Assessment of groundwater recharge potential in a typical geological transition zone in Bauchi, NE-Nigeria using remote sensing/GIS and MCDA approaches

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ABSTRACT

The increasing demand for water occasioned by harsh climatic conditions, population explosion, and increasing urbanization has necessitated more attention and reliance on groundwater resources, particularly in water-limited regions. Thus, judicious management of available groundwater resources becomes crucial to meet the freshwater requirements in such zones. In this study, remote sensing and geographic information system were deployed to delineate groundwater recharge zones in semi-arid geological transition zones of Bauchi, northeastern Nigeria. Seven thematic layers comprising elevation, slope, land use/land cover, drainage density, lithology, magnetic lineament density, and hydraulic head were integrated based on their degree of influence in groundwater recharge. Normalization of the weights was achieved through the analytical hierarchical process (AHP), while the overall integration of the thematic maps was actualized by overlay analysis in ArcGIS 10.3.1 environment to generate a final groundwater recharge zone map of the area.

The resulting map was delineated into three different zones: low, moderate, and high, occupying 20% (627 km²), 77% (2352 km²), and 3% (80 km²) respectively. The overall assessment of recharge zones revealed that a high percentage of the southwestern part of the study are characterized dominantly by poor groundwater recharge potential, attributable to high elevations and impervious rock outcrops with associated steep slopes, thus limited infiltration owing to the high velocity of runoff. The northwestern and parts of the southwestern zones, underlain by migmatite/gneiss, and partly granites, however, exhibited medium-low recharge potential, owing to the occurrence of considerably lower altitudes and occupied by thicker regoliths and underlying rocks of medium-high lineament densities. The sandstones revealed predominantly medium-high recharge potential, attributable to high permeability, lower hydraulic heads, and relatively flat geomorphology which enhances meteoric recharge and base flow processes.

1. Introduction

Groundwater utilization is consequential in meeting the demand of increasing urbanization, rapid industrialization, population growth, and agriculture, especially in arid and semi-arid regions. In terms of volume, the World’s groundwater resources are about 33 times greater than the surface water resources from lakes and rivers (Healy et al., 2007). Consequently, groundwater has become a major component of water management in most rural communities in arid and semi-arid zones. Unlike the surface water resources, groundwater can be located close to the point of need, it has good quality, and it is resilient to the changing climatic conditions. Understanding groundwater recharge is thus very consequential for efficient and sustainable management of groundwater resources (De Vries and Simmers 2001).

Recharge refers to the seeping of water to the water table, thereby replenishing the groundwater reservoir. This mechanism entails the downward drag of excessive soil water (above soil moisture) which occurs in permeable soils and rocks when the rate of infiltration exceeds runoff and evaporation. Recharge areas are regions where water can infiltrate or percolate into the subsurface to replenish aquifers, owing to the absence of a confining layer. In most cases, these zones usually occur in basins, depressions, or valleys. Average recharge in sedimentary basins

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in typical arid to semi-arid zones, (with a mean annual rainfall of 500–550 mm), ranges between 10 mm/year to 30 mm/year in alluvial loamy sediments and coarse-grained sediments (De Vries et al., 2000). According to Issar and Passchier (1990), arid regions with permeable soil or pervious-rock outcrops have recorded regional recharge of a few millimeters per year. Furthermore, recharge areas are very consequential for the overall quality of an aquifer system, and in most cases, such areas are usually protected by laws. Determining the magnitude and location of recharge is critical to the understanding and management of groundwater systems (De Vries and Simmers, 2001; Gleeson et al., 2012). Due to the generally water-limited nature of arid and semi-arid zones, several studies have focused on estimating meteoric recharge to manage the groundwater resources (Simmers, 1997, 1998; De Vries et al., 2000; De Vries and Simmers, 2001; Gleeson et al., 2012).

Groundwater recharge is controlled by an interplay of factors, which include climate, hydrology, land use and land cover, geology, geomorphology, geological characteristics, and structural disposition (Kumar et al., 1999; Mohamed et al., 2015). In semi-arid areas, where evaporation rates generally exceed precipitation, the meteoric recharge is governed by a high frequency of rainfall and in high amounts. Also, suitable topographic slope and elevation (marked by depressions and basins) coupled with permeable rock surfaces are crucial. Recharge is retarded by argillaceous soils, which are generally aquitards with the ability to retain storage during the wet season. Conversely, permeable soil or crystalline rocks coupled with high amounts of rainfall, create favorable conditions for recharge (Sener et al., 2005; Solomon and Quiel, 2006). Furthermore, slope gradient affects the percolation of meteoric water. Steep slopes generally reduce recharge as runoff flows very rapidly and would not permit infiltration. Plains, however, enhance groundwater recharge because higher retention time is provided for rainwater to infiltrate the soils. The role of geology and geomorphology in groundwater recharge in semiarid areas is demonstrated by studies comparing the Kalahari sands and adjoining Precambrian basement rocks in Botswana (De Vries 1997; Selaolo 1998; De Vries et al., 2000). Also, the impact of land use is well documented in Niger, where, rise in groundwater recharge from 5 mm/year to 20 mm/year occurred as a result of removal of vegetative cover, resulting in enhanced recharge (Leduc et al., 2001). In light of the above, a good integration of field data, remote sensing, and GIS technology offers promise for a better understanding of recharge in vast areas owing to their efficacy in generating and analyzing Spatio-temporal data (De Vries et al., 2000). Consequently, several works have been conducted in water-limited arid and semi-arid areas of the globe to delineate groundwater potential zones and natural or artificial recharge potential zones through application geospatial techniques. Many of such studies have employed the geospatial tools to analyze representative thematic maps although, weight assignments have been based on personal discretion and judgment (Madrucci et al., 2008; Dar et al., 2010). Other researchers have gone a step further to apply probabilistic models such as Dempster-Shafer theory and frequency ratio, for groundwater potential mapping (Oh Hyun et al., 2011; Mohamed et al., 2014 and Mogaji et al., 2015). Similar methodologies have been employed in delineating potential zones for recharge (Sener et al., 2005; Solomon and Quiel, 2006; Tweed et al., 2007; Yeh et al., 2009).

