Hydrogeology Journal (2024) 32:785–799
https://doi.org/10.1007/s10040-024-02769-z

REPORT

Delineating groundwater potential zones with GIS and analytic hierarchy process techniques: the case of Great Ruaha River catchment, Tanzania

Ramadhani Twaha[1] · Joel Nobert[1] · Augustina C. Alexander[1] · Deogratias M.M. Mulungu[1] · Mathew Senga[2]

Received: 9 May 2023 / Accepted: 11 January 2024 / Published online: 27 January 2024

Abstract

The Great Ruaha River Catchment (GRC) in Tanzania is facing severe water scarcity due to the growing number of water users in the catchment. The surface-water resources are under stress, leading to increasing dependence on groundwater for water supply. This study aimed to identify and map groundwater potential areas in the GRC using a geographic information system (GIS), remote sensing techniques, and analytic hierarchy process multi-criteria decision analysis (AHP MCDA) tools. The thematic maps representing lithology, lineaments density, precipitation, soil, slope, drainage density, geomorphology, and land use were used to create a groundwater potential zones (GWPZ) map by weighted linear combination (WCL). The results showed that 70% (~60,044 km^2) of the catchment area is in zones with moderate groundwater potential, 21.9% (~18,720 km^2) in high groundwater potential zones, and 7.87% (~6,726 km^2) in low groundwater potential zones. These results highlight the catchment's overall groundwater potential and identify areas with scarce resources that should be prioritized for protective measures. Watershed managers and policymakers can use this information to make informed decisions on groundwater use and protection, and determine suitable areas for new wells that may have greater yield.

Keywords Tanzania · Groundwater potential zones · Remote sensing

Introduction

Groundwater, being the largest reservoir of freshwater beneath the earth's surface, has a crucial role in the hydrological cycle and is of paramount importance in maintaining water balance on the earth's surface (Gleeson et al. 2016). Groundwater occurs in aquifers, which are layers of rock and soil that hold and transmit water (Alramthi et al. 2022). Groundwater is replenished via the recharge process, which happens naturally through precipitation and surface-water infiltration or artificially through the injection of surface water or the construction of recharge wells (Ajami 2021; Lentswe and Molwalefhe 2020). The recharge process guarantees supply of groundwater, which in itself, however, may contain contaminants and impurities (Böhlke 2002; Li et al. 2021). Studying recharge water quality is an essential aspect of groundwater management and for safeguarding the health and quality of aquifers, as well as for ensuring a sustainable supply of this vital resource for future generations (Alramthi et al. 2022). However, in semiarid regions, the amount of water available for recharge is very spatially variable (Saiz-Rodríguez et al. 2019). Some areas may experience heavy precipitation and have more water available for recharge, while others may experience prolonged periods of drought and have limited water available for recharge (Attia and Hamed 2018; Hamed et al. 2018). This variability can create challenges in managing water resources and maintaining a sustainable water supply. Climate change is also expected to increase the frequency and severity of droughts in semiarid regions (Thomas et al. 2016), which can further limit the water available for aquifer recharge and exacerbate the challenges of managing water resources in these regions (FAO 2011). Land use and land-cover change can also impact groundwater recharge, as deforestation, urbanization, and other alterations in land use can result in increased runoff

✉ Ramadhani Twaha
kawisart@gmail.com

[1] Department of Water Resources Engineering, University of Dar es Salaam, Dar es Salaam, Tanzania

[2] Department of Sociology and Anthropology, University of Dar es Salaam, Dar es Salaam, Tanzania

and decreased water infiltration, hindering recharge of aquifers (Alley 2009).

Groundwater serves as a crucial water source for humans, ecosystems, and agricultural production in areas where surface water is scarce or unreliable (Lentswe and Molwalefhe 2020; Mussa et al. 2020). It also provides a reliable water source for irrigation to supplement surface water during dry periods to ensure a consistent water supply to crops. According to recent estimates, worldwide groundwater depletion is ~545 km^3/year (Makonyo and Msabi 2021; Mussa et al. 2020). This trend is a cause for alarm, as it signals that humans are extracting and using more groundwater than is being replenished by natural processes. Generally, groundwater is a finite resource, vulnerable to overuse and pollution, thus communities and agricultural operations must manage it responsibly through monitoring, conservation, and sustainable practices.

The Great Ruaha River Catchment in Tanzania is experiencing severe water scarcity problems due to the large number of water users in the catchment. Since 1993, the Great Ruaha River has been experiencing river drying and extended dry seasons (England 2019; Gervas et al. 2019; McCartney 2008). Due to the catchment's large number of water users, surface-water resources have proven insufficient (URT 2015a). With the rising scarcity of surface water, groundwater has become a critical water source for society, industries, and agriculture; however, information regarding availability and characteristics of this resource in the catchment is limited (Kashaigili 2010). The lack of information needed to conduct comprehensive studies on groundwater resources makes it challenging for water managers and policymakers to make informed decisions about using and protecting this valuable resource, thus necessitating the use of other techniques—such as combined remote sensing (RS) and ground data—to gain a better understanding of the resource.

Groundwater resources assessment is a complex process requiring various techniques and tools to identify and evaluate the resources accurately. There are a variety of methods that are commonly employed in the assessment of groundwater resources, with one approach being the use of traditional techniques, such as geophysical surveys (Kumar and Srinivasan 2016). However, they can be costly and time-consuming and may not provide detailed water quality or quantity information.

Probabilistic models can estimate the likelihood of finding groundwater in a given area based on lithology, topography, and climate (Bailey et al. 2020; Gonzalez et al. 2020). Also, the use of geographic information system (GIS) and remote sensing techniques, in combination with multi-criteria decision analysis (MCDA) tools, such as the analytical hierarchical process (AHP) and fuzzy-AHP (Al-Djazouli et al. 2020; Radulović et al. 2022; Saaty 1994), has recently been featured prominently in groundwater studies. Integrating remote sensing, GIS, and digital image processing, along with multi-criteria analysis, has allowed scientists to map and analyze the surface features of an area to identify more accurately areas with groundwater potential. Combining thematic data, including lithology, topography, vegetation, soil characteristics, lineaments, and land covers, has made it possible to achieve the desired results; however, integrating ground-observed data into traditional GIS models improves the outcomes (Adeyeye et al. 2019). This has been particularly useful for groundwater studies in semiarid and data-scarce regions of sub-Saharan Africa, like the Great Ruaha River Catchment, where other techniques may not be feasible (Arulbalaji et al. 2019).

This research aims to utilize GIS and remote sensing techniques, as well as AHP MCDA tools, to identify and map areas within the Great Ruaha River Catchment with a high groundwater potential. Thus, the main objective of this study is to provide water managers and policymakers with appropriate, comprehensive and in-depth information about the catchment. Given the absence of prior investigations on groundwater potential in the Great Ruaha River Catchment using the techniques employed in this analysis, this study stands to provide valuable insights on the identification of optimal locations for new wells, which, in turn, can enhance the efficiency and yield of extant wells. Furthermore, the present research endeavor seeks to pinpoint areas with particularly scarce groundwater resources that should be prioritized for protection.

Description of the case study area

The Great Ruaha River Catchment, located in southwestern Tanzania, is a large catchment with an area of 85,556 km^2, making up 46.5% of the Rufiji Basin. It is situated between latitudes –5.4° and 9.45°S and longitudes 33.35° and 37.85°E (Fig. 1). It has an elevation range of 101 meters above sea level (m asl) downstream to 2961 m asl in the Poroto Mountains. The area has a tropical climate, with a mean annual rainfall of around 400–1,200 mm (Table 1).

