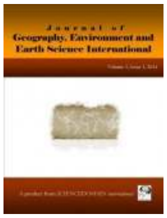

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Predictive Mapping for Groundwater within Sokoto Basin, North Western Nigeria

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Authors' contributions

This work was carried out in collaboration between both authors generally. Both authors EAK and WTA together designed the concept of this study. Author EAK managed aspect of the write-up that centres on literature review, geology/stratigraphy of the basin and the hydrogeology of the study area. Author WTA performed aspects on the GIS analysis and interpretations. Both authors read and approved the final manuscript.

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ABSTRACT

Scarcity of water within and around Northern Nigeria is no longer a wieldy issue. There is an over reliance on groundwater, and this has led to an increase in the number of bore-holes drilled in order to augment the water needs within the study area. Unfortunately the failure of many installed bore-holes has been rampant in this area. This is due to absence of or improper groundwater investigation and interpretation of site suitability. In this study, a remote sensing approach was employed to delineate and classify groundwater potentials of the Sokoto basin. GIS-based groundwater potential map of Sokoto Basin was modelled by producing and subsequently combining thematic maps. The data set includes; drainage, lineament, soil, lithology, elevation, slope and rainfall. Thematic maps of each data set were produced as distinct layers first before combining them together. For each layer, weighting for different classes was performed. The ground water potential map was then reclassified into five classes; very good, good, moderate to good, moderate and poor class. Results from the maps produced show that areas mapped indicating zones of very-good groundwater potential covers approximately 2.2% (1432.66 km^2);

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zones mapped indicating good groundwater potential covers approximately 7.79% (5071.5237 km^2); zones mapped indicating moderate to good groundwater potential covers approximately 27.5% (17577.8 Km^2); zones mapped indicating moderate groundwater potential covers approximate 49.2% (32030.676 km^2) and zones mapped indicating poor groundwater potential covers approximately 13.1% (8528.493 Km^2) of the study area. The study further revealed that the southern part of the study area has a better water potential than the northern part of the study area. There is a close agreement between the groundwater potential map produced and field pump test data obtained previously within the Sokoto Basin according by previous authors.

Keywords: Remote-sensing; Sokoto Basin; formation; groundwater potential; thematic map; weighting.

1. INTRODUCTION

Water is one of the most important natural resources for the sustenance of life on earth [1], [2], next to air. It is known that the largest available source of fresh-water for use occur underground [3]. However, water scarcity issues within and around northern Nigeria is no longer a wieldy issue. It may partly be attributed to the amount of average annual rainfall of about 72624.03 mm [4] in the area, as compared with the rain-forest regions of about 3000 mm/a [5]. The implication of this is that there will be less recharge to aquifers within and around the area compared to the southern part of the country. Furthermore, the occurrence of groundwater could also be influenced by other factors such as; geology which includes the lithology/rock type and structural lineaments, soil, vegetation, drainage, elevation/topography, annual rainfall, slope and so on. These all put together gives an insight to the hydrogeological condition of an area.

Groundwater according to [6,7,8], is a more dynamic, renewable natural resource that is useful for drinking, agricultural and industrial needs. Agriculture (both rain-fed and irrigation farming especially during the dry season) is a major occupation and the main water consumer in the Sokoto Basin, aside other domestic uses. Owing to the peculiar nature of the area, most streams and rivers dry up during the dry season and to sustain the irrigated agriculture there is need to rely on groundwater sources.

Often times, the lack of potable surface-water have resulted to a high dependence on reliable fresh groundwater. Also, there is an ever increasing number of bore-holes drilled in search for groundwater to meet the various demands for its use within and around the basin. But the major challenge here is that these hydraulic structures have not been able to meet the purpose for which they were designed and constructed. Most of the boreholes drilled are no longer in use because they had “failed” and were not able to meet with the purpose for which they were constructed. One obvious reason for this, is that these bore-holes were not located in areas with good water potential arising from the absence of, or even poor ground investigations before the drilling.

Several methods such as geological, hydrogeological, geophysical and remote sensing techniques have been used for investigating, delineating and interpreting site suitability before a borehole can be drilled. Unfortunately, some of these techniques tends to be rather too expensive and cannot be carried out easily. Thus, advancement in space technology however, has helped to develop an approach for groundwater studies that may accommodate large scale water projects with a high degree of effectiveness. Integration of remote sensing data and geographic information system (GIS) have been used to study groundwater prospectivity to delineate groundwater potential zones, by analyzing phenomena related to land and water resources [9,1,10,11,12]. Application of remote sensing to groundwater potential evaluation provides a new, innovative and cost effective method for evaluating ground water potential [13]. This method is further enhanced by its accuracy and time efficiency. The reliability of this method largely depends on accuracy of the data sets used.

This study aims to produce a groundwater map for the Sokoto Basin by identifying and classifying zones according to their potential in-terms of the resource. The objectives is to produce thematic maps using remote sensing and GIS from satellite imageries and existing maps, and to prove the effectiveness of geo-processing techniques to predict and delineate zones groundwater occurrence. Lastly, the accuracy of the remote sensing techniques with GIS employed in the study will be compared to result of pumping test data obtained from previous studies within the study area.

1.1 Location and Geology of the Study Area

Sokoto Basin is located within north-western Nigeria, of the West African Sub-region. It forms part of the southern interior sag Illummeden Basin, where the only younger parts of the stratigraphic succession are found [14]. The study area lies within latitude 3° E to 7° E and longitude 10° N to 14° N, within the Sahel region of Africa. According to [15], the average maximum temperature is 36℃, daily average is 21℃ and rainfall in the area is about 72624.03 mm [4]. There two (2) distinct season – dry and wet season. The wet season lasts from June to October.

