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Research article

Geospatial application on mapping groundwater recharge zones in Makutupora basin, Tanzania

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ABSTRACT

Management of groundwater systems is indispensable to countries that depend on groundwater as the primary source of community water supply (e.g. Dodoma, Tanzania). Urbanization and industrialization lead to groundwater over-pumping and reduced recharge zones in the basin. This study used Remote Sensing and geospatial datasets to determine the groundwater recharge zones (GWRZ) followed by sensitivity analysis to identify the influence of geologic and hydrologic factors on the variation of the GWRZ in the case of the Makutupora basin, Tanzania. The implementation of weighted overlay analysis aimed to determine the GWRZ using different thematic maps created from land use land cover (LULC), drainage density, lithology, lineament density, rainfall, slope and soil datasets. The analytical hierarchy process (AHP) and multi-influencing factor (MIF) are the multi-criteria decision analysis (MCDA) implemented to assign weights to the selected influencing factors. Either, the map removal method was implemented for the sensitivity analysis. Pumping wells were overlaid to validate the GWRZ map determined. The overlay of seven thematic maps resulted in the GWRZ map being categorized as good (35.79% for AHP and 21.68% for MIF), moderate (40.98% for AHP and 58.39% for MIF) and poor (23.22% for AHP and 19.95% for MIF). Good recharge potential areas lie in an area characterized by thick forest, high lineament and water bodies around the northwestern and central-eastern side of the basin. Validation of GWRZ indicated that 33.33% for AHP and 30% for MIF are in good GWRZ, 41.6% for AHP and 28% for MIF are in moderate GWRZ and 25% for AHP and 42% for MIF are in poor GWRZ. The sensitivity analysis revealed the high effect of GWRZ on the removal of the LULC, lithology and lineament thematic layer in both AHP and MIF-generated GWRZ maps. This implies that the expansion of settlements is not considering recharge zone protection. Lineaments are also a very important factor governing groundwater recharge which needs to be protected. The result displays that urbanization dramatically reduced the potential area for groundwater recharge. Protecting the potential recharge zone from any activity that reduces the recharge is vital for the sustainability of groundwater.

1. Introduction

Groundwater is the second-largest global freshwater reservoir accounting for roughly 30% of the global freshwater budget (Achu et al., 2020). Excessive groundwater pumping is a worldwide issue that is exacerbated in surface water-scarce areas such as arid and semi-arid regions (Zghibi et al., 2020). In sub-Saharan Africa, especially in the arid and semi-arid regions, groundwater is essential for supporting livelihoods and reducing poverty (Seddon et al., 2021). Growing agricultural water demand, population increase, and industrialization are key drivers of the demand for freshwater supplies (Abijith et al., 2020). As a result, groundwater abstraction plans have become an important part of water management around the world, particularly in semi-arid regions (Souissi et al., 2018).

The water distribution is highly variable whereby low rainfall leads to seasonal streamflow and insufficient water availability causing repeated

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drought conditions (Taylor et al., 2013a). The recharge of subsurface aquifers is highly localized and varies from place to place due to physical characteristics and anthropogenic influences (Das and Pardeshi, 2018). Groundwater reserve is directly affected by spatial variation of recharge rate. Thus robust freshwater management is vital to avoid critical scarcity of water in arid and semi-arid regions. Based on the studies reviewed so far (Dar et al., 2010; Reddy et al., 2018; Owolabi, 2020; Mahato, 2021) the benefits of mapping the groundwater recharge zone (GWRZ) can be stated in three ways: to find suitable drilling locations for production boreholes; vulnerability mapping and groundwater quality preservation (Pfannkch, 1998; Mohammadi et al., 2009; Thapa et al., 2018; Saidi et al., 2011) and reserve calculation, budgeting and environmental management (De Smedt and Batelaan, 2003). Groundwater recharge zones (GWRZ) can be identified using a variety of methods, including geophysical, hydrogeological, remote sensing (RS), and hydrogeological approaches (Yeh et al., 2016).

Tanzania's Makutupora basin has semi-arid conditions with annual potential evapotranspiration of 2280 mm and rainfall of less than 680 mm (computed from 2000 to 2020 climate data). Extreme dry condition from May to October is causing seasonal river flow and dry-up of reservoirs (Sandstrom, 1995) making groundwater the only source of water to supply more than 80% of the Dodoma city community (Mfinanga, 2021). The basin has recently become a major concern due to the increasing population leading to the development of more boreholes and over-pumping of the existing wells to meet the water demand (Sandstrom, 1995). Accordingly, DUWASA (2015) conducted pumping experiments in the well-field and found a high variation of the yield ranging from 40 m^3/hour to 450 $m^{3/h}$. According to earlier studies in the basin, ephemeral streams flowing through coarse-grained soils within alluvial fans are responsible for episodic recharge (Seddon et al., 2021). Moreover, diffuse recharge occurs through the soil matrix or through soil macropores and fractures that skip the soil matrix (Shindo, 1990). Locating groundwater recharge zones in the Makutupora basin is essential in this regard to foster the necessary intervention for groundwater sustainability. Planning future artificial recharge programs to slow groundwater decrease, it is crucial to identify groundwater recharge zones (GWRZ) (Zghibi et al., 2020).

Geographical information system (GIS) and Remote sensing (RS) methods have been widely used in many studies to assess surface and sub-surface water conditions in different areas (Hammouri et al., 2014; Chenini et al., 2010; Chowdhury et al., 2010; Fagbohun, 2018; Achu et al., 2020; Kaewdum and Chotpantarat, 2021; Mseli et al., 2021). The accuracy of the results is enhanced when GIS is applied while minimizing bias (Mengistu et al., 2022). The implementation of these technologies with Multi-Criteria Decision Analysis (MCDA) has given insight into new scientific inquiry in recent groundwater studies (Malczewski, 2007). Groundwater recharge zones have been mapped using a variety of techniques around the world (Das and Pardeshi, 2018; Dar et al., 2021; Hammouri et al., 2012; Chenini et al., 2019; Magesh et al., 2012). such as fuzzy logic index models, frequency ratio, data mining models, multi influencing factor (MIF), weights of evidence (WOE) and analytical hierarchy process (AHP). The best methods mostly used groundwater assessment methods are MIF and AHP for accurate, quick, and affordable mapping of groundwater recharge zones are specifically techniques.

In particular, MIF and AHP methods are the most beneficial approaches for groundwater assessment for precise, quick, and affordable mapping of groundwater recharge zones (Zghibi et al., 2020; Magesh et al., 2012; Mengistu et al., 2022). This is because they lessen the mathematical complexity of making a decision based on the methodical judgment of the expert. By allocating weights based on professional judgment, the AHP multi-criteria decision analysis (MCDA) technique compares geographical parameters pairwise (Malczewski, 2007; Mengistu et al., 2022). The MIF is a MCDA approach that is used by assigned scores on major and minor influencing factors impacting the groundwater recharge zone. It is based on the spatial relationship between dependent and independent variables (GWRZ) (Das and Pardeshi, 2018; Zghibi et al., 2020; Benjmel et al., 2020; Maples et al., 2020). These two approaches are frequently used due to their simplicity, accuracy and usefulness in practical applications before the initiation of costly field investigations (Kanta et al., 2017).

In the semi-arid region of Singida and Dodoma, Tanzania, similar research was carried out by Mussa et al. (2020), and Mseli et al. (2021). The sensitivity analysis of each element utilized to establish its impact on the GWRZ, however, was not taken into account in these investigations. This study aims to apply the geospatial technique in the determination of GWRZ in the Makutupora basin in central Tanzania based on MCDM using AHP and MIF. Seven thematic layers were applied in this study to enhance the data analysis and interpretation process. To ascertain how each thematic layer would affect the defined GWRZ, sensitivity analysis was also carried out. Based on the location of the pumping wells in the GWRZ, the accuracy of AHP and MIF was assessed. The GWRZ map will serve as significant baseline information for engineering decisions in the aquifer management processes.

2. Description of the study area

The Makutupora basin is situated in Dodoma, Tanzania's capital. The basin is located in the center zone of a semi-arid environment that is marked by an ongoing protracted drought season and a year-round reliance on groundwater. Geographically the basin is located between latitudes 5^0 36′ 59″ and 6^0 14′ 5″ S and longitudes 35^0 36′ 36″ and 36^0 01′ 54″ E making an area of 1500 km^2 (Figure 1). The basin extends from Dodoma city in the southern part towards Chenene hills in the north, whereby the Hombolo reservoir is located on the eastern side. During the rainy season, the hills are drained by the Kinyasungwe river towards the Hombolo reservoir which is an outlet of the basin. The Makutupora wellfield (120 km^2) is found within this basin which serves as the primary source of water supplied in Dodoma city (Kashaigili, 2010).

The basin is flanked by high elevation land up to 2051 m around Chenene hills where the dominant land cover type is thick shrubs and forest while low land up to 1031 m towards the centre is covered with a vast floodplain, barren land with low vegetation coverage (grassland and dwarf shrubs up to 10 m high) and few settlements. Due to the significance of the wellfield, a neighbouring military post, and a soil conservation policy in the basin, agricultural activities are restricted in the area (Seddon, 2019).

A "hot semi-arid" climate with distinct wet and dry seasons and year-round maximum temperatures between 15 and 32 °C characterizes the Makutupora basin (based on in situ data records from 2000 to 2020). The rainy season lasts from November to April and has an average annual rainfall of 680 mm (2000–2020). During the same time, the average annual potential evapotranspiration is predicted to be 2285 mm. Due to an exceptionally lengthy dry spell that occurs every year from June to October, the area suffers from poor river flows and drying of surface water bodies (Shindo, 1989; Rwebugisa, 2008).