The Great Ruaha River Catchment is an intricate and significant water system that underpins a wide variety of water users, including farmers, herders, fisheries, and wildlife. This catchment supplies water resources to numerous small and large-scale farms in the upstream part of the Usangu Plains, which depend on surface water for irrigation. It is home to several protected areas, such as the Ruaha National Park, one of Tanzania's largest national parks and a vital habitat for many wildlife species, including elephants, lions, leopards, wild dogs, and more than 400 bird species. Additionally, the Usangu and Ihefu wetlands, located in the middle of the catchment, are crucial habitats for water birds, fish, and other aquatic

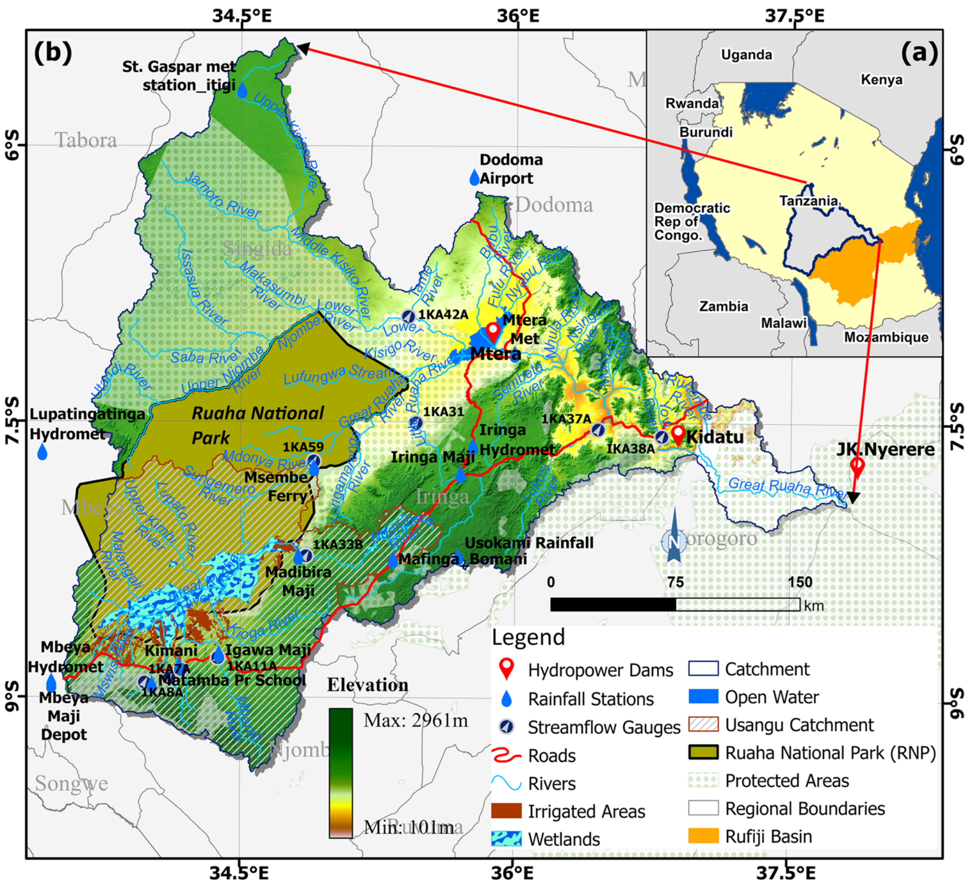

Fig. 1 **a** Location of the study area: Great Ruaha River Catchment (blue outline) in the Rufiji Basin (green area), Tanzania. **b** Study area map

Table 1 Rainfall Stations and their long-term mean annual rainfall (MAR)

Station_ID	Name	Latitude	Longitude	MAR (mm)
9635001	Dodoma Airport	−6.166667	35.766667	583.06
9733000	Lupatingatinga Hydromet	−7.666667	33.416667	1,132.95
9735014	Iringa Maji	−7.78333	35.7	724.53
9735013	Iringa Hydromet	−7.63333	35.76667	854.35
9835033	Mafinga_Bomani	−8.25	35.33333	899.36
9734001	Msembe Ferry	−7.75	34.9	554.77
9834006	Igawa Maji	−8.76667	34.38333	685.65
9834010	Kimani	−8.83333	34.16667	691.63
9834013	Matamba Pr School	−8.93333	34.01667	1,001.63
9833001	Mbeya Hydromet	−8.93333	33.46667	918.25
9833020	Mbeya Maji Depot	−8.916667	33.466667	920.18
9834000	Madibira Maji	−8.233333	34.816667	692.21
9800000	Mtera Met	−7.12816	35.9918	441.7
9800000	St. Gaspar met station_itigi	−5.69639	34.50197	606.7
9800000	Usokami rainfall	−8.23222	35.69028	1,070.7
Catchment average MAR = 785.178 mm				

Source: (URT 2020)

species, as well as being a significant source of fish and other resources for local people. The surface water in the catchment is indispensable for preserving the park's ecosystems. Moreover, the catchment is home to hydropower producers, like Mtera, Kidatu and the freshly constructed Julius Nyerere Hydropower Project, which are situated in the downstream part of the catchment and present an essential source of electricity.

In addition to surface-water resources, the Great Ruaha River Catchment possesses ~442.3 billion cubic meters (BMC) of groundwater resources (URT 2015b). The annual water demand is projected to be an estimated 3.8 BMC by year 2025 (URT 2015a).

Methods

In this study, the analytical hierarchical process (AHP) was employed to delineate the groundwater potential zone of the Great Ruaha River Catchment. Eight thematic maps, including lithology, lineaments density, precipitation, soil, slope, drainage density, geomorphology, and land use/cover were preprocessed using ArcMap10.5 software to ensure their compatibility in extent, spatial resolution, and spatial references. The input data and complete workflow are illustrated in Fig. 2.

Thematic map preprocessing

Lithology

The properties and hydraulic features of surface geology play a crucial role in shaping groundwater replenishment in arid regions (Jaiswal et al. 2003; Zarate et al. 2021). The geological attributes within a specific area have a direct impact on the presence and accessibility of groundwater, affecting the entire recharge process (Uc Castillo et al. 2022). The geological layers of the study area were transformed into digital format using data from the published lithology map (Fig. 3), which was sourced from the Rufiji Basin's Integrated Water Resources Management Development Plan (IWRMDP) groundwater assessment (URT 2015b). To ensure consistency in the layers, the thematic map was converted to a 30-m raster format prior to the weight and rank assignment process.

The geology of the catchment in the south and northern part is characterized by granulite and fine-grained clastic sediment, while metasedimentary rocks are predominant in the downstream area (Fig. 4a). Sandy and gravelly geologies are found in the northernmost part and the middle of the catchment. Granulite with materials such as sand is highly porous and forms aquifers which could serve as potential groundwater sources. Conversely, the most downstream part of the catchment is dominated by nonporous geological features—such as meta-igneous, meta-sedimentary rocks, clastic and coal sediments, granitoids, mafic and ultramafic rocks, meta-sediments, and gneiss—which could lead to low groundwater storage.