The lithostratigraphic succession of the study area is presented in Fig. 1. According to [14], sediments of the Sokoto Basin are Cretaceous to Paleocene in age. The Cretaceous sediments in the Sokoto Basin essentially consists of two parts: a lower clastic succession representing the "Continental Intercalaire" of Late Jurrassic to Early Cretaceous age, and the Rima Group, representing a (Mid to Late) Maastrichian transgressive-regressive circle. The Paleocene Sokoto Group, represents a further transgressive-regressive circle, and it lies above, with Gwandu Formation, representing the "Continental Terminal" [16], comprising the youngest sediment except for superficial deposits and laterites.

The Illo Formation consists primarily of cross-bedded grits containing lenses of clay, ironstone horizons and pebbly sands while in places, a basal quartz-pebble conglomerate is present. At the base, Gundumi Formation is conglomeratic and mainly comprises of massive and cross-bedded, feldspathic clay-rich grits, clays and pebbly sands. [17,18,19] all reported that the Gundumi and Illo Formations are of fluviatile to lacustrine origin. An unconformity representing the greater part of Late Cretaceous time separates the Illo and Gundumi Formations from the Rima Group [17]. The Rima Group was deposited during the only Cretaceous transgressive events which affected the Sokoto Basin [14]. It comprises three formations [20], [21,18,19,22,23], from top to bottom. The Taloka Formation consists of friable fine-grained sandstones and siltstones with shales, carbonaceous mudstones and lignitic horizons. Dukamaje Formation which is the lower part is mainly made up of shales, its middle part consists of marls, yellow clays and shales, while the upper portion again comprises shales [17,22,18,14]. Lastly, the Wurno Formation consists of friable fine-grained sandstones with intercalated siltstones and mudstones.

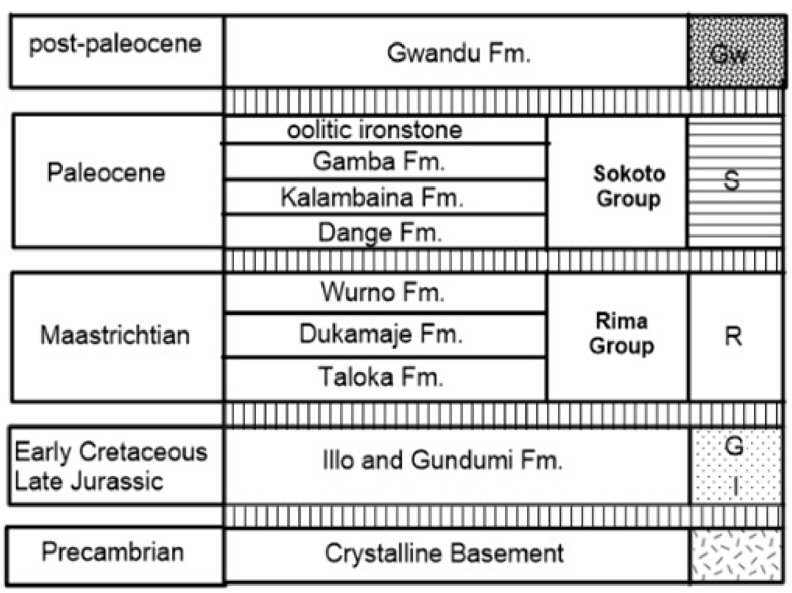

Fig. 1. Lithostratigraphical subdivisions of the Sokoto Basin (modified after [19])

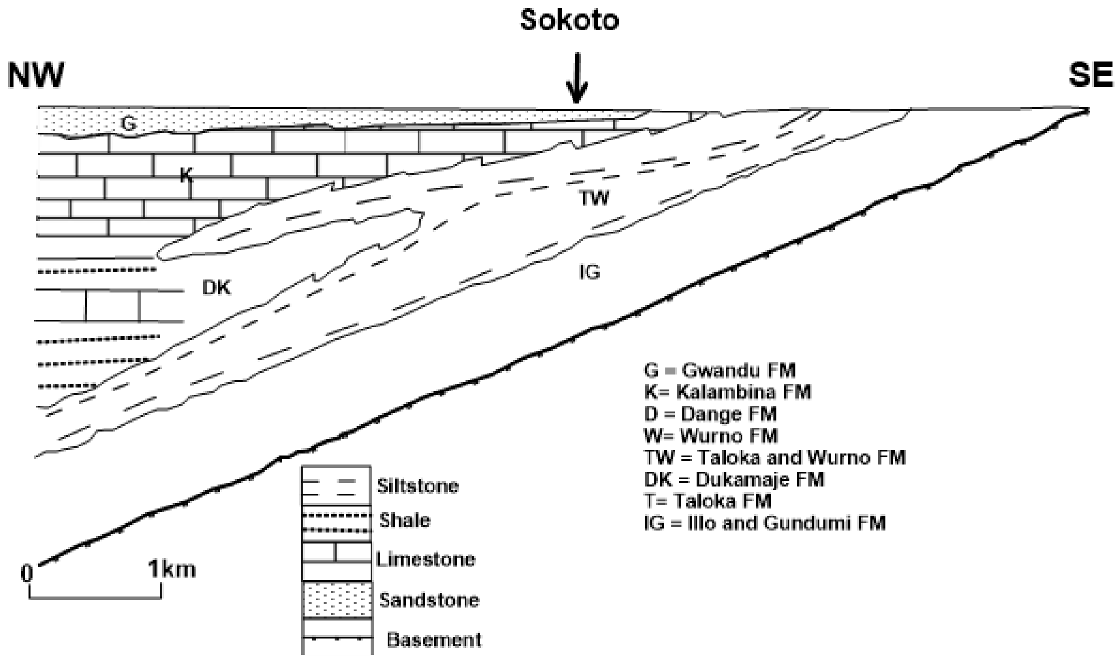

Fig. 2. Stratigraphic section through the Sokoto Basin (after [21])

Authors [24,19,25,26] have previously suggested that an unconformity which marks an interval of weathering and erosion have separated the Rima Group from the overlying late Paleocene Sokoto Group.

