7	GEOLOGY	Migmatite rock series	4	0.26	26%
		Schist Meta sediment and Quartzite	3		
		Igneous (Granites) rock series	2		
8	LINEAMENT	0-6.49	1	0.132	13.20%
		6.49-13.62	2		
		13.62-22.02	3		
		22.02-40.40	4		
9	LAND USE	Water bodies	4	0.027	2.70%
		Settlement	2		
		Bare land / Open space	3		
		Hill Rock Outcrop	1		
		Vegetation	4		

Table 4: Scaled values and weights assigned to different lithological units for Gundumi Formation

Categories	Criterion	Description	Groundwater Potentiality	Scale/Weight	Priority Vector	Weight (%)
Geology	Tuff with Sandstone	Coarse grained, high primary porosity and hydraulic conductivity	Very High	4	0.26	26%
	Gravel and Sand	High primary porosity and high hydraulic conductivity	Very High	4		
	Agglomerate with Sandstone	Moderate permeability with secondary/primary porosity	High	4		
	Sandstone silt and Shale	Moderately sorted, high primary porosity and interbeds limit groundwater movement	Moderate	3		
	Clays grits and Pebble	High primary porosity, coarse/fine particular with low hydraulic conductivity	Moderate	3		
	Alluvium	High primary porosity, coarse grained and hydraulic conductivity with shallow depth	Low	2		
	Clay and Sand	High primary porosity and low hydraulic conductivity	low	2		
	Sandstone clay and Shale	Moderately sorted with shallow depth and interbeds limit groundwater movement	Low	2		
	Shale	Moderate secondary porosity with very low hydraulic conductivity	Very low	1		

RESULTS AND DISCUSSION

All surface and subsurface factors that affect the occurrence of groundwater were acquired, processed, and analysed. The reclassified thematic maps of the nine (9) parameters which were incorporated in the AHP system are shown in figure 3.

Generally, two major hydrogeological Provinces were considered in this analysis (that is, sedimentary and basement hydrogeological provinces). They were analysed separately, and the result were later mosaic as shown in figure 15. Eighty percent (80%) of the study area is underlain by basement complex rock units which comprises of igneous and metamorphic rock units (migmatites, gneiss, schist, quartzites and granites, granodiorites, and diorite) and miscellaneous rock types, mostly post orogenic such as aplite, pegmatite and granite dykes as shown in figure 2.

Nonetheless, twenty percent (20%) of the study area is underlain by Gundumi formation (which are predominantly Alluvium, clay grits and pebbles, clay and sand, sandstone clay and shale, and sandstone silt intercalated with shale) as shown in figure 2.

Generally, massive unfractured lithological units in basement complex setting has little influence on groundwater availability except in cases with secondary porosity through the development of weathered overburden and fractured bed rock units, which form potential groundwater zones. Thus, based on the presence and nature of the regolith units and fracture units in the study area, weightage in terms of increasing groundwater potential was assigned (Table 3).

Whereas in sedimentary formation primary and secondary porosity of the various geologic material were considered for the assigning their weightage value (Table 3).

Lineaments and Lineament Density: Lineaments being a surface manifestation of structurally controlled features such as faults, fractures and rock contacts, their high density may present incipient highly connected fractures that are favourable for the accumulation of groundwater. Therefore, lineament analysis of the study area extracted from both the remotely sensed data and geological investigations gave important information on subsurface features that controls the movement and storage of groundwater (Figure 4).

Consequently, the lineament of the study area is consequent to several tectonic activities in the past. Two major prominent trending directions were identified which are NE-SW and N-S trends. Importantly, lineament density map is a measure of quantitative length of linear feature per unit area which can indirectly reveal the groundwater potentials as the presence of it normally denotes a groundwater permeable zone (Figure 5).