The study area (Bauchi, SE) is rural to a peri-urban zone which lies within the semi-arid zones of northeastern Nigeria. It is drained by the Gongola River (a major tributary of the Benue River). Most of the tributaries of the river are seasonal streams that become over flooded at the peak of the wet season and dry up in the dry season. The maximum rainfall in the Bauchi area is recorded in August (500 mm) and sometimes in July (450 mm), while the lowest (<100mm) in April and October (Ruba et al., 2015). Temperatures of close 40 °C are sometimes experienced in the area in the extreme dry season. Monthly temperatures vary between 25°C to 33°C in December and February, respectively. These adverse weather conditions (low rainfall and high temperatures) periodically bring about drought conditions in the area. This paucity of surface water resources has intensified the reliance of the populace of the study area on groundwater for their domestic, agricultural, and industrial uses. The sporadic nature of groundwater availability in geological transition zones exacerbates the problem (Lawal et al., 2020). Judging by the nexus between water security and food security, there is a great need to protect and sustainably manage groundwater resources. Given that groundwater is a consequential lifeline in semi-arid zones, understanding its recharge is crucial for the safety and sustainable management of groundwater resources in such water-limited settings (De Vries et al., 2000).

While some hydrogeological, geophysical, and hydrochemical studies have been conducted in the study area to investigate groundwater (Umaru and Schoeneick, 1992; Ali et al., 1993; Nur et al., 2005; Shemang and Jiba, 2005; and Akaha and Promise, 2009), the geospatial technique which is a fast, cost-effective and dependable technique has not received much attention in the investigated area. Acworth (1987), pointed out that remote sensing data exemplified by Landsat images are available for most areas including the study area, however, the interpreted versions of this imagery are generally unavailable and that constituted serious limitation. In recent times, however, GIS techniques have been applied to reactivity data to delineate the groundwater potential zones in the study area (Lawal et al., 2020). Lithology, aquifer reactivity, and aquifer thickness layers were integrated in the GIS environment to develop a groundwater potential zone map which was validated with existing pumping test data from the area. The main objective of the present study, however, is to integrate remotely sensed/GIS data with aeromagnetic data, hydrogeological field data with multi-criteria decision analysis to delineate the groundwater recharge zones in the geological transition zones of Bauchi, and to finally develop a groundwater recharge map of the area. This objective was accomplished through the preparation of thematic maps for the 7 most influential factors as far as groundwater recharge is concerned. These thematic maps comprising lithology, lineaments, drainage, topography, slopes, land use/land cover, and hydraulic head were integrated in the GIS environment. Re-examination of well-pumping test data and geophysical data (JICA, 2009; Lawal et al., 2020) were used to validate the groundwater recharge map generated.

2. Description of study area

The study area is an integral section of northeastern Nigeria and covers a land area of 3025 km² (Figure 1). It lies within the Alkalere topographic sheets 150 SW and 150 SE. In terms of geomorphology, it is characterized by generally low to moderately high relief zones (275–706 m above sea level). The Mansuri River drains the eastern parts of the study while the Yashi River drains the southwestern parts. The pattern of rainfall in the study area is similar to those of other West African countries, in that precipitation generally originates in the south and is propelled by the prevailing winds from the southwest, resulting in an increasing dryness northwards, which ultimately triggered the desert condition in the northern fringes.