1.2 Hydrogeology

The Sokoto Basin is drained by the Sokoto River and its tributaries. It is underlain by a sequence of interbedded semi-consolidated gravel, sand, clay, and some limestone as representative of the subsurface geology. Aquifers of the area are recharged from the eastern outcrop that dip westward (Fig. 2 above) beneath the younger formations [27,28,15].

According to [28], the Gwandu Formation is the most prolific of the seven aquiferous formations with a permanent water storage of about 6.8×10^9 m^3. Although, very little is known on the water-bearing character of the Illo Group. [27] reported that the Illo Formation consist of a highly permeable coarse-sand and fine gravel aquifer that is under sub-artesian conditions with good water quality. The Illo Formation thus appears to be hydraulically continuous with the artesian aquifer in the Rima Group at Birnin Kebbi (Figs. 1 and 2).

Groundwater within the Sokoto Basin is found within both confined and unconfined aquifers in most of the permeable members of the Cretaceous-Tertiary sedimentary sequence. Confined water occurs down-dip and at depths in semi-consolidated sand or gravel of at least three important aquifers - the Gundumi Formation, the Rima Group, and the Gwandu Formation.

Results of hydraulic tests data for boreholes tapping the aquifers within the Sokoto Basin were carried-out by Geological Survey Nigeria (GSN) and fully documented by [27,28,15,13]. Water-table conditions occur in the outcrop areas of all the three aquifers. However, a local but important perched groundwater body is present in limestone of the outcrop area of the Kalambaina Formation. Unconfined groundwater also occurs in the Quaternary alluvial fill of the fadamas of the River Sokoto and its larger tributaries.

2. METHODOLOGY

Successful delineation of groundwater potential zones was achieved through the extraction of various data such as; elevation, slope, drainage and lineament density, from a digital elevation model (DEM) satellite imagery which was made available on global land cover facility by the University of Maryland, U.S.A., to produce their thematic maps each. The lithology was extracted from geological map produced by the Nigerian

Geological Survey Agency (N.G.S.A.), rainfall maps was obtained from L'Institut Francais Scientifique pour le development en cooperation (1951 to 1989 rainfall data for west and central Africa) and soil map was sourced from world soil map produced by Food Aid Organization (F. A. O.). Since these factors (lithology, soil, elevation, rainfall, slope, drainage and lineament density) directly or indirectly affect groundwater, a thematic map for each was produced in layers with the use of GIS software known as ARCMAP 10.2 and GLOBAL MAPPER 17. Each layer produced was further sub-divided into different classes and weighting were assigned to these layers using the multi-criteria evaluation (MCE) technique. The factors that are more favorable to groundwater occurrence were assigned a higher weighting than layers less favorable to ground water. A flow chart for the methodology of this study is illustrated by the schematic flow chart (Fig. 3).

2.1 Analytical Hierarchy Procedure (AHP)

Weighting for the different layers were calculated using analytical hierarchy procedure (AHP). Analytical hierarchy procedure is one of the multi-criteria evaluation technique (MCE) methods [29]. This technique provides a measures of the judgment consistency and simplifies preference rating among decision criteria using pair wise comparisons. For accuracy, consistency ratio was calculated. A consistency ratio of 0.1 and below was considered acceptable and any higher value will require re-examination. For convenience, weighting and consistency ratio were calculated using EXPERT CHOICE 11 software.

2.2 Lithological Map

The lithological map for the Sokoto basin was adopted from geological survey (1965), geological map of Sokoto basin. Digitization was carried out and weighting for the different geological units were done based on their porosities. Since the porosity of rocks controls the amount of groundwater it can store. Thus, rocks with high porosity have the ability to store large voluime of groundwater. Thus lithological units with high porosity were given higher weighting than lithological units with less porosity values. Weighting for different lithologies within Sokoto basin is given below (see Table 1). Lithological map for Sokoto basin is shown on Fig. 4.

2.3 Drainage

The presence of a drainage, has a great effect on the groundwater level of any given area. Regions close to the drainage are likely to have high ground water potential than those further away from it. This is so because percolation of water into the ground from a drainage system is greater in areas nearer to the drainages than farther away. Drainage network for the study area was extracted from a digital elevation model (DEM) using the software GLOBAL MAPPER 17. Buffering was performed to create distance layers away from the stream. Regions close to the drainage were given higher weighting than those further away. The drainage distance was then classified into; very close, close, far and very far (Fig. 5), while weightings for different layers are presented in Table 2.

