Sustainable Futures 10 (2025) 100872

Contents lists available at ScienceDirect

Sustainable Futures

journal homepage: www.sciencedirect.com/journal/sustainable-futures

Delineation of groundwater potential zones and recharge using multi-source big data and systematic analysis approach

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ARTICLE INFO

Keywords:
Spatial analysis techniques
Hydrogeology
Water resource sustainability
Aquifer mapping

ABSTRACT

Groundwater is vital for all living things. A thorough comprehension of groundwater management is crucial, as careful use and replenishment can address various concerns. The distribution of groundwater tables, slope, landform, drainage pattern, lithology, topography, geological structure, fracturing density, fracture opening and connectivity, land use, and land cover influence the occurrence and efficiency of groundwater in an aquifer system. The integration of geospatial techniques, such as Remote Sensing (RS), Geographic Information Systems (GIS) and the Analytical Hierarchy Process (AHP), is a crucial tool for analyzing, monitoring, and safeguarding groundwater supplies by identifying potential zones. Twelve groundwater-regulating factors have been considered in the analysis, including rainfall, geology, drainage density, soil, slope, aspect, roughness, hilshade, lineament density, land use/land cover, as well as flood and landslide data. We allocated theme weight and class rank to every thematic layer through weighted overlay analysis. Fieldwork corroborated the results, leading to the creation of a groundwater potential map (GWPZ). The delineated GWPZ watershed is classified into five categories: the very low GWPZ covers 12.5 % of the area, the low GWPZ covers 25 %, the medium GWPZ covers 37.5 %, the high GWPZ covers 20 %, and the very high GWPZ covers 5 % of the area. The northeastern region of the basin is classified as a low groundwater potential zone, whereas the southern area demonstrates a high groundwater potential. The results validated the GWPZ using field data from five wells in the research region, demonstrating a good accuracy rate of 85 %. This study provides a scientific basis for informed decision-making on groundwater usage and conservation for environmental and societal well-being, supporting water resource management and sustainable development.

1. Introduction

Groundwater is a vital source of freshwater necessary for sustaining life on Earth [1]. It is used for many purposes, including consumption, agriculture, and industrial operations worldwide [2]. Over 2.5 billion individuals globally rely exclusively on groundwater resources to meet their daily water requirements (UNESCO, 2015) [3]. Around 71 percent of the Earth's surface is comprised of water, with 96.5 % being salt water (oceans, seas, and bays) [4]. Freshwater utilized for domestic purposes constitutes only 3.5 %, with 68 % of this volume existing on the surface as ice and glaciers [5]. Groundwater stores approximately 30 % below the surface in aquifer materials, while lakes, ponds, streams, and the atmosphere distribute the remaining 2 % [6]. China, the largest developing nation globally, has 41.48 % of its population living in rural regions, encountering considerable difficulties regarding access to clean drinking water. The southwestern part of China, marked by an arid to semi-arid climate with annual precipitation between 25 and 600 mm, is recognized as a critical area of groundwater depletion during the global water crisis. It also has sizable populated areas supported by multilayer aquifers that are used to support civic, industrial, and agricultural activities. Since the 1990s, 15 % to 20 % of the country's water needs have been met by groundwater, and in the southwest Chinese province of Guizhou, up to around 70 % [7].

Groundwater plays a critical role as the primary source of drinking

Abbreviations: AHP, Analytic Hierarchy Process; GIS, Geographical Information System; MCDA, Multi Criteria Decision Analysis; GWPZ, Groundwater Potential Zones.

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https://doi.org/10.1016/j.sftr.2025.100872
Received 7 February 2025; Received in revised form 23 April 2025; Accepted 14 June 2025
Available online 14 June 2025

water in rural areas of China, particularly in Guizhou province, where access to piped or safe drinking water is limited [8]. Moreover, urban dwellers are turning to groundwater more frequently due to inconsistent and insufficient water provisions [9]. The water retention capacity of a region is affected by various geo-environmental factors. Precipitation serves as the principal source for recharging groundwater resources. Drainage density affects surface water infiltration by altering soil porosity and permeability. Lineament density governs groundwater flow by creating conduits through geological fissures such as faults. The slope dictates the rate of surface water infiltration into aquifers. Land use and cover influence processes such as runoff, infiltration, and groundwater utilization, encompassing vegetation, water bodies, towns, and forests. Geology provides insights into subsurface rock formations, with rock porosity determining water permeability. Lithology, geology, drainage density, slope, aspect, drainage network, land use/land cover pattern, and other meteorological conditions used in this study are some of the variables that affect groundwater potential [10].Comprehensive understanding of these aquifer regulating factors is crucial for groundwater management and development, enabling delineation and evaluation of groundwater potential zones (GWPZ) [11,12].

Many countries have assessed groundwater potential zone mapping utilizing various conventional methods that are time-consuming and costly [13,14]. In recent years, there has been a rise in the utilization of Geographic Information Systems (GIS) and Remote Sensing (RS) for mapping, which facilitates the rapid and cost-effective generation of important data and the identification of groundwater potential zones, hence enhancing spatial-temporal scale and conserving time and resources [15]. It may generate data in the spatial and temporal domains, which plays a crucial role in effective analysis, prediction, and validation. It can also provide all the parameters that influence a region's groundwater potential zones and the substantial volume and quality of data handled in GIS software generates groundwater potential zones [16].

Different studies have been conducted in the Kaili district of Guizhou, examining groundwater flow dynamics [17], the influence of climate change on hydrology [18], and the effects of climate change on hydro-climatic variables [19]. Despite these findings, no targeted study on Groundwater Potential Zones (GWPZ) has been conducted in the area, in spite of employing time-consuming approaches such as hydrogeology and seismic analysis [20]. This research utilizes geospatial technologies, multi-source big data, systematic analysis approach, and field checks to assess groundwater potential in the study area, effectively filling existing knowledge gaps. Multi-source big data research in groundwater potential zones is essential for understanding and managing groundwater resources, which support ecosystems, agriculture, and human populations worldwide. This approach integrates multiple data sources to thoroughly analyze potential aspects of groundwater, enabling sustainable management decision-making as water problems worsen, notably in southern China. The mapping of GWPZ in the Kaili watershed is anticipated to substantially influence both the region and the country, promoting sustainable groundwater resource development and enhancing agricultural productivity and domestic water consumption [21].

The primary objectives of this study are to fully examine the factors that affect groundwater, find possible groundwater zones, and then create a groundwater potential map. The study looks at these connections to give important information to people who make decisions, policies, and plans for water resources to ensure that groundwater resources in the area can be managed in a way that is sustainable.Fig. 1

2. Study area

China's Kaili City, which is situated on the eastern side of the Yunnan-Guizhou province, is notable for its wide area of terraced slopes Fig. 2. With an average annual temperature of 16.1°C and extremes ranging from a maximum of 37°C to a minimum of -4 to -7°C, the area has a subtropical humid monsoon climate. With a total discharge of 3.989 billion cubic meters and the potential for 54,000 kW of

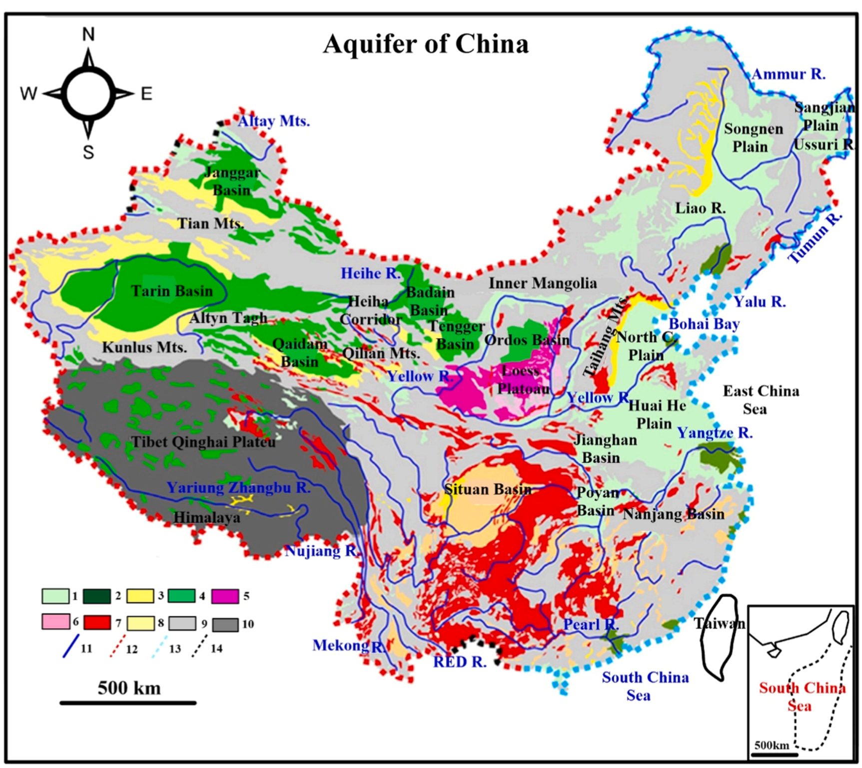

Fig. 1. Aquifer of China, alluvial unit (1); delta unit (2); piedmont unit (3); endorheic clastic unit (4); continuous loess unit (5); discontinuous loess unit (6); karst unit (7); fissured-porous bedrock unit (8); bedrock unit (9); permafrost unit (10); main rivers (11); no f low boundary condition (12); head-dependent boundary condition (13); general head boundary condition (14).