The monthly distribution of mean relative humidity in Bauchi area shows a close similarity with the rainfall distribution, which is unimodal. The relative humidity in the area is usually low (20–40%) during the first quarter of the year (January to April) before it starts ascending from the month of May and reaches its peak (80%) in August, after which it begins to descend up to about 30% in December. The vegetation is typically Sudan Savannah type characterized by widely dispersed trees and shrubs (Acworth, 1987). The Sudan Savannah covers 25% of northern Nigeria and borders the Niger Republic. The geology of the area has variously been presented elsewhere (Dike 1993; Ferre and Caby, 2007; Dada, 2006; Obaje, 2009; Lawal et al., 2020). However, brief highlights of the geological makeup are elucidated. The migmatite and gneissic rocks are the country rocks in the area, which were intruded by granitic rocks during the Pan-African episodes (Lawal et al., 2020). The meta-sedimentary units associated with the crystalline basement rocks also underwent charnockitization during the Neo-Proterozoic period (Ferre and Caby, 2007). The sedimentary zones are, however,
represented by the Kerri-Kerri Formation. The youngest in the series of depositions in the Northern Benue Trough of Nigeria. The formation comprises a series of alluvial fan, braided rivers, and lacustrine sedimentary sequences deposited in the Paleocene. The Kerri-Kerri Formation is a continental sequence characterized by medium to coarse-grained sandstones, pebbly coarse grits and inter-beds of sandy gravels, medium to fine sands, clays, and siltstones (Dike, 1993). The Formation exhibits fining upward sequences in most parts but coarsening upward sequences have been reported at Mainamaji and Duguri in the southeastern regions of the study area (Dike, 1993).

According to Lawal et al. (2020), the Basement Complex zones of the study area comprised of three to four geoelectric layers, which include topsoil, weathered basement rock (clayey sand saprolite), fractured basement rock (in some cases), and fresh bedrock. The saprolites and saprocks constitute the main aquiferous zones in the crystalline basement zones. In the sedimentary zones, 3 to 5 hydrostratigraphic zones have been reported. They consist of a topsoil layer, three sandstone layers of varying grain sizes, and an infinite bedrock has been documented (Figure 2). The main aquifer (third unit) consists of saturated fine to coarse-grained interbedded sandstones. The second hydrostratigraphic layer is made up of a partially saturated sandstone aquifer, while the fourth layer is composed of a mixture of clay with basal conglomerates, clayey sand, and sand. The occurrence of basal conglomerates in this layer indicates possible zones of non-conformity between the Kerri-Kerri and the basement rocks (Dike, 1993). The aquifers generally grew thicker and more arenaceous away from the contact zone (Lawal et al., 2020). The general direction of groundwater flow through the aquifers in the study area is shown in Figure 2. The figure is a three-dimensional representation of individual hydraulic heads calculated from water level and well elevation measurements from wells across the study area. From the 3D model, it can be observed that the groundwater flow in the basement terrain is somewhat erratic or irregular as compared to the hydraulic gradients in the sedimentary setting which, are more uniform (flow is northwards and southwards). The undefined pattern observed in the basement terrain is due to the rugged topography and the limited interconnectivity within the basement aquifers. However, on a general note, the groundwater flows from the undulating basement terrain in the west to the flatter sedimentary zones in the east, although, when the terrains are considered separately the direction of groundwater flow is from south to north.

The yield of boreholes in the basement aquifers ranges from 0.1-1 L per second but could be considerably higher where the saprolitic units are sufficiently thick and underlain by well-developed saprock units (Anudu et al., 2014; Tijani et al., 2016). Tijani et al. (2016), reported that the Kerri-Kerri Formation falls under the consolidated sedimentary rocks hydrogeological setting, which are known to support high yield wells (10–50 l/s). Borehole data from the sedimentary zones indicates that the aquifers are fine to coarse sand. They are argillaceous or gravelly at depths of between 20-155metres, depending on the topography of the location. Borehole data from the northeastern zones of the sedimentary basin, however, suggest that the aquifers are more arenaceous (sandy) in nature (Dike, 1993).

3. Materials and method

This section is divided into two as the name implies, the first aspect covers the description of the materials or dataset and software used for
the second aspect captures the analytical hierarchical process, weight assignment, integration of thematic maps, and validation of the overall groundwater recharge map.

### 3.1. Preparation of input data/thematic maps

In line with the objectives of the present study, the under listed datasets and software were utilized:

- Landsat-7 satellite image (30 m resolution), acquired from National Centre for Remote sensing, Jos, Plateau State
- Digital Elevation Model/DEM from ASTER satellite (ASTER/GDEM), horizontal spatial resolution 30 m, acquired from National Centre for Remote sensing, Jos, Plateau State
- Digital Elevation Model/DEM from SRTM satellite, horizontal spatial resolution 90 m.
- Topographical map of the research area (Alkaleri topographic sheets 150 SW and 150 SE on 1:100,000 scale, source: Bauchi State Ministry of Lands and Survey)
- Geological map covering the study area (Sheets: 1:100,000 scale, source: Nigerian Geological Survey Agency/NGSA).
- Aeromagnetic data acquired by Fugro on behalf of Nigerian Geologic Survey Agency between 2001 – 2009 (Sensor mean terrain clearance of 80 m with a flight line spacing of 500 m and tie line spacing of 5000 m)
- Groundwater level measurements and Well elevation measurement from over 80 wells (acquired in the course of the study)
- Oasis Montaj Geosoft software
- GIS software: ArcGIS 10.3.1.