The linear features, such as faults, rivers, reservoirs, and swamps are mainly trending NE–SW, indicating substantial induced tectonic faulting (Nkotagu, 1996). The basin is covered by a crystalline basement with intrusive ultrabasic complexes of quartzo-feldspathic gneisses, amphibolite, and biotite occurring within the wellfield, and Precambrian synorogenic granites of Dodoman origin (Zarate et al., 2021; Seddon et al., 2021).

The basement rocks are typically covered by deeply weathered regolith that is between 50 and 100 m thick and made up of fractured pedolite, saprock, and saprolite products of Neogene origin with varying chemical decomposition (Kashaigili, 2010; Zarate et al., 2021). The mineralogy of the underlying parent rocks has an impact on the composition of the regolith.

3. Materials and methods

Through a knowledge-based examination of seven variables, including lineament density, lithology, rainfall, soil type, slope, drainage

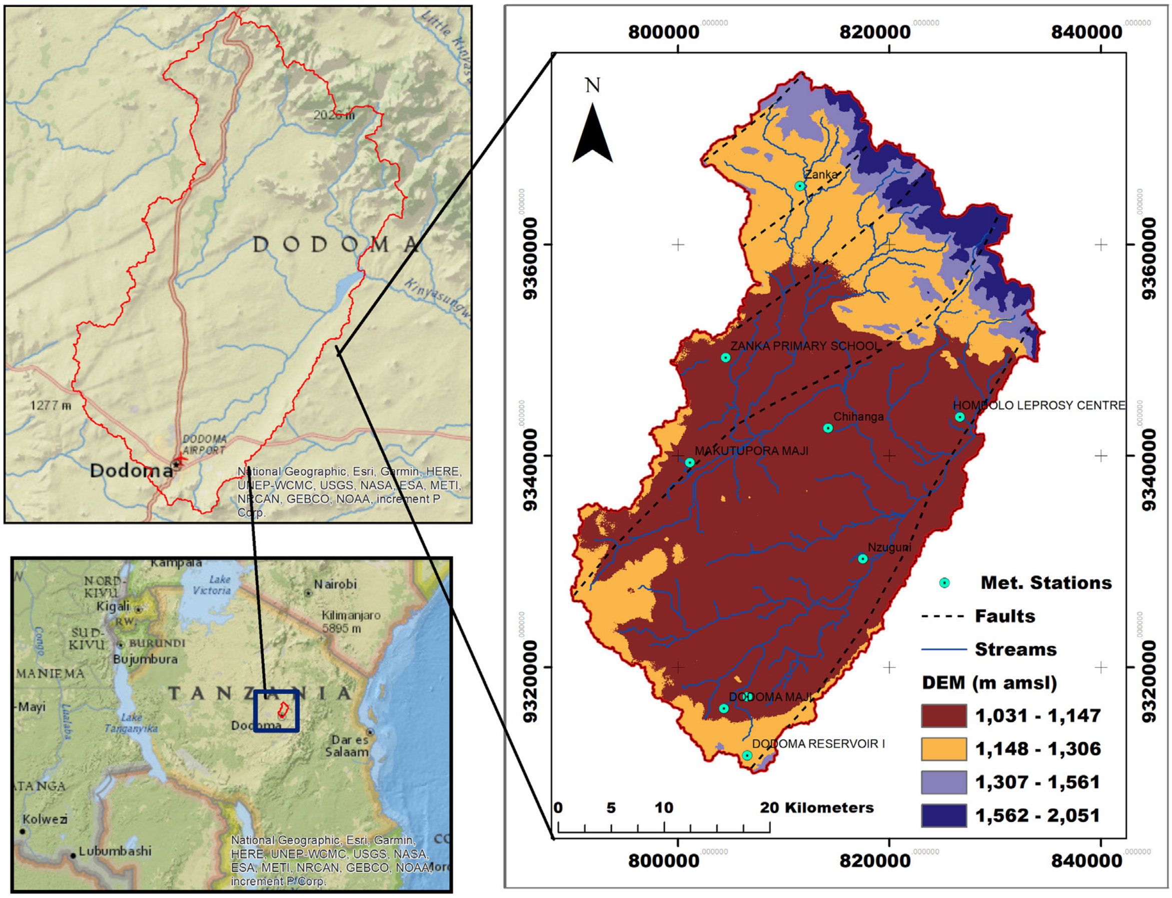

Figure 1. Location map of the Makutupora basin.

density, and land use land cover layers, suitable sites for groundwater recharge were found. These factors were analyzed individually and thereafter reclassified and integrated using overlay analysis in GIS software to come up with a GWRZ map. Figure 2 shows the overview of the workflow followed to conduct this study.

3.1. Preparation of input datasets

The spatial and field datasets were gathered from online and government agencies, prepared and processed using the GIS technique to generate thematic maps. Table 1 provides a summary of the sources of

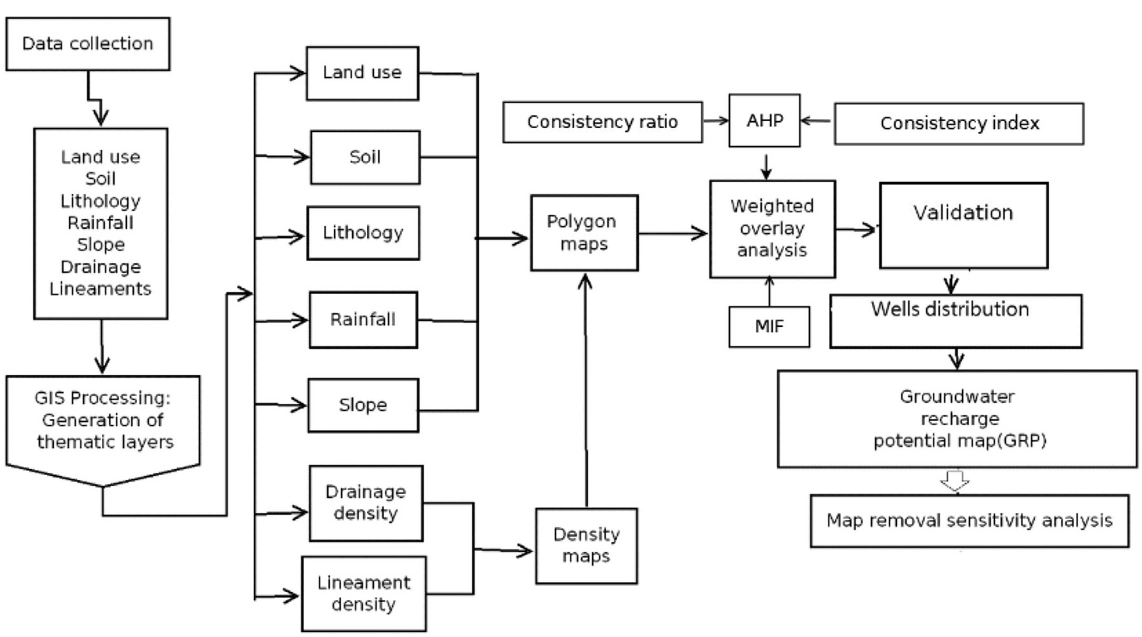

Figure 2. The flowchart for the methodology used in the assessment of GWRZ using GIS techniques.

data and the produced thematic layers. Digital Elevation Model (DEM) data from the Shuttle Radar Topographic Mission (SRTM) are among the primary data used in this investigation. Using unsupervised (modified-normalized difference water index approaches) classification, land use and land cover (LULC) maps were derived from Landsat 8 OLI, 30m horizontal resolution, retrieved from USGForfor the identified LULC map to become sufficiently accurate. The index value was calculated using knowledge from specialists regarding the catchment features and high-resolution Google Earth images. The lineament density was produced from DEM through computer-aided supervised extraction. The total length of all recorded lineaments divided by the size of a catchment under consideration yields the thematic layer for lineament density (LD), Eq. (1).

$$LD = \sum_{i=1}^{i=n} \frac{\mathrm{Li}}{A} \tag{1}$$

where; LD is the lineament density, Li is the recorded lineaments (km) and A is the area (km^2).

To assure high quality for the extracted lineament, the lineament raster was created using a false-colour composite in the spatial analysis tool in Arc GIS 10.2. This was followed by additional modification of the road features and boundary divide line.

In this study, drainage density was created using SRTM DEM and the GIS environment's line density tool, which was then reclassified into the proper classes for overlay analysis. Eq. (2) states that the drainage density is the closeness of the stream channel spacing calculated as the total length of the stream segment of all orders per unit area.

$$\mathrm{Dd} = \frac{\sum_{i=1}^{i=n} Di}{A} \tag{2}$$

where: - Dd is the drainage density, Di (km) total recorded drainage length (km) and A is an area in km^2

The highest rate of change in value from one cell to the neighboring was used to create a slope using the STRM DEM of 30 m resolution (Zghibi et al., 2020). Using the spatial analysis tool in the GIS context, this study produced a slope. then categorization into five different categories. The Harmonized World Soil Database (HWSD) soil map from the FAO was used to create the soil groups using the spatial processing tool in GIS 10.2. The vector layer was griddled before being reclassified using a recharge-weighted rating. Geological information from the Geological Survey of Tanzania (GST) Quarter degree sheets (QDS) 162 of scale 1:100,000 and 143 of scale 1: 12,500 was used to create a lithology map. The maps were combined, and then the geology of the area was extracted in a GIS environment. Using data from long-term average point rainfall for nine locations over 20 years, a rainfall thematic map was produced in GIS 10.2 using the Inverse Distance Weighting (IDW) interpolation method (2000–2020).

Table 1. The sources of data used for mapping groundwater recharge potential zones.