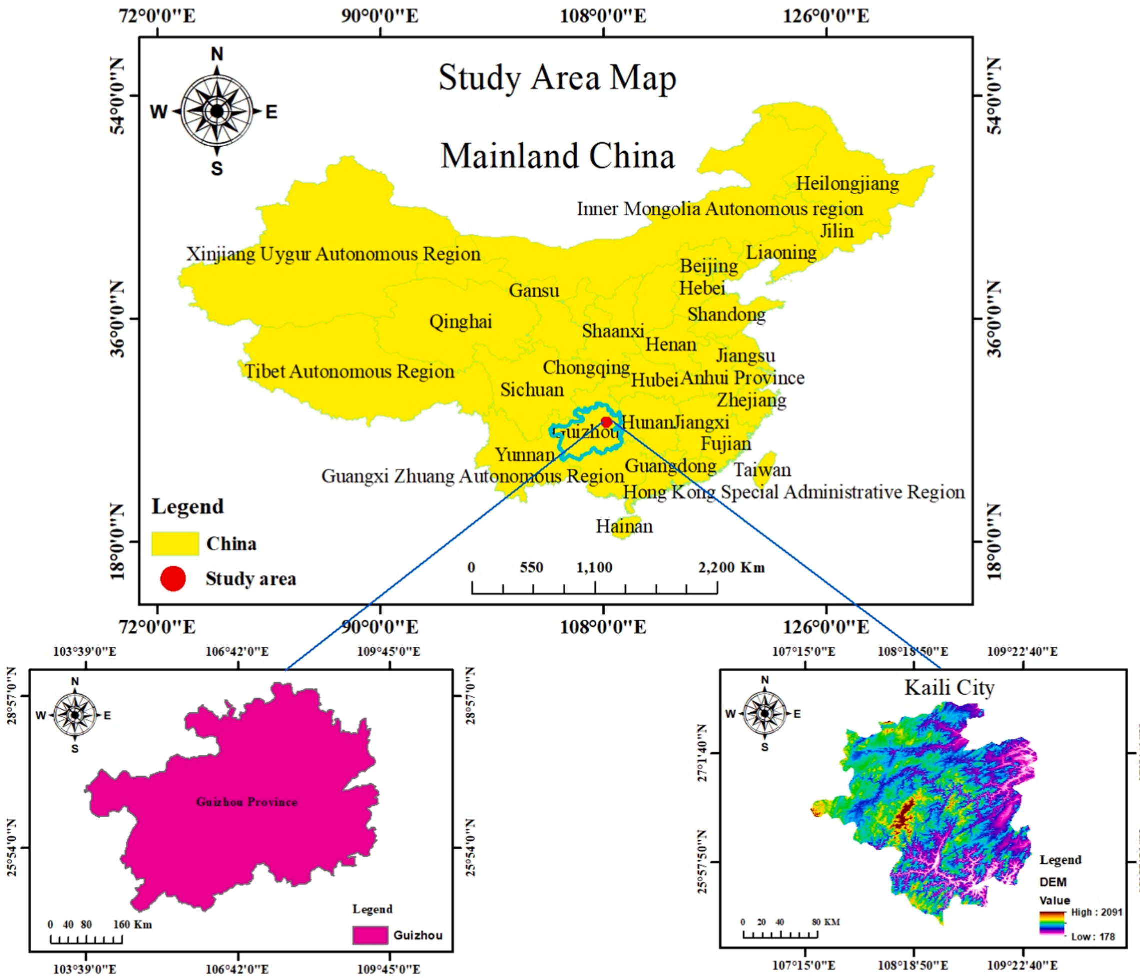

Fig. 2. Study area location map.

hydropower, the city is crossed by 153 rivers and streams, including the Qingshui, Chong'an, and Bara rivers. In addition to 428 types of medicinal plants, a variety of wildlife species, and mineral resources mostly consisting of coal, iron, quartz sandstone, petroleum, and natural gas, Kaili also has one oil and gas extraction site each. The main factor in choosing China, and more specifically the province of Yunnan-Guizhou, as the study area was the area's vital importance for groundwater sustainability and management. Water resources are a major problem for China, the world's largest developing country, particularly in rural areas like Guizhou province. The Yunnan-Guizhou province's eastern side is the study region. It was selected because of its subtropical humid monsoon climate and wide terraced slope zone. This area is crucial for comprehending groundwater dynamics because it is crossed by several rivers and streams.

3. Tectonic setting impact on groundwater exploration

The geological background of the Guizhou region, situated in the northern Yangtze block, profoundly affects groundwater recharge and potential in this area [22]. The Yangtze craton, a geologically stable continental mass, significantly influences the region's hydrogeological characteristics. Groundwater in the Yangtze craton is typically linked to fractured bedrock aquifers, which facilitate uncomplicated conditions for groundwater recharge and extraction owing to their stability and minimal tectonic activity during the past billion years. These aquifers are often dependable sources of groundwater and demonstrate advantageous conditions for recharging owing to their structural integrity and permeability.

The Guizhou fold belt, a hilly area resulting from the tectonic convergence of the Yangtze craton and the South China block, exhibits a complex hydrogeological framework [23]. In this region, groundwater is typically located in both fractured bedrock aquifers and alluvial aquifers [24]. The fractured bedrock aquifers in the fold belt exhibit structural complexity, with narrow and convoluted fissures frequently constraining their recharge capacity and presenting difficulties for extraction [25]. Conversely, alluvial aquifers in this region are generally more productive and demonstrate superior water storage capacity. Nonetheless, their accessibility may be hindered by the difficult terrain, complicating the identification and exploitation of these aquifers [26].

The Jiangnan orogeny, a mountain range resulting from the confluence of the North China block and the Yangtze craton, introduces further complexity to the region's hydrogeological circumstances. In this region, groundwater is mostly located in fractured bedrock aquifers and alluvial aquifers associated mostly to Cambrian and Ediacaran system [27]. Like the Guizhou fold belt, the fractured bedrock aquifers exhibit structural complexity, characterized by small and irregular fissures that may restrict recharge rates and complicate extraction efforts [28]. Alluvial aquifers, although more prolific, are frequently situated in regions where accessibility is hindered by the severe topography of the orogenic belt.

The geological complexity of the Guizhou region, encompassing stable cratonic zones, intricate fold belts, and sedimentary basins, results in differing levels of groundwater recharge capacity and accessibility. Comprehending these geological formations is crucial for precise mapping of water potential zones, especially in regions such as Kaili district, where the interaction of fractured bedrock and alluvial aquifers dictates the accessibility and use of groundwater resources Fig. 3. Topographic map of the study area is shown in Fig. 4.

4. Research methodology

This work addresses the identification of several elements influencing groundwater potential in different degrees. In this study, GIS-based methodologies are employed to delineate the Groundwater Potential Zones (GPZs) of the Kaili district through a knowledge-driven multi-criteria analysis of various parameters (thematic layers), including land use and land cover (LULC), slope, aspect, roughness, contour, hillshade, elevation, geology, lineament density, drainage density, rainfall, flood, and soil data, which were sourced from diverse origins and integrated to establish the GPZs. Thematic layers were initially standardized to guarantee uniform projections and cell dimensions, and raster layers were converted into polygon forms. The LULC map was produced using World LULC ESRI Maps 2023, derived from Sentinel-2 images with a spatial resolution of 10 m, utilizing ArcGIS 10.8 software. Drainage density, slope, hillshade, aspect, and contour shapefiles were produced in ArcGIS utilizing Digital Elevation Model (DEM) data. The drainage density map was produced utilizing the Line Density tool in ArcGIS. The lineament density in km/km^2 was determined via the line density tool in ArcGIS. The ArcGIS slope tool was employed to assess slope changes within the research area, and the slope layers were generated from the projected DEM layer utilizing the Surface function within the Spatial Analyst tool. The soil map was developed using data from the Food and Agriculture Organization's (FAO) World Soil Data. The groundwater modelling map was generated by a weighted index overlay analysis by summing the weighted values of each thematic layer. Validation was achieved by incorporating seven productive boreholes into the ArcGIS platform.

To generate the roughness layer, the minimum (FS_{min}), maximum (FS_{max}), and mean (FS_{mean}) focal statistical layers were produced via the Neighbourhood tool, followed by the application of Eq. (1) (Evans, 1972) via the Raster Calculator (Map Algebra tool). The methodologies employed in this work were explicitly delineated as follows.

$$\text{Roughness} = (FS_{\text{mean}} - FS_{\text{min}})/(FS_{\text{max}} - FS_{\text{min}}) \quad (1)$$

4.1. AHP technique employing multi-IF factors

The analytic hierarchy process (AHP) is used in multicriteria decision analysis (MCDA) [29]. Decision-making, for which we have gathered the majority of our information, has evolved into a scientific discipline. Research in psychology has demonstrated that people exhibit biases while making decisions. An approach that is simple to understand and apply is required for making safe and effective decisions in light of these biases and the growing complexity of today's issues [30]. Nonetheless, a methodology that decision-makers could employ more naturally was needed. Since AHP meets all of these criteria, it has been embraced and applied by several organizations across the globe to address a wide range of decision-making issues.

The analytic hierarchy process (AHP) was developed by Saaty [31]. This method can assist policymakers in establishing priorities and producing appropriate outcomes, and it is a helpful tool for addressing complicated decision-making issues [32]. By reducing composite judgements to a series of pairwise comparisons and discoveries, the AHP supports both subjective and objective aspects of a decision [33]. Additionally, the AHP is a useful technique for assessing the precision of judgments made by decision-makers, which helps eradicate decision-making bias. Decisions are the result of the AHP's integration and coverage of input in the form of spatial data. AHP is a decision-making technique that assesses the relative importance of items by comparing them pairwise [34]. Geology, soil, slope, aspect, roughness,hilshade rainfall, drainage density, lineament density, land use/-land cover, and flood were the variables accounted for in this instance

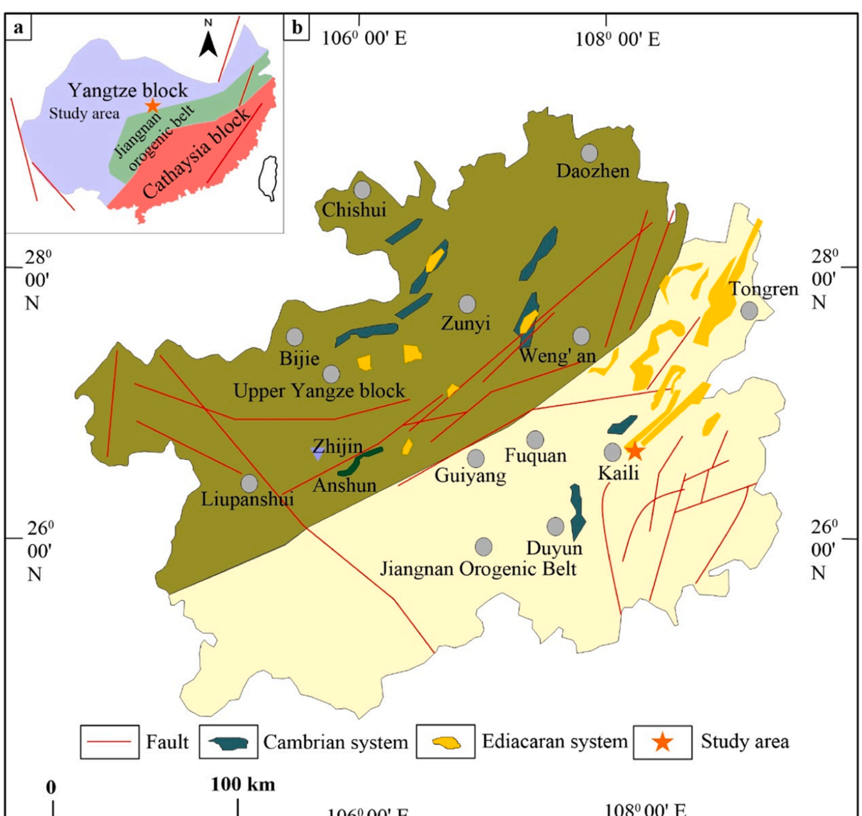

Fig. 3. Tectonic map of the study region.