The techniques employed in creating and processing the thematic maps are summarised in Figure 3. The Landsat 7 image (8 bands) was imported to the Arc map, after which the bands were converted into a composite map using the image analysis tool of the ArcGIS software. The composite map was classified using supervised classification through band classification (a combination of bands). For example, bands 4-3-2 represent the natural color of the terrain, bands 5-6-4 are for water bodies and bare lands; while 5-4-3: (infrared color combination) indicates vegetation. With the aid of the image classification toolbar, training samples were created (by the selection of the region of interest) using all the different band combinations. A signature file was prepared from the training samples and used to classify the image. The resulting land use/land cover map was classified into built-up areas, forest, waterbody, shrublands, and bare land.

The ASTER DEM was initially imported to the Arc map environment using the “Add tool” function. The elevation function of the spatial analyst tool of the ArcGIS 10.31 software was used to generate the elevation map of the study area. The elevation is consequential as it reflects the ruggedness of the terrain and it is a function of the steepness of the topographic gradient. It also controls the hydraulic gradients of an area. Furthermore, elevation determines the direction of flow of surface runoff and influences meteoric recharge (Jha et al., 2010; Magesh et al., 2012). The SRTM image was used to produce the slope map of the area, using the slope function of the spatial analyst tool. In line with the objective of the present study, slope plays a vital role in the infiltration of rainfall, hence, groundwater recharge.

The topographical and geological maps were scanned, imported into ArcGIS 10.1, and georeferenced to the UTM/WGS84 projection system, unlike the digital satellite images. The rivers and stream channels in the topographical map were digitized to produce a drainage map which was updated using the ASTER DEM satellite image and the land-use map generated. The drainage density map was generated using the line density feature of the spatial analyst tool of the ArcGIS, which calculates the density of input features within a neighborhood around each output raster cell. The significance of the drainage map lies in the fact that the drainage characteristics of a region provide information about the permeability of rocks and also give a general idea about the groundwater yield in the area (Fashae et al., 2014). The already scanned and georeferenced geology map was digitized using the ArcGIS software. The digitization entails using polygons to demarcate the different lithological units that constitute the geology with the overall aim of producing a thematic layer for lithological units in the study area. Furthermore, a magnetic lineament map of the study area was generated from high-resolution aeromagnetic data (HRAM) of Nigeria. To achieve this, a horizontal component of tilt derivative was obtained and used as a starting grid for lineaments extraction because of its independence to inclination and declination similar to the analytic signal. Linear structures of basement origin within the study area were extracted using the Centre for Exploration Targeting (CET) grid analysis tool (extension) of Oasis Montaj Geosoft software using step by step edges method of detection. Also, a hydraulic head thematic map of the study area was generated from information gathered from 80 dug wells and boreholes spread across the different rock units in the study area. The data measured from the wells include depth of well, depth to water level, and well elevation. The hydraulic head was calculated by subtracting the water table depth from the well-head elevations. The geographical coordinates of the wells and the hydraulic head values were compiled in a Microsoft Excel spreadsheet and imported to the ArcGIS environment.

![Figure 2. Three-dimensional elevation model showing the (a) aquifer geometry and (b) the hydraulic head distribution and groundwater flow directions in the study area.](Image)
where the data was interpolated using the kriging technique to produce a hydraulic head distribution map of the study area.

### 3.2. GIS operations and methodological approach

Following the creation of the seven thematic maps, other GIS operations followed and this includes; weights assignment and normalization (AHP), conversion of thematic maps to a raster format, reclassification integration of thematic maps, testing/validation of the aquifer recharge zone map. The methodology employed for GIS operation and data analysis summarized in a flowchart (Figure 3) and discussed in the following paragraphs. Suitable weights were assigned to the thematic maps based on their influence or contribution to groundwater recharge as shown in Table 1. Assignment of weights to the thematic layers has been observed to bring about some bias into the analysis since it is somewhat subjective, for example, when personal judgment is used in weight assignment. This is so because in dealing with multi-criteria problems, there is a need to deploy a level of consistency to avert giving an undue advantage to some themes while others are understated. Consequently, a multi-criteria decision analysis (MCDA), specifically the AHP, developed by Saaty (1980), 1986, & 1992, was deployed to normalize and introduce check and balances in the decision-making process and thus, increasing the degree of consistency of the judgments (Fashae et al., 2014). The AHP is a simple mechanism based on a numerical matrix that enables users to logically analyze the relative strength of multiple criteria in several hydrogeological studies dealing with suitability analysis (Jha et al., 2010). In doing so, the thematic layers were assigned weights ranging from 1-9, according to their influence on groundwater recharge and based on similar existing literature on the subject (Mukherjee et al., 2012; Fashae et al., 2014). To implement this, all the selected factors were subjected to a pairwise comparison with each other as outlined in Saaty (1986), and 1992 (Table 2). In the pairwise comparison table, a value of 9 denotes that a row factor is much more suitable (significant) than the column factor with which the comparison was made.

