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Assessment of groundwater accumulation potential in parts of Birnin Gwari, Northwestern Nigeria using geospatial methods

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Abstract: The aim of this research is to identify groundwater potential zones in specific parts of Birnin Gwari utilizing geospatial (Remote Sensing and Geographic Information Systems) data in order to help alleviate the water scarcity problem of the area. Seven (7) parameters were considered: geology, drainage, lineament, rainfall, land use/land cover, slope, and soil. Thematic maps of these characteristics were created, and weightages were assigned based on pairwise comparisons of the elements that appear to be crucial in groundwater potential for this study. Rainfall and lineament density were identified as the most significant contributors, accounting for 36.0% and 16.4% respectively. Five Groundwater Potential Zones (GWPZ) were found as very low, low, medium, high, and very high, corresponding to 0.22%, 23.10%, 60.75%, 15.83%, and 0.10% respectively. The consistency ratio was calculated to be 0.06 which is below the acceptable threshold of <0.1. According to the findings of the study, the south and south-western parts of the study region have very high to average groundwater potential, whereas the north and north-eastern parts have low to very low groundwater potential. The centre region is characterized by average groundwater potential. To validate the accuracy of the delineated groundwater potential zones, Vertical Electrical Sounding (VES) from 30 locations across the study area were used to generate curves type, and the transmissivity of the aquifer was calculated. Based on the transmissivity ratings, 83.3% of the VES points show good accumulation potential while 16.7% show intermediate accumulation potential. The overall result indicated that the remote sensing and GIS techniques provide a reasonable framework for groundwater exploration. It is recommended that surface water development should be carried out in places with limited potential.

Keywords: Drainage, geology, groundwater, potential, remote sensing

INTRODUCTION

Groundwater is one of the most valuable natural resources, providing not only the water needed by populations in both urban and rural regions of established and emerging nations, but also promoting biological diversity, human health, and economic growth. It also has an impact on the socio-economic standing of every country (Yıldırım, 2021). According to several studies (Melloul & Collin, 2001; Das & Pardeshi, 2018a; Andualem & Demeke, 2019; Arabameri *et al*., 2019) groundwater is the most advantageous freshwater reserve for human and commercial use. As such, groundwater exploration and management are crucial to preventing a severe water shortage (Deshmukh & Aher, 2016). According to Al-Garni (2009), the possibility of groundwater exploration in hard rock terrain is mostly dependent on the thickness of the weathered or fractured layer that covers the formation. In Nigeria's basement complex terrain, groundwater occurrence is often minimal and, where it does occur, is influenced by geological, structural, and climatic elements (Idris-Nda *et al*., 2015). This in turn makes it challenging to explore for groundwater in intricate subterranean topography of Nigeria. The study area is currently being faced with the same problem, as most of the inhabitants walk some distance before they can get portable water for consumption. The majority of the boreholes in the study area are manually operated boreholes that have been drilled long time ago and some of these boreholes are no longer functioning probably due to the fact that no in-depth geophysical survey carried out before drilling of these boreholes. In order to create a groundwater management plan and exploration guide, it is necessary to thoroughly investigate the groundwater accumulation potential features of the research region

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within Birnin Gwari Local Government region in Kaduna State due to the shortage of water in the area. Previous related studies carried out within and outside the sphere of the study area includes (Ghazavi & Ebrahimi, 2015; Badamasi *et al*., 2016; Allafta *et al*., 2021; Doke *et al*., 2021; Verma & Patel, 2021; Alimi *et al*., 2022).

Over the years groundwater accumulation potential studies have been carried out using geophysical (electrical) methods, Geographic Information Systems (GIS) and remote sensing in recent years. Previous studies such as Langgeng & Tjahyo (2007); Musa *et al*. (2014); Ebenezer & Eduvie (2017); Ige *et al.* (2021), all used the traditional electrical method to delineate groundwater zones. In recent years, with the increasing use of geospatial approaches, the delineation of the zones has been easier and more accessible (Nampak *et al*., 2014; Şener *et al*., 2018; Murmu *et al.,* 2019; Allafta *et al*., 2021). To reduce costs and hazards, methods and technologies like GIS and remote sensing that can accurately identify potential source zones must be used (Şener *et al*., 2018; Mallick *et al*., 2019; Murmu *et al.,* 2019; Achu *et al*., 2020; Lentswe & Molwalefhe, 2020; Allafta *et al*., 2021; Yıldırım, 2021).

Geospatial techniques help generate and analyze thematic layers (geology, topography, rainfall, slope, vegetation, drainage, lineament, soil, and land use) for the purpose of mapping areas that have the potential to contain groundwater (Dar *et al*., 2010; Singh *et al*., 2013; Maniar *et al*., 2017). An approach to measuring, known as the Analytic Hierarchy Process (AHP), uses pairwise comparisons and expert judgments to establish precedence scales. The rank of absolute judgments approach, which shows how the elements relate to one another with respect to a certain characteristic, is used to make the expert judgments (Saaty, 1980). Seven parameters (geology, drainage, lineament, rainfall, land use/land cover, slope, and soil) were used for this research work considering all factors that contribute to the accumulation of groundwater in basement complex area. Using GIS methods, the current study aims to identify areas in the study region with significant groundwater accumulation potential and generate a groundwater potential zone map.

Study area

The study area, which is located within the Northwestern Nigeria Basement complex, is bounded by latitudes 10° 29′ 44″ N and 11° 16′ 01″ N and longitudes 006° 7′ 00″ E and 007° 7′ 38″ E, covering an area of approximately 4967.78km^2. The study region borders Katsina state to the north, Zamfara and Niger state to the west, Giwa and Igabi Local Government region to the east, and Chikun Local Government Area to the south (Figure 1). Major paved highways and unpaved smaller roads, as well as walkways, provide access to the study area. The study area is distinguished by high elevation, hilly, and forested terrain. Its maximum elevation is 767 m above mean sea level at the far northeast of the mapped area, and its minimum elevation is 240 m above mean sea level towards the southwest of the mapped area. The study area exhibits a progression of elevation increase from the southwest to the northeast.