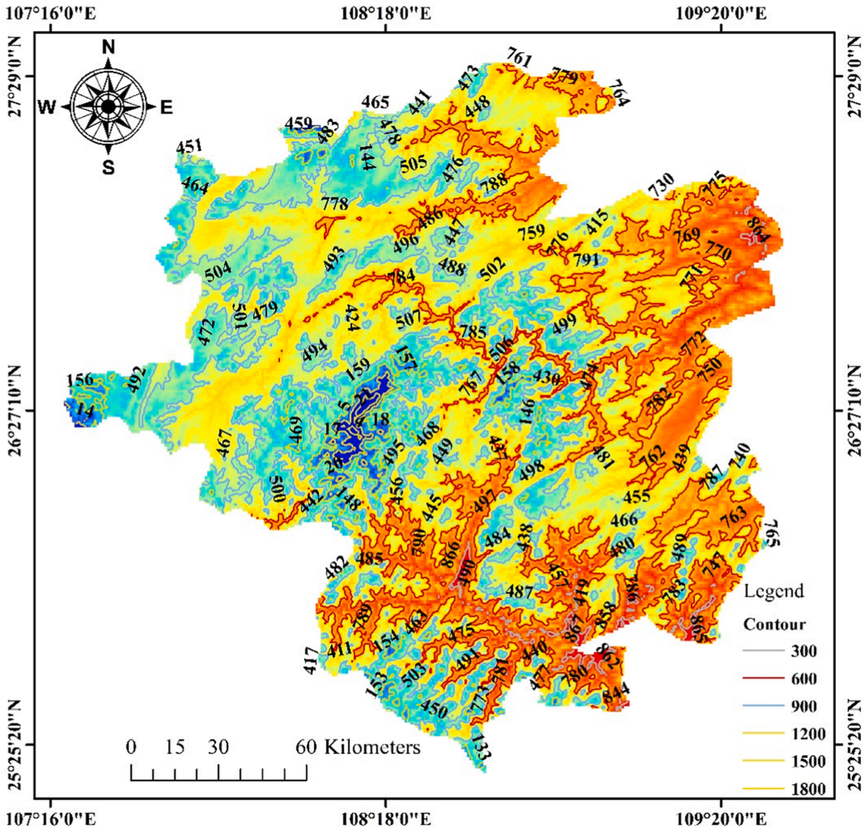

Fig. 4. Contour map of the study area.

Fig. 5.

4.2. Data collection

For this study, we utilized various types of data to create thematic layers within the GIS system. There are both ground data and satellite images in the application data. The ground data came from field trips to the study area and from different research articles related to the study area. Satellite data, on the other hand, were gathered from a number of foreign open-source platforms to create the study's parameters. Table 1 shows all the information about the satellite data records.

4.3. Consistency check

The reliability of the pairwise comparisons conducted among the theme layers and their subclasses was validated by evaluating the consistency ratio (CR) utilizing equations [35]:

$$CI = (\lambda max - n)/(n - 1) \quad CR = CI\ /RI \qquad (2,3)$$

Where n represents the quantity of elements, *RI* denotes the Random Index, and *CI* signifies the Consistency Index.

An ACR value of ≤ 0.10 is considered appropriate for doing weighted overlay analysis utilizing the AHP. If the *CR* exceeds 0.10, it is essential to reassess the judgments in order to identify the source of inconsistency and correct it until the CR is less than or equal to 0.10. The *CR* in this trial was −0.81 and is deemed consistent.

5. Result

All the important data needed to define the groundwater potential zone was added, processed, rasterized, and split into 30 m pixels in order to build the overlay analysis of each model in the ArcGIS platform. The composite GWP model map is produced by utilizing the integrated methodologies of RS, the GIS-based AHP of the thematic layers, and weight determinations. The subjectively and clearly defined controlling parameters for the GWP zone mapping were hierarchically formulated in the matrix and converted into numerical values based on the expertise, judgment, and prior studies of the researchers. This allowed for the creation of the suitability modeling map of the GWP zone in the area by determining the relative impotency (rating) of each thematic layer. The 12 influencing elements for the GWP zone mapping were compared pairwise, and their respective weights were established. These range from (highest) to (lowest). The remaining parameters' weights were established between these weighted values, as indicated in Table 2 below. Each parameter's weight was determined by the number of features in each thematic layer and its relative importance for groundwater occurrence. In accordance with Saaty (1980), the values were examined to ensure that their pairwise comparison matrix of theme layers was acceptable. Each of the following regulating factors for the GWP zone mapping is covered in detail.

5.1. Thematic layers

The 12 thematic layers are employed to construct groundwater potential zone maps via the Analytic Hierarchy Process (AHP). The conceptual layers are elaborated about in detail below.

5.1.1. Rainfall

Precipitation is the principal water source in the hydrological cycle and the primary determinant of groundwater in a region [36]. Groundwater recharge is a critical hydrologic variable, significantly influenced by the intensity and duration of rainfall within the catchment area [37].

This analysis utilized rainfall data from 2011 to 2020. The ArcGIS platform's spatial analysis tool applied inverse distance weighting to

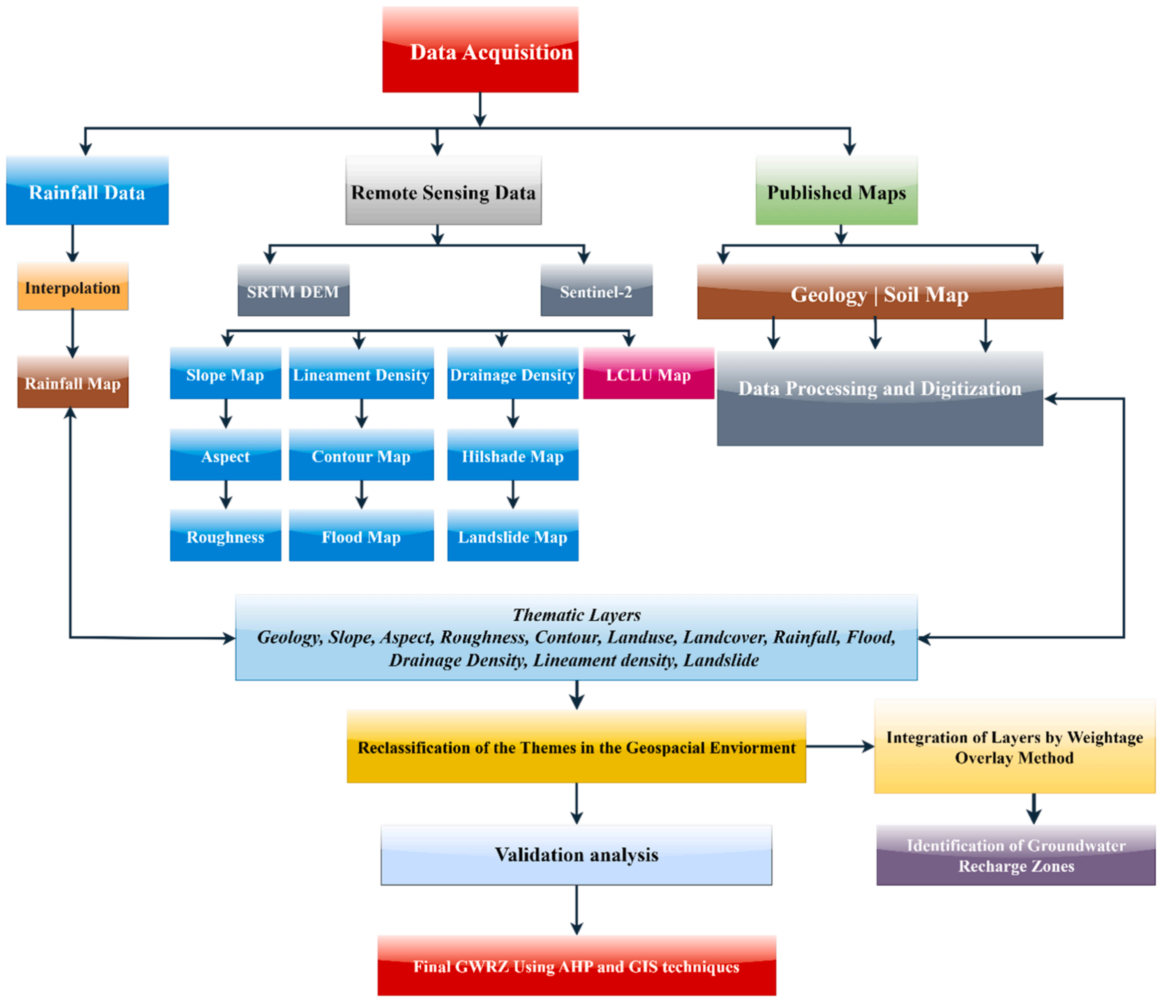

Fig. 5. Flowchart of the study methodology.

Table 1
Data type and their sources.