Parameter	Data source	Location	Product
Lithology map	Geological Survey of Tanzania (GST)	https://www.gst.go.tz/	LI
Land use land cover	Landsat 8 OLI 30 m resolution Downloaded on 20 DEC 2021	https://earthexplorer.usgs.gov/	LULC
Slope (°)	Shuttle Radar Topography Mission (SRTM) DEM 30 m resolution	https://earthexplorer.usgs.gov/	SLP
Drainage density (km/km^2)	SRTM DEM 30 m resolution	https://earthexplorer.usgs.gov/	DD
Lineament density (km/km^2)	SRTM DEM 30 m resolution	https://earthexplorer.usgs.gov/	LD
Soil type	Harmonized World Soil Database (HWSD)	https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/	SL
Rainfall	Tanzania Meteorological Agency (TMA) (2000–2020)	https://www.meteo.go.tz/	RN

3.2. Analytical hierarchy process

The Analytic Hierarchy Process (AHP) is a powerful method for making decisions (Saaty, 1988) developed and introduced to handle various decision-making problems by providing priorities in multi-criteria decisions (Mengistu et al., 2022). The AHP makes it easier to evaluate pairwise comparisons between the pertinent elements by utilizing the findings of each level of the hierarchy's solution algorithm to determine the relative relevance of various criteria (Saaty, 1988, 2004). As an advanced multi-criteria decision-making procedure, the AHP is used to determine the weights assigned to different thematic layers and their relevant attributes (Zghibi et al., 2020). The multi-criteria decision problem is organized using a hierarchy that is created by comparing the relative weights of various criteria and sub-criteria in pairs inside the judgment matrix (Kanta et al., 2017; Saaty, 2004). When choosing prospective recharge zones from competing sets of characteristics, the hierarchy enables analysis to take into account several features independently (Zghibi et al., 2020). The method consisted of four steps that were used to determine potential groundwater recharge zones in the Makutupora basin: (1) choosing the factors that influence these zones; (2) creating a matrix for pairwise comparisons; (3) calculating relative weights; and (4) assessing the matrix's consistency.

3.2.1. Influencing factors for groundwater recharge zones

Based on the suggestions of experts and the semi-arid characteristics of the area under consideration, factors affecting groundwater recharge zones were chosen. Using the pairwise comparison method, each variable that impacts recharging is given a score between 1 and 9, based on its importance in comparison to other variables (Saaty, 2004). The relative influence of parameters was represented using a conventional Saaty's 1–9 scale (Table 2), where a score of 1 denotes equal influence and a score of 9 denotes the largest importance of a parameter on groundwater recharge relative to the other components.

3.2.2. The pairwise comparison matrix

The AHP method integrates spatial data (input) and changes it into decisions (output), where the qualitative information of certain thematic layers and features is converted into quantitative scores based on Saaty's scale. A pairwise comparison matrix (PCM) is generated using Saaty's score from the previous phase (Saaty, 2004). The matrix column in the PCM is constructed using a descending order of parameter influence on recharging. If the first component is evaluated against itself, it receives a

Table 2. 1–9 (Saaty, 2004) scale of relative importance.

Scale	Importance
1	Equal importance
2	Weak importance
3	Moderate importance
4	Moderate plus
5	Strong plus
6	Strong importance
7	Very strong importance
8	Very very strong importance
9	Extreme importance

score of 1 (Table 3). When comparing a most influencing parameter to a less influencing parameter, the actual Saaty's score is utilized to fill other rows' components or reversed when comparing a least influencing parameter to a most influencing parameter. Table 3 lists the PCM for the parameters used in the study area. Since lithology has a bigger impact on recharge potential than the other parameters, it was chosen as the matrix's initial parameter and given the value of 1. The second most significant factor affecting recharge was determined to be land use/land cover, followed in descending order of importance by slope, lineaments, drainage, rainfall and soil parameter. Saaty's score was given in each parameter based on how each parameter in the chosen set affects recharge.

3.2.3. Estimation of relative weights

Weights were assigned to the variables based on an "expert" opinion to quantify each variable's relative impact on recharging and determine its relative importance concerning other variables (Lentswe and Molwalefhe, 2020). Upon normalizing the pair comparison matrix (NPCM), weights were applied to the layers (Zghibi et al., 2020). The values of the thematic element were divided by the relevant total column values from the PCM (Eq. (3)) to create the NPCM elements (Table 4).

$$X_{ij} = \frac{C_{ij}}{L_{ij}} \tag{3}$$

where C_{ij} is the value given to each criterion at the ith row and jth column, L_{ij} is the total value in each column of the pair-wise matrix, and X_{ij} is the normalized pair-wise matrix value at those locations.

As a result, each member of the normalized pairwise matrix was divided by the criterion number (n) to determine a standard weight for variable i (Eq. (4))

$$W_i = \frac{X_{ij}}{n} \tag{4}$$

where Wi is a standard weight.

For identifying constraints and calculating the percentage influence of each theme layer, eigenvector and eigenvalue calculations are crucial (Table 5). In Table 4, the eigenvector was calculated by dividing column items by column total. By averaging the rows, the fundamental eigenvector was generated to identify the relative weights of each parameter (Lentswe and Molwalefhe, 2020). To construct a consistent vector, the values of the normalized pair-wise matrix and the pair-wise comparison matrix from particular thematic layers were multiplied using Eq. (5) (Zghibi et al., 2020).

$$\lambda = \sum C_{ij} X_{ij} \tag{5}$$

where λ is the consistency matrix.

The matrix divergence from consistency is measured by the principal eigenvalue (λ_{max}), which is the sum of the eigenvalues (Table 5). A pairwise comparison matrix is said to be consistent if its primary eigenvalue (λ_{max}) is greater than or equal to the number of parameters (n) taken into consideration (Saaty, 2004). The 7 × 7 matrices yielded a major eigenvalue of 7.18, which was used to calculate the consistency index (Table 5).

Table 3. Matrix for pairwise comparisons across all parameters.

Parameter	LI	LULC	SLP	LD	DD	RN	SL
Lithology (LI)	1.00	2.00	3.00	4.00	5.00	6.00	7.00
Land use/Land cover (LULC)	1/2	1.00	2.00	3.00	4.00	5.00	6.00
Slope (SLP)	1/3	1/2	1.00	2.00	3.00	4.00	5.00
Lineament (LD)	1/4	1/3	1/2	1.00	2.00	3.00	4.00
Drainage (DD)	1/5	1/4	1/3	1/2	1.00	2.00	3.00
Rainfall (RN)	1/6	1/5	1/4	1/3	1/2	1.00	2.00
Soil (SL)	1/7	1/6	1/5	1/4	1/3	1/2	1.00
TOTAL	**2.59**	**4.45**	**7.28**	**11.08**	**15.83**	**21.50**	**28.00**

3.2.4. Assessment of matrix consistency

After determination of the Consistency Index (CI) (Eq. (6)) and Consistency Ratio (CR) (Eq. (7)) the consistency of the matrix was checked (Zghibi et al., 2020; Mengistu et al., 2022).

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{6}$$

$$CR = \frac{CI}{RI} \tag{7}$$

CI is the consistency index, λ_{max} is the Eigenvalue of the highest matrix n: number of variables (thematic layers), CR is the consistency ratio and RI is the Random Index value given depending on the number of variables.

A decision-maker with perfect consistency should always arrive at $CI = 0$. However, if the *CI* is less than 0.1, minor values of consistency may be accepted (Saaty, 2004; Zghibi et al., 2020). A satisfactory *CI* value of 0.03 was attained. The *RI* is 1.32 for a matrix with seven variables (Table 6).

The imposed weighting produced a CR of 0.02, demonstrating the consistency of the weights (Table 5) given to the characteristics in the GIS thematic layers. Additionally, the pairwise comparison decisions must be reevaluated if the CR is higher than 0.1.

3.3. Multi-influencing factors (MIF)

A common MCDM technique called MIF is used for mapping groundwater recharge sites. It gives individual features and components the right weights based on how they affect groundwater flow and storage (Ghosh et al., 2016; Abijith et al., 2020; Vasileva, 2019; Achu et al., 2020; Kaewdum and Chotpantarat, 2021). Each factor is given a weight based on the importance of the role it plays in groundwater recharge. There were found to be major and minor influential correlations between the variables (Figure 3). The weightage score of each component is determined by considering how these factors interact and have an impact on one another. Each main and minor variable's influence is assigned a score of 1 or 0.5, accordingly. The major and minor relationships between the parameters impacting the GWRZ are depicted by the solid and broken lines, respectively (Figure 3).

The comparative rates computed using the total weight of both major and minor influencing factors are shown in Table 7 as estimated by Ghosh et al. (2016), Vasileva (2019), Abijith et al. (2020), Achu et al. (2020) and Kaewdum and Chotpantarat (2021). The summation of the major and minor influences of each variable determines the overall weight of each variable (Table 7). The weight value denotes how significant a component is in determining the potential of the groundwater recharge map. Groundwater recharge zones are affected more significantly by factors with greater weights than by factors with lower weights Das and Pardeshi (2018); Eq. (8) was used to get the anticipated weight for each affecting element as a percentage.

$$\text{Proposed Score} = \left[\frac{\text{Mj} + \text{Mn}}{\sum \text{Mj} + \text{Mn}}\right] \times 100 \tag{8}$$

where; Mj is the major effect within two corresponding factors and Mn is the minor effect within two corresponding factors.

The use of major and minor influences is shown in Table 7 to determine the proportional weight of each affecting factor.

The weighted overlay tool in ArcGIS 10.2 is then used, based on the seven thematic layers and their associated percentage influence on recharge, to map the spatial distribution of groundwater recharge (Zghibi et al., 2020; Serele et al., 2020). The map layers were uniformly projected

Table 4. Normalized pair-wise comparison matrix for all parameters and assigned weight.