The Birnin Gwari Schist Formation underlies the research region geologically (McCurry, 1976; Rahaman, 1976). The Formation is composed of semi-pelitic schists, pelitic schists, garnet and staurolite schists, pebbly and cobbly schists with subordinate gneisses. There are also greywackes, pebbly mudstones, rhyolites and dacites. The synclinal axis of the schist belt is occupied by the Birnin Gwari Schist Formation. The bottom portion is composed of biotite-muscovite schists of greater grade in the east and finely banded phyllites in the west. Overlying them is the Durimi pebbly schist, a metamorphosed conglomerate of mudstone that includes some strata of impure quartzite or meta greywacke (Obaje, 2009).

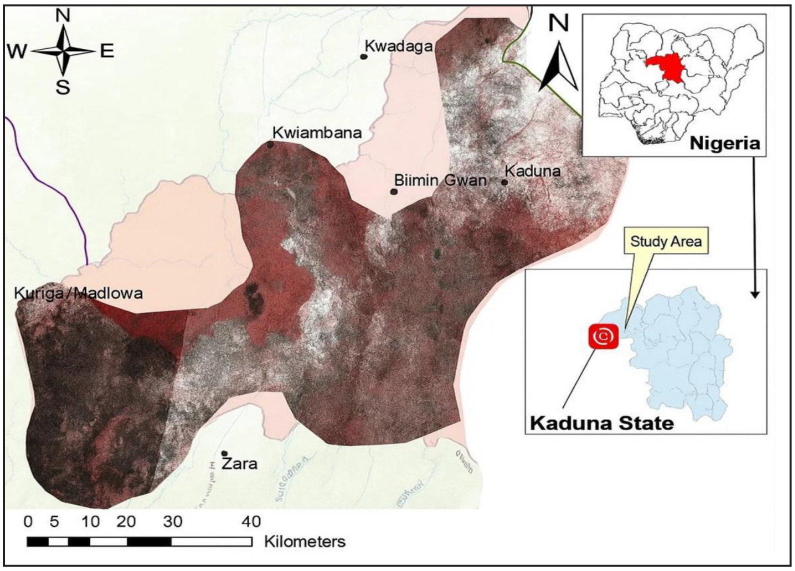

Figure 1: Study area and location map (extracted from Landsat 8 OLI Imagery).

MATERIALS AND METHODS

Materials

As indicated in Table 1a, the secondary data sources for this study were the soil map from the Food and Agriculture Organization of the United Nations (FAO), the rainfall data from NiMet, the geological map from the Nigerian Geological Survey Agency (NGSA), and the satellite imagery from Landsat 8 OLI and SRTM DEM. The IRS LISS-111 software was used for image processing and classification; ArcGIS 10.7 was used for digitizing and groundwater analysis; PCI Geomatica v10.0 was used for lineament extraction; and Microsoft Excel was used for graphical representation of charts. Various software programs were used to delineate groundwater potential zones in the study area.

Methods

Groundwater potential zones were identified in the research region using GIS and remote sensing techniques. In addition, there were seven steps in the used method: (i) criterion selection; (ii) thematic layer preparation; (iii) Pairwise Comparison Matrix (PCM) based on AHP; (iv) weight computation; (v) weighted overlay analysis; (vi) accuracy evaluation; and (vii) the production of the GWPZ map. The modified sequence of the approach (Doke *et al*., 2021) is shown in Figure 2.

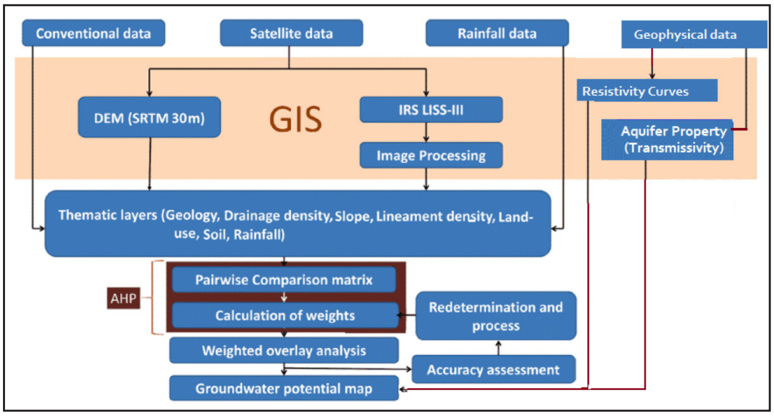

Figure 2: Flow chart of the method used for this study (Modified after Doke *et al*., 2021).

Table 1a: Various sources of geospatial data that were used for this research work.

S/N	Data Sources	Scale/Resolution
1	SRTM DEM	https://earthexplorer.usgs.gov 30 m
2	Landsat 8 OLI	https://earthexplorer.usgs.gov 30 m
3	Geological map of the Nigerian Geological Survey Agency (NGSA)	1:100,000
4	Soil map Food and Agriculture Organization of the United Nation (FAO)	1:1,000,000
5	Rainfall Nigerian Meteorological Agency (NiMet)	

Table 1b: Weights of the entire Groundwater Factor Map.

	Annual Rainfall	Lineament Density	Drainage Density	Slope	LULC	Geology	Soil	Weight	Weight Percent-age (%)
Annual Rainfall	1	3	3	3	5	5	5	0.36	36
Linea-ment Density	1/3	1	3	1	3	1	3	0.164	16.4
Drainage Density	1/3	1/3	1	1	3	1	3	0.118	11.8
Slope	1/3	1	1	1	5	1	3	0.145	14.5
LULC	1/5	1/3	1/3	1/5	1	1	1/3	0.048	4.8
Geology	1/5	1	1	1	1	1	1	0.095	9.5
Soil	1/5	1/3	1/3	1/3	3	1	1	0.07	7.0

This research took into account seven elements, and thematic maps were created for each of them. Geology, rainfall, drainage density, lineament density, land use/land cover, slope, and soil are all aspects taken into account. Infiltration, percolation, storage, recharge potential are key relevance to groundwater accumulation. The seven parameters selected can be used to delineate these relevant factors to groundwater accumulation potential, hence, the seven parameters considered for this research work. The flowchart outlines the steps taken to create thematic maps; the process of delineating Land Use/Land Cover (LULC), lineament, drainage density, and slope was created from Digital Elevation Model (DEM) using an unsupervised classification approach.