![Figure 3. Flowchart showing the methods involved in GIS mapping of aquifer recharge zones.](image)

| Themes                | Assigned Weight | Normalized Weight |
|-----------------------|-----------------|-------------------|
| 1 Lithology           | 9               | 0.20              |
| 3 Lineament density   | 8               | 0.18              |
| 4 Slope               | 5               | 0.11              |
| 5 Elevation           | 6               | 0.13              |
| 6 Land use/cover      | 7               | 0.16              |
| 8 Hydraulic head      | 6               | 0.13              |
| 9 Drainage density    | 4               | 0.09              |
Conversely, a value of 1 implies that factors are of the same significance. Fractions indicate that a factor is less influential than the factor with which it is been paired. The conversion of the thematic maps to raster format followed. In doing so, maps that were in vector format (drainage density and lithology) were converted to raster to homogenize the layers before reclassification in line with the AHP results. The final integration of the maps was through the weighted overlay technique. The overlay technique involved the integration of the thematic maps. The ranks of individual cells that constitute the rasters were multiplied by the weight assigned to the themes. The resultant values were then summed to obtain overall suitability values, which will be reflected in the cells of the final output layer (Eastman 2001; Ndatuwong and Yadav, 2014). The final map was delineated into good, moderate, and poor aquifer recharge zones. The validation of the aquifer recharge map of the area was done with existing geophysical and pumping test data (JICA, 2009; Lawal et al., 2020).

4. Results and discussion

Seven thematic maps were produced from the remote sensing/GIS assessment, namely: land use/land cover, slope, elevation, drainage lithology, lineament, and hydraulic head. Given the overall goal of this research, which was to define groundwater recharge zones, the parameters were carefully considered based on their role in groundwater recharge. The thematic maps are presented in Figures 4, 5, 6, 7, 8, 9, and 10.

4.1. Description of input data

The land use/land cover (LULC) of an area influences the occurrence and recharge of aquifers in the area as it provides important clues about the level of utilization and requirement of groundwater (Edet et al., 1997; Fashae et al., 2014). As revealed by the land use/land cover thematic map (Figure 4), five major land use/cover classes were delineated in the area. These include water body (3%), forest (17%), bare land (48%), and scrubland (31%), and built-up areas (1%), with the bare land being the dominant LULC in the area. Water bodies (streams and lakes) that constitute good sources of groundwater recharge are equally distributed in the basement and sedimentary zones of the study area. However, the vegetated areas and scrubland which predominate the sedimentary terrain are known to minimize runoff and enhances groundwater recharge. Bare land (rock surfaces or open bare soil surfaces), and built-up areas, generally lack vegetation cover and are not favorable for groundwater recharge.

The topographic slope of an area plays a key role in the movement of surface water and its subsequent infiltration into the subsurface (Fashae...
et al., 2014). The slope in the study area (Figure 5) is between 5% to >20%, which is a reflection of the variability of movement of run-off water and recharge which translates to differing aquifer recharge potential within the various lithological settings in the study area. In terms of recharge, the areas with the minimal slope (0–5%) which constitute 73% of the study area and predominant in the sedimentary zones, suggests more promising recharge areas compared to areas with moderately steep to very steep slopes in the Basement Complex setting (15–20%). Slope plays a vital role in determining the infiltration and percolation of rainfall. A high slope region gives rise to limited infiltration/recharge,
Figure 7. Drainage density thematic map.

Figure 8. Lithology thematic map.
and thus, would have poor recharge prospects. Gentle slopes, on the other hand, are associated with high rainwater infiltration and good groundwater recharge potential.

Elevation represents the height of a geographical location as measured from a fixed point of reference (a datum plane). The elevation map of the study area is shown in Figure 6. As shown in the figure, the elevation of the area ranged between 275-706m. Low-moderate relief areas, such as those found in sedimentary zones, naturally favor more groundwater recharge, while moderate-to-high relief areas, such as those found in the western half of the investigated region and made up
of large crystalline rocks, are more likely to have a high run-off. Drainage density refers to the proximity of stream channels and a measure of the overall length of the stream segments per unit area (Magesh et al., 2012). Drainage density is inversely proportional to the groundwater infiltration, thus a vital index in delineating groundwater recharge potential. The estimated drainage density in the study area as presented in Figure 7 indicated a dendritic and low-moderate density drainage network with values of 0.34 km/km² to highly dense networks greater than 1.72 km/km². The high drainage density areas (1.03–1.37 and 1.37–1.72) constitute about 106.7 km² (3.49 % of the total area), while the low drainage density makes up 2388.6 km² (78.05 %). The infiltration of rainwater into the subsurface to recharge the groundwater reserves is governed by certain petrophysical properties (porosity and permeability) of the rocks and formations that underlie the area (Sreedhar et al., 2009). The transmissivity of a rock is determined by its porosity and permeability. High transmissivity contributes to overall groundwater recharge. Consequently, unweathered and impervious Crystalline Basement rocks would generally have limited contribution to groundwater recharge. Conversely, deeply disintegrated crystalline rock units coupled with porous and permeable sedimentary formations would form potential groundwater recharge zones (Fashae et al., 2014: Lawal et al., 2020).