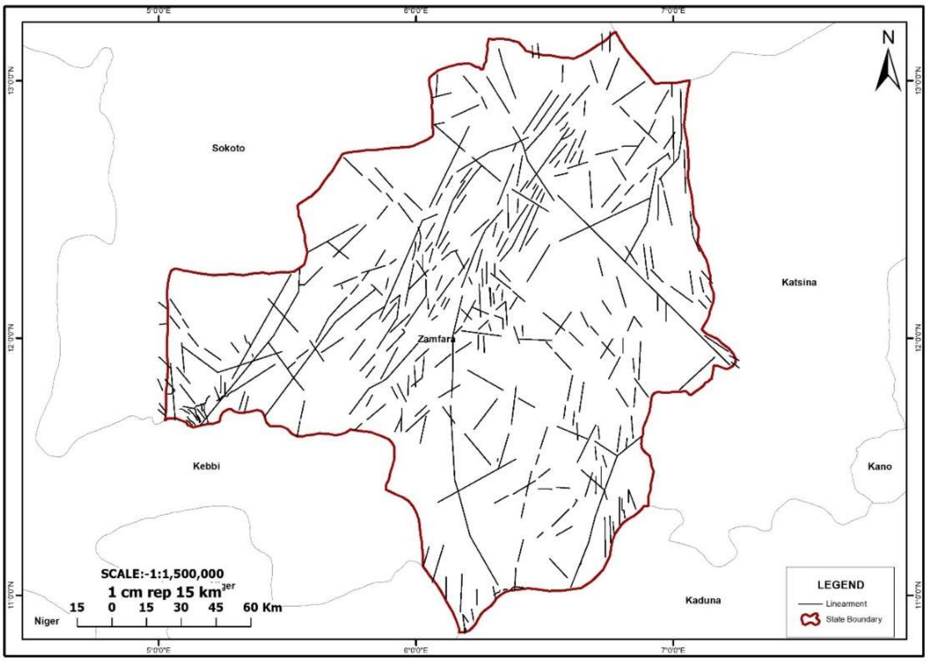

Figure 4: Lineament map of the study area

Though the lineaments are widespread across the study area, however, the distribution of lineaments suggests geologic control with area underlain by migmatites, gneiss and granites having relatively moderate lineament density compared with area underlain by metasediments. However, low lineament density dominates sedimentary environment with the study area. Thus, area with higher lineament density is regarded as good for groundwater development. Thus, weightage values were assigned based on the lineament density variation (Table 12), from one rock units to the other.

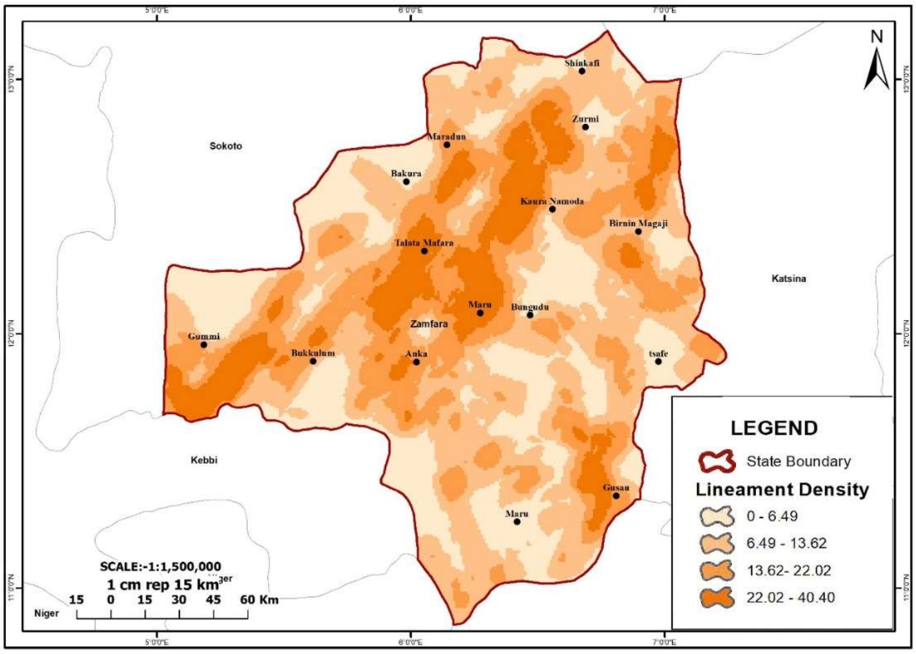

Figure 5: Lineament density map of the study area

Geomorphology: In this research, four main topographic units were identified and delineated with respect to their respective elevations from the remotely sensed imagery of the study area (Figure 6). It is an acceptable fact that groundwater flows from high elevation to the lower elevation, this shows that differences in landform elevation influence groundwater potential. In this study sedimentary formation form the lowland and plains including part basement terrain that are highly weathered.