Table 1. Weighting for different lithologies within the River Sokoto Drainage Basin

S/N	Layer class	Weighting	Consistency ratio
1	Alluvial	48	0.05
2	Gwandu Formation	23	
3	Gundumi Formation	11	
4	Illo Formation	11	
5	Rima group	5	
6	Sokoto Group	3	

Table 2. Weighting for drainage distances

S/N	Layer class	Weighting	Consistency ratio
1	Very far	6	0.013
2	Far	13	
3	Close	28	
4	Very close	53	

2.4 Elevation

Elevation play very important role in determining groundwater level. It is believe that water flows from high areas to lowlands, hence there will be less percolation of groundwater in elevated areas than in lowland areas. The lowland areas will therefore have a high groundwater potential than elevated areas. Elevation data for the study area was extracted from digital elevation model (DEM) and classified into extremely high, very high, high, moderately high, low, very low and extremely low (Fig. 6). Weighting for these layers are here presented (see Table 3).

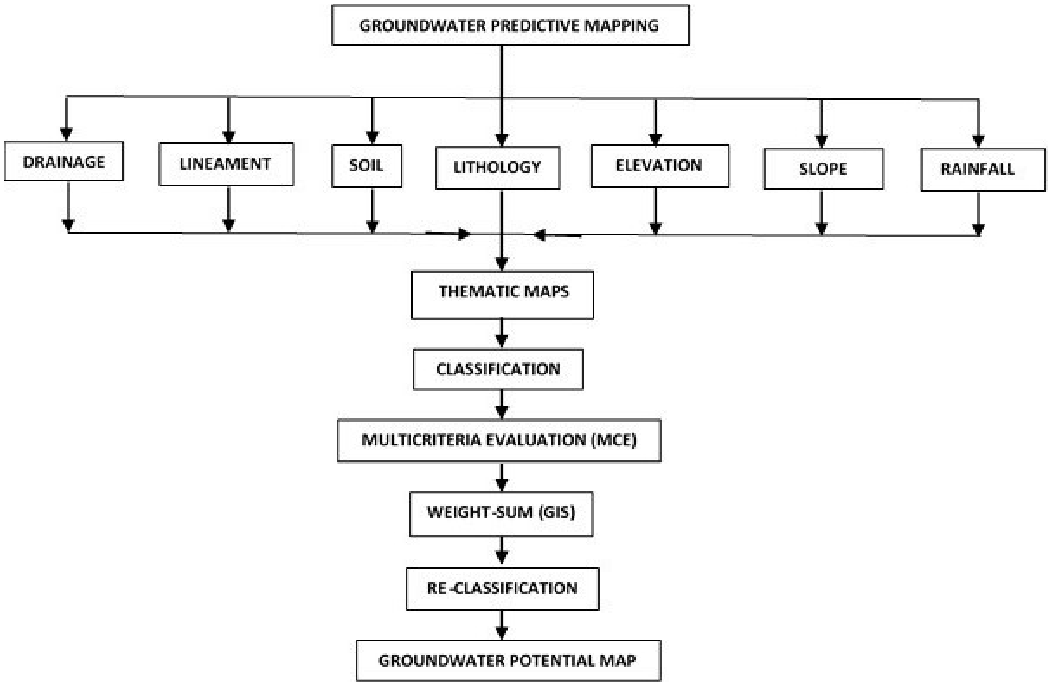

Fig. 3. Flow chat representation of a GIS-based methodology adopted for the study