Parameter	LI	LULC	SLP	LD	DD	RN	SL	Eigen Vector	% Influence	AHP Weight
Lithology (LI)	0.39	0.45	0.41	0.36	0.32	0.28	0.25	0.4	40.00	0.35
Land use Land cover (LULC)	0.19	0.22	0.27	0.27	0.25	0.23	0.21	0.22	22.00	0.23
Slope (SLP)	0.13	0.11	0.14	0.18	0.19	0.19	0.18	0.14	14.00	0.16
Lineament (LNT)	0.10	0.07	0.07	0.09	0.13	0.14	0.14	0.09	9.00	0.12
Drainage (DD)	0.08	0.06	0.05	0.05	0.06	0.09	0.11	0.06	6.00	0.07
Rainfall (RN)	0.06	0.04	0.03	0.03	0.03	0.05	0.07	0.05	5.00	0.04
Soil (SL)	0.06	0.04	0.03	0.02	0.02	0.02	0.04	0.04	4.00	0.03
TOTAL	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**100.00**	**1.00**

Table 5. Principle Eigenvalue calculation for ranking parameter influence.

Parameter	(1) Relative Weight for each Factor (from Table 3)	(2) Eigenvector Values	Eigenvalues (1) × (2)
Lithology (LI)	2.59	0.4	1.04
Land use Land cover (LULC)	4.45	0.22	0.98
Slope (SLP)	7.28	0.14	1.02
Lineament (LNT)	11.1	0.09	1.00
Drainage (DD)	15.8	0.06	0.95
Rainfall (RN)	21.5	0.05	1.08
Soil (SL)	28	0.04	1.12
Principal Eigenvalue (λ_{max})			**7.18**

Table 6. Random indices (Saaty, 2004).

n	2	3	4	5	6	7	8	9
RI	0	0.58	0.9	1.12	1.24	**1.32**	1.41	1.49

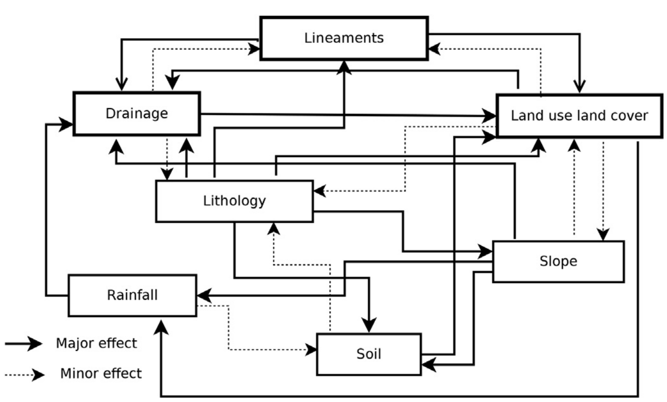

Figure 3. Dependency of factors influencing groundwater recharge.

into WGS84, UTM zone 36S followed by assigning the relevant scores and weights. The overlay analysis is a tool that helps in decision-making when working with multi-criteria analysis to understand a complex system (Kaewdum and Chotpantarat, 2021). The overlay process involves the conversion of thematic layers into a raster image with a defined pixel size (30 × 30 m) and the re-projection of thematic layers. Thereafter the reclassification of the raster files was conducted in a range of 1–5 to make all classes of respective factors into a uniform scale. Finally, the GWRZ was determined by the weightage overlay analysis (WOA) Eq. (9). Therefore, the resultant map was categorized as a poor, moderate and good GWRZ.

Table 7. Computation of relative weights of each influencing factors.

Factor	Major effect (Mj)	Minor effect (Mn)	Assigned relative rates (Mj + Mn)	Assigned weight (Pi)
Lithology	1 + 1+1 + 1	0	4	25
Land use land cover	1 + 1	0.5 + 0.5+0.5	3.5	22
Slope	1 + 1	0.5	2.5	16
Lineament	1 + 1	0	2	13
Drainage	1	0.5	1.5	9
Rainfall	1	0.5	1.5	9
Soil	1	0	1	6
			Σ 16	**Σ100**

$$GWRZ = RNwRNr + LIwLIr + DDwDDr + SLwSLr + SLPwSLPr + LUwLUr + LDwLDr \quad (9)$$

where GWRZ is the groundwater recharge zone, RN is the rainfall, LI is the lithology, DD is the drainage density, SL is the soil cover, LU is land use land cover, SLP is the slope and LD is the lineament density. Weight and the rate of a factor's distinct classes are denoted by the subscripts w and r, respectively.

3.4. Sensitivity analysis

Groundwater recharge zones are affected by both weights and rates assigned to each factor considered in delineating the groundwater recharge map (Zghibi et al., 2020; Kaewdum and Chotpantarat, 2021), therefore, sensitivity analysis is conducted to determine the more important factor to GWRZ among the selected factors (Thapa et al., 2018). The map removal technique was employed in this study to conduct sensitivity analysis (Kaewdum and Chotpantarat, 2021). to determine the change in spatial coverage (area) of potential recharge zones, since the method is simple, flexible and effective in determining sensitivity analysis. In this respect after estimation of the GWRZ map in weighted overlay analysis by using all selected rasterized seven thematic maps, the resulting GWRZ map was categorized as very poor, poor, moderate and good and contributing areas of each class were calculated. Further analysis was conducted by removing a single thematic map at a time and reassigning weights into the remaining six thematic layers to make a total of a hundred percent. Weighted overlay analysis was repeated using six remaining thematic maps and calculation of area coverage of resulting GWRZ classes. The process was performed for each of the seven thematic maps to see how each would affect the output GWRZ classes if it were to be removed.

3.5. Validation of groundwater recharge zone

One of the most important phases of evaluating a model's effectiveness is validation, which establishes the connection between the degree of groundwater availability and the GWRZ map (Maples et al., 2019; Zghibi et al., 2020). The spatial distribution of pumping wells accessible in the Makutupora basin in the appropriate groundwater recharge zones was calculated as an aspect of the validation of the GWRZ map (Kaewdum and Chotpantarat, 2021). Overlaid wells are expected to fall within very good to moderate recharge zones.

4. Results

4.1. Weights assigned to factors controlling groundwater recharge zones

The final weights of the elements affecting GWRZ are shown in Table 8, and each one is described further as follows.

Lithology (LI): Groundwater recharge is influenced by the types of lithological settings and composition found on the surface (outcrops) by limiting the amount of water penetrating and determining the recharge zones (Souissi et al., 2018; Vasileva, 2019). LI controls the porosity and permeability of aquifer rocks through physio-mechanical properties that control the ability of aquifer material to convey water and the rate at which groundwater flows. This in turn impacts the occurrence and distribution of groundwater recharge (Zghibi et al., 2020). The study area's predominant rocks are silty-clay soil with marshes and alluvium red soil, Synorogenic granite, Quartzo feldspathic Gneiss, Quartzo feldspathic schist, Plagioclase amphibolite, Tonalite, Soapstone and talc schist with the ratings varying from 1 to 5 (Figure 4 and Table 8). The unsaturated overburden ranges between 50 and 100 m (Seddon et al., 2021), underlain by a crystalline basement, thus the recharge type is both focused and diffuse (Taylor et al., 2013a; 2013b) through the exposed silty soil and the secondary structures such as faults and weathered bedrocks. The network of faults in the saturated zone is thought to be the reason for the unexpectedly high transmissivity (400–4000 $m^2 d^{-1}$) around the wellfield (Maurice et al., 2019). Alluvium red soil and Silty-Clay soil with Swamps were merged and assigned the highest rank of 5, The Quartzo feldspathic Schists and Gneiss followed with the rank of 4, Plagioclase Amphibolite was assigned a rate of 3 followed by Quartzite and finally Granite with the rate of 1. The units assigned with the rate of 5 depict the areas with the highest chance of allowing rainfall infiltration to allow groundwater recharge to take place.

Table 8. Assigned scores and weights for the AHP and MIF approaches for each criterion.

			MIF		AHP	
Factor	Classes	Rank	Weight	Weighted Rating	Weight	Weighted Rating
Lithology (LI)	Alluvium red soil	5	0.25	1.25	0.35	1.75
	Quartzo feldspathic schist	4		1		1.4
	Amphibolite	3		0.75		1.05
	Quartzite	2		0.5		0.7
	Synorogenic granite/diorite	1		0.25		0.35
Land use/land cover (LULC)	Water bodies	5	0.22	1.1	0.23	1.15
	Forest	4		0.88		0.92
	Shrubland	3		0.66		0.29
	Wasteland	2		0.44		0.46
	Buildup area	1		0.22		0.23
Slope (%) (SL)	0-3	5	0.16	0.8	0.16	0.8
	3.1–5	4		0.64		0.64
	5.1–10	3		0.48		0.48
	10.1–16	2		0.32		0.32
	16.1–89.9	1		0.16		0.16
Lineament Density (km per km^2) (LD)	0.82–0.5	5	0.13	0.65	0.12	0.6
	0.5–0.4	4		0.52		0.48
	0.4–0.3	3		0.39		0.36
	0.3–0.1	2		0.26		0.24
	0–0.1	1		0.13		0.12
Drainage (km/km^2) (DD)	45-54	1	0.09	0.09	0.07	0.07
	35-45	2		0.18		0.14
	26-35	3		0.27		0.21
	16-26	4		0.36		0.28
	16-7	5		0.45		0.35
Rainfall (mm/year) (RN)	795-844	5	0.09	0.45	0.04	0.2
	749-791	4		0.36		0.16
	706-746	3		0.27		0.12
	661-705	2		0.18		0.08
	610-660	1		0.09		0.04
Soil (SL)	Loam	4	0.06	0.24	0.03	0.12
	Silty clay	2		0.12		0.06
	Clay	1		0.06		0.03