On the other hand, ridges and inselbergs represent a chain of an undulated ridges and hills that form elevated crest within the study area. These geomorphological features based on the respective significance with respect to groundwater occurrence are weighted and classified as sown in table.

The classification revealed that the lowlands and plains are to the SW/NW parts of the study area. Thorough view of the figure 9 shows that the highest elevation is at the SE grading into moderate lowland to plain landform. Therefore, the entire study area portrayed a slated slope, making runoff potential to be much higher to that of infiltrating component of precipitation during wet season.

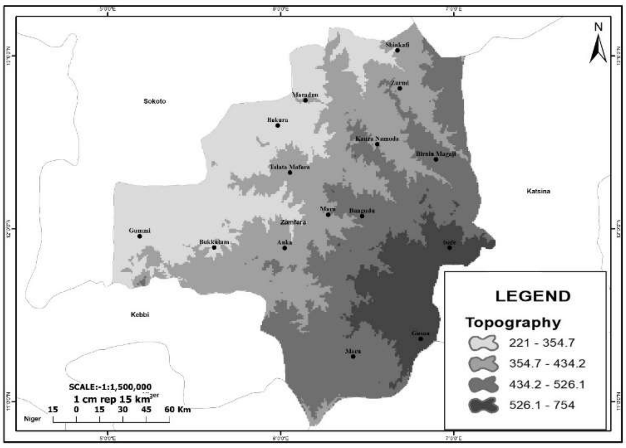

Figure 6: Geomorphological map of the study area

Slope: This is an essential component of geomorphologic features, slope is one of the factors controlling the infiltration and recharge of groundwater system, thus the nature of slope alongside other geomorphic features can give indication of groundwater prospect of an area. In the low slope area, the surface runoff is low allowing more time for infiltration of precipitation, while high slope area enhances high runoff with short residence time for infiltration and recharge. The slope thematic map is presented in figure 7, it revealed slope ranging from 0 – 1 and to extent of 1.43 -4.80 %, the wide range and distribution of the slopes in the study area indicate varied degree of runoff and recharge which imply varied groundwater potential characteristics of the crystalline basement setting.

Nonetheless, the sedimentary formation has low slope indicating high rate of recharge in those sedimentary rock units.

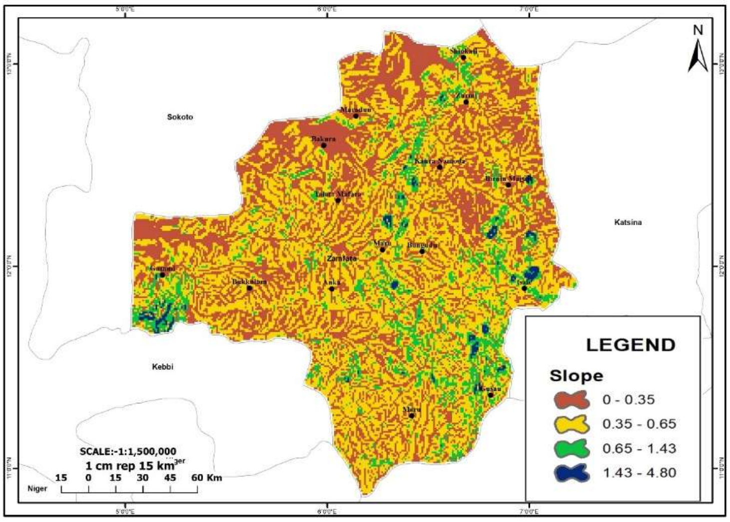

Figure 7: Slope map of the study area

Drainage and Drainage Density: Comparison of the drainage system of the study area and structures has shown that the drainage system of the area is structurally controlled following lineaments directions. Dendritic and parallel drainage pattern are recognized, which are indicative of the presence of structures that act as conduits or storage for sub-surface water (Figure 8). Structurally controlled drainage patterns of the study area are trending N-S and NW direction as it flows from eastern part towards the NW direction. Dendritic are formed on impervious rock whereas parallel drainage system forms a uniform gentle slope. Most of the drainage originate from the granitic hills and inselberg in the eastern part of study area.