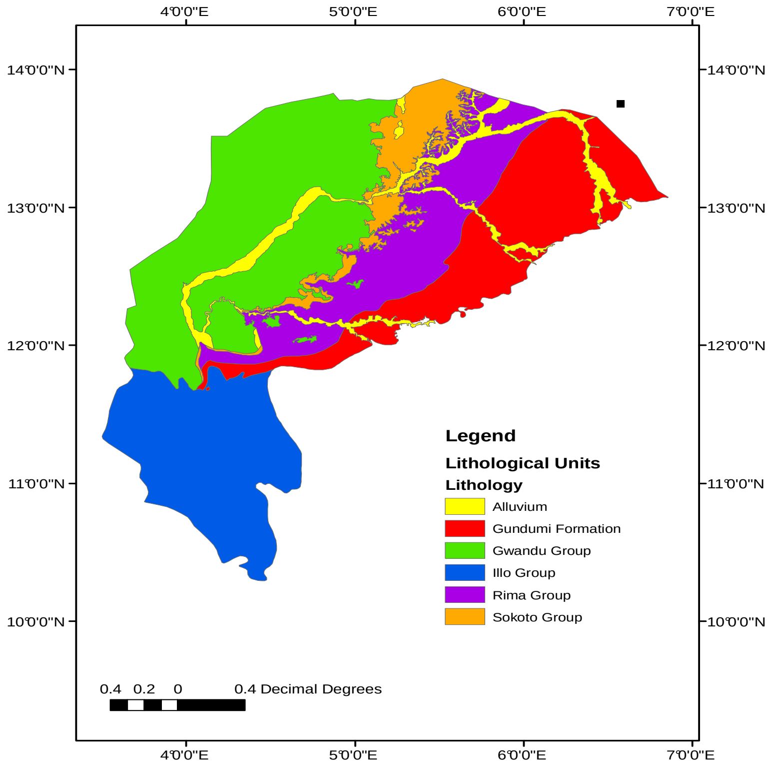

Fig. 4. Lithological class for Sokoto Basin

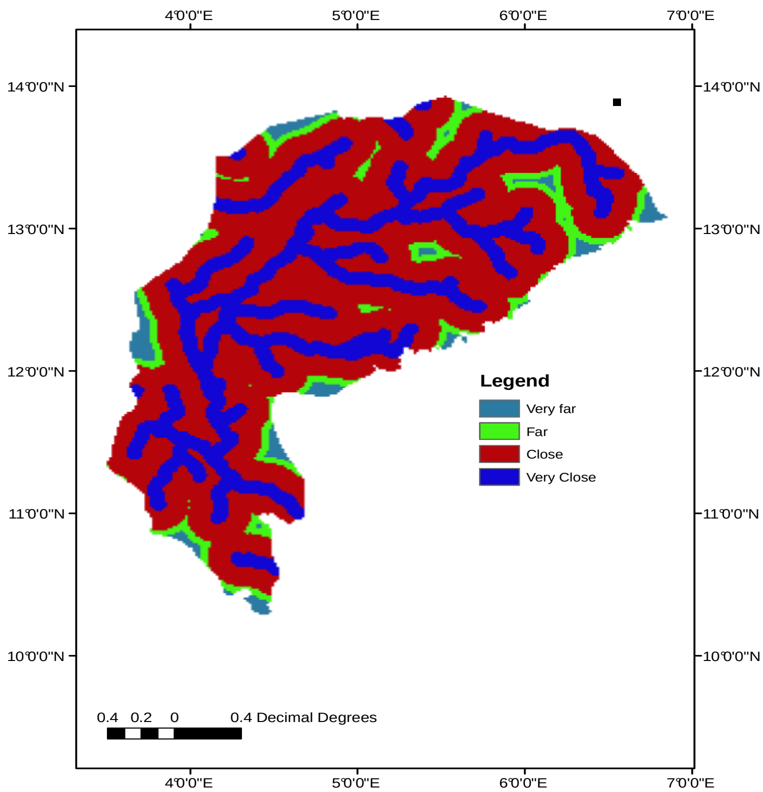

Fig. 5. Drainage proximity classes for the Sokoto Basin

Table 3. Weighting for elevation data

S/N	Layer class	Weighting	Consistency ratio
1	Extremely High	24	0.03
2	Very High	30	
3	High	14	
4	Moderately High	8	
5	Low	6	
6	Very Low	4	
7	Extremely Low	4	

2.5 Slope

The Slope of any terrain contributes greatly to its groundwater potential because, very steep slopes will allow flow of water and thus, there is less time for percolation of the water into the ground. On the other-hand, very gentle to flat slopes will allow more time for percolation of surface water into the ground. They tend to have a higher groundwater potential. Slope data was extracted from digital elevation model (DEM) and classified into; steep, moderate and flat (Fig. 7).

Weighting for different layers was carried out and presented on Table 4.

Table 4. Weighting for slope within the study area

S/N	Layer class	Weighting	Consistency ratio
1	Steep	8	0.02
2	Moderate	14	
3	Gentle	23	
4	Flat	55	

2.6 Rainfall

The average rainfall distribution has a significant impact on the groundwater of any area. Regions that experience a higher rainfall distribution, tends to have good groundwater potential due to an increased percolation and subsequent infiltration of surface water into the subsurface. A thematic map of the rainfall data for Sokoto Basin was produced and the regions were classified into; low, medium and high zones (Fig. 8). The weighting assigned for the rainfall zones are presented in Table 5.