The lithology map of the area revealed four major rock types namely: migmatisite/gneiss, biotite hornblende granites, and bauchite (charnockite), representing the Basement Complex rocks and the Kerri-Kerri Formation, representing the Tertiary sedimentary units. The migmatite/gneisses cover about 30.07% of the study area (Figure 8) and occupy the northwest, central, and portions of the southwestern part of the study area, occurring in most cases as low-level outcrops. The gneisses are medium - fine-grained rocks with characteristic alternation of light-colored bands (felsic minerals) and dark-colored ones (mafic minerals). The biotite hornblende granites, underlie about 15.25% (466 km²) of the area and are exposed in the northern, western, and southwestern part of the investigated area and occurring as low level, medium, and high-level outcrops. The granites have intruded the migmatite/gneiss rocks and mostly form unweathered and impervious massive and impermeable rock types. As can be observed from Table 8, the hydraulic head in the study area was divided into five classes (292–356, 357–403, 404–457, 458–500, and 501–561 m). Considering that water naturally flows from a zone of the high hydraulic head to a region of the lower head along a hydraulic gradient, in the same manner in which heat would also flow towards lower temperature regions, higher ranks were assigned to the regions with the lower head, compared to the zones with higher hydraulic heads which were scored low.

4.2. Description of AHP results and overall integration of maps

The consistency ratio (C.R) obtained from the criteria utilized to delineate aquifer recharge zones within the study area was in tandem with the C.R threshold value of less than 0.1, proposed by Saaty (1986 and 1992). Using the AHP approach, the thematic layers were assigned individual weights of between 1 and 9 (Table 1), based on the assignment scale proposed by Saaty (1980), which indicates the relative contribution of the respective themes to groundwater recharge. The pair-wise comparison matrix of the thematic maps following Saaty (1986, 1992) is shown in Table 2. The normalized weights and ranks of the thematic layers and their subclasses are presented in Table 3. As shown in Table 3, elevations in the study area ranged between 275–706m and were grouped into five classes and given ratings in the range of 1–5. The highest rank of 5 was allocated to the lowest elevation (275–382m) while the lowest rank was allocated to the highest elevation (576–706m). Generally, low relief areas are more likely to enhance infiltration groundwater, whereas moderate to highly elevated zones, exemplified by the western half of the Bauchi transition zone, comprising the Basement Complex rocks, hence, ranked low. Sajjad et al. (2014), opined that areas with low elevations are characterized by more permeable and softer lithology, while high relief areas reflect massive and impermeable rock types. As can be observed from Table 3, the five major LULC classes identified in the area include water body (3%), forest (17%), bare land (48%), scrubland (31%), and built-up areas (1%), with the bare land being the dominant LULC in the geological transition zones of Bauchi. Water bodies (stream and lakes) are considered as good sources of groundwater recharge and ranked highest, while vegetation area and scrubland which have vegetative cover to retard runoff and encourage groundwater recharge were ranked second and third respectively, the lowest priorities were assigned to bare land (rock surfaces or open bare soil surfaces), and built-up areas, because of lack of vegetation cover. It is noteworthy that land use/cover of an area influences the occurrence and recharge of groundwater in an area, as it provides important clues about the level of utilization and requirement of groundwater (Jha et al., 2010; Magesh et al., 2012). As revealed in Table 3, the slope of the investigated area was grouped into five classes (with 5 being the highest weight) and the areas with the minimal slope (0–5%), which constitute 73% of the study area, were adjudged to be more promising as far as meteoric recharge is concerned and are ranked highest (5) as opposed to areas with moderately steep to very steep slopes (15–20%), which generally have low to very low groundwater recharge potential and are thus ranked low (2 and 1 respectively). The general idea is that areas with minimal slope would

Hydraulic head is a fundamental parameter in describing groundwater flow in rocks. It is a function of the ratio of mechanical energy to the unit weight of fluid in the aquifer system because the water flows between two points in response to unequal distributions of the water's mechanical energy (Ge and Gorelick, 2015). The hydraulic head map of the study area is presented in Figure 10. Hydraulic head is defined as the sum of the pressure head and elevation head at a particular point. During precipitation, hydraulic heads are known to increase with an increase in the inflow of water through recharge, particularly in unconfined aquifer settings. In the present study, hydraulic heads were computed from depth to the water table and surface elevation measurements were undertaken for 80 wells. The hydraulic head of the investigated area ranges from 292m in the eastern parts of the area underlain by the sedimentary units to 561m in crystalline basement zones in the western half of the study area. As can be observed from Figure 10, the hydraulic head in the study area was divided into five classes (292–356, 357–403, 404–457, 458–500, and 501–561 m). Considering that water naturally flows from a zone of the high hydraulic head to a region of the lower head along a hydraulic gradient, in the same manner in which heat would also flow towards lower temperature regions, higher ranks were assigned to the regions with the lower head, compared to the zones with higher hydraulic heads which were scored low.
provide more time for recharge from precipitation water as compared to steeper areas. The estimated drainage density in the research area presented in Table 3, indicated a low-moderately dense drainage network with values of 0.34 km/km² to highly dense networks greater than 1.72 km/km². Given that low drainage density translates to higher recharge and thus better groundwater potential as compared to higher drainage density zones, higher weights (4 and 5) was assigned to the areas with low drainage density (0–0.34, 0.34–0.68 km/km²) which make up 2388.6 km² (78.05 %) of the study area. However, the high drainage density areas (1.03–1.37 and 1.37–1.72 km/km²) which constitute about 1.37 km² (0.49 %) of the total area were scored lower (between 1 and 2) while areas with moderate drainage density (0.6–1.03) were ranked 3. This is in agreement with the studies conducted by Fashae et al. (2014).