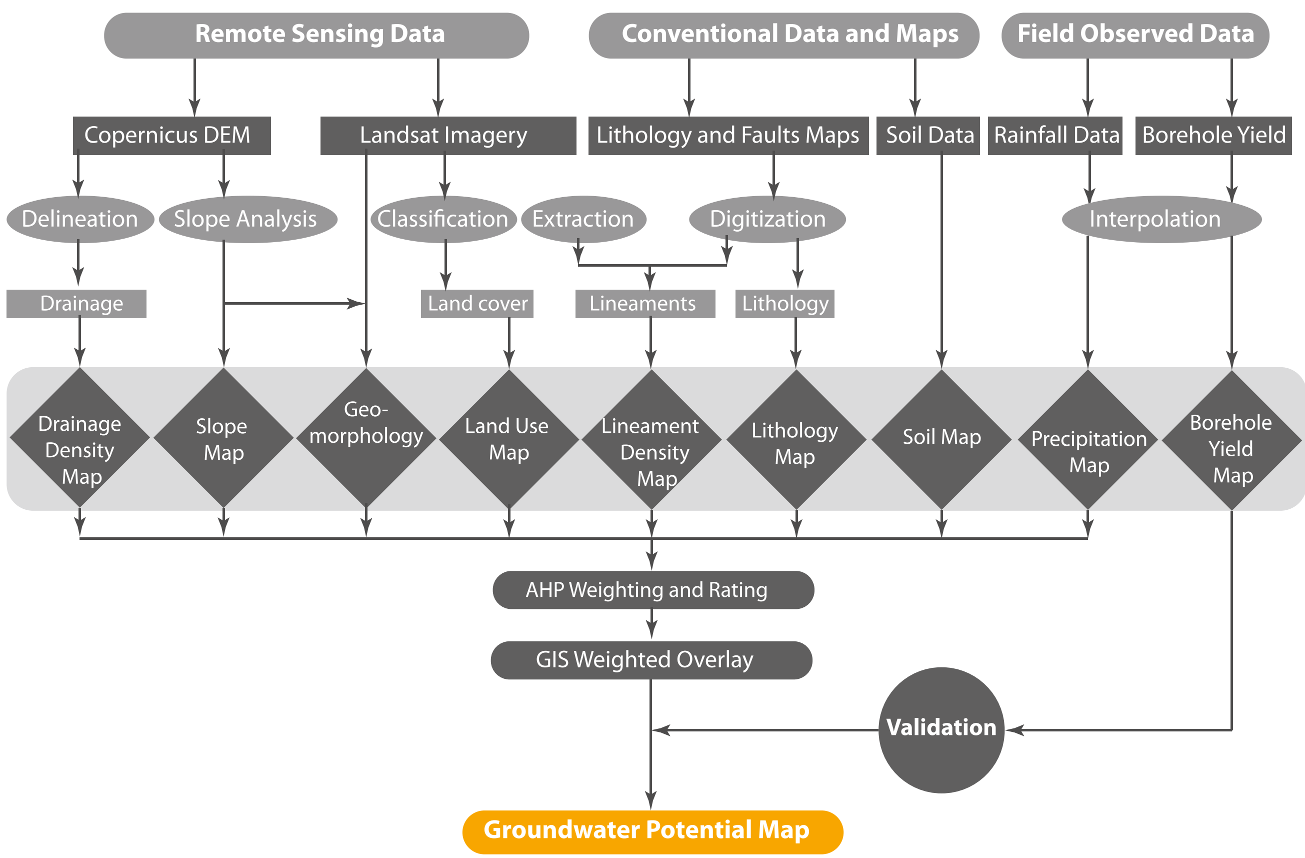

Fig. 2 Groundwater potential analysis flow chart

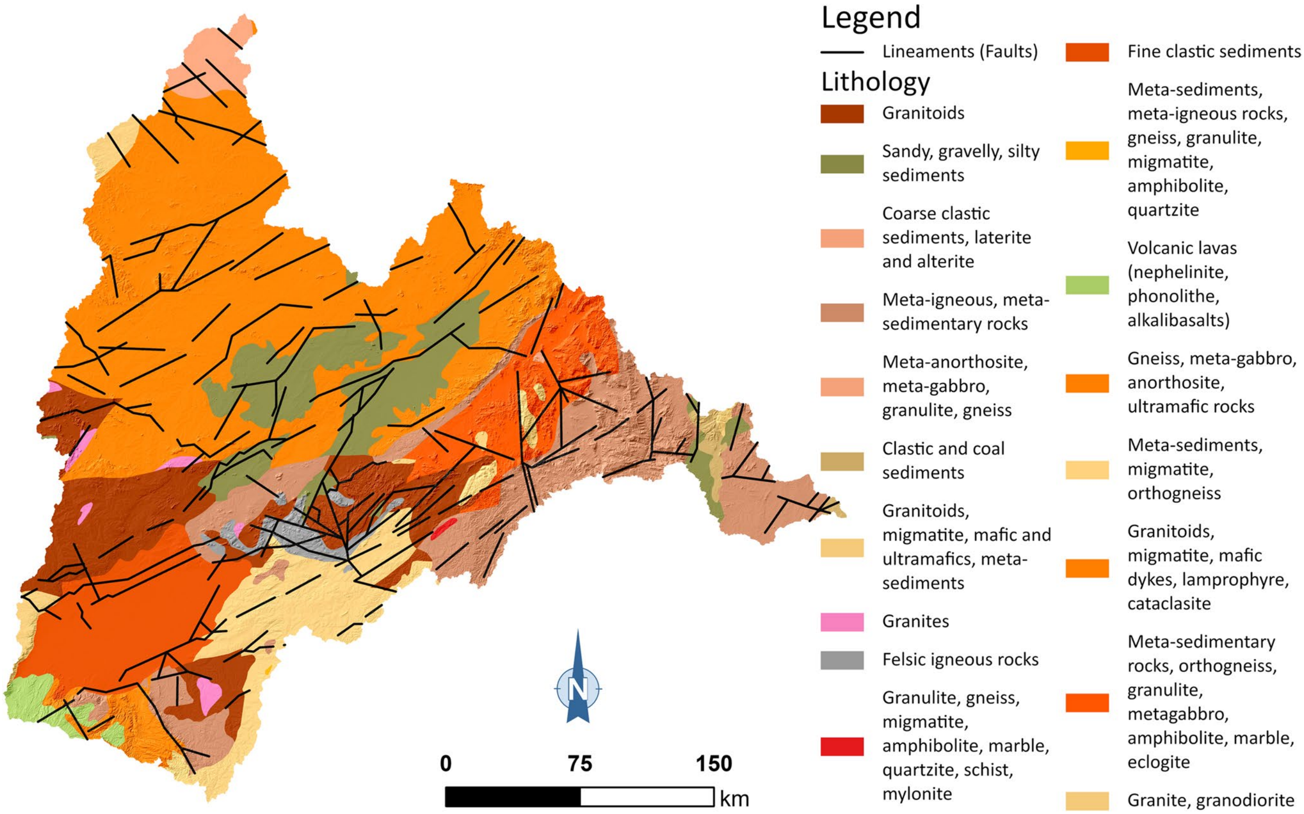

Fig. 3 Digitized lithology layers and faults (Source: URT 2015b)

Lineament density

Lineaments are linear or nearly straight geological features that influence the subsurface permeability and are widespread across the Earth's surface (Ni et al. 2016; Suganthi et al. 2013). The lineaments can encompass various elements including faults, fractures, or joints with inherent permeability and porosity characteristics (Masoud et al. 2022; Pradhan 2009; Pradhan and Youssef 2010; Rajaveni et al. 2017). These features have a significant impact on the process of surface runoff infiltrating into the subsurface and are crucial for the storage and movement of groundwater. Lineaments serve as conduits for water infiltration into the subsurface, playing a vital role in the dynamics of groundwater storage and movement (Gupta and Singhal 2010; Subba Rao et al. 2001). In this study, lineaments were extracted from a 15-m panchromatic band of Landsat 8 imagery through automatic lineament extraction method. The latter was combined with the digitized faults from the published geological map (Fig. 3) to create an ensemble of ground and RS data. The lineament density (Ld, km^{-1}) was determined by calculating the total length of all recorded lineaments and dividing it by the area within the study area, as represented by Eq. (1) (Edet et al. 1998; Rahmati et al. 2015). Subsequently, a lineament density map was generated using the "Line Density" tool in ArcGIS 10.8.

$$\mathrm{Ld} = \sum\nolimits_{n=1}^{i=n} \frac{L_i}{A} \quad (1)$$

where ΣL_i represents the cumulative length of all lineaments (in kilometers) within the grid i, and A denotes the area of the grid (in square kilometers).

Notably, areas with high lineament density (>0.2 km/km^2) were predominantly observed in the central and downstream regions of the catchment (Fig. 4b).

Geomorphology

The geomorphology of an area provides essential insights into the characteristics and origin of its landforms, a manifestation intricately linked to the structural development of its geological composition (Gupta 2003; Rajaveni et al. 2017). It encompasses both erosional and depositional landforms, which has a significant influence on the rate at which precipitation infiltrates the soil, ultimately dictating groundwater recharge, subsurface movement, and storage at any given location (Kumar et al. 2016; Thomas et al. 2009).

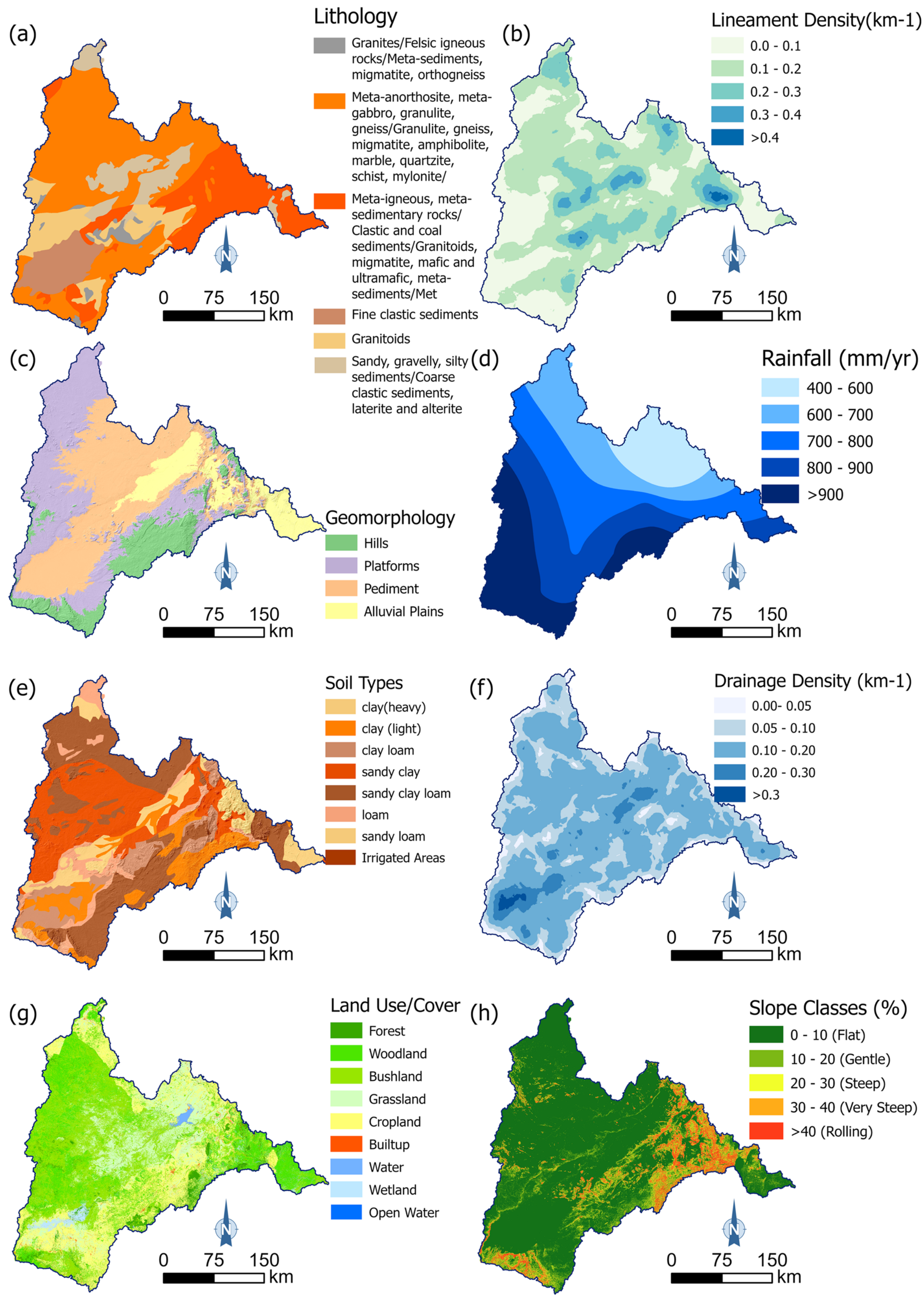

Fig. 4 Seven thematic layers for the study area: **a** lithology, **b** lineament density **c** geomorphology **d** rainfall **e** soil type **f** drainage density **g** land use/cover **h** slope