ArcGIS 10.7.1 was used to create thematic layers. The contour and drainage layers were created using Landsat pictures of the research region at a resolution of 1:50,000. The contour map obtained by DEM was utilized to determine the slope, soil, geology, and lineament of the area, the land use/land cover was obtained from satellite imagery. The right band combinations were used to generate both the supervised and unsupervised classification, after which supervised classification of maximum likelihood was used to create the final LULC map. The slope map depicted the topography parameters of the research region. The World Geographic System 84 (WGS84) was used to geo-reference all input datasets. After evaluating relative contribution qualities, weights were assigned to thematic aspects for categorization purposes. The layers used in the analysis were then merged into the GIS environment. The lineament was extracted using the PCI Geomatica v10.0 program, and a lineament density map was produced on the ArcGIS 10.7.1 platform.

The pairwise comparison is calculated using the weightage concept and ranges from 1 to 9, with 1 representing equal relevance and 9 representing high importance (Saaty & Vargas, 1991). The AHP was used to determine which factors were more important and which were less important. Table 1b displays the pairwise comparison matrix used to assign weights to each component. The weighted overlay approach was used to create the groundwater potential zones map of the research region by combining all of the produced layers; this was accomplished using the formula:

$$GWPZ = GL+RF+LD+DD+SL+LULC+S$$

Where;

GL = Geology, RF = Rainfall, LD = Lineament Density, DD = Drainage Density, SL = Slope, LULC = Land Use/Land Cover, S = Soil

The weighting of parameters in this study was carried out using the Analytic Hierarchy Process (AHP), a structured and mathematically robust multi-criteria decision-making approach developed by Saaty (1980). In this research, parameters such as slope, land use/land cover, soil type, lithology, drainage density, lineament density, and rainfall were considered due to their known influence on groundwater potential. These parameters were organized in a hierarchical structure, with the overall objective at the top level and the parameters at the lower level.

Pairwise comparisons were performed based on expert evaluations of the relative importance of each parameter. The experts consulted have backgrounds in hydrogeology, geospatial analysis, and environmental management and their assessments reflect both field experience and literature-informed insights. Each parameter was compared using Saaty's fundamental scale, and a comparison matrix was formed.

To ensure the consistency and reliability of the judgments, the Consistency Ratio (CR) was calculated using the formula: CR = CI/RI where CI is the Consistency Index and RI is the Random Index based on number of parameter (n). A CR value of 0.06 was obtained, which is below the acceptable threshold as suggested by Saaty (1980). This confirms that the judgments were consistent and that the resulting weights are valid and reliable for use in the weighted overlay analysis.

Furthermore, the weights derived in this study are in alignment with those reported in similar research by Mallick *et al*. (2019); Murmu *et al.* (2019); Achu *et al*. (2020); Lentswe & Molwalefhe (2020); Allafta *et al*. (2021) and Yıldırım (2021).

Uncertainty analysis

Understanding the uncertainties that arise in GIS and remote sensing studies is crucial for understanding the reliability of data and results because it helps to identify and quantify potential errors and limitations in data collection, processing and analysis. The possible uncertainties that can arise from different sources are:

(i) Data acquisition: this can arise from errors in sensor calibration, atmospheric conditions and satellite geometry;
(ii) Data processing: the limitation of this source can originate from errors in image registration and data format conversion;
(iii) Data analysis: the limitation from data analysis can be caused by errors in classification algorithms, spatial interpolation and model parameters;
(iv) Data integration: the limitation from this can emerge from inconsistencies or conflicts when combining data from different sources, and
(v) Model limitations: this can emanate from assumptions made in the model itself.

The above listed uncertainty analysis affects the final GWPZ map in the following ways:

(i) Coarse resolution of the soil map sourced from Soil map Food and Agriculture Organization of the

United Nation (FAO) at 1:1M, and this is because this resolution may overlook small scale hydrological features.

(ii) The remote sensing data may have a noise or calibration issue which introduces uncertainty and thus have an impact on the final GWPZ map.

(iii) Another uncertainty analysis that may affect the final GWPZ map may be the lack of integration of dynamic factors such as seasonal variation in groundwater recharge.

(iv) The integration of the parameter thematic maps may also affect the final GWPZ map, because the combination method may amplify or dampen certain spatial patterns leading to misinterpretation.

RESULTS AND DISCUSSION

To map the groundwater potential regions in various parts of Birnin Gwari, seven elements related to groundwater occurrence in an area were thoroughly analyzed, including geology, drainage density, lineament density, rainfall, land use/land cover, slope, and soil. All of these aspects are discussed below.

Geology

Since lithology has a direct influence on the porosity and permeability of aquifer rocks, properly examining lithology allows for a better understanding of groundwater origin and status. A substantial part of the research region is covered in biotite gneiss. The southwestern half of the study area is dominated by older granites, whereas the northeastern part is covered with schist and phyllite, and the eastern part has granite. Quartzite is found in only a small part of the southern research region (Figure 3a). Badamasi *et al.* (2016) found that places covered in granitic rock have a high potential for groundwater, whereas areas covered in gneiss and schist have a moderate to low potential. According to the aforementioned statement, the geology of the research region indicates low, moderate, and good groundwater potential, with moderate groundwater potential accounting for around 70% of the study area.

Drainage density

Drainage density is an important indication of hydrological landscapes, determining infiltration and underlying lithology and groundwater recharge is