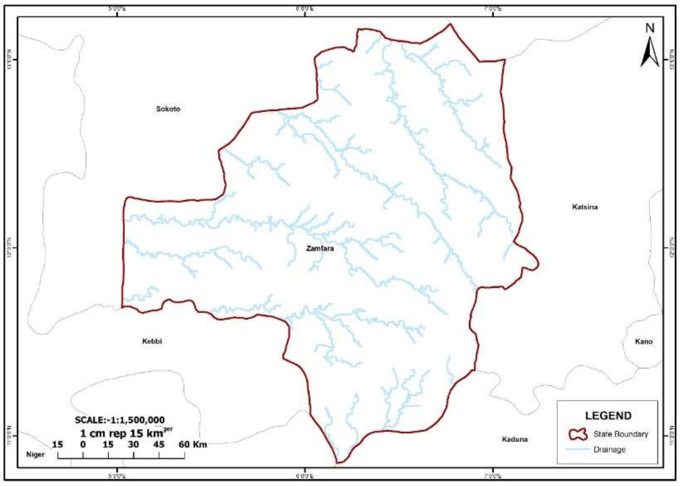

Figure 8: Drainage map of the study area

In the study area the drainage system tends to evenly distributed, the distribution is mainly attributed to the weak zones that are created due to faulting, shearing and geological contacts.

Weightage values were assigned because the area of very high drainage density represents more closeness of drainage channels and vice versa; hence, the higher the drainage density, the lower the runoff and the higher the probability of recharge or potential groundwater zone (Figure 9). More so, it has been suggested that a measure for permeability is drainage density (that is, total length of drainage channels per unit area), in the sense that permeability conditions are associated with low drainage density and vice versa (Meijerink, 2007). The study area is moderately dense drainage network.

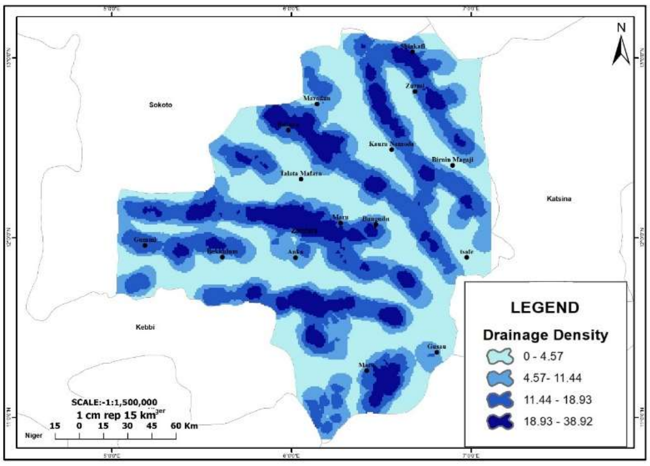

Figure 9: Drainage density map of the study area

Rainfall: The rainfall distribution in the study area is shown in figure 10. The entire study area receiving less than 1,000mm of rainfall annually, suggesting sudano-sahelian tropical terrain. Area with higher amount of rainfall have the highest weightage factor likewise the area with moderate or low rainfall amount were assigned respectively (Table 3).

Area underlain by sedimentary formation has the highest rainfall amount (western part up to NW of the study area) as shown in figure. However, extreme part of SE equally displayed high amount compared to other zones, though this area is underlain by basement rock units.

