



An integrated groundwater resource management approach for sustainable development in a tropical river basin, southern India

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Abstract Evaluation of aquifer potential is essential, as the potable water demand has increased globally over the last few decades. The present study delineated different zones of groundwater potential and groundwater quality of the Kallada River basin (KRB) in southern India, using geo-environmental and hydrogeochemical parameters, respectively. Geo-environmental variables considered include relative relief, land use/land cover, drainage density, slope angle, geomorphology, and geology, while hydrogeochemical parameters include pH, electrical conductivity (EC), Cl^- , Fe^{3+} , and Al^{3+} concentrations.

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Analytical hierarchy process (AHP) was used for categorizing groundwater potential and quality zones. Nearly 50% of KRB is categorized as very high and high groundwater potential zones, occupying the western and mid-land regions. The central and west-central parts of KRB are characterized by excellent groundwater quality zones, while the eastern and western parts are characterized by good and poor groundwater quality zones, respectively. By integrating the groundwater potential and groundwater quality, sustainable groundwater management is observed to be necessary at about 54% of the basin, where site-specific groundwater management structures such as percolation ponds, injection wells, and roof water harvesting have been proposed using a rule-based approach. This integrated groundwater potential-groundwater quality approach helps policymakers to implement the most suitable management strategies with maximum performance.

Keywords Groundwater potential zones · AHP ·
Groundwater quality · Kallada River Basin

Introduction

Groundwater is crucial for domestic, irrigation, and industrial water supply. The uncontrolled groundwater extraction resulted in global water stress (Achu et al., 2020a; Chatterjee & Dutta, 2022; Ghosh et al., 2022), which has led to a subsequent decline in the groundwater level and groundwater contamination all over the world (Asoka et al., 2017). As the global

groundwater depletion rates have been accelerating ever since (Margat & Van der Gun, 2013), the usage of water resources needs to be ensured in a sustainable and equitable manner.

In semi-arid regions like India, most rivers are perennial, and the groundwater resources are extensively extracted to meet various needs (Arulbalaji et al., 2019). Niti Ayog (2018) reported that fresh water is not adequately available to approximately 0.6 billion people in the country, resulting in high to extremely high-water stress and nearly three-fourths of the households face acute shortage of potable water. As the current depletion rate is rapid, the persistence of the present scenario, with no adequate mitigation strategies, would make the country a water stress zone by 2025 and a water scarcity zone by 2050 (World Bank, 2006). Furthermore, the rainfall patterns show considerable spatial variations across the country, with increased heavy rainfall events and more frequent extreme events towards the southern states (Mishra et al., 2010). Basin-scale analysis of groundwater behavior is necessary for effective groundwater management and water resource development.

Kerala, one of the most densely populated states in the country, with a relatively high average annual rainfall of 3000 mm/year and plenty of water resources in the form of rivers, lakes, and ponds, also reels under similar water stress conditions (Hima Hari, 2015) due to increased water demands as a result of high population density, urbanization, mismanagement of water resources (Shaji et al., 2009), and changing patterns of precipitation (Chakrapani et al., 2014; Hima Hari, 2015). The state is also reported to have the highest chemical/bacterial contamination in drinking water (UNICEF, 2012). The water demand in the state is relatively higher due to the traditional high consumption of water for domestic needs with less adoption of water harvesting structures. More than 80% of rural and 50% of urban domestic water needs and 50% of the irrigation water needs in the state are met from groundwater (Chakrapani et al., 2014). The annual rainfall and monsoon show a declining trend over the last century with the increased decadal frequency of droughts (Subba Rao et al., 2009; Mishra & Shah, 2018), which aggravates the water stress. Many parts of the state have been facing acute water shortages (Thomas & Prasannakumar, 2016) and saline water intrusion along the coastal zones during summer, even with a high average annual rainfall. This makes it necessary to manage the excess water effectively to ensure water availability during the dry season.