Furthermore, the shape of landforms can dictate the path of runoff, affecting the volume of water that permeates the soil (Elubid et al. 2020). In this investigation, the delineation of geomorphic features was achieved through the visual interpretation of digitally enhanced images, complemented by geomorphological data sourced from the Rufiji Basin Annual Hydrological Report (URT 2020), in conjunction with elevation and slope data classifications. Within the study area, four principal geomorphological units were identified, as depicted in Fig. 4c. The pediment geomorphology was identified in the Usangu plains and certain portions of the protected areas located in the northern segment of the catchment. Hilly formations were noted in the upstream region of the catchment as well as the downstream vicinity near Kidatu Dam. Additionally, other formations, such as platforms, were prevalent in most of the northern part of the catchment, while alluvial plains were observed in areas characterized by relatively gentle slopes in proximity to Mtera Dam.

Rainfall

Rainfall, as the primary source of recharge, significantly influences the availability of water for percolation into the groundwater system, making it a crucial hydrologic element in this study. It also significantly influences groundwater potential and the efficiency of MCDA (Adiat et al. 2012) and it has been noted that areas with higher precipitation rates tend to have more significant recharge rates, as the water can more easily infiltrate through the soil and reach the groundwater (Thomas et al. 2016). The precipitation thematic map was created from 15 stations (Table 1) using an inverse distance weighted (IDW) interpolation method to generate the spatially distributed mean annual precipitation. The map showed that the mountainous areas upstream of the catchment have significantly higher precipitation amounting to a mean annual average of >900 mm compared to the northern areas, with mean annual precipitation values ranging from 400 to 700 mm (Fig. 4d).

Soil

The importance of soil in delineating the groundwater potential zones is undeniable (Kumar et al. 2016). Rukundo and Doğan (2019) note that soils such as sands and gravels allow for increased water infiltration into the subsurface and a higher groundwater recharge rate. Conversely, less porous soils like clay can impede infiltration and reduce groundwater recharge levels; furthermore, clay layers in the subsurface can act as a barrier to groundwater recharge. The soil types in the catchment were extracted from the FAO Harmonized World Soil Database (HWSD) shapefile (FAO and IIASA 2023) and used to create a soil thematic map. It was found that ~60% of the catchment is predominantly comprised of sandy clay loam and sandy clay, with clay and sandy clay populating the middle of the catchment, particularly in the Usangu Plains (Fig. 4e).

Drainage density

Drainage density, defined as the ratio of total watercourse length to the surface area of the basin, is a fundamental concept in hydrogeology (Adiat et al. 2012; Horton 1955, 1932; Jaiswal et al. 2003; Mogaji et al. 2015). This parameter plays a crucial role in groundwater occurrence, with a well-established inverse relationship: high drainage density is associated with reduced infiltration, while low density promotes higher infiltration rates (Horton 1945; Magesh et al. 2012; Saranya and Saravanan 2020). It is important to recognize that the drainage pattern is influenced by a multitude of factors, including slope gradient, soil absorption capacity, rainfall patterns, vegetation cover, climate, topography, and subsurface characteristics (Gao et al. 2022; Manap et al. 2013). As a consequence of these dynamics, areas with low drainage density are deemed conducive for groundwater development (Kumar et al. 2007; Magesh et al. 2012; Rahmati et al. 2015). In this study, the drainage pattern in the catchment was delineated from the European Space Agency Copernicus Global Digital Elevation Model (European Space Agency and Sinergise 2021) of 30-m resolution. The delineated stream patterns were used to generate the drainage density (Dd, km^{-1}) maps using "Line Density" tool in the spatial analyst tool of ArcGIS 10.8 software, using Eq. (2).

$$\mathrm{Dd} = \sum_{n=1}^{i=n} \frac{D_i}{A} \quad (2)$$

where ΣD_i represents the cumulative length of all streams within the grid i (measured in kilometers), while A denotes the area of the grid (measured in square kilometers). Figure 4f, shows that high drainage density (>3 km/km^2) areas are predominantly in the upstream and middle of the catchment.

Land use/cover

Land cover influences the rate of infiltration, impacting how quickly water penetrates the soil and reaches the groundwater (Elubid et al. 2020; Pandey and Purohit 2022). Areas with more vegetation such as forests or grasslands, tend to have higher infiltration rates than highly urbanized land or areas covered in asphalt (Kumar et al. 2016). In this analysis the land use/cover in the catchment were extracted from Landsat 8 OLI and TIRS satellite imagery of 2020 using the maximum likelihood algorithm for classification in ERDAS

15 software. The accuracy assessment report yielded an overall kappa coefficient of 86%.

Results from the study indicate that the catchment is dominated by woodland, bushland and grassland, particularly in protected areas and downstream of the catchment. Furthermore, the Usangu Plains and northern parts of the catchment were identified as being predominantly cultivated (Fig. 4g).

Slope

The slope serves as a surface indicator for identifying groundwater conditions (Al Saud 2010; Ettazarini 2007). The recharge process is inversely influenced by the slope (Adiat et al. 2012). Steeper slopes result in increased runoff and reduced infiltration, whereas flatter areas typically exhibit slower infiltration rates (Maqsoom et al. 2022; Sapkota et al. 2021). The slope map for the study area (Fig. 4h) was created using the European Space Agency Copernicus Global Digital Elevation Model with a 30-m resolution using ArcGIS 10.8 software. The study area was found to consist of flat slopes, covering the Usangu Plains and specific sections of the protected areas in the northern part of the catchment. Rolling slopes were identified in the uppermost region of the catchment and the downstream area near Kidatu Dam (Fig. 4h).

Delineation of groundwater potential zones

This study utilized eight thematic maps to analyze the potential of groundwater occurrence. The maps included lithology, lineament density, precipitation, soil, slope, drainage density, geomorphology, and land use, which have all been previously identified to influence groundwater (Dar et al. 2020; Elubid et al. 2020; Makonyo and Msabi 2021; Uc Castillo et al. 2022). The weighting and ranking of thematic map categories were based on prior research criteria as described by Kumar et al. (2016), Uc Castillo et al. (2022), Al-Djazouli et al. (2020) and Arulbalaji et al. (2019). All variables with significant influence on groundwater were given high weights. Low weights were assigned to variables that had little impact on groundwater potential. The values in the thematic maps were grouped into five categories—very low, low, moderate, high, and very high (Table 2)—and were assigned weights based on a scale ranging from 1 to 9 to indicate their relative significance in determining the groundwater potential (Makonyo and Msabi 2021).

Normalization of weights

The analytic hierarchy process (AHP) was employed to assign weights to the thematic layers. The pairwise comparison matrix by Saaty (2002) was used to establish these weights on a scale from 1 to 9, with 9 indicating extreme importance and 1 denoting equal importance. Each thematic layer underwent pairwise comparisons against all the others, adhering to Saaty's method. To ensure a realistic analysis, Saaty (2002) recommends a consistency ratio (CR) falling within the range of 0.1–0. In this investigation, the consistency ratio was computed with the assistance of the extAHP 2.0 ArcGIS add-in. The following equation is used to calculate the CR.

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{3}$$

where RI represents the random consistency index, and CI denotes the consistency index, which can be mathematically expressed as follows:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} \tag{4}$$

where λ signifies the principal eigenvalue of the matrix and can be readily computed based on the matrix itself, while n denotes the number of thematic layers.