Data Collected	Sources	Resolution	Output layer
Rainfall	https://crudata.uea.ac.uk/cru/data/hrg/	30 m	Rainfall Map
Soil Data	FAO/UNESCO Soil Map of the World	30 m	Soil Map
Geology	https://www.usgs.gov	30 m	Geology Map
DEM	https://earthexplorer.usgs.gov/	30 m	Elevation, Slope, Hilshade, Aspect, Roughness, Contour, Drainage Density, Lineament Density, Flood Map
Landslide	https://gpm.nasa.gov/landslides/	30 m	Landslide Map
LCLU	Sentinel-2	10 m	Landcover Map
Study area	https://diva-gis.org/	30 m	Location Map

generate the precipitation map of the watershed, dividing the annual rainfall into four categories Fig. 6. Rainfall has a direct correlation with GWP and increased rainfall in the area enhances percolation and infiltration; hence, recharging the groundwater zone**.** As Fig. 6 shows, the district gets less rainfall in the eastern section and more in the western part. Covering approximately 5 %, 8 %, 40 %, and 26 % of the study area, the rainfall of the district has been divided into four classes: low (1100–1000 mm), moderate (1200–1300 mm), high (1300–1200 mm), and very high (1400–1300 mm).

5.1.2. LCLU

The area's land use and cover have a significant impact on both surface and subsurface conditions, including soil erosion, soil moisture, soil fertility, surface runoff, infiltration, interception, evapotranspiration, and other entities [38]. Various studies confirmed that land cover and use have a major impact on groundwater occurrences in a given area [39,40]. We took the land use and land cover map of the current study area from Sentinel 2 at a resolution of 10 m using the free download link https://livingatlas.arcgis.com/ . We used the ArcGIS platform to calculate the area or percentage coverage of each land use, clipping the TIFF data according to the area of interest and processing it in ArcGIS 10.8 software. Given the presence of water, trees, flood vegetation, crops, snow/ice, clouds, bare ground, and barren places, the area recognizes eight land use categories, precisely defining their spatial extent Fig. 7. Table 2 assigns the relative weight of the pairwise comparison matrix based on the significance ranking of groundwater. Forests, vegetated areas, and well-managed and farmed soils significantly reduce runoff. Long-term water retention increases the rate of infiltration in those areas. Consequently, these locations receive a significant portion of the weights. Conversely, we give low weight rates to uncultivated, barren, and poorly maintained lands because they increase runoff in the catchment.

Table 2
Average theme weight and class rank assigned to different thematic layers in weighed overlay analysis.

Groundwater Conditioning Layers	Features	Qualitative Rank	Classes	Average Weight
Rainfall mm/year	1400 - 1300	Very high	06	20
	1300 - 1200	High	04	
	1200 - 1100	Moderate	03	
	1100 - 1000	Low	01	
Landcover/land use	Water	Very high	08	13
	Tress	High	07	
	Flood vegetation	Moderate	06	
	Crops	Low	05	
	Snow/ice	Low	04	
	Clouds	Low	03	
	Bare ground	very low	02	
	Built area	very low	01	
Drainage Density (km/km^2)	2.39–3.08	Very High	02	10
	2.12–2.48	high	04	
	1.77–2.12	Moderate	06	
	1.63–1.76	Low	08	
	1.62–1.52	Very low	10	
Lineament Density ($km/km^{2)}$	1.37–1.68	Very high	02	10
	1.14–1.36	High	04	
	0.72–1.14	Moderate	06	
	0.60–0.81	Low	08	
	0.07–0.39	Very low	10	
Soil type	Silt-loam	Very High	08	13
	Clay	High	06	
	Sandy clay	Moderat	04	
	Clay loam	Low	02	
Geology	Permian-	Very high	24	24
	carboniferous	High	18	
	Carboneferous	High	16	
	Cambrian	High	14	
	Ordovician-	Moderate	12	
	cambrian	Moderate	12	
	Devonian	Moderate	10	
	Ordovician-	Low	08	
	silurian	Low	08	
	Permian	Very low	04	
	Triassic-permian	Very low	04	
	Upper paleozoic	Very low	02	
	Proterozoic			
	Silurian			
	Silurian-			
	devonian			
Slope (degree)	0.01911 - 4.323	Flate	10	10
	4.324 - 7.793	Gentle	08	
	7.794 - 11.82	Moderate	06	
	11.83 - 17.37	Steep	04	
	17.38 - 35.42	Very Steep	02	
Aspect	-1	Flate	10	10
	0–22.5	North	09	
	22.5–67.5	Northeast	08	
	67.5–112.5	East	07	
	112.5–157.5	Souteast	06	
	157.5–102.5	South	05	
	202.1–247.5	southwest	04	
	247.5–292.5	West	03	
	292.5–337.5	Northwest	02	
	337.5–360	North	01	
Elevation (m)	2019	High	04	08
	178	Low	02	
Hilshade	184	High	04	08
	0	Low	02	
Roughness	0.56986 -	Very high	08	10
	0.802231	High	06	
	0.482724	Moderate	04	
	-0.569861	Low	02	
	0.398005			
	-0.482724			
	0.184997			
	-0.398005			
Flood	500	High	06	20
	400	Moderate	04	
	300	Low	02	
Landslide	N/A	N/A	N/A	N/A

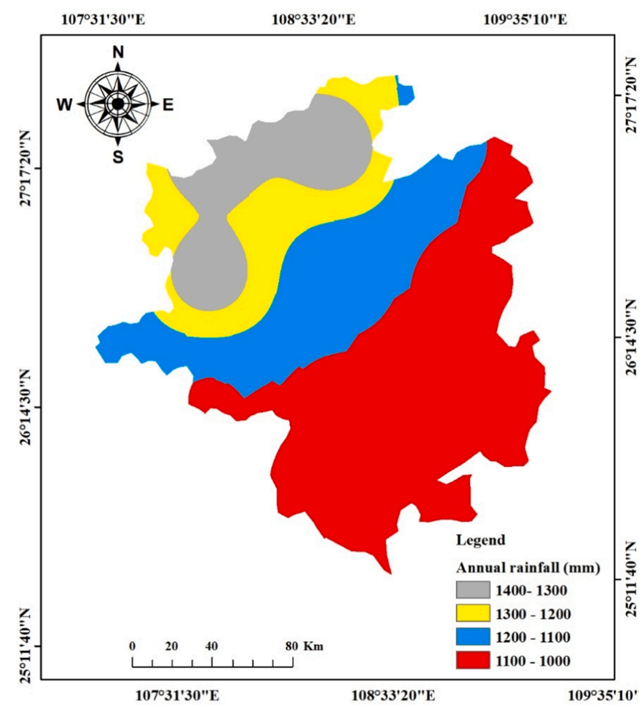

Fig. 6. Rainfall map of Kaili district.

5.1.3. *Drainage density*

The conversion of rainfall into runoff is mostly determined by the drainage density of the basins [41]. Greater groundwater potential and weights are correlated with lower drainage density values. Furthermore, increased rainfall penetration is suggested by a lower drainage density. By dividing the basin area by the unit length, the drainage density is determined and can be written as follows:

$$DD = DL/DA \quad (4)$$

where *DD* stands for drainage density, *DL* for drainage length, and *DA* for drainage unit area [42]. According to Fig. 8, the groundwater potential generally tends to rise from the southern portion of the study region to the northern portion, which corresponds to the lower drainage density.

5.1.4. *Lineament density*

Lineament serves as a primary indicator of underlying geological discontinuities, such as faults, fissures, joints, fractures, and bending planes [43]. Its direct association with groundwater and recharge events serves as a channel for groundwater flow [44]. Lineament density (*Ld*) is defined as the cumulative length of all lineaments within the entire study area, calculated using Eq. (5):

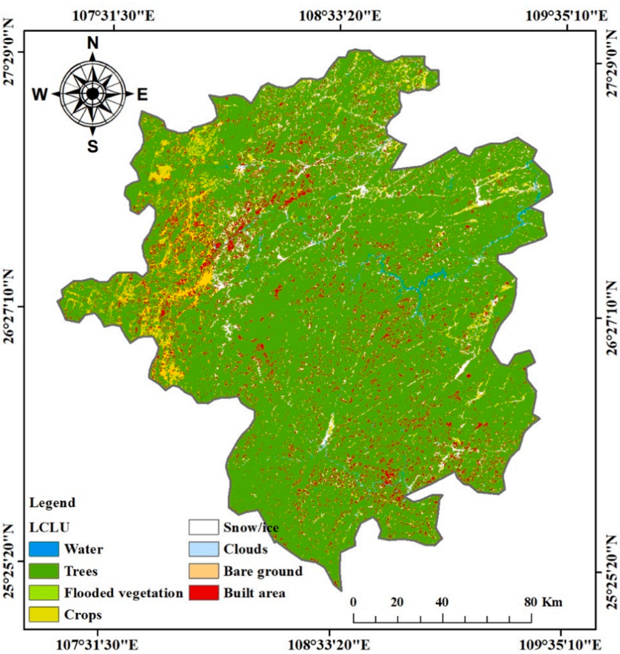

Fig. 7. Land use landcover map of Kaili district.

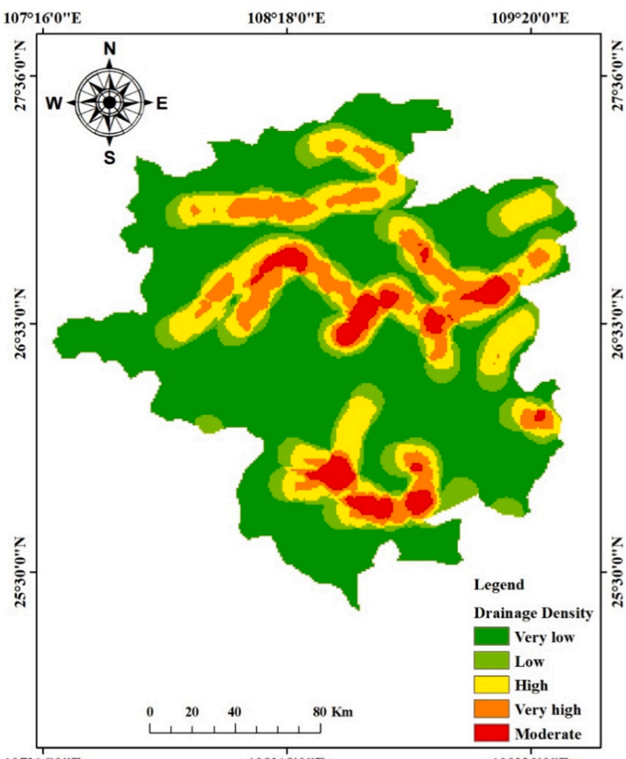

Fig. 8. Drainage density map of Kaili district.

$$L_d = \frac{\sum_{i=1}^{n} \mathrm{LP}}{A} \left(\mathrm{km} / \mathrm{km}^2 \right) \quad (5)$$

where $\sum ni = 1\ Li$ represents the total length of all lineaments (km) in the watershed, and A signifies the total area of the watershed (km^2) [45]. We generated the lineament density map of the Kaili watershed from lineament features using the ArcGIS spatial analysis tool for line density Figure 9. The lineament density of the study was categorized into five classes of suitability: areas with very high lineament density (0.45–0.76 km/km^2) are classified as very highly suitable, while areas with very low lineament density (0–0.07 km/km^2) are deemed very lowly suitable, comprising approximately 2.7% and 64.9% of the watershed, respectively, based on their potential for groundwater recharge.