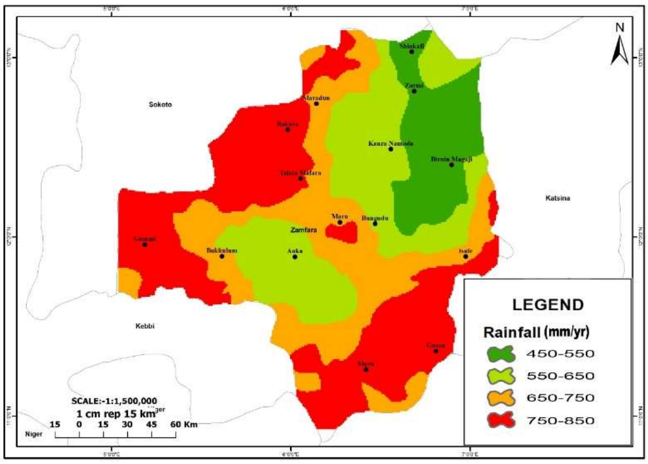

Figure 10: Rainfall map of the study area

Land use/Land cover (LULC): The land use/land cover play an important role in groundwater development of an area. In the study area LULC were classified into bare land/open space, hills (rock out crop), settlement, vegetation, and water body (Figure 11). Weightage values were assigned based on each item importance to groundwater potential as shown in table 3.

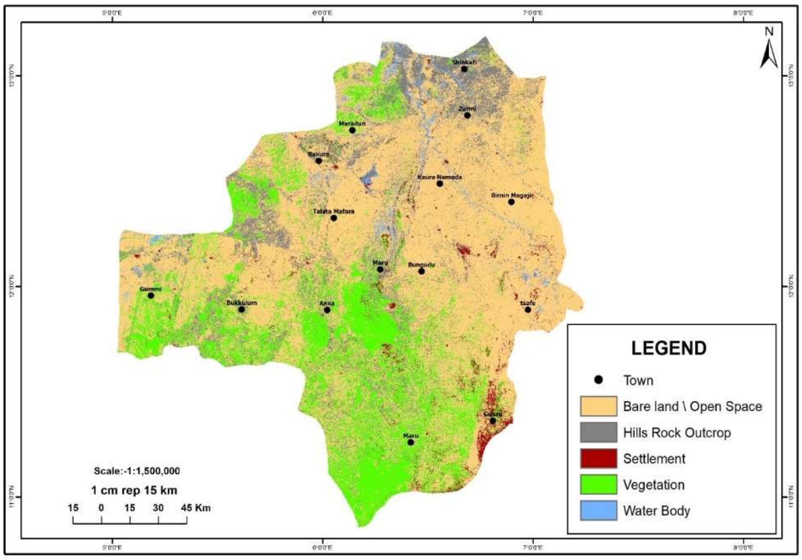

Figure 11: Land use/Land cover map of the study area

Soil Zones: Topsoil play a vital role in in degree of surface water infiltration. Fine grained soils limit infiltration due to apparently low permeability unlike coarse-grained soil materials where water can infiltrate easily because of high permeability. In this study four main soil zone were classified (loamy sand, sand, sandy clay loam and sandy loam) as shown in figure 12.

Given the relationship between the sand content/coarse-grained materials and permeability, higher weightage was given to soil with relatively higher permeability as shown in table 3.

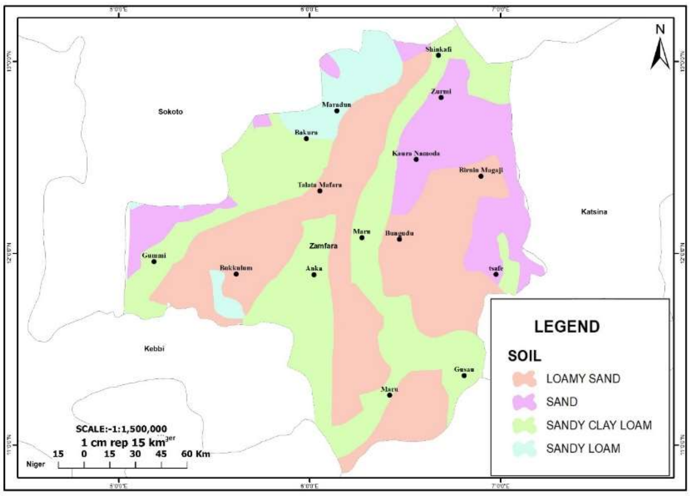

Figure 12: Soil map of the study area

Depth to Groundwater Bearing/Aquifer Thickness: These are major components of subsurface data or information input into AHP model. The depth to groundwater bearing revealed the potentiometric/piezometric surface of groundwater and its flow kinetic (Figure 16). This help determined the recharge and discharge zone respectively, based on this, analogues weightage value was assigned appropriately (that is, recharge zones were assigned the highest weightage value with respect to groundwater potential).