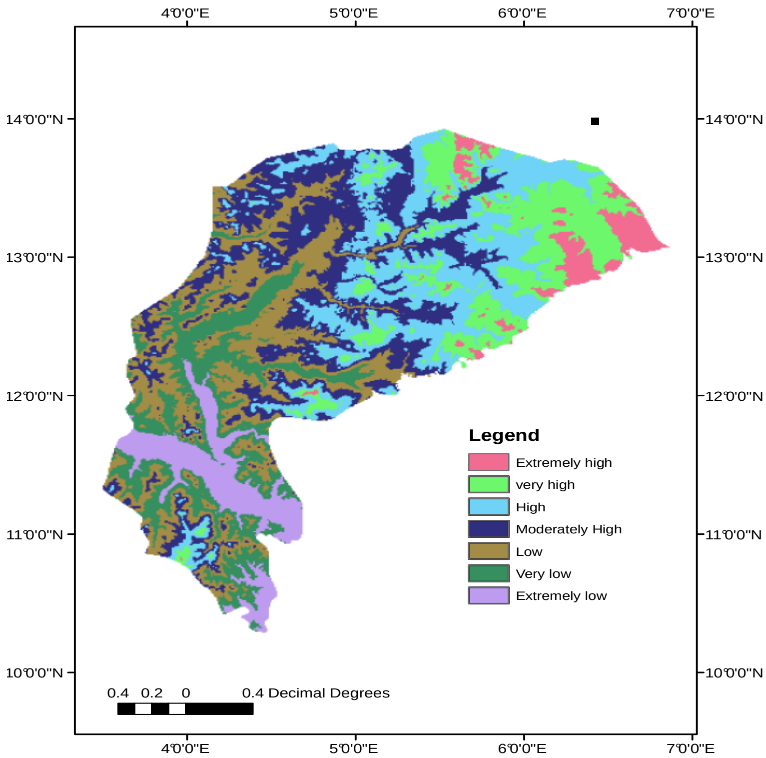

Fig. 6. Elevation classes for the Sokoto Basin

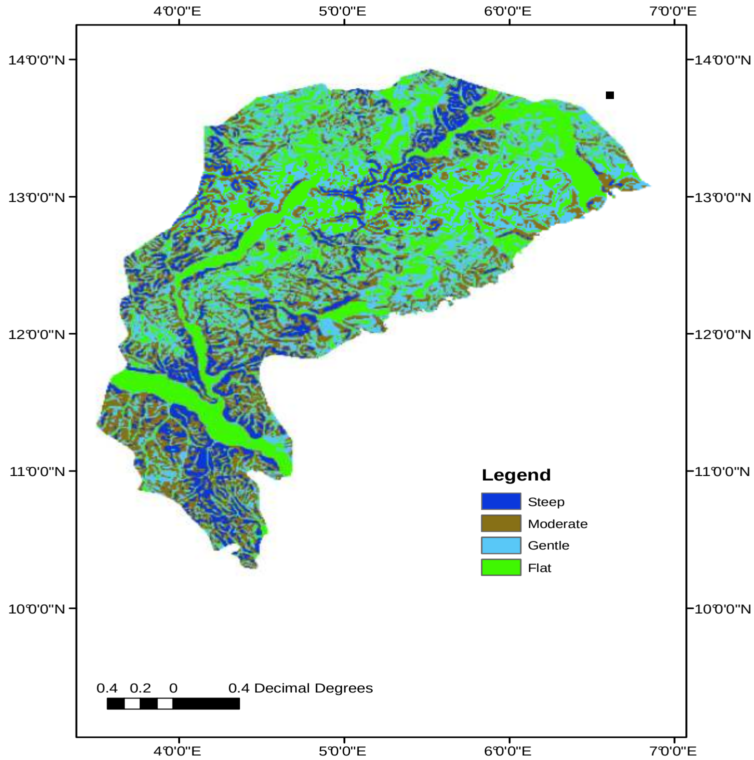

Fig. 7. Slope class for River Sokoto Drainage Basin

Table 5. Rainfall data for the study area

S/N	Layer class	Weighting	Consistency ratio
1	Low	14	0
2	Medium	29	
3	High	57	

2.7 Soils

The type of soil present in an area have a great impact on the availability of groundwater. Highly porous soils allow easy percolation and infiltration of surface water into the subsurface, and this is ideal for a favorable groundwater potential. Soil map for the study area was produced as subsets from FAO soil map. Soil cover-type within the study area consist of; lithosols, luvisols, acrisols, gleysols, fluvisols, nitisols, arenosols, regosols and water (Fig. 9). The weighting assigned to each soil class is presented on Table 6.

Table 6. Weighting for soils within the study area

S/N	Layer class	Weighting	Consistency ratio
1	Gleysols	27	0.04
2	Fluviosols	21	
3	Water	21	
4	Arenosols	13	
5	Regosols	6	
6	Lithosols	6	
7	Acrisols	3	
8	Nitosols	2	
9	Luvisols	2	

2.8 Lineament Density

Lineaments are linear topographical or tonal features on the ground representing zones of structural weakness [30]. These zones of structural weakness can actually serve as pathways for percolation of surface water into the subsurface. Lineament density is a reflection of