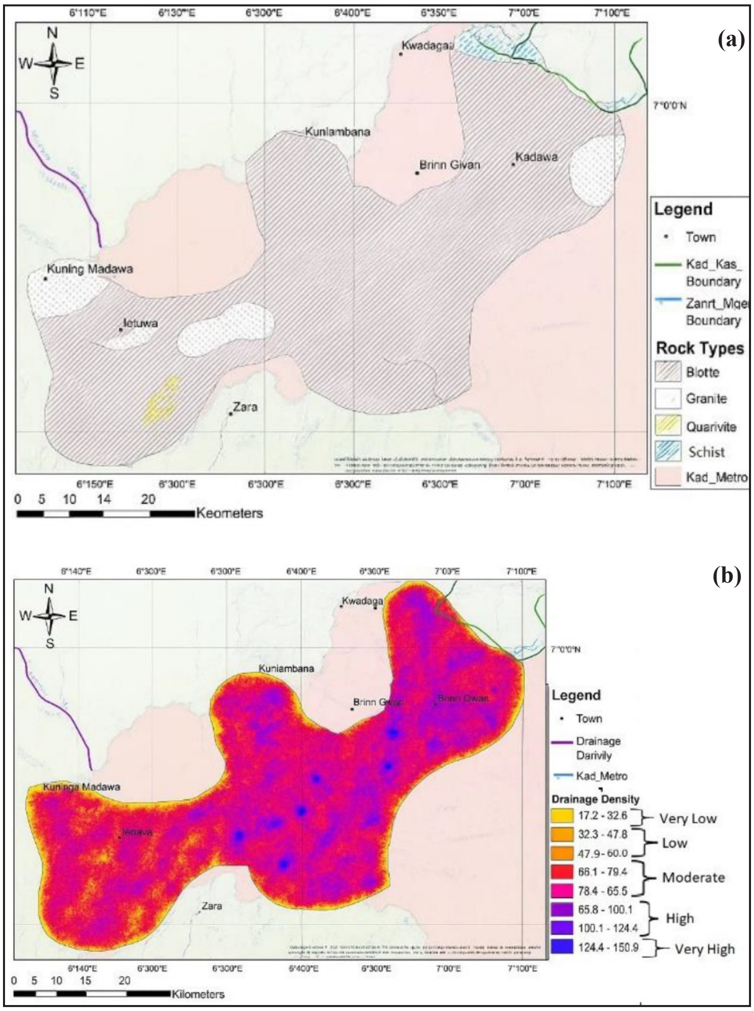

Figure 3: (a) Geology map of the study area, (b) Drainage density map of the study area.

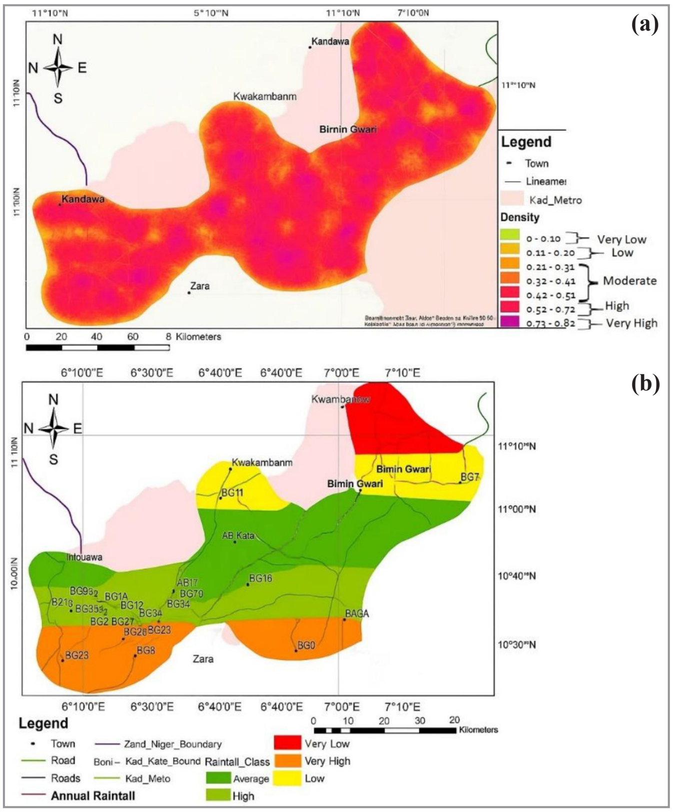

Figure 4: (a) Lineament density map of the study area, (b) Annual rainfall map of the study area.

controlled by the parameters of the drainage system (Murmu *et al*., 2019), the recharge rate of groundwater is inversely proportional to drainage density, meaning that the higher the drainage density, the lower the recharge rate of groundwater. The research region has drainage density values that range from moderate to high. The southern part of the research region has intermediate drainage density values, whereas the centre area extending eastward and northeast has extremely high drainage density values (Figure 3b). This suggests that the centre area towards the east has a low groundwater recharge rate, and hence the groundwater potential is quite low. The southern section of the research region has a moderate groundwater recharge rate, indicating a moderate groundwater potential.

Lineament density

Another essential hydrological element to consider while looking for a groundwater potential zone is the lineament. Groundwater potential zones are determined using lineament characteristics such as joints, faults, and fractures (Das & Pardeshi, 2018c). These lineament characteristics govern the flow of water at the subsurface as well as the rate of infiltration. Lineament density is directly linked to the rate of groundwater recharge; that is, the higher the lineament density, the faster the groundwater recharge. According to the lineament density map of the research area (Figure 4a), some portions of the southwestern area, extending to the centre part of the study area, have high lineament density, implying that groundwater potential is high in these places. The extreme southwest, northeast, and a portion of the centre region have low lineament density, implying that groundwater potential in these locations is poor. A bigger section of the studied region has moderate lineament density, indicating moderate groundwater potential.

Rainfall

Rainfall is another key hydrological characteristic to consider when mapping a site for groundwater potential. Rainfall has a direct impact on the downward flow of surface water, which increases groundwater recharge. However, topography (such as slope) influences the link between rainfall and groundwater recharge (Maity & Mandal, 2019). In light of the aforementioned idea, annual rainfall data for the research region was gathered and scores were carefully allocated. The annual rainfall map of the research region (Figure 4b) reveals that the south and southwestern parts of the study area have the greatest annual rainfall values, with a gradual reduction towards the north and northeastern parts of the study area. This means that the centre region of the study area has a significant groundwater potential. This is because the rainfall in this area is not strong enough to create high surface runoff; therefore, the rate of infiltration in this area will be higher than that in the northern half with low rainfall and the southern section with probable high surface runoff.