The depth to groundwater equally assists in deciphering the groundwater potential of area. As it revealed the aquifer thickness of the different geology formation. In this study weightage value were assigned since the deeper the aquifer the more possibility for its productivity (Figure 14).

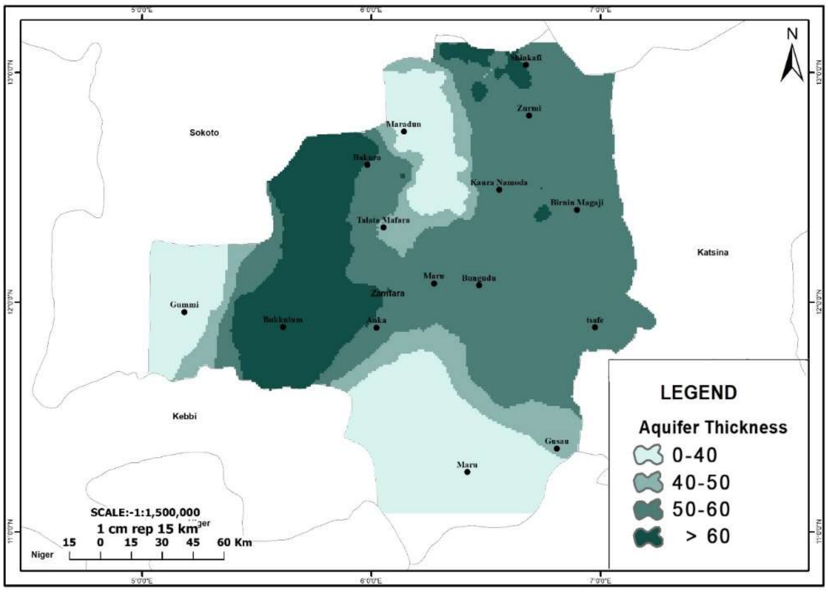

Figure 14: Aquifer Thickness of the Study Area

Characterization of Groundwater Potential Zone: The map produced from the integration of the nine thematic maps was reclassified and four categories of groundwater potential zones were produced as shown in figure 15. The general spatial distributions of the various groundwater potential zones obtained from the model shows regional patterns of lineaments, drainage, landform, lithology, and rainfall as well as the depth to groundwater in various geological media.

The potential groundwater zones of the study area revealed four distinct zones, namely, low medium, high and very high zones whose distribution extents are 6,378.90 km^2 (18%), 8,201.44 km^2 (24%), 9,235.39 (28%), and 10,724.96 km^2 (30%) respectively. However, each geological formation was considered separately during analysis. The basement complex rock underlain about 80% of the study area while the sedimentary formation underlain the remaining 20%.

Furthermore, spatial distributions of groundwater potential zone (that is low, medium, high, and very high zones) within the basement rock units are as follows: 5,250.10 km^2 (19%), 6,639.022 km^2 (24%), 17,333.48 km^2 (26%) and 8,472.39 km^2 (31%) respectively. However, the spatial distribution of groundwater potential zones within the sedimentary Hydrogeological province of the study area is order of low: 1,264.96km^2 (16%), medium: 1,609.17 km^2 (20%), high: 2,326.43 km^2 (30%) and very high: 2,715.64 km^2 (34%).

The groundwater potential map gives a quick assessment of the occurrence of the groundwater resources in the study area. The potential map revealed that the northeaster-southern part of the study area shows low to moderate potentials (this area is underlain by basement rock units). Though where there is significant weathered/fractured density including favourable slope shows high to very high which only occur in few localities of the study area.

The entire sedimentary terrain of Gundumi formation shows high to very high groundwater potentials. Nonetheless, area where it revealed low to moderate potential are zone of high slope and contact between the basement rock units.

Consequently, a thorough assessment of the groundwater potential map revealed that the distribution reflects the rainfall, lineament density, and depth to groundwater bearing, soil, aquifer thickness and geological control. The area underlain by schistose rock units due to presence of lineaments and apparently deep weathering exhibit very high groundwater potentials.