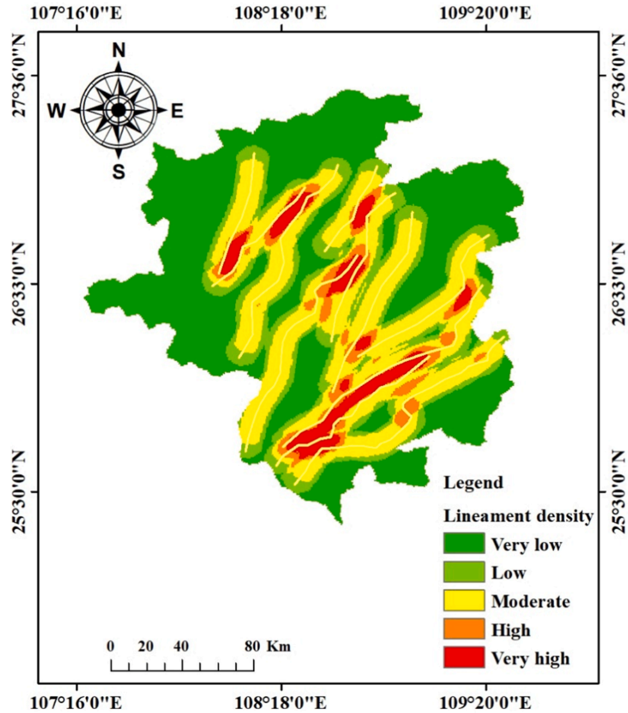

Fig. 9. Lineament density map of Kaili district.

5.1.5. *Soil*

One of the primary factors in identifying potential groundwater zones is the soil. Various methodologies and technologies, such as GIS and AHP modeling, are presently employed in groundwater research

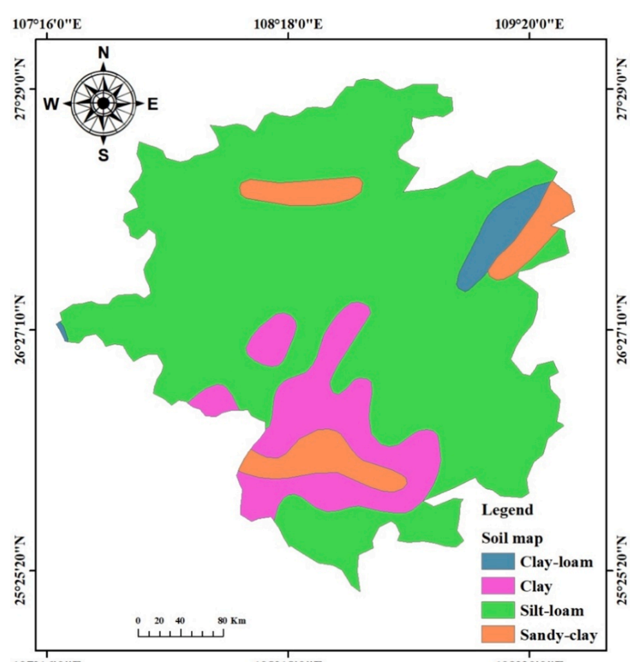

Fig. 10. Soil map of Kaili district.

and water resources planning. Consequently, four varieties of soil, namely clay loam, clay, silt loam, and sandy clay, are depicted in Fig. 10.

5.1.6. Geology

Lithology refers to the physical characteristics of rocks, and these formations have an impact on groundwater by regulating the permeability and porosity of the aquifer through their conductivity and penetrability [46]. The primary factor influencing groundwater potential is geology, where the permeability or conductivity of different rock types predominantly govern infiltration [47]. The geological map supplies information regarding the subsurface geological formations of our study area. These material qualities influence groundwater occurrence, retention, and movement. We digitized and generated the lithological map for the present study from the World Geology Maps https://www.usgs.gov using ArcGIS 10.8 Fig. 11.

5.1.7. Slope

The slope of the land greatly impacts the flow of surface water, dictating the rates of infiltration and runoff. Flat terrain possesses the ability to hold and promote water infiltration into the soil, therefore improving groundwater recharge. In contrast, steep slopes enhance runoff and impede the infiltration of surface water into the soil [48]. The basin's slope is classified into five distinct classifications: flat (0.01–4.3 degrees), gentle (4.3–7.7 degrees), moderate (7.7–11.8 degrees), steep (11.8–17.37 degrees), and very steep (17.30–35.4 degrees). The south-western section of the basin features primarily flat to gentle slopes, although other areas exhibit different degrees of steep to very steep inclines. Fig. 12 depicts the distribution.

5.1.8. Aspect

The aspect map of the watershed was produced using a DEM file. Aspect groups are represented by distinct colors in Fig. 13.

The prepared map delineates a total of nine directions based on degrees: north (336.5° to 22.5°), northeast (22.5° to 66.5°), east (66.5° to 112.5°), southeast (111.5° to 156.5°), south (156.5° to 201.5°), southwest (201.5° to 246.5°), west (246.5° to 290.5°), northwest (290.5° to 336.5°), and also includes flat terrain. The map analysis indicated that 0.98 %, 11.02 %, 10.07 %, 11.41 %, 13.36 %, 16.03 %, 14.14 %, 12.02 %, and 10.96 % of the watershed area corresponded to flat, north,

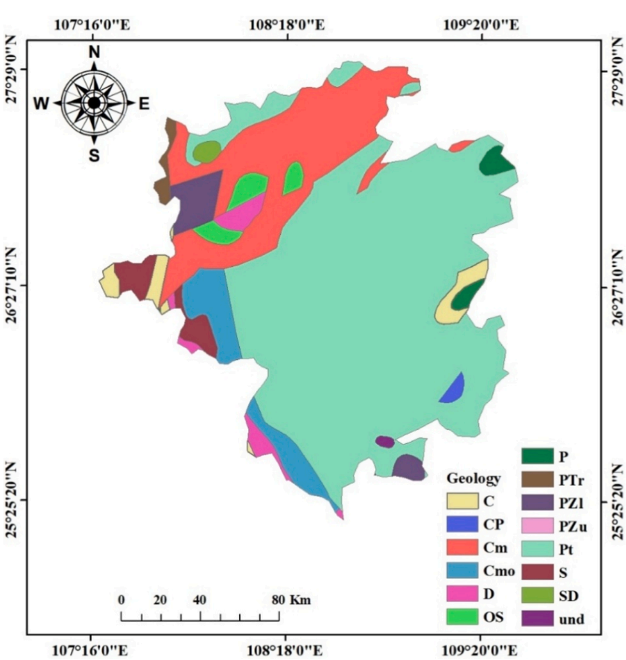

Fig. 11. Geology map of Kaili district.

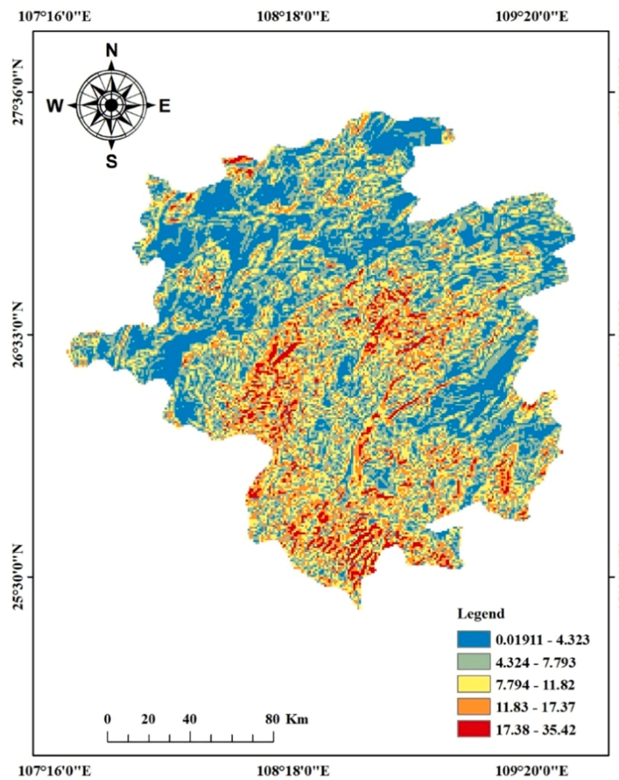

Fig. 12. Slope map of the Kaili district.

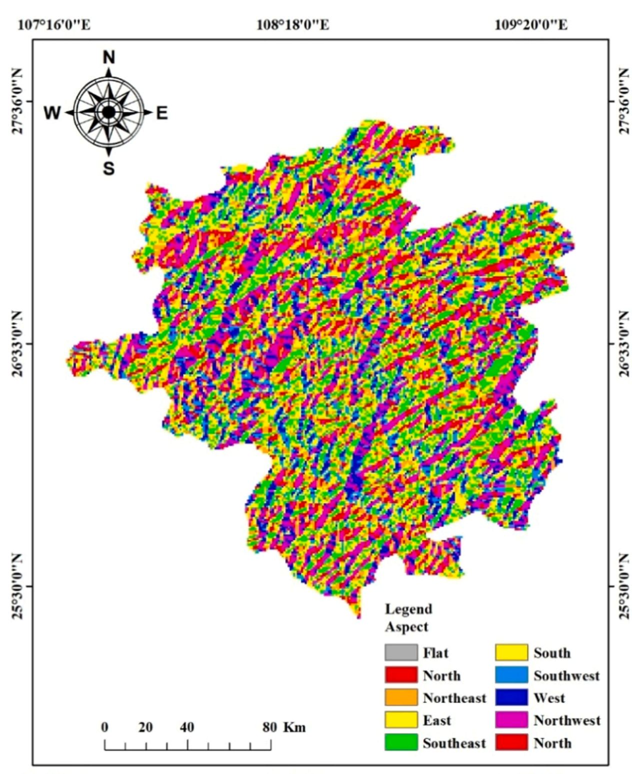

Fig. 13. Aspect map of Kaili district.

northeast, east, southeast, south, southwest, and west, northwest and north directions, respectively.