The density of the lineaments in the study area varies between 0.176 km/km² (0.91 % of the total area) while areas underlain by the granitic/charnockitic rocks scored high (1.72 km/km²) which constitute about 106.7 km² (3.49 % of the total area) were scored lower (between 1 and 2) while areas underlain by the migmatite/gneiss (oldest rocks) were ranked 1. As shown in Table 3, the different lithological units were assigned weights ratings in the range of 1–5 based on the influence of the rocks on groundwater recharge in the study area. The highest rank of 5 was assigned to the Kerri-Kerri Formation, which is dominantly sandstones while the migmatite/gneiss, granites, and charnockites were ranked 3, 2, and 1 respectively. Unlike the basement rocks which have limited permeability controlled by weathering of the rocks, sandstones exhibit both primary and secondary porosities and as a result, possess well-interconnected pores for groundwater storage (Eduvie, 2006). The migmatite/gneiss was rated higher than the granites and charnockites because they showed a higher degree of deformation judging by their lineament densities (0.35–0.88 km/km²).

Based on the calculated hydraulic head values obtained from measured well parameters (depth to the water table and surface elevation), the hydraulic head values from the contact zones of Bauchi ranges from 292m in the eastern parts of the area underlain by the sedimentary units to 561m in crystalline basement zones in the western half of the study area. As can be observed from Table 3, the hydraulic head in the investigated area was divided into five classes (292–356, 357–403, 404–457, 458–500, and 501–561m) and ranked 5, 4, 3, 2, and 1 respectively. This ranking was necessitated by the fact that water flows from a zone of high hydraulic head to regions of a lower head under the influence of gravity and on this basis, higher ranks were assigned to the regions with lower head typified by most of the sedimentary settings as compared to the crystalline basement zones with higher hydraulic heads which were scored low.
The overall integration of the thematic maps which was actualized, through overlay analysis, yielded a groundwater recharge zone (GWRZ) map. The GWRZ map of the investigated area (Figure 11) classified the contact zones of Bauchi into three distinct zones, namely: low zones, covering 627.2 km² (20%), moderate zones, occupying 2352 km² (77%), and high recharge zones constituting 80 km² (3%) of the study area. As can be observed from the GWRZ map, the Basement Complex setting is generally occupied by moderate and low recharge zones, while the sandstones revealed moderate recharge capability with pockets of high recharge potential zones in the north, northeastern, and southeastern region of the research area. The latter is due to a favorable combination of hydrological, and hydrogeological factors, such as a low slope, low elevation, low-moderate drainage density, permeable lithology, and low hydraulic head. The scenario in the basement setting (low-moderate potential) can, however, be attributed to the generally undulating topography and medium-high slopes, moderate-low drainage density, high-moderate hydraulic head, and moderate-high lineament densities, etc. From the above statistics, 77% of the study area revealed moderate groundwater recharge capacity which predominates the sedimentary basin and characterizes close to 50% of the basement areas, underlain by the migmatite/gneiss and partly biotite hornblende granite (northwestern and parts of the southwestern). Approximately, 20% of the total study region falls within the poor or low potential zone, as reflected by a sizeable part of the southwestern flanks of the study area, underlain dominantly the bauchite and partly biotite hornblende granites. Furthermore, pockets of low GWRZ can also be observed along the contact zones. According to Fashae et al. (2014), the medium to low groundwater potential in the basement areas, as revealed by the present study, is a reflection of the marginal aquifer productivity known to be associated with fracture-type aquifers in most basement terrain. The above assertion is also in agreement with Tijani et al., 2016. Furthermore, the role played by lineaments is limited in the sandstones as compared to the basement parts of the study. This scenario further confirms the dominance of secondary porosities in Basement Complex rocks as suggested by Eduvie (2006) and Anudu et al. (2014).