A better understanding of the available groundwater resources and identification of the appropriate site-specific water management strategies are necessary to cope with this, as groundwater contributes a significant part of the freshwater resources of the state. This is critical for long-term resource management, as it assists planners, decision-makers, and policymakers in ensuring the qualitative and quantitative protection of groundwater resources. There have been several methods for water resource management in river basins, which include probabilistic models such as frequency ratio (Ozdemir, 2011; Razandi et al., 2015), multi-criteria decision analysis (MCDA) (Chowdhury et al., 2009), weights of evidence (Pourghasemi & Beheshtirad, 2015; Rahmati et al., 2015), logistic regression (Pourghasemi & Beheshtirad, 2015; Pourtaghi & Pourghasemi, 2014), evidential belief function (Pourghasemi & Beheshtirad, 2015; Mogaji et al., 2015), machine learning techniques such as random forest (RF), maximum entropy (ME) (Rahmati et al., 2016), weighted overlay method (Brindha & Elango, 2012), and statistical methods (Badeenezhad et al., 2020; El-Hames et al., 2013). Though remote sensing and GIS have been applied for faster estimation of natural resources, evaluating and ranking various alternatives based on multiple criteria are most effective using MCDA methods. The close interval data requirement in MCDA, which is practically challenging, can be overcome by applying expert knowledge, fuzzy logic, and other techniques (El-Hames et al., 2013).

The most widely utilized multi-criteria decision-making method is the analytic hierarchy process (AHP) (Arabi Aliabad et al., 2019; Ahmad et al., 2023; Farhat et al., 2023), which helps to determine the relative importance of different criteria and alternatives in complex decision-making situations (Saaty, 1980). It involves breaking down of a complex decision problem into a hierarchy of criteria and alternatives based on different factors considered unilaterally or objectively in the decision process (Putra & Fatrilia, 2020). AHP uses pairwise comparisons of elements of a problem in response to their relative impact on a property (weight) and mathematical calculations to determine the relative weights of the different criteria and alternatives, followed by generating conclusions based on the predetermined variables for achieving best decisions (Saaty, 1990; Saaty & Kearns, 1985). AHP is widely used for the delineation of groundwater potential and groundwater

quality zonation due to its efficiency and simplicity (Achu et al., 2020b; Aju et al., 2021; Farhat et al., 2023; Arshad et al., 2020; Chowdary et al., 2013; Asgher et al., 2022), and useful information can be generated for the managers and policymakers using GIS and AHP (Appukuttan & Reghunath, 2022; Guru et al., 2017).

Though several researchers have used these tools, an integrated groundwater potential-groundwater quality zonation is less discussed in literature. Such a study has been carried out in the Kallada River basin, located in the southern part of Kerala, India, where drinking water shortage has been reported in several areas during the summer season, with the complete drying of many open wells and ponds (Fig. 1a and b), though the seasonal rainfall availability is relatively high.

Particularly, the lateritic aquifers along the slopes and hilltops of KRB, where the well yield values range from 0.5 to 6 m³/day, experience water shortage during the summer season (Aju et al., 2019). Furthermore, some coastal areas are affected by saline water intrusion (CGWB, 2013). The low-lying areas of the KRB, especially in the western areas, have been facing a serious threat of water upwelling, salinity problems, poor drinking water quality, and agricultural failure for more than one and a half decades (Chithra et al., 2022). In this context, the present study aims to delineate the areas in the Kallada River basin (KRB), a tropical river basin in Kerala, where groundwater management is necessary for the sustainable development of water resources. Though groundwater scarcity has been reported in parts of KRB (Aju et al., 2019), a basin-scale integrated approach to the water resource management of KRB has not been done so

far. In this context, this study integrates the groundwater potential and the groundwater quality to demarcate suitable areas for groundwater recharge and identify the site-specific recharge methods for their better performance. This research will serve as a valuable resource for groundwater resource planners and policymakers, offering guidance in formulating sustainable groundwater strategies for the planning and development of the basin.