5.1.9. Elevation

Elevation greatly influences the presence of groundwater [49]. Groundwater typically flows from places of elevated pressure to areas of low pressure and from high elevations to low elevations, with a few small exceptions for surface irregularities [50]. As shown in Fig. 14, the elevation of the watershed under consideration varies between 2091 and 178 m The western and west-central regions of the watershed exhibit lower elevations, while other areas exhibit higher elevations. There is more infiltration and recharging of water in lower-lying, plainer areas because the water stays there for longer. In contrast, higher elevations experience more runoff and less infiltration. Table 2 shows the results of average weight given to higher-elevation zones and lower-elevation areas.

5.1.10. Hillshade

An essential GIS tool for simulating solar illumination on terrain, a hillshade map improves the visualization of topographic features, including ridges, valleys, and slopes [51]. This illustration is essential for determining water potential since it shows where water collects (usually in darker hues) and where steep terrain (usually in lighter hues) is less likely to collect water Fig. 15. Analysts can gain a thorough understanding of how topography affects water drainage and retention by combining hillshade maps with other data layers, such as soil types and land cover [52]. Effective management of water resources, agricultural planning, and environmental preservation—especially in areas experiencing water scarcity—all depend on this knowledge.

5.1.11. Roughness

The multispectral land characteristics significantly influence continuing surface processes. The topographic variation, or the height disparity between adjacent cells in the digital elevation model (DEM) for a specific area, is characterized by roughness. Regions with elevated roughness facilitate significant floods or runoff, while places with reduced roughness retain runoff water, allowing it to enter or percolate to replenish groundwater [53]. The topographic roughness index is calculated using the formula first established by Guisan [54].The

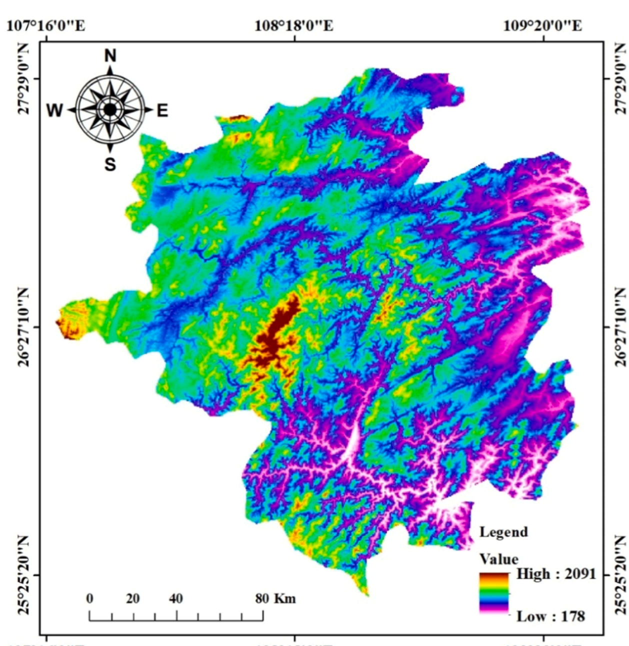

Fig. 14. Elevation of Kaili district.

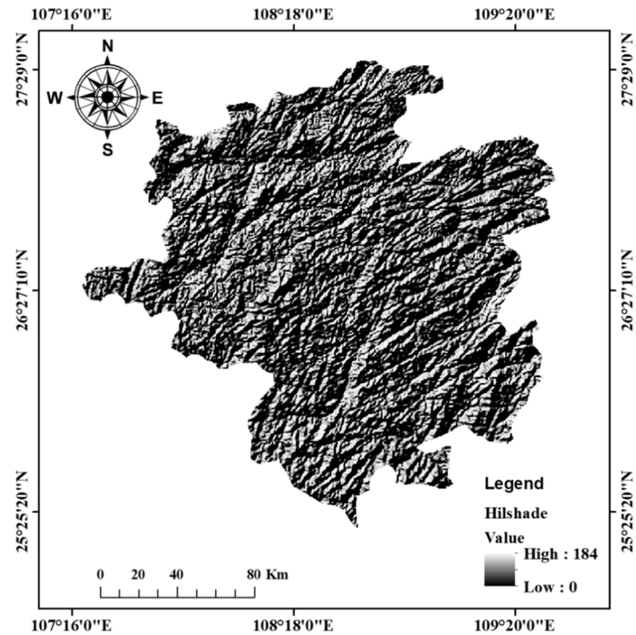

Fig. 15. Hilshade map of Kaili district.

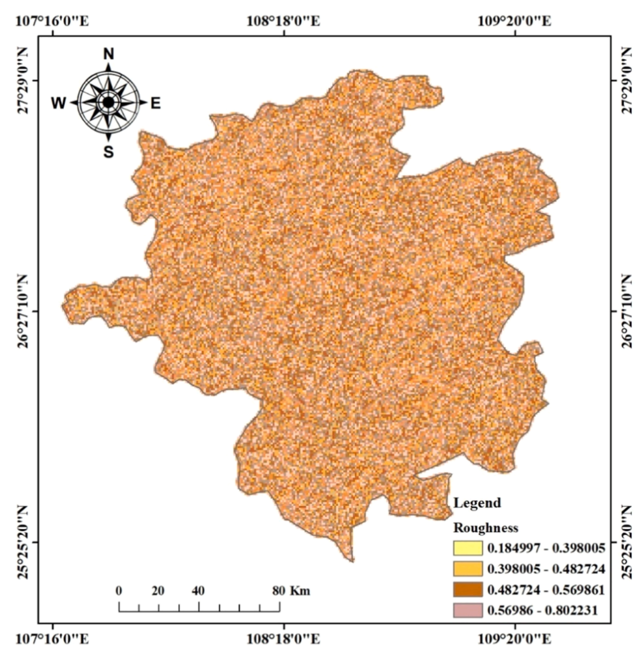

Fig. 16. Roughness map of the Kaili district.

roughness map of the Kaili watershed ranged from 0.18 to 0.80 and was divided into five classes.Fig. 16

5.1.12. Flood

Flood risk include susceptibility to water-related damage and pollution [55].

The repercussions of floods are acutely experienced in emerging nations, particularly by the local rural populace. Flooding issues, irrespective of topographical and climatic conditions, are intensifying due to environmental alterations such as land use changes, rapid urbanization, and climate change [56]. As flood risks are inevitable, they can be mitigated by implementing effective management measures. Over the past two decades, numerous studies have using multi-criteria decision analysis (MCDA) to assess index-based flood hazard and risk by examining the parameters that influence floods. GIS-based MCDA analyses intricate decision-making issues by structuring the criteria hierarchically [57].

Various literature evaluations indicated that over 82 % of the studies employed Multi-Criteria Decision Analysis (MCDA), predominantly conducted in Asian and European nations (85 %). Furthermore, roughly 72 % of these studies utilised the Analytical Hierarchy Process (AHP) inside the MCDA framework, despite variations in perspective and the number of parameters considered.

In this investigation, the hazard index was categorized into three classes. A majority of 36.63 % of the study area is situated in the high flood hazard zone, followed by moderate hazard zones that encompass 26.17 % and 21.55 % of the region, respectively. Only 6.70 % and 7.85 % of the area are situated in low flood hazard zones, respectively. Flood inundation maps for the Kaili district of Guizhou province are illustrated in Fig. 17.

5.1.13. Landslide

Many researchers have clarified the complex relationship between hydrogeology and landslide dynamics in the context of landslides, highlighting the critical role that this field plays in reducing related hazards [58]. Given that groundwater recharge is not exclusively reliant on precipitation or snowfall, special attention has been paid to this process. Importantly, a significant amount of water can come from deep-water circulation, seeping up into deposits from landslides, or from the existence of several aquifers at different depths [59].

Such catastrophes are common in China, a country vulnerable to geological disasters. Landslides are the main geological hazard in Guizhou Province, which is notable for its complicated topography, human development activities, and climatic circumstances [60]. The province is located at the meeting point of tectonic plates. In Guizhou Province, landslide disasters have caused a sharp increase in deaths and disappearances in recent years, along with significant financial losses. Therefore, early detection and ongoing monitoring are critical to lessen the negative effects and financial consequences resulting from landslides. We sourced the data for the landslide study from the link https://gpm.nasa.gov/landslides/. The research utilized a 30 m Digital Elevation Model dataset from the USGS and radar satellite imagery from

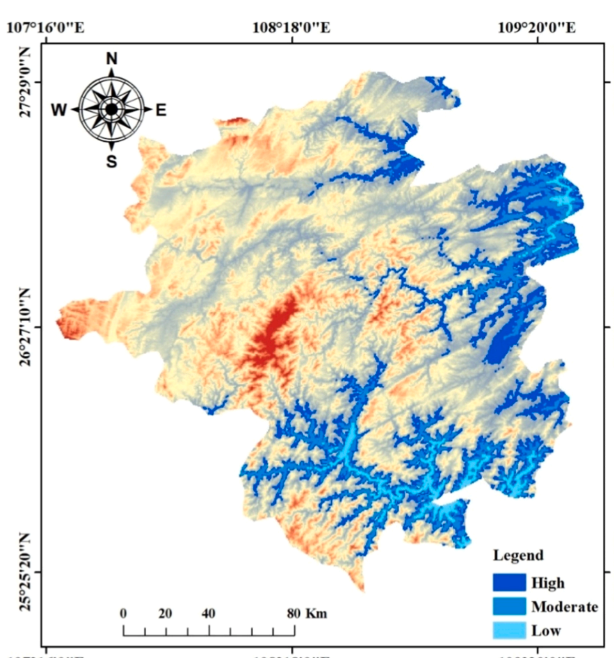

Fig. 17. Flood risk map of the Kaili district.