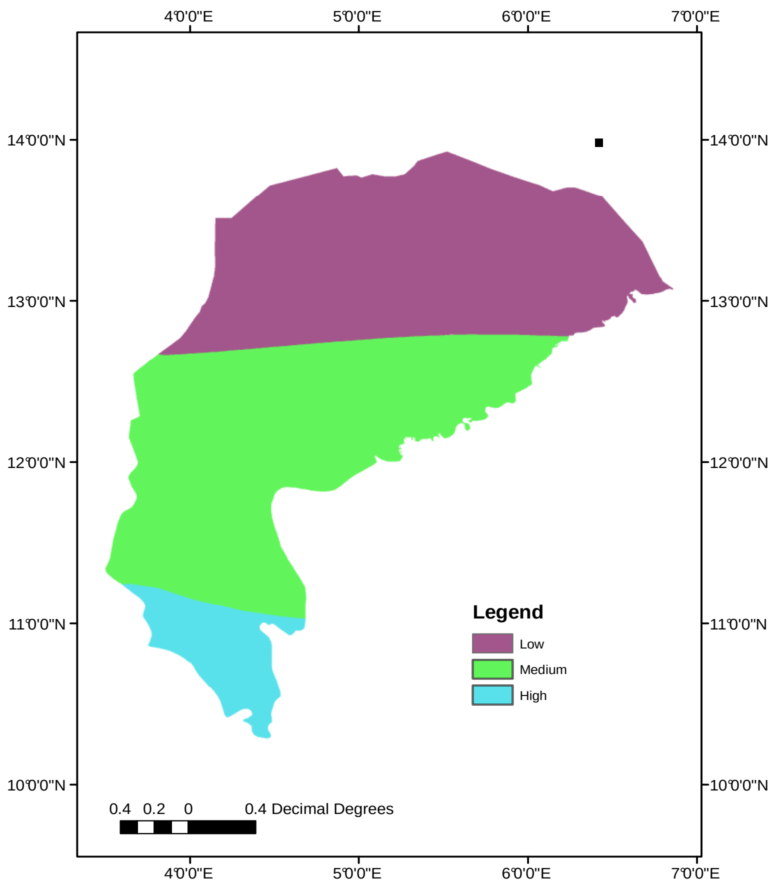

Fig. 8. Rainfall class for River Sokoto Drainage Basin

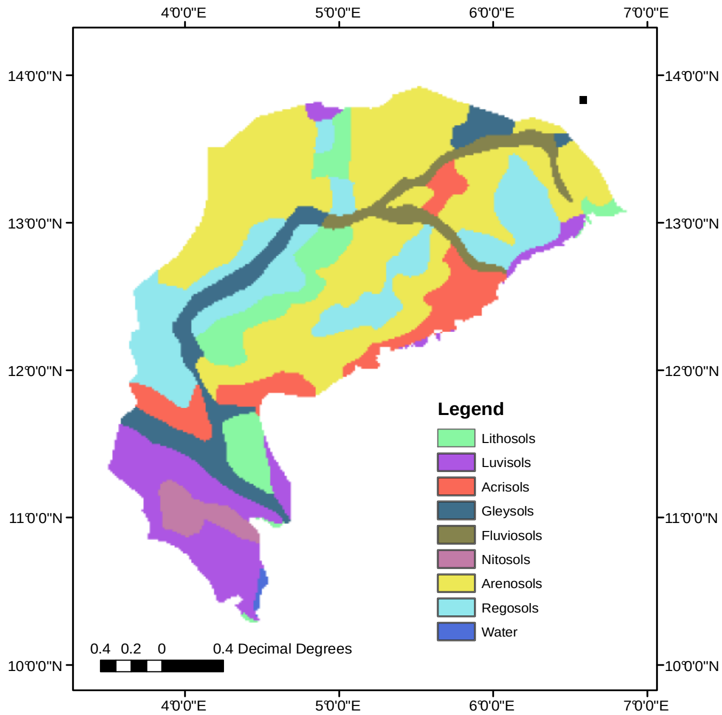

Fig. 9. Soil class for Sokoto Basin

the number of lineaments per unit area. Since lineaments are path for percolation of water into the subsurface, the higher the number of lineaments per unit area the greater the percolation of ground water will be. Thus areas with high lineament density are more favorable than areas of low lineament density. Lineaments for the study area was classified into; very high, high, moderate, low, very low and extremely low (Fig. 10). Weighting for lineaments is given on Table 7.

Table 7. Weighting for Lineament density within the study area

S/N	Layer class	Weighting	Consistency ratio
1	Very High	39	0.04
2	High	26	
3	Moderate	17	
4	Low	10	
5	Very Low	5	
6	Extremely Low	3	

2.9 Groundwater Potential Map (GWPM)

The extraction of various data and subsequent production of different thematic maps for factors that determine groundwater occurrence, was followed by combining the different layers using Arc-GIS Spatial analysis tools. With this, the different thematic layers were combined using the weight-sum in the manner represented below:

$$GWPM = \text{LITHOLOGY} + \text{DRAINAGE DISTANCE} + \text{ELEVATION} + \text{SLOPE} + \text{RAINFALL} + \text{SOIL} + \text{LINEAMENT DENSITY}$$

Thus, a groundwater potential map for the study area was produced from combining all thematic layers acquired from remotely sensed satellite imageries. It was then re-classified into five classes showing the favorable areas for groundwater occurrence. The classes are; poor, moderate, moderate to good, good and very good (Fig. 11). Statistical analysis of the groundwater potential map reveals that the class corresponding to good groundwater potential occupies an area of 14,322.66 km^2, which accounts for 2% of the total area. Similarly, the region with good groundwater potentials covers a total area of 5,071.5237 Km^2 (7.79% of the study area). The region that represents moderate to good groundwater potential, covers a total surface area of 17,577.8 km^2 and accounts for 27.5% of the study area. Further, the region mapped out as having moderate potential covers a total area of 32,030.676 km^2 and it represents about 49.2% of the study area. Finally, the region corresponding to poor groundwater potential zones covers a total surface area of 8,528.493 km^2, which accounts for about 13.1% of the total area. (Table 8).

Table 8. Ground water potential classes characteristics

S/N	Ground water potential	Area coverage (km^2)	Percentage coverage (%)
1	Poor	8528	13.1
2	Moderate	32030.676	49.2
3	Moderate to Good	17577.8	27.5
4	Good	5071.5237	7.79
5	Very Good	1432.66	2

3. DISCUSSION

The use of remote sensing technique and GIS softwares in this study reveals some variations in groundwater occurrence within the Sokoto Basin. Remotely sensed data acquired for the study area together with classified thematic maps using GIS applications, have successfully delineated areas of high groundwater potential from those with low groundwater potential. It is worthy to note that the accuracy of any groundwater potential model depends on the reliability of the data used to build the model. As a matter of precaution, consistency levels for each of the thematic maps were prevented from exceeding the recommended 0.1 level so as to ensure a high degree of accuracy.

The final groundwater potential map produced, reveals that the southern portion of the study area have a higher groundwater potential than the Northern parts. The north-eastern part represents areas with the least groundwater potential, these corresponds to regions with low groundwater yield. Thus, there may not be enough groundwater to meet the need of densely populated towns within the area. However, in sparsely populated towns or village there may just be water to sufficient to meet house hold domestic use. Furthermore, the method adopted for the investigation reveals that there is a close