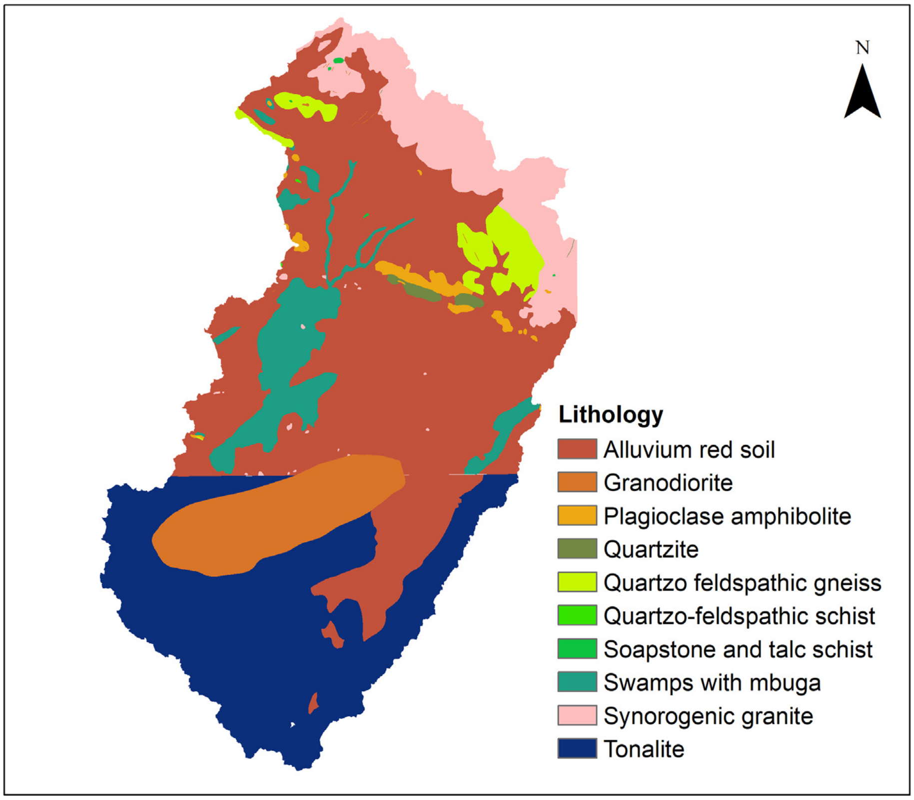

Figure 4. The lithology map of the Makutupora basin.

Land use land cover (LULC): LULC is considered to be an important factor in groundwater recharge processes (Yeh et al., 2009; Arshad et al., 2020; Kaewdum and Chotpantarat, 2021). The recharge rate is affected by variations in land utilization. It is controlled by the distribution of residential areas, soil deposits and vegetation cover (Yeh et al., 2009). Vegetation cover enhances the recharge mechanism by retarding the

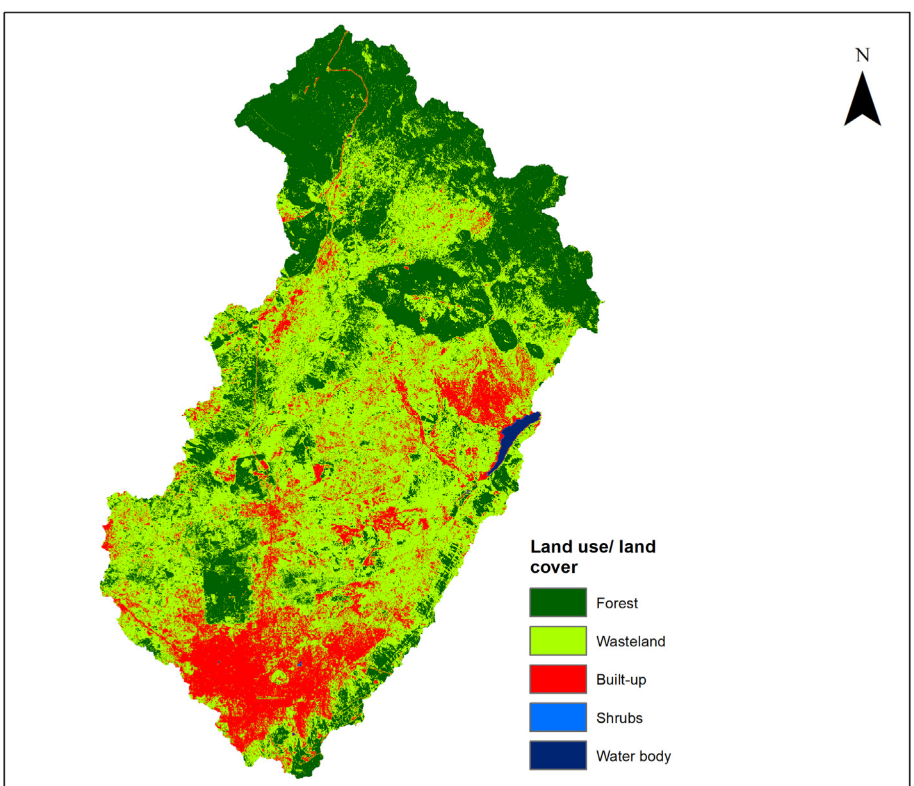

Figure 5. Land use land cover map of Makutupora basin.

surface runoff while the percolation is limited to impervious surfaces (Achu et al., 2020). LULC alters hydrological actions such as evapotranspiration, surface runoff, and infiltration (Kirubakaran et al., 2016) which makes it a very important parameter in determining the GWRZ. Analysis of the LULC map was classified into five distinctive features of the forest (19.9%), water bodies (0.35%), shrubs (23.98%), wasteland (43.96%) and buildup areas (11.63%) and the spatial distribution of the land use classes is indicated (Figure 5 and Table 8). The area comprises protected land in large part for groundwater conservation purposes, thus human activities such as agriculture are limited in the area. Water bodies are few mainly seasonal rivers and ponds. The highest rank (5) and second rank (4) are assigned to water bodies and forests respectively due to their capacity to retain water and allow infiltration into the subsurface formation shrub-land and wasteland (3 and 2 ranks) can moderately allow recharge while surface runoff is also high in this area while the lowest ranked build-up area facilitates more surface runoff while reducing the infiltration rate due to paved land and rooftops.

Slope (SLP): The gradient of the variability of the land surface is referred to as the SLP of the topographical surfaces. The slope of a surface influences the rate of infiltration of rainfall (Mseli et al., 2021). It is one of the key elements required to improve the processes of water recharge into the underground aquifer. Similar to the classification made by Mseli et al. (2021) the slope of the Makutupora basin was divided into five primary types. The flat surface at 0–3° occupies 20.29% of the basin, a gentle slope of 3.1–5° occupies 43.83%, a moderate slope of 5.1–10° occupies 17.5%, a steep slope of 10.1–16° occupies 7.46% and a very steep slope of 16.1–89.9° occupies 10.9% (Figure 6 and Table 8). The flat and gentle slope locations were considered very high potential for groundwater recharge because it is relatively flat and therefore high infiltration rate and occupies the largest percentage of the basin compared to other classes.

Lineament Density (LD): Lineaments density are geologic feature formed due to the movement of the Earth in which its intersection is highly substantial in the groundwater occurrence and movement, especially in crystalline terrain (Thilagavathi et al., 2015; Achu et al., 2020). The presence of lineament structures such as joints, faults, open fractures and cleavage increases the secondary structures and permeability of a rock (Maurice et al., 2019 Kaewdum and Chotpantarat, 2021). Due to its higher widths, lengths, and ability to operate as conduits and superior interconnections with adjacent fractures, major lineament zones present better targets for groundwater recharging than joints (Abdalla, 2012). Lineaments and areas surrounding lineaments plays important role in supporting the recharge of the groundwater regime. A high degree of fractures means high interconnections thus indicating a zone with high levels of potential groundwater recharge. The lineaments delineated in the Makutupora basin are trending along NE-SW with lengths ranging from 0 to 0.68 km/km^2 (Figure 7 and Table 8). Higher lineaments dominate in the northern zone, central eastern and southeast zone of the basin (Figure 4d). The areas of high lineament concentration are considered as more potential for infiltration during rainfall.

Groundwater recharge zones are characterized by the structural characteristics of the drainage network, which is known as drainage density (DD) (Yeh et al., 2009; Kaewdum and Chotpantarat, 2021). The DD and groundwater recharge are inversely associated; places with low DD have high groundwater recharge levels, whereas areas with high DD are defined by low recharge and high surface runoff levels (Mussa et al., 2020; Mseli et al., 2021). The DD created using DEM is shown in Figure 8 and Table 8. The basin's five groups of DD, which vary from 7 to 54 km/km^2, were identified. High weight was assigned to the area of low drainage density (7–16 km/km^2), designating this area as promising for GWRZ mapping, while the area of highest drainage density (45–54 km/km^2) was assessed with a low rank in recharging groundwater.