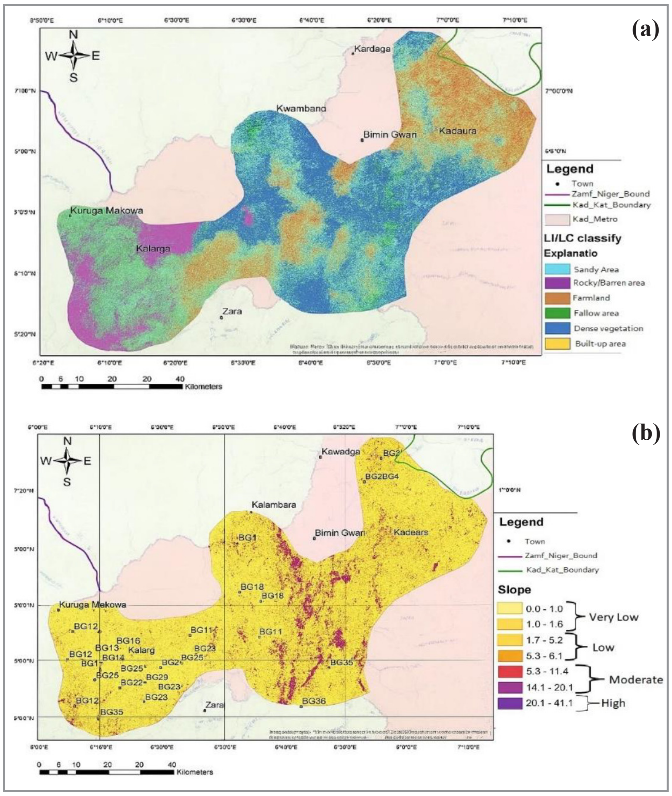

Figure 5: (a) Land use/Land cover map of the study area, (b) Slope map of the study area.

Land use/land cover

Land use/land cover offers efficient and accurate information for water resource management planning in every location. Land use/land cover pattern may also impact groundwater permeability and infiltration, as well as surface runoff, which has a link with infiltration rate; the rate of groundwater recharge is determined by the infiltration rate. A location with thick vegetation will have a higher infiltration rate and less runoff, resulting in a higher groundwater potential. The land use/land cover of the research area has been categorized into six categories with precisely given weights. The land use/land cover map of the research area (Figure 5a) reveals that thick vegetation covers 60% of the study area, cropland covers about 20% of the study area, fallow and rocky/barren areas cover about 8% each, and built-up areas cover less than 5% of the study area. The land use/land cover map shows that the middle section of the research region has the largest potential for groundwater.

Slope

The slope of an area represents the angle at which the ground surface is slanted. The slope, like height, has a direct influence on surface runoff, which in turn impacts infiltration and groundwater recharge rates in the area. A location with high slope gradients will have high surface runoff and low infiltration rate, whereas a low slope gradient will have low surface runoff and high infiltration rate, allowing for a high rate of groundwater recharge and water storage within the aquifer. The research region has a slope gradient ranging from 0° to 41.1°. In general, the slope map (Figure 5b) of the research area reveals that the area has a low gradient, with the exception of some parts in the centre region. This means that surface runoff in the research region will be low, allowing for substantial infiltration. The slope map reveals that the research region has a high potential for groundwater.

Soil

Groundwater recharge is influenced by soil texture, porosity and grain size. Soil condition can have a significant impact on water infiltration. The soil composition of the research area includes ferruginous loam soil, ferruginous sand, ferruginous tropical soil, and silty sand soil (Figure 6). A variety of factors influence soil formation including climate, parent rock, vegetation, wildlife, and physiography. These elements also influence runoff and infiltration, which recharge groundwater. The ability of a given soil to hold and enable water penetration is determined by its type and permeability. According to the soil map, the southern portion of the research area has a soil type that allows for a high rate of infiltration, indicating a high groundwater potential zone in the region. The soil type in the northern part of the research region allows for a very slow rate of penetration; hence the groundwater potential is relatively low.

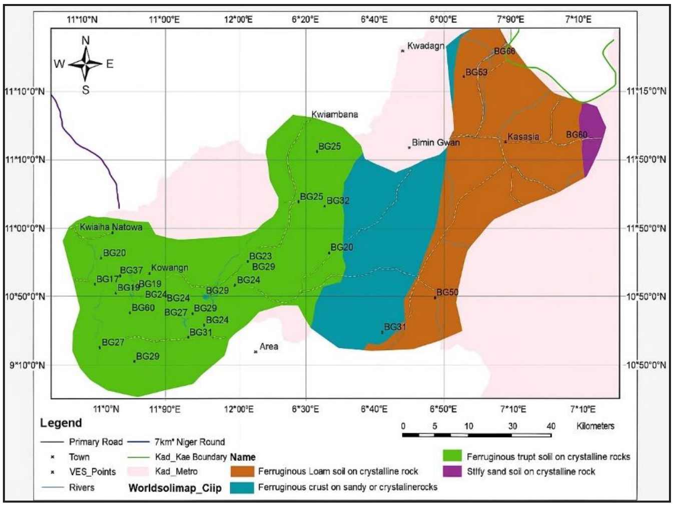

Figure 6: Soil map of the study area.

Groundwater Potential Zone Map

To compute the groundwater potential zones in sections of Birnin Gwari L.G.A., the thematic maps of the elements influencing groundwater recharge in the area were weighed and combined in the order proposed by Saraf & Choudhury (1998). Table 2 shows the weights of the groundwater regulating elements, whereas Figure 7 depicts the groundwater potential zones in the research region. Groundwater potential zones were delineated by reclassifying them into five categories: Very High, High, Average, Low, and Very Low, using the raster calculator in the ArcGIS spatial analyst tool. Rainfall was weighed the most (36%), followed by lineament (16.4%) and slope (14.5%). Soil and land use/land cover provide the least amount of groundwater in the study region, accounting for 7.0% and 4.8%, respectively (Table 2). Rainfall was assigned the highest weight in the AHP-derived parameter ranking due to its primary role in recharging basement aquifers. In basement complex areas, groundwater is largely derived from recent recharge via rainfall, given the lack of sedimentary storage or fossil aquifers. The seasonal distribution and intensity of rainfall directly influence the amount of water that percolates into the fractured and weathered zones of the subsurface. Therefore, areas receiving higher rainfall generally exhibit greater groundwater potential, particularly where other factors such as slope and soil support infiltration. This rationale is supported by findings in similar basement terrains where rainfall consistently emerges as a dominant factor in groundwater potential mapping (Saaty, 1980; Obot *et al*., 2017; Akinlolu *et al*., 2020).