The AHP method utilizes pairwise comparisons of all thematic layers as input, generating relative weights for thematic layers as output (Table 3). The ultimate weightings are normalized eigenvector values linked to the highest eigenvalues of the ratio matrix (Adiat et al. 2012; Jha et al. 2010; Rahmati et al. 2015). The pair-wise comparison matrix (Table 3) yielded a consistency ratio of 0.00, which is the perfect score according to (Malczewski 1999; Saaty 1980).

Weighted linear combination (WLC) of thematic layers

The groundwater potential index was obtained by integrating all thematic maps (Fig. 5) by weighted linear combination (WLC) using Eq. (5)

$$\mathrm{GWPI} = \sum \left(W_i R_i\right) \tag{5}$$

Where GWPI = groundwater potential index, W_i is the scored weight of each map, and R_i is a thematic map with scored subclasses.

Results

Groundwater potential zones

The generated groundwater potential zones were classified into five categories labeled: very low, low, moderate, high, and very high, with class ranges described in Table 4. However, based on the values obtained in the generated GWPI, only three classes (low, moderate, and high) were obtained (Fig. 6).

Table 2 Weights and rankings assigned to different thematic layers and their associated classes

Variable	Weight	Classes	Rank
Lithology	8	Granitoids	8
		Sandy, gravelly, silty sediments	9
		Coarse clastic sediments, laterite, and alterite	9
		Meta-igneous, meta-sedimentary rocks	6
		Meta-anorthosite, meta-gabbro, granulite, gneiss	5
		Clastic and coal sediments	6
		Granitoids, migmatite, mafic and ultramafics, meta-sediments	6
		Granites	4
		Felsic igneous rocks	4
		Granulite, gneiss, migmatite, amphibolite, marble, quartzite, schist, mylonite	5
		Fine clastic sediments	7
		Meta-sediments, meta-igneous rocks, gneiss, granulite, migmatite, amphibolite, quartzite	6
		Volcanic lavas (nephelinite, phonolithe, alkalibasalts)	5
		Gneiss, meta-gabbro, anorthosite, ultramafic rocks	5
		Meta-sediments, migmatite, orthogneiss	4
		Granitoids, migmatite, mafic dykes, lamprophyre, cataclasite	5
		Meta-sedimentary rocks, orthogneiss, granulite, metagabbro, amphibolite, marble, eclogite	6
		Granite, granodiorite	5
Lineament density	7	Very low (0.0–0.1)	2
		Low (0.1–0.2)	5
		Moderate (0.2–0.3)	6
		High (0.3–4)	8
		Very high (>0.4)	9
Geomorphology	7	Hills	4
		Platforms	5
		Pediment	7
		Alluvial plains	8
Rainfall	6	Very low (400–600)	5
		Low (600–700)	6
		Moderate (700–800)	7
		High (800–900)	8
		Very high (>900	9
Soil	6	Clay(heavy)	1
		Clay (light)	2
		Clay loam	4
		Sandy clay	5
		Sandy clay loam	7
		Loam	8
		Loamy sand/sandy loam	9
Drainage density	5	Very low (0.0–0.05)	7
		Low (0.05–0.1)	6
		Moderate (0.1–0.15)	4
		High (0.15–0.2)	3
		Very high (>0.2)	1

Table 2 (continued)

Variable	Weight	Classes	Rank
Land use	4	Built-up	2
		Grassland	3
		Cropland	4
		Bushland	5
		Woodland	6
		Forest	7
		Wetland	8
Slope	3	Flat (0–10)	8
		Gentle (10–20)	7
		Steep (20–30)	6
		Very steep (30–40)	5
		Rolling (>40)	4

Table 3 Matrix for pairwise comparison of eight criteria for the Analytic Hierarchy Process (AHP)

Variable	Lithology	Lineaments density	Geomorphology	Rainfall	Soil	Drainage density	Land use	Slope	Final weight
Lithology	8/8	8/7	8/7	8/6	8/6	8/5	8/4	8/3	0.174
Lineaments density	7/8	7/7	7/7	7/6	7/6	7/5	7/4	7/3	0.152
Geomorphology	7/8	7/7	7/7	7/6	7/6	7/5	7/4	7/3	0.152
Rainfall	6/8	6/7	6/7	6/6	6/6	6/5	6/4	6/3	0.130
Soil	6/8	6/7	6/7	6/6	6/6	6/5	6/4	6/3	0.130
Drainage density	5/8	5/7	5/7	5/6	5/6	5/5	5/4	5/3	0.109
Land use	4/8	4/7	4/7	4/6	4/6	4/5	4/4	4/3	0.087
Slope	3/8	3/7	3/7	3/6	3/6	3/5	3/4	3/3	0.065

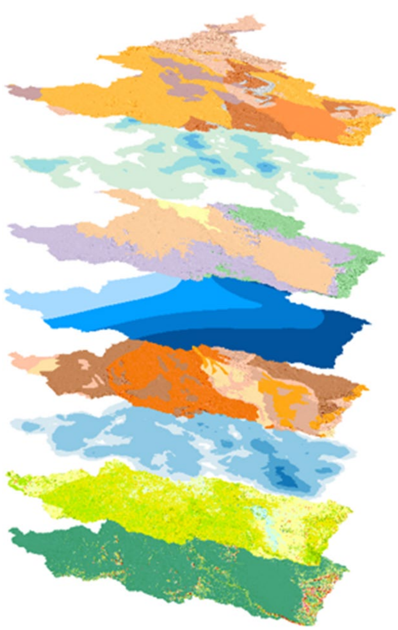

Fig. 5 Integration of weighted thematic layers

Table 4 Weight ranges for categorized Groundwater Potential (GWP) zones

GWP indices	Groundwater category
1–2	Very low
3–4	Low
5	Moderate
6–7	High
8–9	Very high

The groundwater potential index (GWPI) revealed that 70.23% (60,044.92 km^2) of the catchment was found to be in moderate groundwater potential zones, which were observed primarily in the northern part of the catchment in the Ruaha National Parks and in the southwest area of the catchment where there is a high prevalence of irrigation activities. The high groundwater potential zones, making up 21.9% (18,720.2 km^2) of the catchment, were mostly found in the middle and downstream parts of the catchment, particularly in the Usangu wetlands and in the areas close to the Mtera and Kidatu dams, respectively. Low groundwater potential zones, on the other hand, were determined to account for 7.87% (6,726.41 km^2) of the catchment and were randomly dispersed throughout the catchment.

Validation

The validation of the GWPI entailed the use of interpolated borehole yield data sourced from a dataset encompassing 345 boreholes situated both within and in the vicinity of the catchment area. The steady borehole yields were interpolated using the Kriging method in the ArcMap software. The resulting map was then categorized into five classes (as illustrated in Fig. 7 and detailed in Table 5) to align with the GWPI classification scheme.

The agreement between the borehole yield map and GWPI was assessed using the kappa index of agreement and coefficient of determination (R^2). Approximately 500 accuracy assessment points (Fig. 8a) were randomly generated on the regions with concentrated and well distributed boreholes (Fig. 8b). These points were created using the "Create Accuracy Assessment" tool in ArcMap 10.8. Subsequently, the overall kappa agreement index was calculated using the Confusion Matrix tool in ArcMap 10.8. Lastly, the coefficient of determination (R^2) was calculated in R v4.3.2.

The evaluation revealed a robust correlation between groundwater potential zones and interpolated borehole yields, boasting a 0.68 kappa index of agreement and 0.64 coefficient of determination (R^2). Given the scarcity of boreholes in the area, the suitability map was crafted by intersecting the GWPI and borehole yield maps, as illustrated in Fig. 9.

The visual interpretation of the suitability map showed a strong agreement with the GWPI map; however, there is a minor discrepancy in the central region of the catchment where the GWPI indicated a high potential, but the suitability map indicated the 'not suitable' category. This incongruity can be attributed to several factors, including uncertainties in the remotely sensed data, the methodology applied, and the absence of borehole data in these regions.

The analysis of the coverage areas for each category, as outlined in Table 6, indicated a noteworthy concurrence between the generated groundwater potential zone map and the interpolated borehole yield map. This alignment is particularly evident in the areas characterized by low, moderate, and high groundwater potential.