Rainfall (RN): In the research area, rainfall is the primary climatic component that regulates the potential zone for river discharge and recharge, which varies geographically (Vasileva, 2019). According to an analysis by Souissi et al. (2018) association between precipitation and elevation, regions with high rainfall concentration show a high

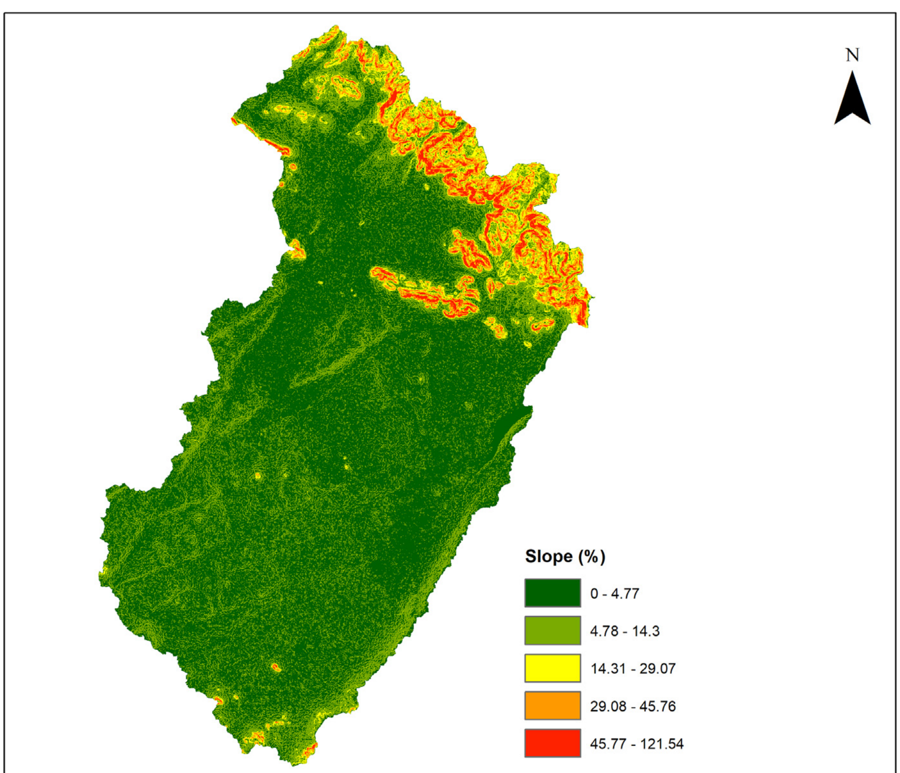

Figure 6. The slope map of the Makutupora basin.

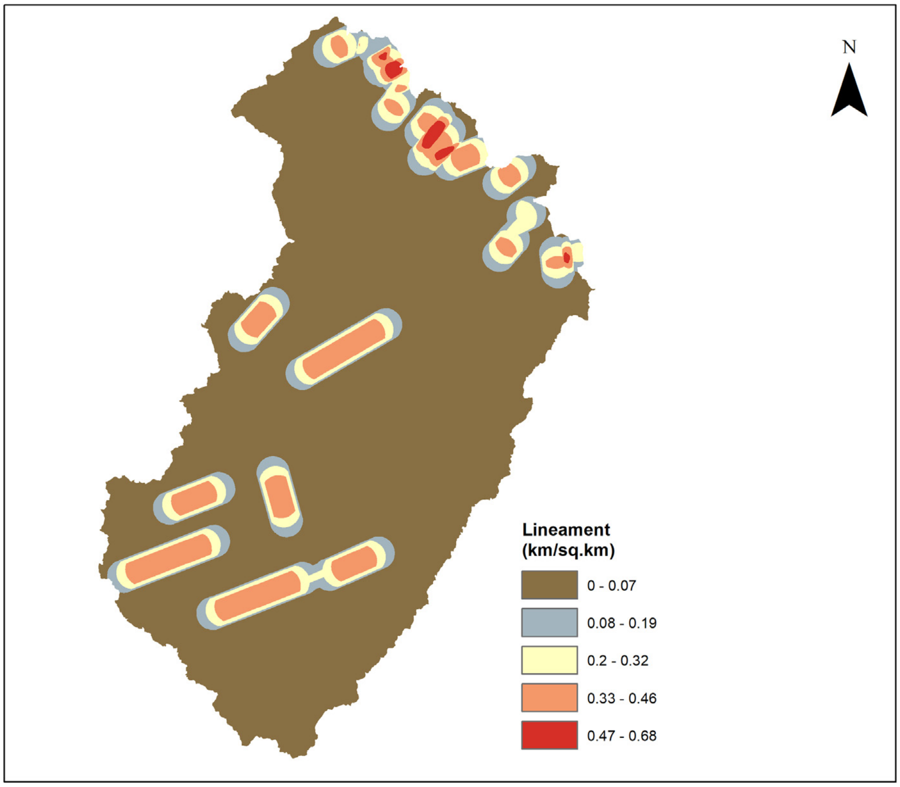

Figure 7. The lineament map of the Makutupora basin.

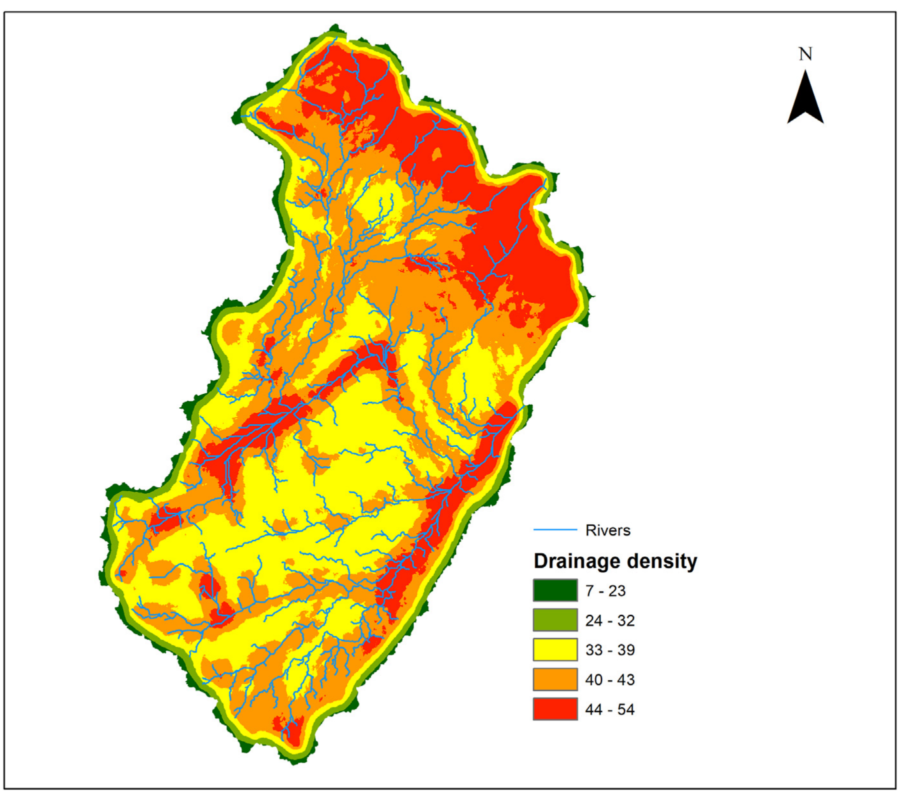

Figure 8. The drainage density map of the Makutupora basin.

groundwater potential compared to low rainfall concentration zone. The distribution map of rainfall is shown in Figure 9. The basin receives 610–844 mm of rain on average annually (Table 8).

The rainfall map was categorized into five equal classes lowest being 610–660 mm/year and the highest 792–844 mm/year. The highest rate was given to the high range meaning that the increase in rainfall increases groundwater recharge potential. Most of the heavy rainfall was recorded in the basin's high elevation region, while moderate rainfall predominates in the low land and low to very low rainfall distribution was recorded in the buildup region in the south.

Soil (SL): The soil is among the significant influencing factors of groundwater recharge (Kaewdum and Chotpantarat, 2021; Mseli et al., 2021). The kind of soil determines its characteristics, including its ability to hold water and its transmissivity and permeability. Either soil type can either encourage or prevent groundwater recharge. The soil map of the Makutupora basin (Figure 10) is divided into three main classes (Table 8), with silt clay making up a large portion of the basin (78.58%), clay making up the majority of the central and northern portions (21.42%), and loam soil making up a negligibly small portion (0.001%) of the southern margin.

4.2. Generation of groundwater recharge maps

4.2.1. Analytical hierarchy process

Eq. (10) was used to determine the GWRZ based on the rates and weights of the seven thematic layers

$$GWRZ = 0.35 \times LI + 0.23 \times LU + 0.16 \times SLP + 0.12 \times LD + 0.07 \times DD + 0.04 \times RN + 0.03 \times SL \tag{10}$$

Figures 11a and 12 show the GWRZ mapping outcome that was attained using the AHP approach. The GWRZ indicates that good groundwater recharge zones cover an area of 546.9 km^2 (21.68% of the total area). The well-field is situated in this area, according to the GWRZ map of the region, where the good recharging zone is shown to be in the eastern north of the basin and to gently sloping ground in the center (the area defined by flood plain). This is mostly explained by the existence of high alluvial red soil in plain areas with high to extremely high lineament densities (0.41–0.54 km/km^2) and along river courses. The good recharge zone is also extending to the north where the area is characterized by a forest type of LULC. Quartz feldspathic gneiss is dominating in this area surrounded by alluvium red silty soil. The GWRZ designated as moderate is found in the south towards the center which covers about 626.21 km^2 (40.98% of the area). The moderate recharge land is characterized by a moderate slope of about 5.1–10% shrub land and silty clay soil types. The poor GWRZ is defined in northern and southern about 354.83 km^2 (23.22% of the area). The poor recharge zones are found in impermeable Synorogenic granite rocks and high slope >16.1% in the north and granodiorite rock in the south-central. The poor recharge zone in the southern part is characterized by a settlement type of LULC.

4.2.2. Multi-influencing factors (MIF)

The MIF approach was utilized to compute the GWRZ map using Eq. (11)

$$GWRZ = 0.25 \times LI + 0.22 \times LU + 0.16 \times SLP + 0.13 \times LD + 0.09 \times DD + 0.09 \times RN + 0.06 \times SL \tag{11}$$

The results of GWRZ mapping obtained in the MIF technique are presented in Figures 11b and 12. The resulting GWRZ map was categorized into a good potential recharge zone of about 331.27 km^2 (21.68%). The forest cover, high lineament and low drainage density, high rainfall, and water bodies are all indicators of a good recharge potential area. These features may be found across the basin, from the northwest to the middle and eastern regions. Moderate potential recharge zone of about 892.21 km^2 (58.39%). The moderate recharge zone occupies the largest area about 58.39% visible throughout the basin. Poor recharge zones of roughly 34.82 km^2 (19.93%) are shown on the GWRZ map in the basin's northern and southern regions. Poor GWRZ zones are found in areas with synorogenic granite outcrops, high drainage densities, and steep slopes, and areas with granodiorite outcrops (located centrally toward the south) and settlement areas in the south-east due to the presence of rooftops and paved land, both of which lower infiltration rates.