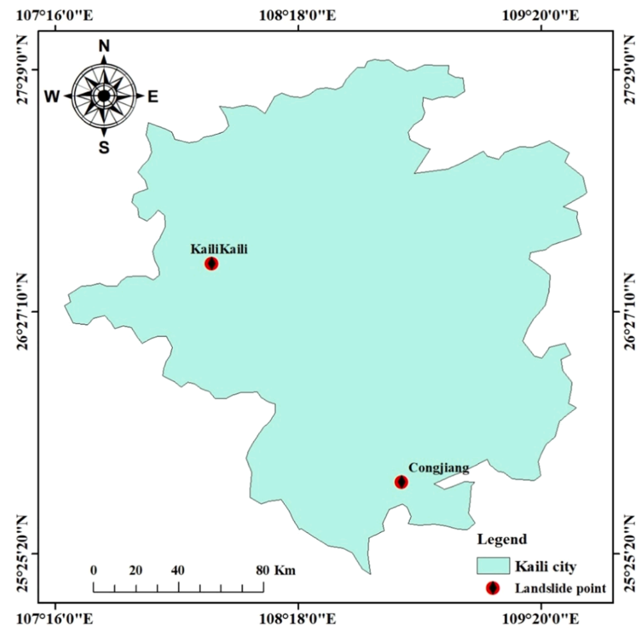

Fig. 18. Landslide map of the Kaili district.

Sentinel-1A. Fig. 18 reveals the discovery of two landslide zones in the Kaili district.

The radar satellite imagery employed in this study is obtained from the Sentinel-1A satellite, including a resolution of 5×20 m. Table 3 provides comprehensive details about the Sentinel-1A radar satellite imagery that this paper utilizes. Fig. 19 illustrates the data coverage. Fig. 20

6. Validation

A field validation has been conducted following the construction of thematic maps. The investigation results also revealed the recharge, discharge, and drainage conditions of the aquifers. We utilized data from the incorporated boreholes and wells to validate the results of the developed and projected groundwater potential map. Seven verification boreholes have been built in the study area. Initial evaluations from pumping experiments indicate that CK-1 exhibits a significant water production of around 460 tons per day Fig. 21. In contrast, the other demonstrates a markedly medium and low water output. Fig. 22 shows cross section of the well CK-1 and the surrounding study area.

The selection of the drilling site was predicated on the existence of current work and a hypothesized fault F2, as evidenced by previous studies. This highlights the challenges inherent in precisely predicting groundwater dynamics. The yield rates were categorized into five classifications: very low yield (<6.7 m^3/hour), low yield (<10.7 m^3/hour), medium yield (10.8–20.6 m^3/hour), high yield (>21.6 m^3/hour) and very high (>24.6 m^3/hour). A comparative analysis was conducted by reclassifying the resultant map into five categories: very low, low, medium, high and very high. The borewell locations and their corresponding yield classes were overlaid into the groundwater potential map, as depicted in Fig. 23.

Table 3
SENTINEL-1A Data Used in this Study.

Study area	Number	ascending/descending	data
Kaili city	60	Ascending	20,170,327–20,190,621
Congjang town	32	Ascending	20,180,806–20,190,813

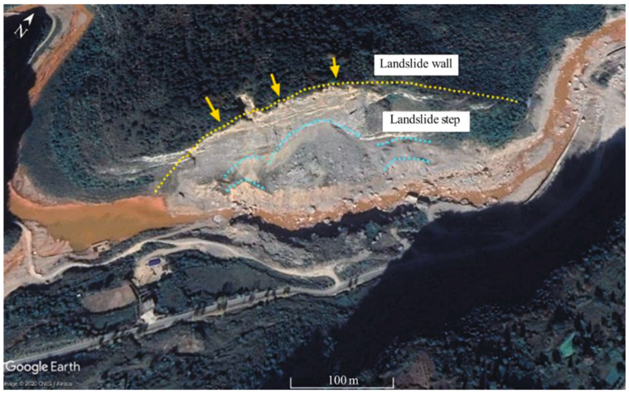

Fig. 19. Google Earth remote sensing images of known landslides in Kaili city.

7. Discussion

In China's Guizhou province, groundwater is a vital natural resource that supports domestic water supply, industrial development, and agricultural activities [62]. However, because of the complexity of groundwater distribution, identifying groundwater potential zones is difficult [63]. In order to overcome these obstacles, this work combines RS and GIS methods to offer a quick and affordable groundwater potential mapping solution. A 30 m spatial resolution DEM, Sentinel-2 satellite images with a 10 m resolution, and other data sources were used to create the study's twelve theme layers. Slope, contour, elevation, rainfall, drainage density, lineament density, lithology, soil, hillshade, aspect, roughness, flood, and land-use/land-cover were among the theme layers. These elements were chosen because of their impact on the occurrence and recharge of groundwater. Each thematic layer was reclassified and given a weight based on its contribution to groundwater potential using the AHP. The weight assignment procedure was directed by expert knowledge, guaranteeing a thorough and precise evaluation. Our findings offer a broader perspective compared to similar studies conducted on these techniques. For example, Mahmoudi [64] used a similar methodology to assess groundwater recharge capacity in arid regions of Tunisia, finding that the results are highly dependent on site-specific factors and the weights of the chosen influential variables. This variation highlights how crucial local context is when making decisions about groundwater management. Additionally, the research by Shah [65] advocates for GIS-based multi-criteria analysis as an effective technique for delineating groundwater recharge potential zones in Henan, China. Taking a comprehensive strategy is essential to creating multifaceted, sustainable plans for managing water resources [66]. Dechasa [67] used similar methods to find suitable places for groundwater recharge in Gidabo watershed, Ethiopia and found similar results when looking at the important criteria. The need for a thorough evaluation framework is further supported by their finding that results are significant only when a sufficient number of affecting factors are taken into account [68,69]. The efficacy of groundwater recharge projects may be compromised if important criteria are disregarded because this could produce false or misleading findings [70]. Similar to the current study, the aforementioned studies identified groundwater potential zones by integrating many parameters, including lithology, slope, soil, lineament density, rainfall, drainage density, and land use/land cover [71]. We used weighted overlay analysis in ArcGIS to define the groundwater potential zones. The results revealed that the study area exhibited high groundwater potential, the high-potential zones were found in southern flat terrain, high rainfall, and densely packed lineaments, all facilitating groundwater recharge. Conversely, the low-potential zones were located on northeastern steep slopes, low permeability soil, and poor infiltration rates, which hindered groundwater storage. These findings align with the previous studies, where areas classified under poor groundwater potential were linked to similar factors such as steep slopes and low permeability [72]. The groundwater potential zones were delineated using weighted overlay analysis in ArcGIS, which allowed for the integration of all the thematic layers based on their assigned weights [73]. We validated the groundwater potential map using field data from five wells in the research region, and overlaid the groundwater potential map with the well yield data to compare the anticipated potential zones with the actual well yields. The delineated GWPZ watershed is classified into five zones: very low yield (<6.7 m^3/hour), low yield (<10.7 m^3/hour), medium yield (10.8–20.6 m^3/hour), high yield (>21.6 m^3/hour), and very high yield (>24.6 m^3/hour). With an overall accuracy of 85 %, the results demonstrated a high link between the actual well yields and the anticipated groundwater potential zones. The study's conclusions offer insightful information to those making decisions about the planning and management of water resources in the Kaili district. We can use the groundwater potential map to priorities regions for groundwater extraction,

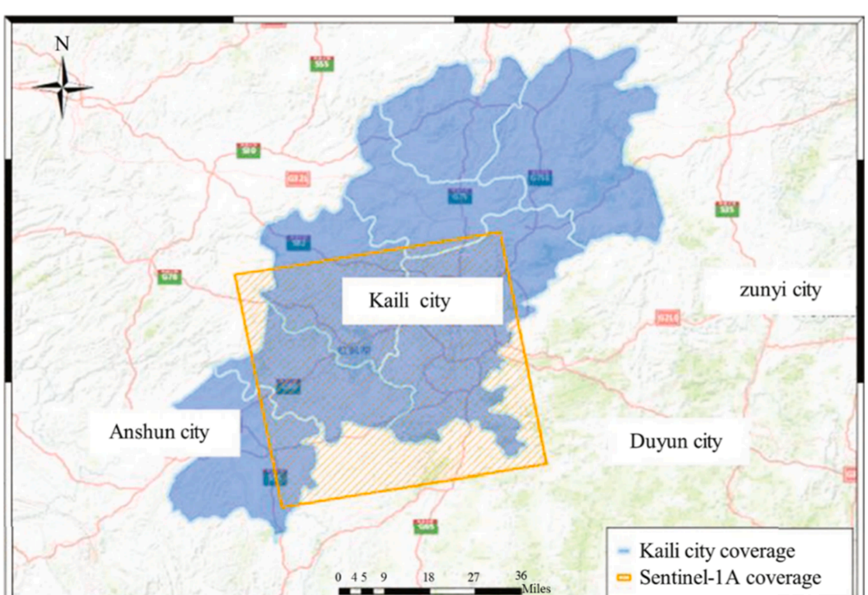

Fig. 20. Coverage map of Sentinel-1A data of Kaili city.