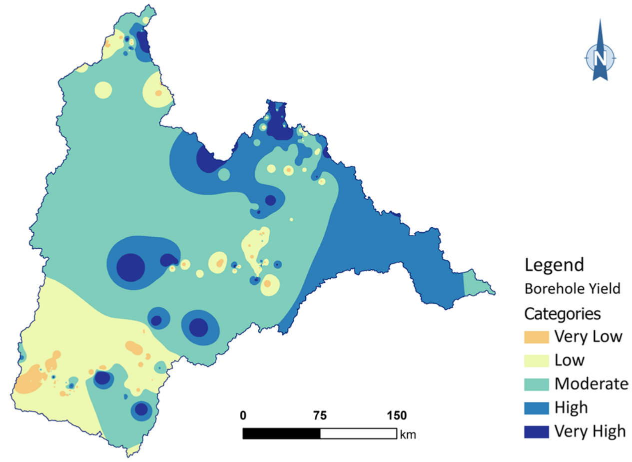

Fig. 7 Map of interpolated borehole yield

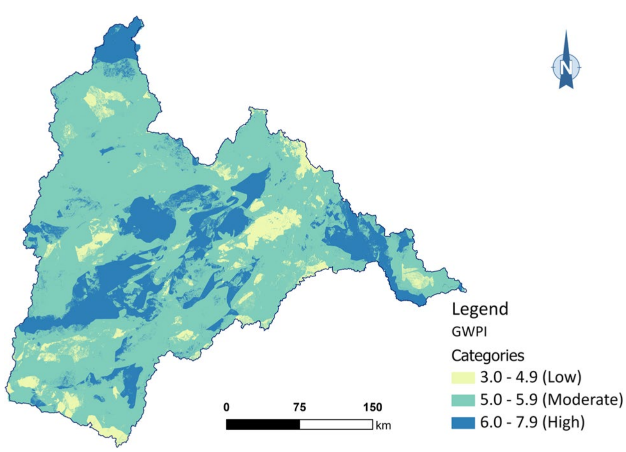

Fig. 6 Groundwater potential zone map

Discussion

The GWPI map revealed that a significant portion of the catchment has moderate to high groundwater potential zones, making it suitable for various economic activities such as agriculture. The study found that 70.23% of the catchment falls in moderate groundwater potential zones, primarily in the northern part of the catchment in the Ruaha National Parks and in the southern-west area with a high prevalence of irrigation activities. The high groundwater potential zones, comprising 21.9% of the catchment, were mostly found in the middle and downstream parts of the

Table 5 The categories of interpolated borehole yield map

Borehole yield (m^3/h)	Category
<2.5	Very low
2.5–5	Low
5–7.5	Moderate
7.5–10	High
>10	Very high

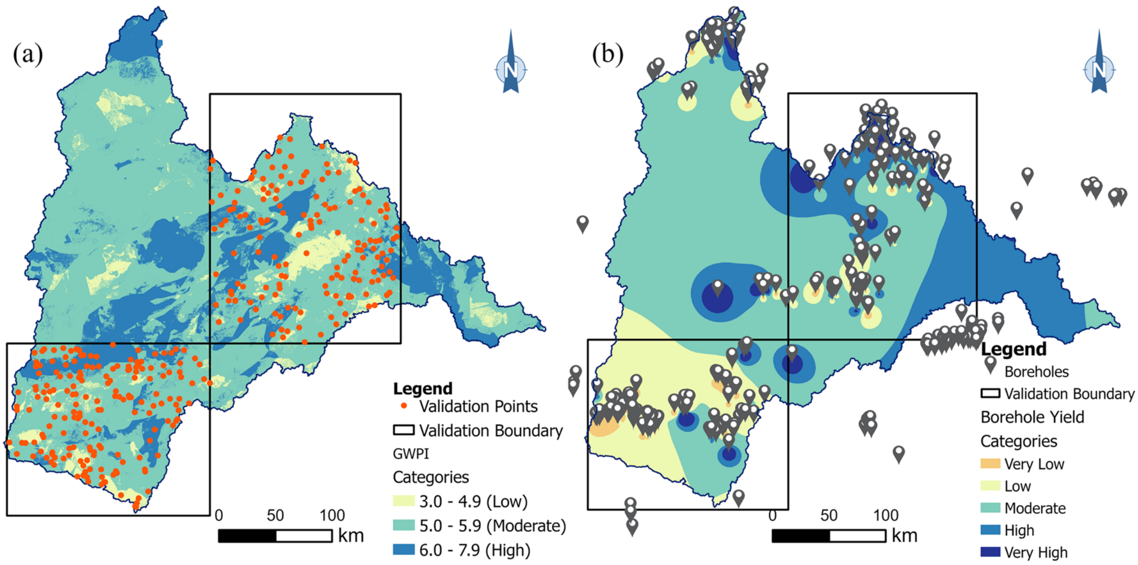

Fig. 8 **a** GWPI with randomly created accuracy assessment points **b** interpolated borehole yield with borehole locations

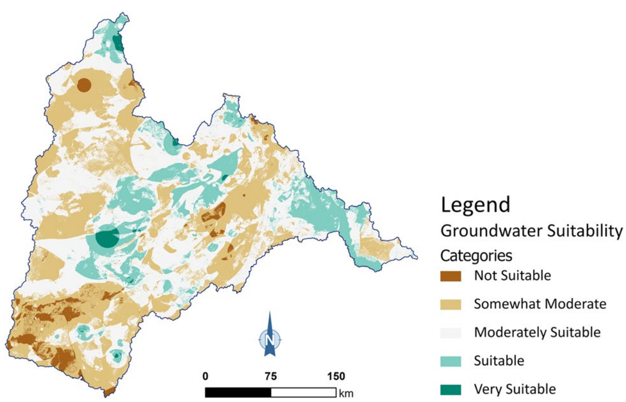

Fig. 9 Suitability map of groundwater potential

catchment, particularly in the Usangu wetlands and in the areas close to the Mtera and Kidatu dams, respectively.

The low groundwater potential zones, accounting for 7.87% of the catchment, were randomly dispersed throughout the catchment and were associated with steeply sloped terrains, which cause increased runoff velocity and reduced infiltration. These findings are consistent with other studies by Adeyeye et al. (2019), and Indhulekha et al. (2019), which noted that steeply sloped terrains have low groundwater potential.

The GWPI map also showed that areas with geomorphological features, such as alluvial plains and pediments, have moderate to high groundwater potential, which is consistent with the findings of other studies by Indhulekha et al. (2019), and Makonyo and Msabi (2021). Drainage density was also found to have an impact on groundwater potential, with areas of high drainage density having lower groundwater potential, and vice versa, as noted by Al-Djazouli et al. (2020) and Dar et al. (2020). This was observed in the upstream regions of the catchment, where low-to-moderate groundwater potential was found due to the high drainage density, which drains off most of the surface runoff and hinders infiltration.

Lineament density, geological composition, and rainfall levels were also observed to have an impact on groundwater potential. Areas with high lineament density, particularly in the middle and downstream parts of the catchment, have high groundwater potential. This was also noted by Arulbalaji et al. (2019). The areas with sandy and gravelly geological features in the northern part of the catchment and granulite geological features in the middle part of the catchment were noted to have the high groundwater potential same as noted by Adeyeye et al. (2019). This is because

Table 6 Areas covered by each category in GWPI and Interpolated Borehole Yield

Variable	Categories				
	Very low	Low	Moderate	High	Very high
GWP area (km^2)	0.00	6,726.41	6,0044.92	1,8720.27	0.00
Borehole yield area (km^2)	1,261.16	1,4606.08	4,7800.08	1,9075.68	2,802.72

granulite has varyied permeability and porosity, and the presence of fractures or sand and gravel materials facilitates making it a productive aquifer.

Also, higher rainfall intensity contributes to higher infiltration and thus higher groundwater potential, which was observed mainly in the middle and downstream regions of the catchment. Soil type and land use/cover have a role to play in the surface runoff infiltration (Shaban et al. 2006) but no direct major impact was observed on the generated GWPI map in the present study. This stems from the prevalence of factors that hold more weight. Generally, the catchment has good groundwater potential, and it was observed that the high groundwater and moderate potential zones were found in areas with gentle slopes which are suitable for economic activities such as agriculture.

These findings are very important in determining the most appropriate locations to construct new wells and in improving the efficiency and yield of the existing wells. Additionally, it highlights those areas with particularly scarce groundwater resources which should be prioritized for protection. This research showcases the value of combining remote sensing and ground data to gain a more comprehensive understanding of groundwater resources.

Conclusions

This research aimed to map the potential groundwater zones in the Great Ruaha River Catchment by utilizing GIS, remote sensing, and AHP MCDA tools to provide information to support informed decision-making by water managers and policymakers. Results of the study indicate that 70.23% of the catchment is in moderate groundwater potential zones, while high groundwater potential zones make up 21.9% and low groundwater potential zones make up 7.87%. These findings are significant as they provide a detailed picture of the groundwater resources within the catchment, including areas with high potential for new wells and areas that require protection due to their scarce groundwater resources. This knowledge can be employed to make prudent decisions on the use and protection of this valuable resource, improving the efficiency and yield of existing wells, and ensuring sustainable water management practices. However, the investigation employed data from diverse sources and with multiple resolutions, potentially affecting the computed statistics. Therefore, it is imperative to exercise prudence in the interpretation of the results. Also, the limited information on groundwater presents a significant challenge in determining its sustainability for future use. The lack of understanding regarding the amount of groundwater available, the rate of depletion, and the effects of factors such as climate change and land use, make it difficult to assess the long-term viability of current use patterns. Hence, there is a need for further studies to gain a deeper understanding of groundwater storage and characteristics, groundwater/surface-water interaction, and the impact of climate change on groundwater recharge. Additionally, it is recommended to implement monitoring and management strategies, such as increasing water storage capacity, improving water conservation and efficiency, and promoting land use practices that support aquifer recharge.