However, high slope percentage, inselberg, predominance of rock outcrops can be attributed to the observed low groundwater potentials in some certain studied area. Such area is spatially attributed mainly along ridges where slope class is very high, the lithology compact/massive and far from lineaments.

More so, drainage (surface flow), high rainfall, low slope percentages, primary porosity of the sedimentary rock units which can enhance infiltration of water into the groundwater system can be attributed to the observed high groundwater potential generally exhibited by sedimentary rock units (Gundumi formation) as shown in figure 15.

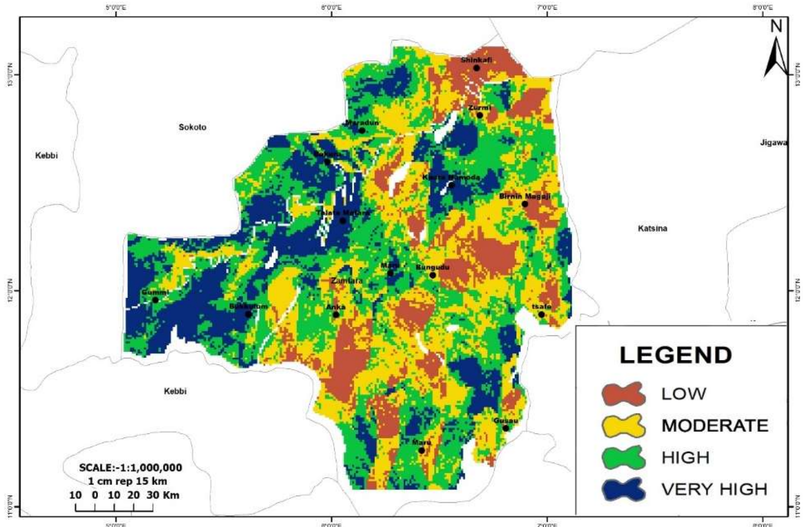

Figure 15: Groundwater Potential Map of the Study Area

Validation of the Groundwater Potential Model

The results obtained from GPM where validated based on the following field observations and measurements. Firstly, water level measurements in production wells that spread over the study area were used in constructing a groundwater level contour map using spatial analyst extension in ArcGIS (Figure 16). It can be seen from the map that the groundwater flows mainly toward the north-western part of the study area, though there are localize sink of groundwater recharge points. This is one of the reasons that made the western part of the study area has high potential for groundwater development.

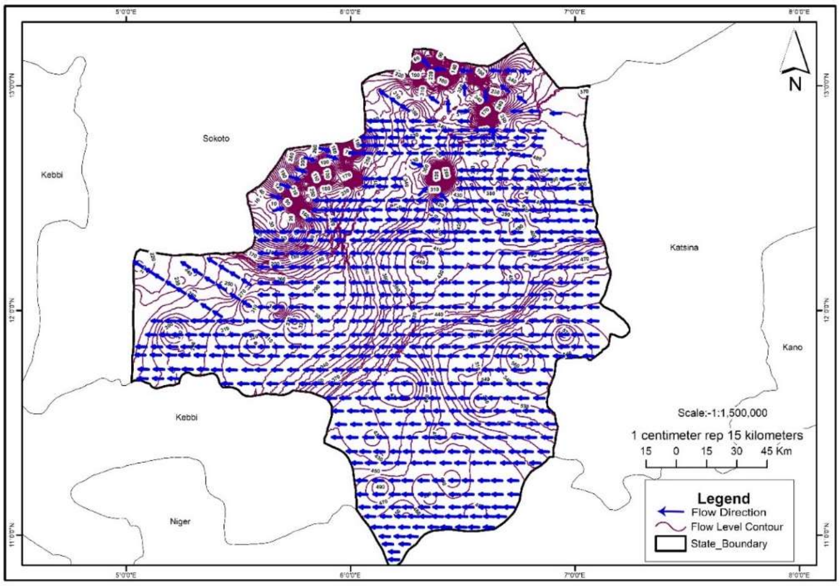

Figure 16: Groundwater Flow Pattern of the Study Area

Secondly, several production wells in the study area were tested for their yield. The average yield of production well is shown in table 4. It is very clear that aquifer capacity of the Gundumi formation has more, and excellent yield compared to the aquifers of basement environment. Though the variation in the yield within the Gundumi formation could be due its thickness along the dip/ strike of the varying lithologic framework.