4.3. Validation of groundwater recharge zones (GWRZ) map

The result of the present study is in tandem with Lawal et al. (2020), who applied a more precise and definitive vertical electrical sounding approach to characterize the groundwater potential in the geological transition zones of Bauchi. In the aforementioned study, the resulting groundwater potential map was validated with data from 125 existing wells. The geophysical results obtained by Lawal et al. (2020) revealed that the basement zones generally consist of clayey overburden materials which will naturally have higher water retention and low recharge potential while the sedimentary terrain is dominated by sandstones which are more permeable materials and as such would enhance meteoric recharge. Furthermore, the re-examination of the pumping test data from 125 existing wells in the study area (JICA, 2009), as captured in Lawal et al. (2020) suggests that wells with low and moderate yields, (50 m³/day) and (50–100 m³/day) respectively, predominates the Basement Complex zones while the more prolific wells (>100 m³/day) dominate the sedimentary setting. By implication, 83% of the wells in the Kerri-Kerri sandstones are of high yield as compared to less than 25% average in the basement zones respectively. Based on these statistics it can be concluded the sedimentary zones of the present study which are predominated by moderate to high recharge potentials is justifiable as rainwater remains the dominant source of groundwater recharge in most hydrogeological settings and this corroborates the result of the present investigation.

4.4. Interpretation

The overall assessment of recharge zones of the Bauchi area indicates that areas underlain by charnockites (Bauchite) and biotite hornblende
granite, as reflected by the southwestern flanks of the investigated area indicated poor to marginal (dominantly poor) groundwater recharge characteristics, attributable to high relief and impervious rock outcrops with associated steep slopes, thus limited infiltration owing to the high velocity of runoff and generally high hydraulic heads consequently, detrimental to meteoric recharge and base flow. Conversely, areas underlain by migmatite/gneiss, and partly biotite hornblende granites, displayed mostly medium-low (predominantly moderate) groundwater recharge potential which is probably as a result of the occurrence of thicker weathered regolith’s and saprocks as revealed by the medium to high lineament densities and in tandem with conclusions by Tijani et al., (2016) and Lawal et al. (2020). The Kerri-Kerri sandstones, however, have medium-high potential (dominantly moderate), which can be linked to their primary porosities, permeable soils, lower hydraulic heads, and relatively flat geomorphology that facilitates recharge through precipitation and base flow processes.

5. Summary and conclusion

In this investigation, the aquifer recharge zones of a typical geological transitional zone known for their hydrogeological complexity and groundwater exploitation difficulties were explored using combined remote sensing, GIS, and MCDA techniques. The study which entailed the integration of seven thematic maps comprising of remotely sensed data, conventional maps, aeromagnetic and hydrogeological data that govern the infiltration and movement of meteoric recharge was applied to the semi-arid region of Bauchi, northeastern Nigeria. The thematic maps used for the study include elevation, slope, land use/land cover, drainage density, lithology, magnetic lineament density, and hydraulic head. Suitable representative weights were assigned to these thematic layers based on their degree of influence on meteoric recharge. The assigned theme weights were normalized using analytical hierarchical process (AHP) multi-criteria decision analysis proposed by Saaty. The reclassified thematic layers were integrated using the weighted overlay process in ArcGIS 10.3.1 software to delineate the aquifer recharge zones of the study area. The resulting map was validated with existing research that utilized a more precise and site-specific geophysical technique.

Based on the above premise, the geological transition zone of Bauchi was delineated into three different groundwater recharge zones: low, moderate, and high, occupying 20% (627 km²), 77% (2352 km²), and 3% (80 km²) of the investigated area respectively. The overall assessment of recharge zones of the contact zones revealed that some parts crystalline basement settings, notably the southwestern parts of the study are characterized dominantly by poor groundwater recharge potential, attributable to medium to high slope percentages, the predominance of rock outcrops, and generally high hydraulic heads. Furthermore, the northwestern zones, underlain by migmatite/gneiss, and partly biotite hornblende granites, displayed mostly medium-low groundwater recharge potential which is probably as a result of the occurrence of medium to high lineament densities and while areas underlain by sandstones are predominated by medium-high potential, attributable to their primary porosities, lower hydraulic heads and relatively flat geomorphology which enhances recharge through precipitation and base flow processes. The distribution of the groundwater recharge potential in the study area reflects the permeability and the porosity characteristics of the different rock types. The basement settings known for their limited porosities and permeability displayed a highly variable recharge potential while the sedimentary terrain comprising of permeable sandstone units displayed more homogeneous recharge characteristics. It is also worthy of mention that considering that a large portion of the study area exhibits moderate recharge potential, which would even decrease in the face of increased population, civilization (built-up regions), and climate change. Therefore, there is a need for efficient groundwater resource protection and management.

This study has shown the efficiency of the remote sensing/GIS in large-scale groundwater recharge exploration, which could serve to help delineate favorable zones for more detailed site-specific exploration techniques, especially when the GIS technique is employed as a stand-alone technique. However, when the remote sensing/GIS technique is integrated with other techniques with higher precision like the vertical electrical sounding, the reliability is enhanced greatly. The GIS-based recharge map is a very valuable tool for water managers and town planners and would go a long way in aiding decision-makers in developing economically viable groundwater exploration and exploitation initiatives.

Declarations

Author contribution statement

Lawal Abdullateef, Moshood N. Tijani: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.
Nabage A. Nuru, Shirputda John, Aliyu, Mustapha: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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Data will be made available on request.

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The authors declare no conflict of interest.

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