Funding This work is supported by the United Kingdom Research and Innovation Global Research Challenges Fund (UKRI GCRF) [Grant number: ES/T015330/1] for the African Research Universities Alliance Water Centre of Excellence (ARUA Water CoE).

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

Adeyeye OA, Ikpokonte EA, Arabi SA (2019) GIS-based groundwater potential mapping within Dengi area, north Central Nigeria. Egypt J Remote Sens Sp Sci 22:175–181. https://doi.org/10.1016/j.ejrs.2018.04.003

Adiat KAN, Nawawi MNM, Abdullah K (2012) Assessing the accuracy of GIS-based elementary multi criteria decision analysis as a spatial prediction tool: a case of predicting potential zones of sustainable groundwater resources. J Hydrol 440–441:75–89. https://doi.org/10.1016/j.jhydrol.2012.03.028

Ajami H (2021) Geohydrology: groundwater. In: Alderton D, Elias SABT-E(eds) Encyclopedia of geology, 2nd edn. Academic, Oxford, pp 408–415. https://doi.org/10.1016/B978-0-12-409548-9.12388-7

Al-Djazouli MO, Elmorabiti K, Rahimi A, Amellah O, Fadil OAM (2020) Delineating of groundwater potential zones based on remote sensing, GIS and analytical hierarchical process: a case of Waddai, eastern Chad. GeoJournal 86:1881–1894. https://doi.org/10.1007/s10708-020-10160-0

Al Saud M (2010) Mapping potential areas for groundwater storage in Wadi Aurnah Basin, western Arabian Peninsula, using remote sensing and geographic information system techniques. Hydrogeol J 18:1481–1495. https://doi.org/10.1007/s10040-010-0598-9

Alley WM (2009) Encyclopedia of inland waters. Elsevier, Amsterdam, pp 684–690

Alramthi SM, Ali GH, Shaban AM, Abdou TA, Elthagafi AM, Eldosari SH, Zhu B-K, Safaa HM (2022) Quality characterization of groundwater for drinking purposes and its network distribution to assure sustainability in southern region of Saudi Arabia. Water 14:3565. https://doi.org/10.3390/w14213565

Arulbalaji P, Padmalal D, Sreelash K (2019) GIS and AHP techniques based delineation of groundwater potential zones: a case study from southern western Ghats. India Sci Rep 9:1–17. https://doi.org/10.1038/s41598-019-38567-x

Attia EG, Hamed Y (2018) Climate change and water resources management in Arab countries. In: Recent advances in environmental science from the Euro-Mediterranean and surrounding regions. Springer, Cham, Switzerland

Bailey RT, Park S, Bieger K, Arnold JG, Allen PM (2020) Enhancing SWAT+ simulation of groundwater flow and groundwater-surface

water interactions using MODFLOW routines. Environ Model Softw 126:104660. https://doi.org/10.1016/j.envsoft.2020.104660
Böhlke JK (2002) Groundwater recharge and agricultural contamination. Hydrogeol J 10:153–179. https://doi.org/10.1007/s10040-001-0183-3
Dar T, Rai N, Bhat A (2020) Delineation of potential groundwater recharge zones using analytical hierarchy process (AHP). Geol Ecol Landscapes 5:292–307. https://doi.org/10.1080/24749508.2020.1726562
Edet AE, Okereke CS, Teme SC, Esu EO (1998) Application of remote-sensing data to groundwater exploration: a case study of the Cross River State, southeastern Nigeria. Hydrogeol J 6:394–404. https://doi.org/10.1007/s100400050162
Elubid BA, Huang T, Peng DP, Ahmed EH, Babiker MM (2020) Delineation of groundwater potential zones using integrated remote sensing, GIS and multi-criteria decision making (MCDM). Desalin Water Treat 192:248–258. https://doi.org/10.5004/dwt.2020.25761
England MI (2019) Contested waterscapes: irrigation and hydropower in the Great Ruaha River basin, Tanzania. Agric Water Manag 213:1084–1095. https://doi.org/10.1016/j.agwat.2018.08.018
Ettazarini S (2007) Groundwater potentiality index: a strategically conceived tool for water research in fractured aquifers. Environ Geol 52:477–487.https://doi.org/10.1007/s00254-006-0481-0
Sinergise ESA (2021) Copernicus global digital elevation model. OpenTopography. https://doi.org/10.5069/G9028PQB
FAO (2011) Climate change, water and food security. FAO water report 36, Food and Agriculture Organization of the United Nations, Rome
FAO and IIASA (2023) Harmonized world soil database version 2.0. FAO, Rome; IIASA, Luxembourg
Gao H, Liu F, Yan T, Qin L, Li Z (2022) Drainage density and its controlling factors on the eastern margin of the Qinghai–Tibet Plateau. Front Earth Sci 9:1–15. https://doi.org/10.3389/feart.2021.755197
Gervas R, Deogratias MM, Mulungu J, Nobert K (2019) Assessment of surface water resources in Great Ruaha River sub-basin Tanzania: application of WEAP model for water allocation and utilization impacts analysis Tanzania. J Eng Technol 38:27–46. https:https://doi.org/10.52339/tjet.v38i1.494
Gleeson T, Befus KM, Jasechko S, Luijendijk E, Cardenas MB (2016) The global volume and distribution of modern groundwater. Nat Geosci 9:161–164. https://doi.org/10.1038/ngeo2590
Gonzalez D, Janardhanan S, Pagendam DE, Gladish DW (2020) Probabilistic groundwater flow, particle tracking and uncertainty analysis for environmental receptor vulnerability assessment of a coal seam gas project. Water (Switzerland) 12:1–15. https://doi.org/10.3390/w12113177
Gupta RP (2003) Remote sensing geology, 2nd edn. Springer, Berlin pp 460–477, 2nd edn. Springer, Heidelberg, Germany. https://doi.org/10.1007/978-3-662-05283-9
Gupta RP, Singhal BBS (2010) Applied hydrogeology of fractured rocks, 2nd edn. Springer, Dordrecht, The Netherlands. https://doi.org/10.1007/978-90-481-8799-7
Hamed Y, Hadji R, Redhaounia B, Zighmi K, Bâali F, El Gayar A (2018) Climate impact on surface and groundwater in North Africa: a global synthesis of findings and recommendations. Euro-Mediterranean J Environ Integr 3:25. https://doi.org/10.1007/s41207-018-0067-8
Horton RE (1955) Erosional development of streams and their drainage basins, hydrophysical approach to quantitative morphology. Nihon Ringakkai Shi/J Japan For Soc 37:555–558. https://doi.org/10.1130/0016-7606(1945)56
Horton RE (1932) Drainage-basin characteristics. Eos Trans Am Geophys Union 13:350–361. https://doi.org/10.1029/TR013i001p00350
Horton RE (1945) Erosional development of streams and their drainage basins, hydrophysical approach to quantitative morphology. GSA Bull 56:275–370. https://doi.org/10.1130/0016-7606(1945)56[275:EDOSAT]2.0.CO;2
Indhulekha K, Mondal KC, Jhariya DC (2019) Groundwater prospect mapping using remote sensing, GIS and resistivity survey techniques in Chhokra Nala Raipur district, Chhattisgarh, India. J Water Supply Res Technol - AQUA 68:595–606. https://doi.org/10.2166/aqua.2019.159
Jaiswal RK, Mukherjee S, Krishnamurthy J, Saxena R (2003) Role of remote sensing and GIS techniques for generation of groundwater prospect zones towards rural development: an approach. Int J Remote Sens 24:993–1008. https://doi.org/10.1080/01431160210144543
Jha MK, Chowdary VM, Chowdhury A (2010) Groundwater assessment in Salboni block, West Bengal (India) using remote sensing, geographical information system and multi-criteria decision analysis techniques. Hydrogeol J 18:1713–1728. https://doi.org/10.1007/s10040-010-0631-z
Kashaigili JJ (2010) Assessment of groundwater availability and its current and potential use and impacts in Tanzania. International Water Management Institute, Colombo, Sri Lanka
Kumar G, Srinivasan D (2016) Evaluation of groundwater potential index (GWPI) using geophysical survey in Kallar watershed, Tamil Nadu, India. Int J Earth Sci Eng 9:1902–1906
Kumar P, Herath S, Avtar R, Takeuchi K (2016) Mapping of groundwater potential zones in Killinochi area, Sri Lanka, using GIS and remote sensing techniques. Sustain Water Resour Manag 2:419–430. https://doi.org/10.1007/s40899-016-0072-5
Kumar PKD, Gopinath G, Seralathan P (2007) Application of remote sensing and GIS for the demarcation of groundwater potential zones of a river basin in Kerala, southwest coast of India. Int J Remote Sens 28:5583–5601. https://doi.org/10.1080/01431160601086050
Lentswe GB, Molwalefhe L (2020) Delineation of potential groundwater recharge zones using analytic hierarchy process-guided GIS in the semi-arid Motloutse watershed, eastern Botswana. J Hydrol Reg Stud 28:100674. https://doi.org/10.1016/j.ejrh.2020.100674
Li P, Karunanidhi D, Subramani T, Srinivasamoorthy K (2021) Sources and consequences of groundwater contamination. Arch Environ Contam Toxicol 80:1–10. https://doi.org/10.1007/s00244-020-00805-z
Magesh NS, Chandrasekar N, Soundranayagam JP (2012) Delineation of groundwater potential zones in Theni district, Tamil Nadu, using remote sensing, GIS and MIF techniques. Geosci Front 3:189–196. https://doi.org/10.1016/j.gsf.2011.10.007
Makonyo M, Msabi MM (2021) Identification of groundwater potential recharge zones using GIS-based multi-criteria decision analysis: a case study of semi-arid midlands Manyara fractured aquifer, north-eastern Tanzania. Remote Sens Appl Soc Environ 23:100544. https://doi.org/10.1016/j.rsase.2021.100544
Malczewski J (1999) GIS and multicriteria decision analysis. Wiley, Chichester, England, 408 pp
Manap MA, Sulaiman WNA, Ramli MF, Pradhan B, Surip N (2013) A knowledge-driven GIS modeling technique for groundwater potential mapping at the upper Langat Basin, Malaysia. Arab J Geosci 6:1621–1637. https://doi.org/10.1007/s12517-011-0469-2
Maqsoom A, Aslam B, Khalid N, Ullah F, Anysz H, Almaliki AH, Almaliki AA, Hussein EE (2022) Delineating groundwater recharge potential through remote sensing and geographical information systems. Water (Switzerland) 14:30. https://doi.org/10.3390/w14111824
Masoud AM, Pham QB, Alezabawy AK, Abu El-Magd SA (2022) Efficiency of geospatial technology and multi-criteria decision analysis for groundwater potential mapping in a semi-arid region. Water (Switzerland) 14. https://doi.org/10.3390/w14060882