The map created shows that the groundwater potential of the research area is primarily determined by rainfall, lineaments, geology, slope, soil, drainage, and landuse/landcover. The map also shows that the places with the highest groundwater potential are in the south, while those with the

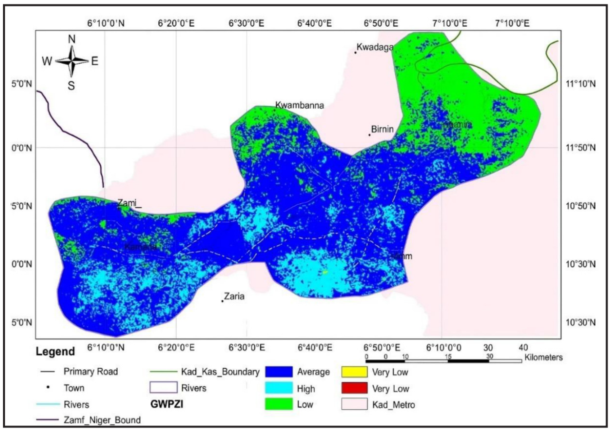

Figure 7: Final Groundwater Potential Zone map of the study area.

Table 2: Parameter estimate for each thematic layer using AHP.

	Criterion Comment	Weights	+/-
1	Annual Rainfall	36.0%	8.1%
2	Lineament Density	16.4%	8.0%
3	Drainage Density	11.8%	4.5%
4	Slope	14.5%	4.9%
5	Land Use / Land Cover	4.8%	2.3%
6	Geology	9.5%	4.0%
7	Soil	7.0%	3.3%
8	For 9 & 10 unprotect the input sheets and expand the question section (**in row 66)	0%	0%
9		0%	0%

Result	Eigenvalue Lambda: 7.510	41.2%
	Consistency Ratio 0.06 GCI 0.23 Psi 5.7% 6.3%	6.3%

lowest potential are in the north. The developed thematic maps show that locations with the greatest groundwater potential in the south and southwest are characterized by high lineament density and flat or mild slopes.

Table 3 and Figure 8 shows the areal coverage of groundwater potential zones and the percentage coverage of the potential zones respectively; which implies that very high groundwater potential occupies 4.97 km^2 (0.10%) of the study area; high potential zones occupy approximately 786.32 km^2 (15.83%) of the study area; average potential areas occupy 3018.13 km^2 (60.75%); and low and very low occupy approximately 1147.44 km^2 (23.10%) and 10.92 km^2 (0.22%) of the study area, respectively.

Validation of results

To validate the groundwater potential model developed using the Analytic Hierarchy Process (AHP), Receiver Operating Characteristic (ROC) analysis was employed. The AHP-based potential map was first reclassified into binary categories representing presence or absence of groundwater potential. Ground truth data points were then overlaid on the map to extract corresponding model-predicted values. Using the extracted values from the model output and randomly generated background points, ROC curves were plotted, and the Area Under the Curve (AUC) was computed. The AUC provides a single measure of model accuracy: values closer to 1.0 indicate better predictive performance, while values around 0.5 suggest no better than random guessing (Melese & Belay, 2021). In this study, the ROC analysis was conducted using GIS software and statistical packages, such as ArcGIS (Pedregosa *et al.*, 2011). The resulting AUC was 0.82, indicating a good level of agreement between the model and actual groundwater locations. The ROC-based validation yielded an AUC value of 0.82, confirming the effectiveness of the AHP model in predicting groundwater potential zones within the study area. This level of performance reflects a strong correlation between the derived groundwater potential classes and actual borehole and spring distributions. The validation supports the use of AHP as a reliable multi-criteria decision-making technique for hydrogeological modeling in basement complex terrains. Figure 9 shows the ROC curve used to validate the predictive performance of the AHP model. The similar AUC value (0.829) reported by Melese & Belay (2021), in groundwater potential assessment supports the reliability of using ROC and AUC for spatial model validation in hydrogeological studies.

Also field validation of the results from the GIS and remote sensing from parts of the study area was carried out using Vertical Electrical Sounding (VES) data. The VES method which measures the subsurface resistivity is a reliable indicator of groundwater potential. For this validation, VES data from 30 different locations were employed. The hydraulic conductivity values were estimated from the subsurface resistivity using the equation as given by Heigold *et al*. (1979) (Table 4).

$$\text{Hydraulic conductivity, } K = 386.40\, R_{rw}^{-0.93283} \text{ (m/day)}$$

Where R_{rw} = aquifer resistivity.

While the transmissivity was estimated using the formula;

$T = Kb$

Where T = Transmissivity; K = hydraulic conductivity; b = aquifer thickness

The transmissivity values were subsequently used to validate the result. The rating of Todd (1980) was used to generate the different groundwater potential ratings (Figure 10) which classifies the groundwater

Table 3: Areal coverage of groundwater potential zone.

Groundwater Potential Zone	Area (km^2)
Very low	10.92
Low	1147.44
Average	3018.13
High	786.32
Very high	4.97

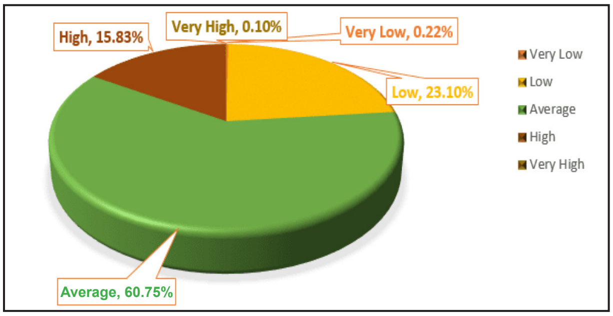

Figure 8: Pie chart distribution of groundwater potential within the study area.

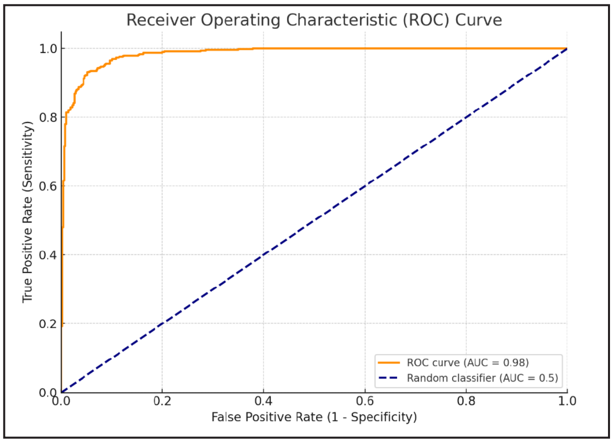

Figure 9: ROC curve showing the predictive performance of the AHP-based groundwater potential model.