4.3. Sensitivity analysis

In Map Removal Sensitivity Analysis (MRSA) for AHP and MIF approaches, the thematic layers were removed one at a time and the remaining six layers were then utilized to map the GWRZ. The aim was to determine the impact of each factor on the classes of recharge zones generated. The computed GWRZ indicated changes in spatial coverage of zones categorized as very poor, poor, moderate and good in each map removed Table 9. The computed coverage of GWRZ indicated the highest area of good GWRZ (65.12% for AHP and 26.86% for MIF) when the LULC layer was removed while the highest moderate GWRZ (75.21% for AHP and 64.66% for MIF) was recorded when lithology was removed. The highest very poor GWRZ (9.60% for AHP and 22.15% for MIF) was recorded when the lineament was removed. Despite having a high assigned weight for lithology (35 percent for AHP and 25 percent for MIF), its removal produced a lower area of good GWRZ and a very high area of poor GWRZ.

4.4. Validation of groundwater recharge zones

GWRZ determined by a geospatial technique using AHP and MIF is confirmed by comparing them to inventory data that already exists (Mengistu et al., 2022). It was feasible to confirm the accuracy of the aquifer recharge map by superimposing the inventory well point data with the made GWRZ map. Maps generated by both AHP and MIF were overlaid with the sixty (60) pumping well data records collected from the basin. According to the validation points of the GWRZ generated from AHP and MIF the spatial distribution of pumping wells was determined (Figure 13). Pumping wells situated in good GWRZ from AHP and MIF methods are 33.33% and 30% respectively, and moderate GWRZ indicated 41.6% and 28% of wells in maps generated from AHP and MIF respectively. The pumping wells distribution in GWRZ generated from AHP and MIF are 25% and 42% respectively.

5. Discussion

AHP and MIF procedures in the GIS 10.2 environment were used in this work to determine the GWRZ. By defining seven influencing parameters, such as land use, rainfall, soil, slope, drainage density, lineament density, and geology, the multi-criteria decision-making approach (MCDMA) was used to establish the groundwater recharge zones of the Makutupora basin. Weights were assigned accordingly in the selected influencing factors whereby the lithology had the highest weight (35% for AHP and 25% for MIF) land use/land cover (23% for AHP and 22% for MIF), slope (16% for AHP and 16% for MIF), lineament (12% for AHP and 13% for MIF), drainage (7% for AHP and 9% for MIF), rainfall (4% for AHP and 9% for MIF) and the soil had the lowest weight (3% for AHP and 6% for MIF) (Table 8). This study assigned the highest weight to lithology followed by land use and the least weight was given to soil. Lithology is considered a key factor in groundwater recharge because this area is characterized by crystalline basement formation, therefore the type of lithology and lineament characteristics is the key to water infiltration (Das and Pardeshi, 2018; Serele et al., 2020). Similar studies (Zghibi et al., 2020; Mengistu et al., 2022) also assigned the highest weights to lineament followed by LULC and reasonable results were obtained.

The GWRZ resulting from weighted overlay analysis categorized 35.79% for AHP and 21.68% for MIF as a good recharge potential while the moderate potential zone occupies 40.98% for AHP and 58.39% for MIF and the poor recharge zone occupies 23.22% for AHP and 19.95% for MIF of the total area.

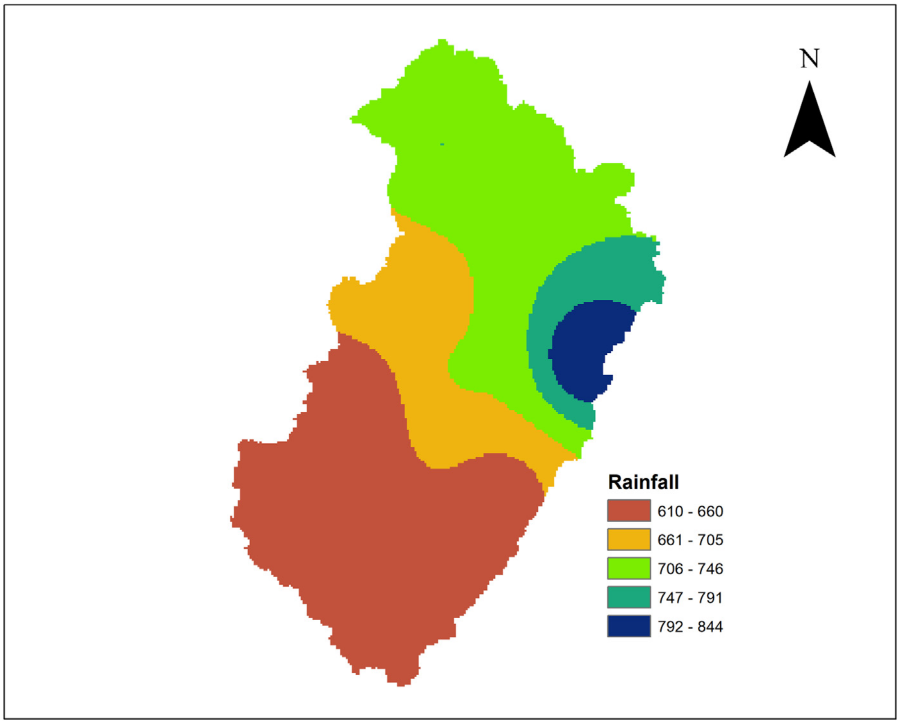

Figure 9. The annual rainfall distribution map of the Makutupora basin.

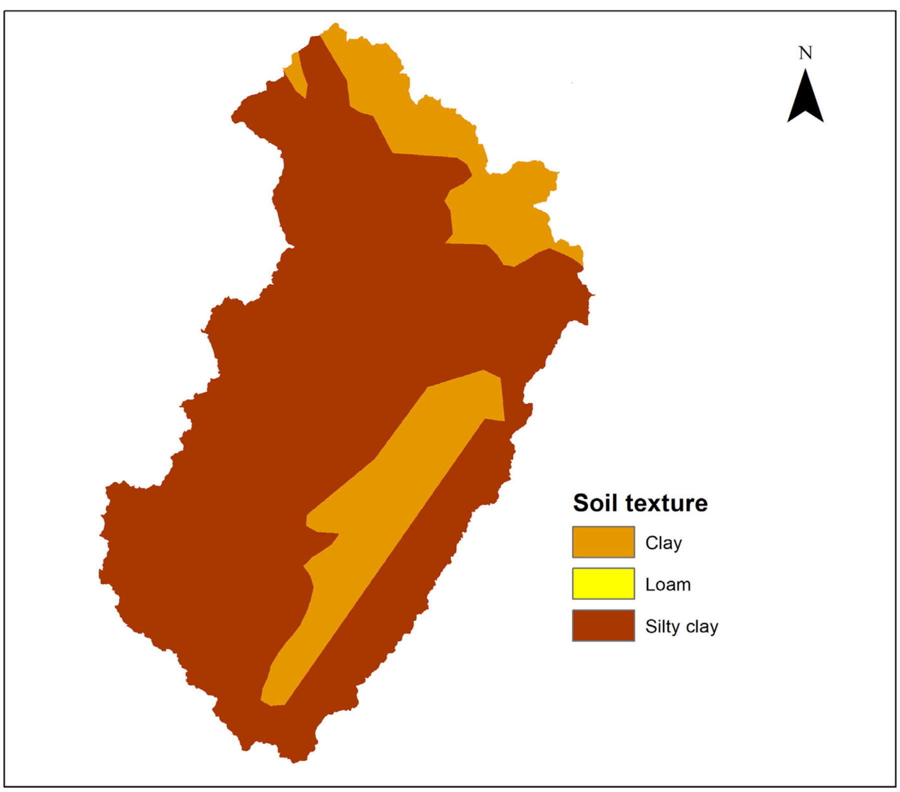

Figure 10. The soil map of the Makutupora basin.

The sensitive parameters affecting the GWRZ were determined and the results indicated that upon removal of the land use thematic map, the percentage of good recharge zone increased because the area categorized as a settlement (poor recharge zone) in the land use map turned into a recharge zone. This is caused by the assumption that there is no conversion of land for human activities (paved land and rooftops) thus GWRZ is determined considering other hydrological factors. This scenario implies that the area was previously a good recharge zone but later the land was converted into settlements and other human influences which led to reduced recharge zones, this is why there are many

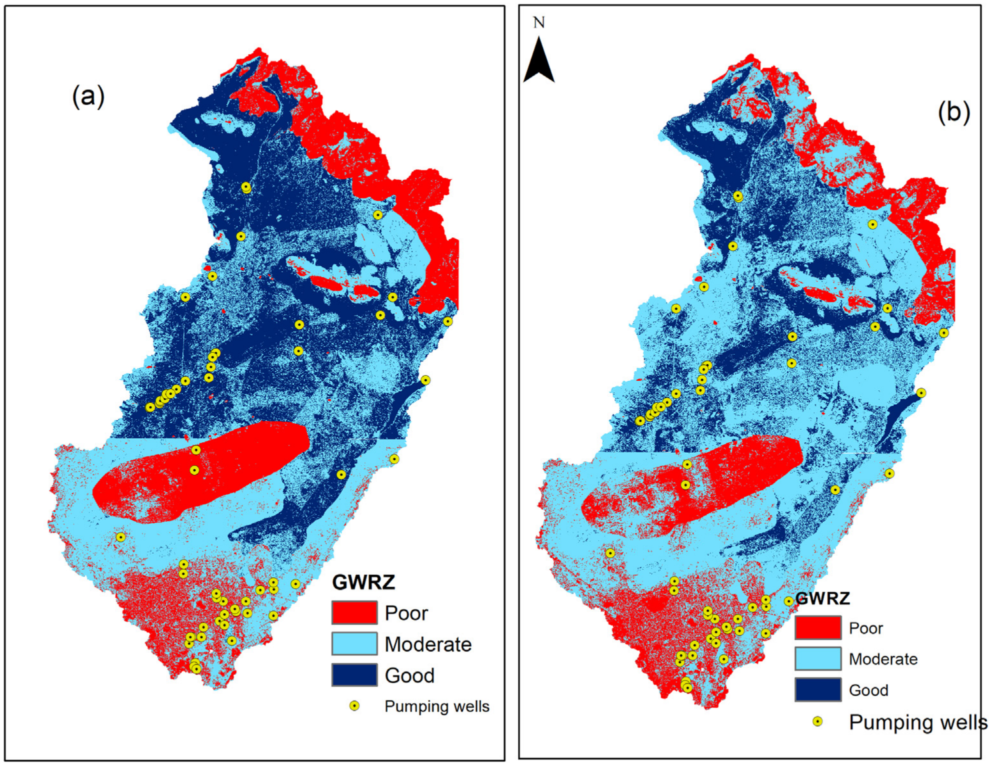

Figure 11. Makutupora basin groundwater recharge zones (a) using the AHP approach and (b) using the MIF technique.