McCartney MP, Kashaigili JJ, Lankford BA, Mahoo HF (2008) Hydrological modelling to assist water management in the Usangu wetlands Tanzania. Int J River Basin Manag 6:51–61 . https://doi.org/10.1080/15715124.2008.9635337
Mogaji KA, Lim HS, Abdullah K (2015) Regional prediction of groundwater potential mapping in a multifaceted geology terrain using GIS-based Dempster–Shafer model. Arab J Geosci 8:3235–3258. https://doi.org/10.1007/s12517-014-1391-1
Mussa KR, Mjemah IC, Machunda RL (2020) Open-source software application for hydrogeological delineation of potential groundwater recharge zones in the Singida semi-arid, fractured aquifer, Central Tanzania. Hydrology 7:30. https://doi.org/10.3390/HYDROLOGY7020028
Ni C, Zhang S, Liu C, Yan Y, Li Y (2016) Lineament length and density analyses based on the segment tracing algorithm: a case study of the Gaosong field in Gejiu tin mine, China. Math Probl Eng 2016. https://doi.org/10.1155/2016/5392453
Pandey A, Purohit R (2022) Impact of geological controls on change in groundwater potential of recharge zones due to watershed development activities, using integrated approach of RS and GIS. J Sci Res 66:53–62. https://doi.org/10.37398/jsr.2022.660106
Pradhan B (2009) Groundwater potential zonation for basaltic watersheds using satellite remote sensing data and GIS techniques. Cent Eur J Geosci 1:120–129. https://doi.org/10.2478/v10085-009-0008-5
Pradhan B, Youssef AM (2010) Manifestation of remote sensing data and GIS on landslide hazard analysis using spatial-based statistical models. Arab J Geosci 3:319–326. https://doi.org/10.1007/s12517-009-0089-2
Radulović M, Brdar S, Mesaroš M, Lukić T, Savić S, Basarin B, Crnojević V, Pavić D (2022) Assessment of groundwater potential zones using GIS and fuzzy AHP techniques: a case study of the Titel municipality (northern Serbia). ISPRS Int J Geo-Inform 11. https://doi.org/10.3390/ijgi11040257
Rahmati O, Nazari Samani A, Mahdavi M, Pourghasemi HR, Zeinivand H (2015) Groundwater potential mapping at Kurdistan region of Iran using analytic hierarchy process and GIS. Arab J Geosci 8:7059–7071. https://doi.org/10.1007/s12517-014-1668-4
Rajaveni SP, Brindha K, Elango L (2017) Geological and geomorphological controls on groundwater occurrence in a hard rock region. Appl Water Sci 7:1377–1389. https://doi.org/10.1007/s13201-015-0327-6
Rukundo E, Doğan A (2019) Dominant influencing factors of groundwater recharge spatial patterns in Ergene river catchment, Turkey. Water (Switzerland) 11:25.https://doi.org/10.3390/w11040653
Saaty TL (1980) The analytic hierarchy process: planning, priority setting, resource allocation. McGraw-Hill, New York
Saaty TL (1994) How to make a decision: the analytic hierarchy process. Eur J Operational Res 48(1):9–26
Saaty TL (2002) The analytic hierarchy process (AHP) and the analytic network process (ANP) for decision making decision making involves setting priorities and the AHP/ANP is the methodology for doing. In: Convergence and hybrid information technologies. InTech Open, pp 1–109. https://www.intechopen.com/books/3788. Accessed January 2024
Saiz-Rodríguez JA, Lomeli Banda MA, Salazar-Briones C, Ruiz-Gibert JM, Mungaray-Moctezuma A (2019) Allocation of groundwater recharge zones in a rural and semi-arid region for sustainable water management: case study in Guadalupe Valley, Mexico. Water (Switzerland) 11:1586. https://doi.org/10.3390/w11081586
Sapkota S, Pandey VP, Bhattarai U, Panday S, Shrestha SR, Maharjan SB (2021) Groundwater potential assessment using an integrated AHP-driven geospatial and field exploration approach applied to a hard-rock aquifer Himalayan watershed. J Hydrol Reg Stud 37:100914. https://doi.org/10.1016/j.ejrh.2021.100914
Saranya T, Saravanan S (2020) Groundwater potential zone mapping using analytical hierarchy process (AHP) and GIS for Kancheepuram District, Tamilnadu, India. Model Earth Syst Environ 6:1105–1122. https://doi.org/10.1007/s40808-020-00744-7
Shaban A, Khawlie M, Abdallah C (2006) Use of remote sensing and GIS to determine recharge potential zones: the case of Occidental Lebanon. Hydrogeol J 14:433–443. https://doi.org/10.1007/s10040-005-0437-6
Subba Rao N, Chakradhar GKJ, Srinivas V (2001) Identification of groundwater potential zones using remote sensing techniques in and around Guntur town, Andhra Pradesh, India. J Indian Soc Remote Sens 29:69–78. https://doi.org/10.1007/bf02989916
Suganthi S, Elango L, Subramanian SK (2013) Groundwater potential zonation by remote sensing and GIS techniques and its relation to the groundwater level in the coastal part of the Arani and Koratalai river basin, southern India. Earth Sci Res J 17:87–95
Thomas BC, Kuriakose SL, Jayadev SK (2009) A method for groundwater prospect zonation in data-poor areas using remote sensing and GIS: a case study in Kalikavu Panchayath of Malappuram district, Kerala, India. Int J Digit Earth 2:155–170. https://doi.org/10.1080/17538940902767393
Thomas BF, Behrangi A, Famiglietti JS (2016) Precipitation intensity effects on groundwater recharge in the southwestern United States. Water (Switzerland) 8:12–17. https://doi.org/10.3390/w8030090
Uc Castillo JL, Cruz D, Ramos-Leal J, Tuxpan J, Tapia S, Marín A (2022) Delineation of groundwater potential zones (GWPZs) in a semi-arid basin through remote sensing, GIS, and AHP approaches. Water 14:1–29
URT (2015a) Rufiji Basin IWRMD Plan. Final report, Ministry of Water, Rufuji, Tasmania
URT (2015b) Rufiji Basin IWRMD Plan: groundwater assessment for Rufiji Basin. Final report, Ministry of Water, Rufuji, Tasmania
URT (2020) The United Republic of Tanzania. Annual hydrological report 2019/2020, Rufiji Basin Water Board, Rufiji, Tanzania
Zarate E, Hobley D, MacDonald AM, Swift RT, Chambers J, Kashaigili JJ, Mutayoba E, Taylor RG, Cuthbert MO (2021) The role of superficial geology in controlling groundwater recharge in the weathered crystalline basement of semi-arid Tanzania. J Hydrol Reg Stud 36:100833. https://doi.org/10.1016/j.ejrh.2021.100833

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.