Table 4: VES Data with the calculated hydraulic conductivity and transmissivity values.

VES ID	Location	Coordinates		No of Layers	Resistivity (Ωm), ρ					Thickness (m), b				Hydraulic Conductivity (m/day)	Transmissivity (m^2/day), T	Groundwater Potential based on Transmissivity
		X	Y		ρ1	ρ2	ρ3	ρ4	ρ5	T1	T2	T3	T4			
BG1	UngwanMadaki	6.335	10.731	4	250	460	74	113	4500	2	5.2	10	24.3	4.697	114	Good
BG2	Shada	6.285	10.679	4	373	81	900	34	2000	1.4	2.5	4.3	51.1	14.402	736	Good
BG3	Ungwan Musa	6.254	10.619	3	140	0	650	85	3400	1.8	0	7.4	45	6.127	276	Good
BG4	Shada	6.241	10.69	4	400	43	760	68	3500	1.3	2	8.6	42	7.544	317	Good
BG5	UngwanMadaki	6.385	10.725	4	152	390	65	100	3100	1.3	7.9	9.6	23	5.265	121	Good
BG6	Kandagi	6.183	10.695	4	228	158	775	130	9999	0.5	1.8	8.5	22	4.122	91	Intermediate
BG7	Ungwan Musa	6.244	10.637	4	250	652	3500	39	5000	0.1	1.1	2.1	20.1	12.672	255	Good
BG8	Karauchi III	6.198	10.63467	4	311	370	270	57	2500	0.8	3.2	9.5	53	8.894	471	Good
BG9	Shiryo	6.179667	10.60833	4	3700	60	600	85	5400	4	7	16.5	39	6.127	239	Good
BG10	Kimbi	6.195667	10.65067	4	750	220	420	97	2000	0.6	1.5	5.8	49	5.416	265	Good
BG11	Kimbi	8.1815	10.65	3	290	0	153	70	4500	0.5	0	2.7	23	7.343	169	Good
BG12	Shiryo	6.161	10.569	4	157	77	350	219	5660	0.1	2	5.7	26.2	2.534	66	Intermediate
BG13	Kimbi	6.192333	10.65983	4	320	190	784	114	3000	0.4	1.6	5.1	42.1	4.659	196	Good
BG14	Kandagi	6.21	10.70983	3	1700	0	700	63	2200	1	0	3.6	25	8.101	203	Good
BG15	Kunun Gaya	6.149833	10.679	4	540	155	56	173	1800	0.4	2.9	7	21.5	3.157	68	Intermediate
BG16	SarkinPawa	6.178333	10.723	3	540	0	65	90	1000	7	0	10	60	5.808	349	Good
BG17	Kandagi	6.243	10.729	4	160	450	150	55	3000	2	4	10	18	9.195	166	Good
BG18	UngwanMadaki	6.311	10.717	3	112	0	890	110	3251	0.4	0	11	21.5	4.817	104	Good
BG19	Ungwan Musa	6.274	10.619	4	550	90	3100	112	3000	0.2	0.9	2.9	34	4.737	161	Good
BG20	SabonLayi	6.352	10.64633	4	102	50	380	95	3000	1.5	3	10	27	5.522	149	Good
BG21	UngwanJatua	6.379	10.58	4	365	110	400	78	5500	1.8	7.1	12.6	27	6.638	179	Good
BG22	UngwanJatua	6.329333	10.58483	4	1065	820	37	90	1500	0.4	14	24.7	53	5.808	308	Good
BG23	SabonLayi	6.314	10.665	4	356	800	290	128	1000	0.3	0.8	2.5	25	4.182	105	Good
BG24	UngwanZakora	6.275	10.588	4	807	395	44	120	700	1.4	8.8	4.6	12.2	4.441	54	Intermediate
BG25	Kwigo	6.302333	10.55667	4	400	30	1200	50	1000	0.3	0.8	2.5	25	10.050	251	Good
BG26	TasaunKegi II	6.391	10.66517	4	1500	150	320	60	9999	1.1	5	10	23	8.479	195	Good
BG27	UngwanZakora	6.298833	10.59783	3	293	0	520	120	2000	0.3	0	0.9	21	4.441	93	Intermediate
BG28	Ungwan Musa	6.301667	10.628	3	380	0	650	65	9999	1.5	0	4	25	7.869	197	Good
BG29	Kanamo	6.3075	10.6115	4	1000	850	1000	120	850	0.4	2.5	10	25	4.441	111	Good
BG30	Shiryo	6.232	10.577	4	50	170	1000	75	1000	0.5	2	4.5	50	6.885	344	Good

potential of the region as intermediate and good as the value ranges from 54 m^2/day to 736 m^2/day (Table 4). 83.22% of the study shows good transmissivity which is important for groundwater accumulation, while 16.7% shows intermediate transmissivity which falls within the region of low to very low accumulation potential zones.

Overall, it has been established that the validation process demonstrated that the integrated use of remote sensing and GIS provides a reasonable framework for delineating groundwater potential zones. The result highlight the method's potential to support groundwater exploration and management, although, further refinement and incorporation of additional subsurface data could enhance predictive accuracy.

Comparing the final GWPZ map and the transmissivity map, it can be observed that the area with good ratings on the transmissivity map falls within the high and average zones in the final GWPZ map This further validates the use of spatial data in the delineation of groundwater potential zones.

Comparison with other studies

The final result from this study was compared using existing studies on groundwater accumulation potential within Kaduna state and other regions and these have been summarized in Table 5.