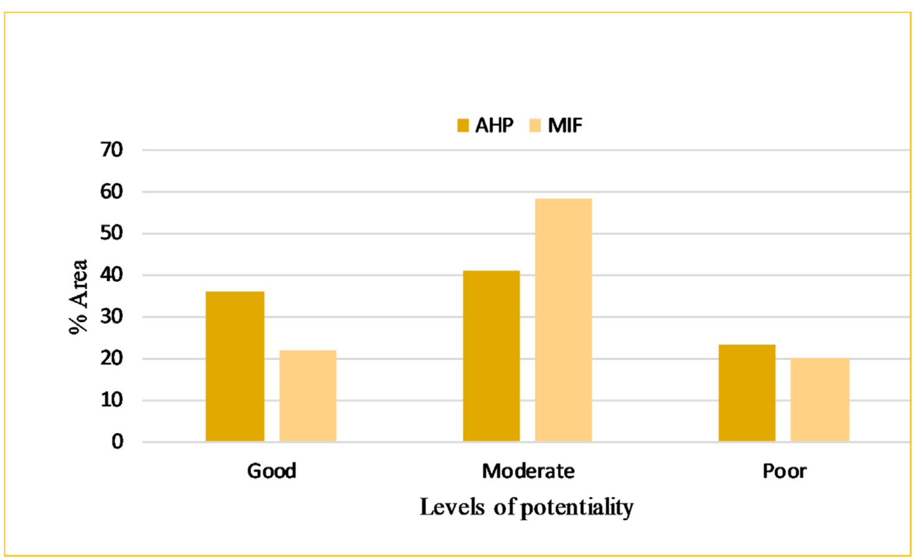

Figure 12. The distribution of groundwater recharge classes for AHP and MIF.

production wells in this zone which are categorized as poor recharge zone. This result is similar to the sensitivity analysis results obtained by (Zghibi et al., 2020) which indicated that LULC has more impact on the GWRZ compared to other factors. The increase of very poor recharge zones and decrease of good recharge zone on the removal of lineament indicates that the recharge of the area relies on the lineament features. In absence of lineaments, areas of good recharge zones are very low, this is caused by the nature of the geology type (crystalline basement rocks) whereby the main recharge of the basin is controlled by secondary geological structures i.e. lineaments.

To cross-validate the accuracy of the AHP and MIF methodologies, a total of sixty (60) wells that were sunk in the studied region were overlaid on the GWRZ map. The wells have yield and specific capacity ranging between 18–440 $m^{3/h}$ and 0.818–42 $m^{2/h}$ respectively. Pumping wells situated in good GWRZ from AHP and MIF methods are 33.33% and 30% respectively, and moderate GWRZ indicated 41.6% and 28% of wells in maps generated from AHP and MIF respectively. The pumping wells distribution in GWRZ generated from AHP and MIF are 25% and 42% respectively. The distribution of the pumping wells in the GWRZ generated from AHP indicated a high concentration of pumping wells in both good and moderate GWRZ while the majority of pumping well fall in the poor GWRZ generated by MIF. Both methods indicated reasonable results however AHP technique is considered to perform better than the MIF method in the Makutupora basin.

Table 9. The percentage area coverage for GWRZ classes was computed by map removal using AHP and MIF.

	Good		Moderate		Poor		Very poor	
Layer Removed	AHP	MIF	AHP	MIF	AHP	MIF	AHP	MIF
Rainfall	14.52	6.70	60.72	59.90	24.59	32.77	0.24	0.61
Lineament	0.06	0.04	54.23	33.02	36.11	44.78	9.60	22.15
Lithology	1.16	0.57	75.21	64.66	23.14	34.67	0.50	0.10
Land use land cover	65.12	26.86	22.32	48.05	11.15	23.82	1.41	1.28
Soil	39.12	16.07	50.45	58.03	9.98	25.89	0.42	0.01
Slope	29.69	6.67	51.80	58.89	18.00	34.29	0.54	0.14
Drainage	38.52	19.12	49.21	53.92	12.00	26.95	0.30	0.01
All Layers	**35.79**	**21.68**	**40.98**	**58.39**	**23.2**	**19.95**	**0.02**	**0.01**

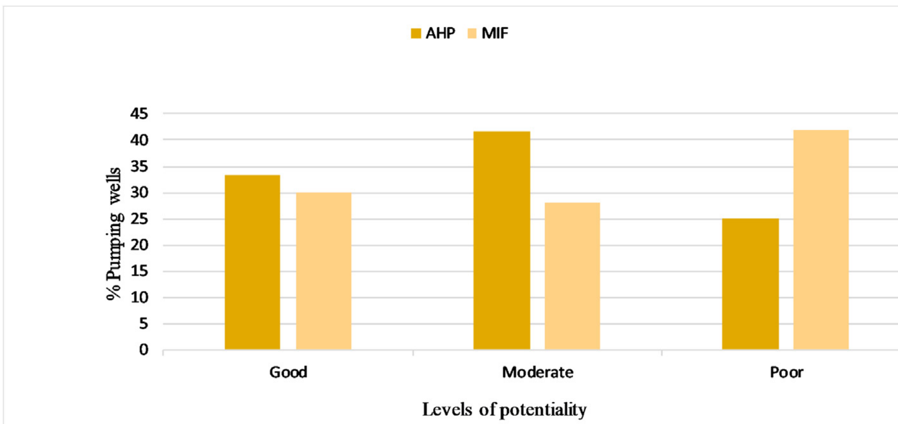

Figure 13. Distribution of pumping wells in the GWRZ generated by AHP and MIF in the study area.

6. Conclusion and recommendations

6.1. Conclusion

Analytical Hierarchy Processes (AHP) and Multi-influencing factor (MIF) analysis were used in a geospatial framework to determine GWRZ in the Makutupora basin, central Tanzania. Lithology, lineament density, land use, rainfall, slope, drainage density, and soil cover are among the variables taken into account in the study. The GWRZ was rated as good (35.79%), intermediate (40.98%), and bad (23.22%) using the AHP technique. According to the classification made using the MIF approach, 19.93% of the research area is classified as a poor recharge zone, 58.39% as moderate, and 21.68% as having strong recharge potential.

The use of the weighted overlay analysis resulted in the GWRZ map from AHP being categorized as good (9.55%), moderate (62.2%) and poor (28.24%) when applying the seven raster maps described in the method section. The sensitivity analysis conducted using weighted overlay analysis considered the map removal technique to determine the spatial variation of the GWRZ classified as very poor, poor, moderate and good potential recharge zones upon removal of each thematic map. The LULC is the most sensitive factor which caused an elevated area of the good recharge zone up to 26.86% for MIF and 65.12% for AHP on its removal. This suggests that the increased LULC conversion into settlements, roads and other uses is a threat to groundwater recharge in the Makutupora basin. Either, lineaments are very crucial factors in recharge processes since their removal indicated a very low GWRZ 0.04% for MIF and 0.06% for AHP and a very high poor GWRZ (22.15% for MIF and 9.6% for AHP). Thus it is important to demarcate the lineament features for protection measures to avoid lowered recharge or contaminated groundwater. Therefore, all the influencing factors applied in this study are equally important and revealed changes in GWRZ on their removal, thus it is recommended to consider all these factors when mapping GWRZ in a semi-arid region characterized by fractured crystalline basement rocks.

The GWRZ map was validated using data from 60 production wells that were obtained from the research region. The AHP method indicated that 33.33% of pumping wells are found in the good GWRZ, 41.6% of wells were located in the moderate GWRZ and 25% of wells are in poor GWRZ. The MIF method indicated 30% in good recharge zone, 28% in moderate recharge zone while 42% of wells were found in poor GWRZ. Although both MCDM approaches produced GWRZ with acceptable accuracy, the validation step shows that the AHP performed better than the MIF in the Makutupora basin due to the highest percentage distribution of pumping wells in the good and moderate GWRZ map.

6.2. Recommendations

- ➢ The results obtained in this study are highly important for the formulation of groundwater development plans and strategies necessary for groundwater resources management such as; artificial recharge schemes, land use planning and protection of natural recharge zones for sustainable groundwater management.
- ➢ The remote sensing-generated GWRZ map is a benchmark for additional groundwater exploration utilizing hydro-geological and geophysical techniques to find new production and monitoring wells.
- ➢ Future research might take into account how the shifting of the groundwater recharge zones is influenced by climate variability and land LULC change.

Declarations

Author contribution statement

Clarance Paul Kisiki; Tenalem Ayenew: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Tilaye Worku Bekele: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Ibrahim Chikira Mjemah: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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