Table 4: Yield (Aquifer Discharge M^3/day) of Various Rock Units

Rock Units	Minimum	Maximum	Mean
Gundumi Formation	34.56	345.6	116.84
Granites	19.86	259.2	50.5
Younger Meta-sedimentary Unit	17.28	138.24	45.12
Older Meta-sedimentary Unit	22.9	82.94	44.1

Well data were used to derive yield map using Kriging method in Geo-statistical Analyst extension in ArcGIS (Figure 17) shows that the higher yield wells are concentrated or very close to the area of high groundwater potential areas.

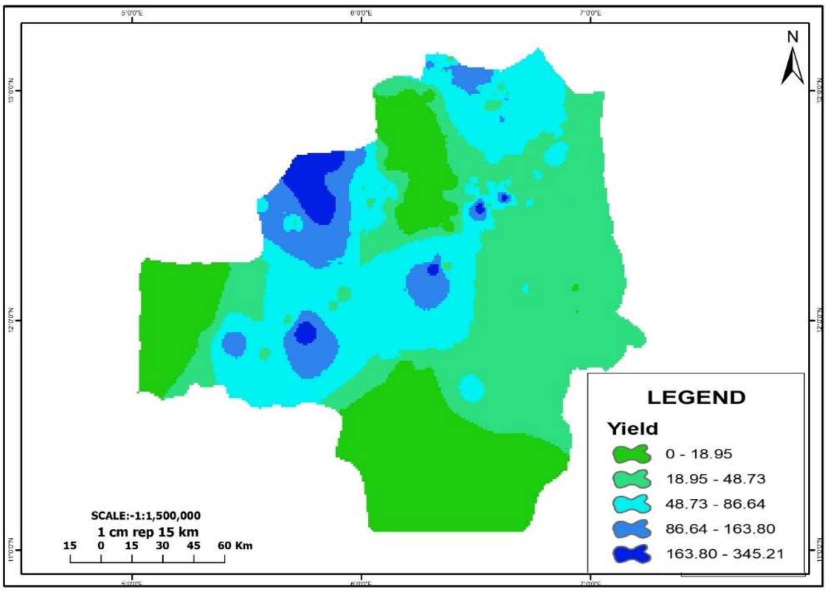

Figure 17: Geospatial Distributions of Yield of the Aquifers of the Study Area

CONCLUSIONS

The main objective of this study is to use remote sensing and GIS techniques for the assessment, evaluation, and analysis of spatial distribution of groundwater potential zone within the study area. Groundwater potential map (GPM) has been produced using nine thematic maps from satellite images, existing data, and field data. GPM were compared and validated by existing discharge data obtained from different production wells spread in the study area. The result showed a significant correlation or agreement with the discharge data and the higher yield wells are concentrated or very close to the areas of high groundwater potential *vis a vis*.

The analysis of this study has shown that there is large spatial variability of groundwater potential while the most promising potential zone is related to sedimentary rock unit of which is affected, by secondary structure and having interconnected pore spaces, with gentle slope and less drainage density, including the fact that the area underlain by this formation receives much of the baseflow from highland occupied by the basement rocks.

The overall potential map suggests the dominant influence of geology, lineaments, and geomorphological features in the delineation of the groundwater zone; the areas underlain by younger metasediments (quartzites, schists, phyllites) bedrock settings has moderate to high groundwater potential because of their degree of fracture density compared to areas underlain by migmatite, banded and augen gneissic and intrusive igneous rocks has low to moderate groundwater potential.

It can be concluded that parts of the area that characterized with surface expression of lineaments are considered hydrogeological insignificant due to high slope for those area. The low drainage density areas cause more infiltration and result in good groundwater potential zones as compared to high drainage density areas. High density indicates unfavourable site for groundwater occurrence especially in eastern part of the study area.

It must be noted that this research can be applied only for regional studies for the purpose of groundwater development, providing quick prospective guides for groundwater exploration.

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