All these researches have shown the importance of all the factors which has enhanced the groundwater potential

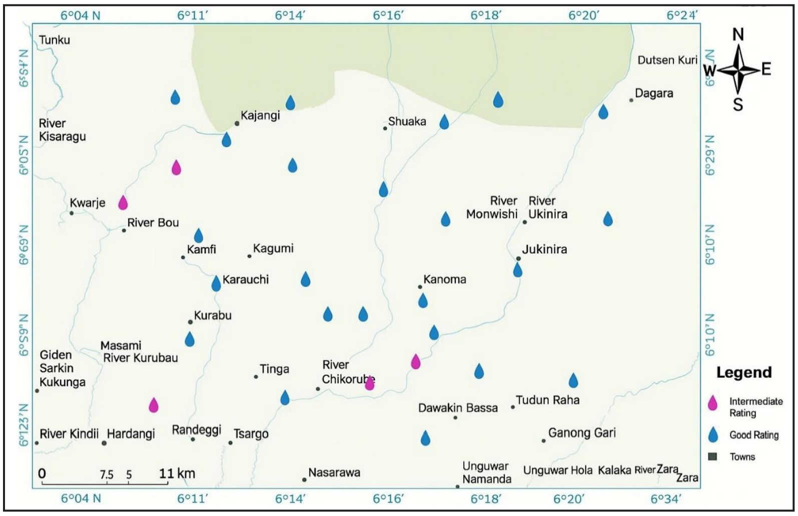

Figure 10: Transmissivity map of the study area.

Table 5: Comparison with findings from previous researchers.

Authors	Location	Key Influencing Factors Identified	Findings on Groundwater Potential Zones	Relevance/Comparison with Present Study
Siraj *et al.* (2024)	Ethiopia	Lithology and rainfall	The central part of the basin had moderate potential, good to very good areas are identified with gentle slope	Agrees with present study on importance of lthology and rainfall
Alimi *et al.* (2022)	Kaduna State, Nigeria	Geology	Western region showed high to very high potential; geology was the dominant factor	Supports present study's emphasis on geology and confirms high potential zones in overlapping area
Clarance *et al.* (2022)	Tanzania	Lithology	The GWPZ map of the region, where the good recharging zone is shown, is explained by the existence of high alluvial red soil in plain areas with high to extremely high lineament densities	Supports the present study in considering lithology as one critical factor to enhance recharge and infiltration
Tariku *et al.* (2025)	Ethiopia	Rainfall, lithology, linearment density and drainage density	Spatial distribution of GWPZ in the Ziway Lake Watershed is closely linked to lithological characteristics and physiographic features	Reinforces present study's conclusion on the influence of rainfall on groundwater potential
Melese & Belay (2021)	Ethiopia	Rainfall and slope	High potential in Kutye basalt because of the lithology such as eluvial in Muga watershed	Aligns with present study by highlighting rainfall as major contributor

evaluation of the different research areas, this analysis is also applicable to this present study.

CONCLUSIONS

Seven thematic maps of factors contributing to groundwater recharge were created and integrated in an ArcGIS environment using a weighted sum overlay in the spatial analyst tool; and the groundwater potential zone in parts of Birnin Gwari Local Government Area was divided into five categories: very high, high, average, low, and very low. The weights of the elements impacting groundwater prospects suggest that rainfall and lineament density were weighed the most (36% and 16.4%, respectively) due to their primary role in recharging basement aquifers. The results of the study from the processed remote sensing and GIS data show that very high groundwater potential zones occupy a coverage of about 0.10%, high groundwater potential constitute 15.83%, average groundwater potential occupies 60.67%, and low and very low constitute 23.10% and 0.22% of the research area respectively. The study found that the extremely good groundwater potential zones are in the south and southwest of the study region. This study also found that there is significant regional diversity in groundwater potentiality within the studied area. The rainfall, slope, drainage density, lineament density, geology, and soil of the research area all showed significant heterogeneity. The most desirable prospective zone in the area is characterized by high annual rainfall, high lineament density, low drainage density, and a low slope. The majorities of zones with fair to poor groundwater potential receives little rainfall, and are located far away from lineaments, and have a high slope.

In order to validate the accuracy of the delineated groundwater potential zones, VES data from 30 locations within the study area were used to generate resistivity curves and the transmissivity values which were used to delineate groundwater accumulation potential for the study area. The spatial relationship of GIS and VES in groundwater exploration is synergistic: VES provides critical subsurface data at specific points, while GIS enables the spatial extrapolation, integration and visualization of this data across large areas. This study therefore enhances sustainable groundwater management by identifying potential accumulation zones using geospatial methods, aiding water resources planning, reducing drilling failures and supporting climate resilience and rural water access. It is recommended that surface water development in the difficult low to very low groundwater potential region (at the north to the north-eastern region of the study area) against the prevailing groundwater development so as to help habitat around the area access to sufficient water. This will include the construction of dams and reservoirs, ponds and tanks etc. to meet the need of the populace for domestic and agricultural use.

Limitation and further studies

All studies and research work have limitation(s) which will allow for further studies. The limitations in this research work are:

(i) Limited Depth Penetration: The Remote sensing data acquired for this study is limited to near-surface features captured in the satellite imagery and therefore lacks depth penetration. Subsurface parameters crucial for groundwater studies like aquifer thickness, transmissivity, hydraulic conductivity, hence the study integrate the use of geophysical survey (VES).

(ii) High Cost of High-Resolution Data: High resolution satellite data is expensive, which results to this study been carried out with a mix of the free available data and a little of higher resolution data.

Further studies which can be carried out to improve on this research include:

(i) Integration with Geophysical and Borehole Data: Further studies can focus on integrating GIS and RS with geophysical surveys (e.g., Vertical Electrical Sounding, Electromagnetic, and Seismic methods) and borehole data. This would enable a more accurate assessment of subsurface aquifer properties such as depth, thickness, porosity, and water-bearing capacity.

(ii) Development of Dynamic Groundwater Monitoring Systems: Further studies can be directed toward developing real-time or near-real-time monitoring frameworks by integrating remote sensing with Internet of Things (IoT) sensors and telemetry systems. This would provide continuous updates on groundwater conditions and address the lack of temporal validation.

(iii) Use of High-Resolution Commercial Satellite Imagery: Further studies should assess the cost-benefit of using high-resolution commercial datasets versus freely available data to optimize the balance between quality and affordability.

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AUTHORS CONTRIBUTION

OIM: Software, formal analysis, conceptualization, investigation, IOO: validation, review and editing, supervision, OOL: methodology, project administration, resources, writing original draft, visualization.

DECLARATIONS

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