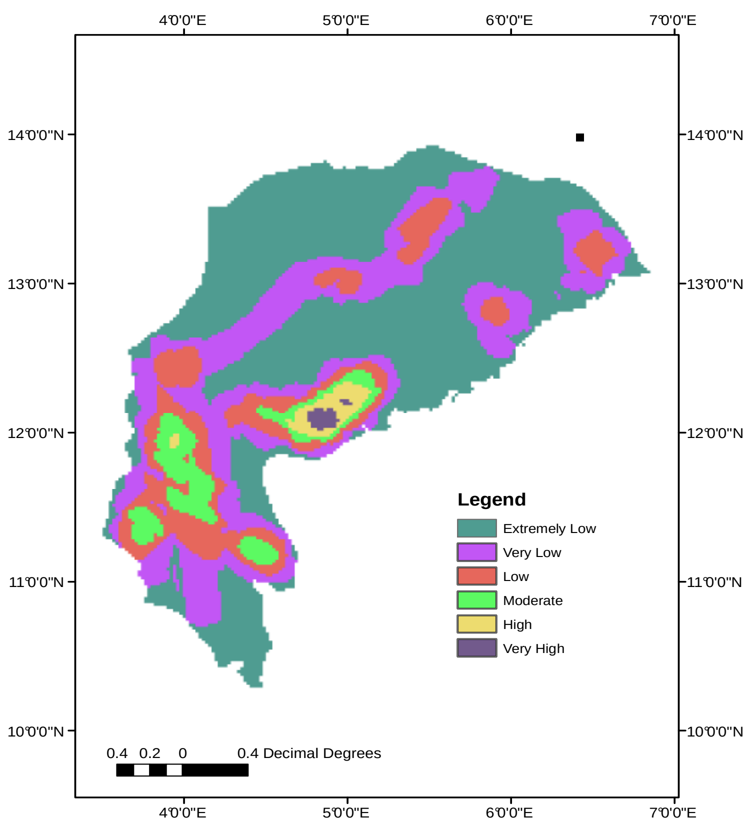

Fig. 10. Lineament density class for study area

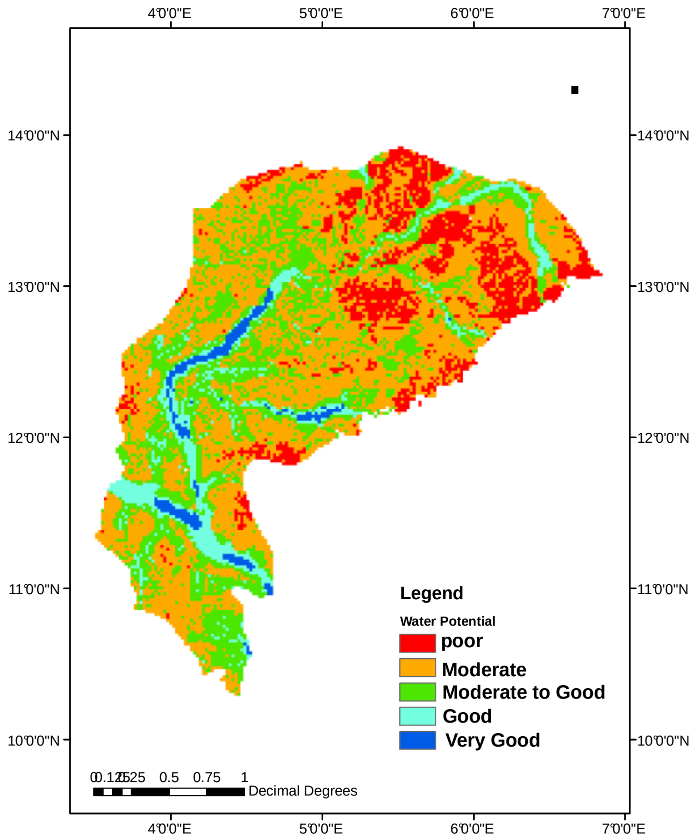

Fig. 11. Ground water potential for the study area

Table 9. Comparisons between yield and groundwater potential class of some selected localities

Locality	Latitude	Longitude	*Yield	Present study
Dukamaje	13.7473°N	5.8191°E	Low	Poor
Bale	13.4685°N	4.6790°E	High	Moderate to Good
K. Sarki	13.2754°N	4.5181°E	High	Moderate to Good
Sokoto	13.0611°N	5.2373°E	High	Moderate to Good
Kware	13.2183°N	5.2639°E	High	Moderate to Good
Bakura	12.5667°N	7.7333°E	High	Moderate to Good
Illela	13.7220°N	5.7069°E	High	Poor
Girawsi	13.0684°N	5.1876°E	High	Poor

[27,28,15,13]

agreement in the groundwater potential map produced in this study, and the pump test data obtained previously within the Sokoto Basin by the authors: [27,28,15,13]. There is a close agreement in terms of the groundwater yield in the areas presented in Table 9 above.

The study also proves the effectiveness of the remote sensing technique and GIS to predict the potential occurrence of groundwater in an area. Regions with the highest ground water potentials are located within stream channels running from the central to the southern part of the study area. In terms of areal extent, it is the least of the entire study area. It covers about 1432.66 km^2 of the entire Sokoto Basin, constituting 2% of the study area. However, the region classified with poor groundwater potential covers a total area of 8528 km^2 making 13.1% of the total area.

4. CONCLUSION

From this study, groundwater favorability of the southern part of the study area is far better than that within the northern parts. The north-eastern part of the study area appears unsuitable for efficient groundwater exploitation. Therefore, it is recommended that borehole citing within the Sokoto Basin should be carried out within the southern part of the study area because of it high potential. Boreholes cited within most the northern and north-eastern part of the study area may not yield sufficient groundwater to meet its demand, except for few areas. However, boreholes cited within regions of moderate and moderate to good potentials, will yield a sufficiently higher quantity of groundwater to meet more water needs. Finally, the close agreement between the groundwater potential map produced from the study and the pump test data obtained previously has shown the effectiveness remote sensing technique and GIS in predictive mapping of groundwater potential in the Sokoto Basin.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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