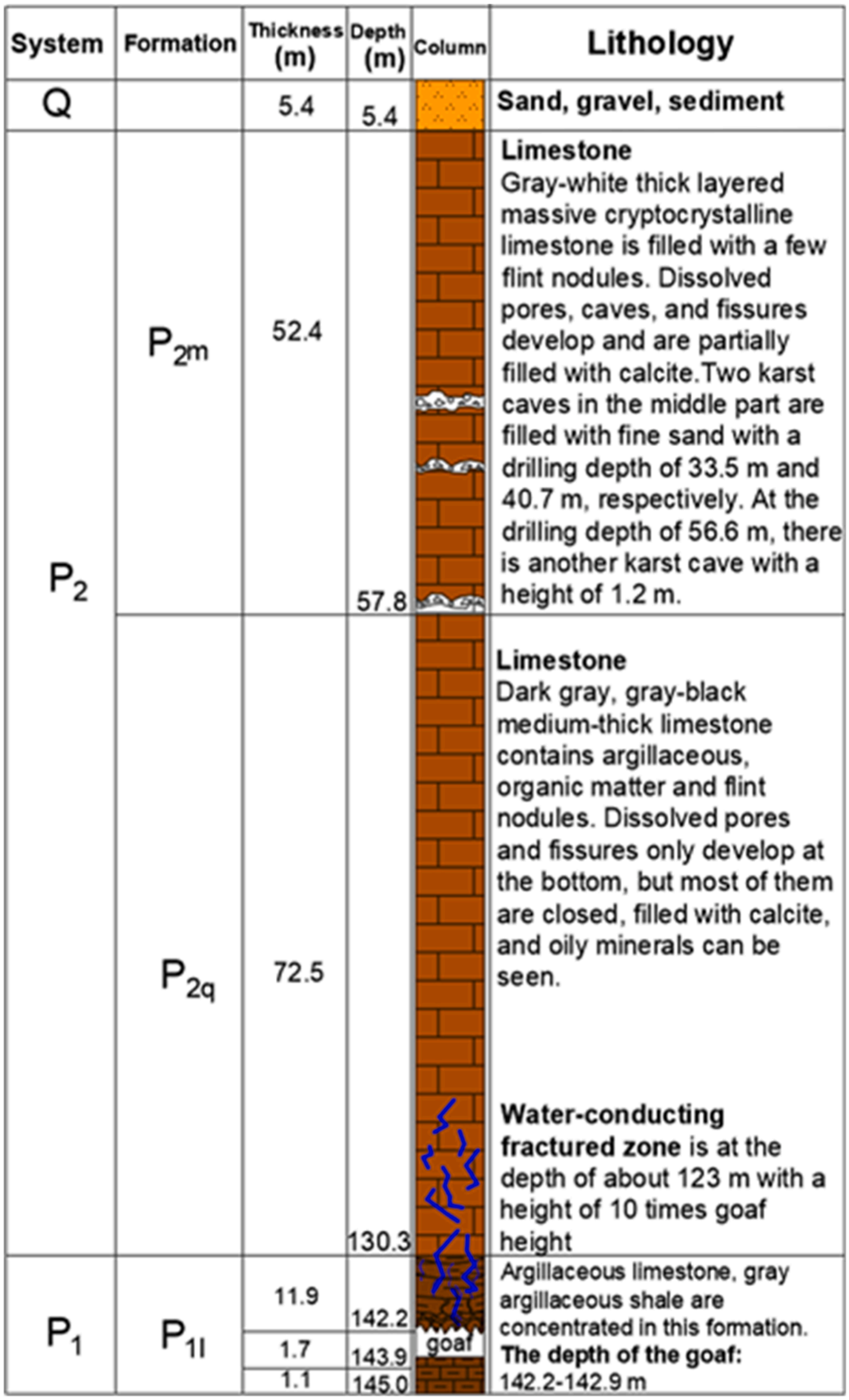

Fig. 21. Drilling verification borehole chart of Well CK-1 modified after [61].

agricultural growth, and urban planning [74]. GIS and AHP effectively and efficiently accomplished groundwater potential mapping as an economical substitute for conventional field surveys [75]. The study also emphasizes how crucial it is to combine many data sources and narratives to increase the precision and dependability of groundwater assessment.

8. Advantages of GIS method in groundwater monitoring

GIS is essential to groundwater monitoring, because it integrates geographical data, makes analysis easier, and supports decision-making. GIS applications in groundwater monitoring are very helpful as it let us do spatial analysis, model and simulate groundwater processes, combine different datasets, use Decision Support Systems (DSS) to help us make decisions, and make the best use of monitoring network designs. These skills help manage groundwater resources more sustainably and effectively, reducing environmental effects and guaranteeing their availability for future generations. GIS is still essential to improving the knowledge and management of groundwater systems around the world as technology develops. Table 4 lists the advantages of GIS usage in groundwater monitoring.

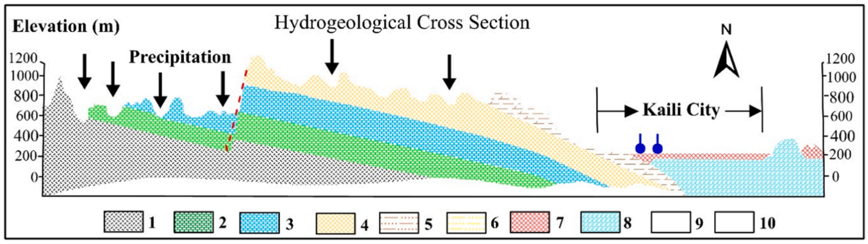

Fig. 22. Hydrogeological cross section of Kaili district from north to south. 1. Geniss. 2. Limestone and shale. 3. Oolitic limestone. 4. Shale and limestone. 5. Dolomite limestone. 6. Limestone. 7. Soil. 8. Diorite. 9. Fault. 10. Spring.

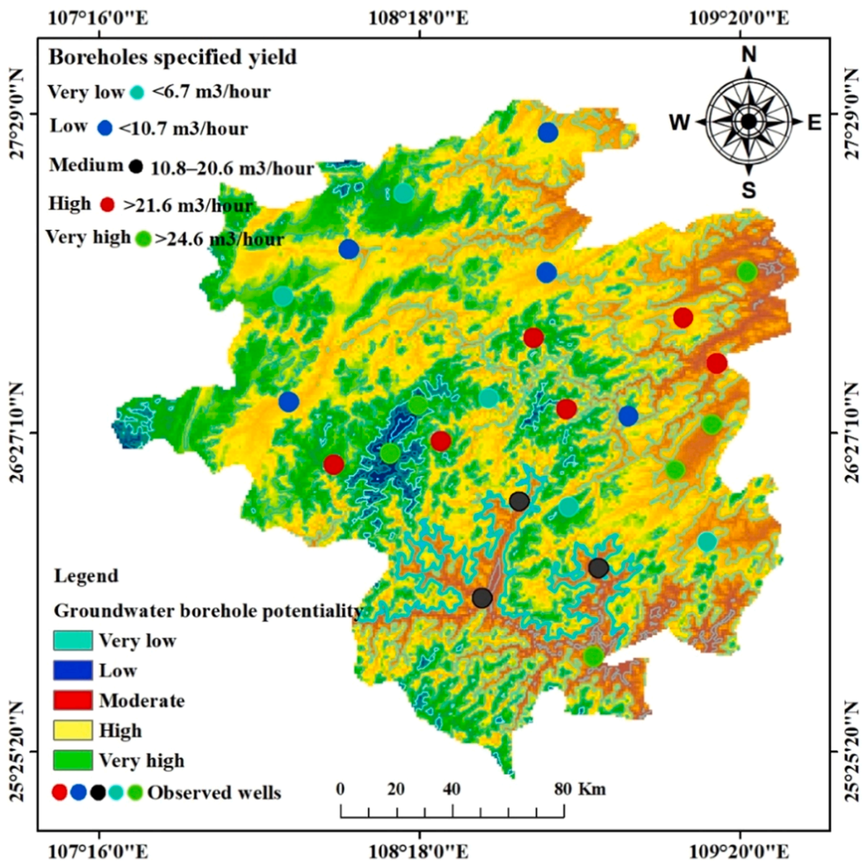

Fig. 23. Groundwater potential zone validation map.

Table 4
GIS-methods in groundwater monitoring and their advantages.

Method	Application
Well monitoring	Water level measurement
Pumping test	Water level qualities
Piezometer	Groundwater pressure measurement
Water chemistry analysis	Laboratory analysis
Field observation	Visual inspection

9. Overcoming challenges

Researchers should combine several data sources to get over the challenges and limitations associated with using GIS and remote sensing techniques for groundwater monitoring. For example, integrating ground-based measurements and modeling with remote sensing data may offer a more thorough comprehension of groundwater dynamics. In terms of technological developments, enhanced sensors and data processing methods are constantly extending the potential for groundwater monitoring. In addition, getting rid of barriers related to lack of skills means teaching stakeholders how to use GIS and remote sensing tools for managing groundwater. Therefore, creating regulations that include data from remote sensing into frameworks for groundwater management can aid in resolving regulatory issues. Even though GIS and remote sensing have a lot of promise for groundwater monitoring, overcoming their inherent drawbacks necessitates a multidisciplinary strategy that includes capacity training, policy support, and technology development.

10. Conclusion

The research effectively identified groundwater potential zones in Kaili District, Guizhou, China, employing an integrated methodology that merged geographical information systems with the analytical hierarchy process. The investigation categorized the GWPZ into five categories: very low at 12.5 % of the area, low at 25 %, medium at 37.5 %, high at 20 %, and VERY high at 5 % of the area. The results revealed that regions characterized by flat terrain, heavy rainfall, and densely arranged lineaments were most favorable for groundwater recharge, while areas with steep slopes and low soil permeability shown lower potential. RS, GIS and AHP demonstrated a cost-efficient, prompt, and precise approach for groundwater potential mapping. The validation of the groundwater potential map utilizing field data from wells demonstrated that the model achieved an accuracy of 85 %, signifying a strong correlation between anticipated and actual groundwater potential. It is recommended that local authorities concentrate on formulating sustainable groundwater extraction plans in the identified high-potential zones. Effective planning is crucial to avert over-extraction, which might deplete groundwater resources. Regions exhibiting high to very high groundwater potential should be prioritized for groundwater development initiatives, including boreholes and wells, to satisfy the increasing demands of agriculture, domestic consumption, and industry. In areas with limited groundwater potential, conservation strategies must be enacted to avert over-exploitation, which may further restrict groundwater recharge. It is essential to educate local stakeholders and resource managers in the application of RS, GIS, and AHP methodologies for continuous groundwater monitoring and management.

Future research may enhance the precision of groundwater potential evaluations by incorporating machine learning methodologies, such as Random Forest or Artificial Neural Networks, alongside GIS and RS data. It should also contain more parameters, including aquifer thickness, groundwater quality, and socio-economic aspects of water utilization, for a more comprehensive evaluation.

CRediT authorship contribution statement

Osama Abdul Rahim: Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization. **Hailong Yin:** Writing – review & editing, Software, Formal analysis, Conceptualization. **Sajid Ullah:** Writing – review & editing, Supervision, Resources, Investigation, Conceptualization. **Ayesha Noor Durrani:** Writing – review & editing, Visualization, Validation, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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