Study area

Kallada River is one of the main west-flowing rivers in south Kerala and lies between latitudes 8° 44'N and 9° 10'N and longitudes 76° 31'E and 77° 16'E. The Kallada River originates at Karimalaikodakkal in the Western Ghats, at an elevation of 1757 m above sea level (Fig. 1) and enters into the Arabian Sea through the Ashtamudi backwater with a total length of 121 km. The initial south westerly course of the river changes to a westerly course at Parappar and to north westerly in the midland, with an increase in elevation from 7.5 to 75 m. The three major tributaries of the Kallada River are the Kulathupuzha River, Kalthuruthy River, and Chenduruni River, which join together at Parappar in the Kollam district. The basin is characterized by a humid tropical climate with mean annual precipitation ranging from 2225 to 4038 mm (Source: India Meteorological Department). The rainfall in the basin is mainly contributed by the south-west monsoon from June to September and the north-east monsoon from October to November. The average population density of the study area is 1129 per km² as per the 2011 census.



Fig. 1 Photographs from the north-western parts of KRB showing **a** dried well and **b** dried pond during May 2019

Hydrogeology

The major aquifers and geological formations in the basin include crystalline-rock aquifers, tertiary sedimentary rock aquifers, alluvial aquifers, and lateritic aquifers. The crystalline rock aquifers are shallow, covering the majority of the basin, and constitute khondalites, charnockites, granite gneisses, and intrusives which are high to moderately weathered and fractured up to a depth of 20m. The well yields of shallow khondalitic aquifers and the shallow charnockitic aquifers range from 6 to 12 m³/day and 4 to 5 m³/day, respectively. On the other hand, the deeper fractured aquifers below 20 m are characterized by crystalline rocks with comparably higher well yield than shallow aquifers (CGWB, 2013). Groundwater occurs at phreatic conditions in coastal zones where tertiary sedimentary beds such as Alleppey beds, Vaikom beds, Quilon beds, and Warkalli beds are predominant, and the potential is relatively higher in the aquifers in Vaikom and Warkalli beds. These largely developed aquifers are a major source of the village and town water supply. However, the well yields of tertiary sedimentary aquifers are inconsistent throughout the basin due to the widely varying thickness. Large-diameter open wells with high yields are constructed in thick, saturated zones in the potential lateritic aquifers in the valleys and the topographic lows of the basin. The phreatic aquifer in the recent alluvial deposits is extensively developed by dug wells and filter point wells used for domestic and irrigation needs.

Data collection and methodology

The methodology adopted for the study is detailed in the methodology flow chart (Fig. 2). The geo-environmental factors and hydrogeochemical parameters were considered for categorizing groundwater potential and groundwater quality of KRB, and their details are discussed in the following subheads.

Geo-environmental factors

The groundwater potential zones in the study area were delineated based on geo-environmental factors such as relative relief, land use/land cover (LU/LC), drainage density, slope, geomorphology, geology, lineament density, and groundwater level fluctuation (GLF).

Relative relief

Relative relief is the difference between the lowest and highest range of elevation in a unit area. Relative relief measures the overall steepness of a drainage basin and indicates the intensity of erosion processes operating on the slopes of the basin, thereby affecting the occurrence and movement of groundwater (Ghimire et al., 2019). The details of relative relief were generated from SRTM DEM (1Arc second) using the SAGA GIS package.

Land use/land cover (LU/LC)

The land use/land cover affects the hydrogeological and geo-hydroclimatic processes such as runoff, infiltration, and evapotranspiration, and impacts the groundwater recharge of the basin (Uc Castillo et al., 2022). The LU/LC map (scale 1:50,000) of the area for 2016 was procured from the Kerala State Land Use Board.

Drainage density

The drainage density is defined as the ratio of the total length of the water courses in a basin to the surface area of the drained basin (Horton, 1945). Drainage density exhibits an inverse relationship with the permeability of the formation materials, which influences the runoff and recharge of the basin (Rajasekhar et al., 2022). Drainage density and distance from the drainage were assessed from the drainage lines extracted from the Survey of India topographic maps (1:50,000 scale).

Slope angle

The slope angle depicts the local and regional relief, which significantly influences groundwater recharge into the aquifers (Allafta et al., 2020). Slope angle influences the infiltration of rainfall (Al Saud, 2010) and thereby directly controls the groundwater potential. The details of the slope angle were generated from SRTM DEM (1Arc second) .

Geology

Geological setting plays a vital role in the occurrence and distribution of groundwater in any terrain

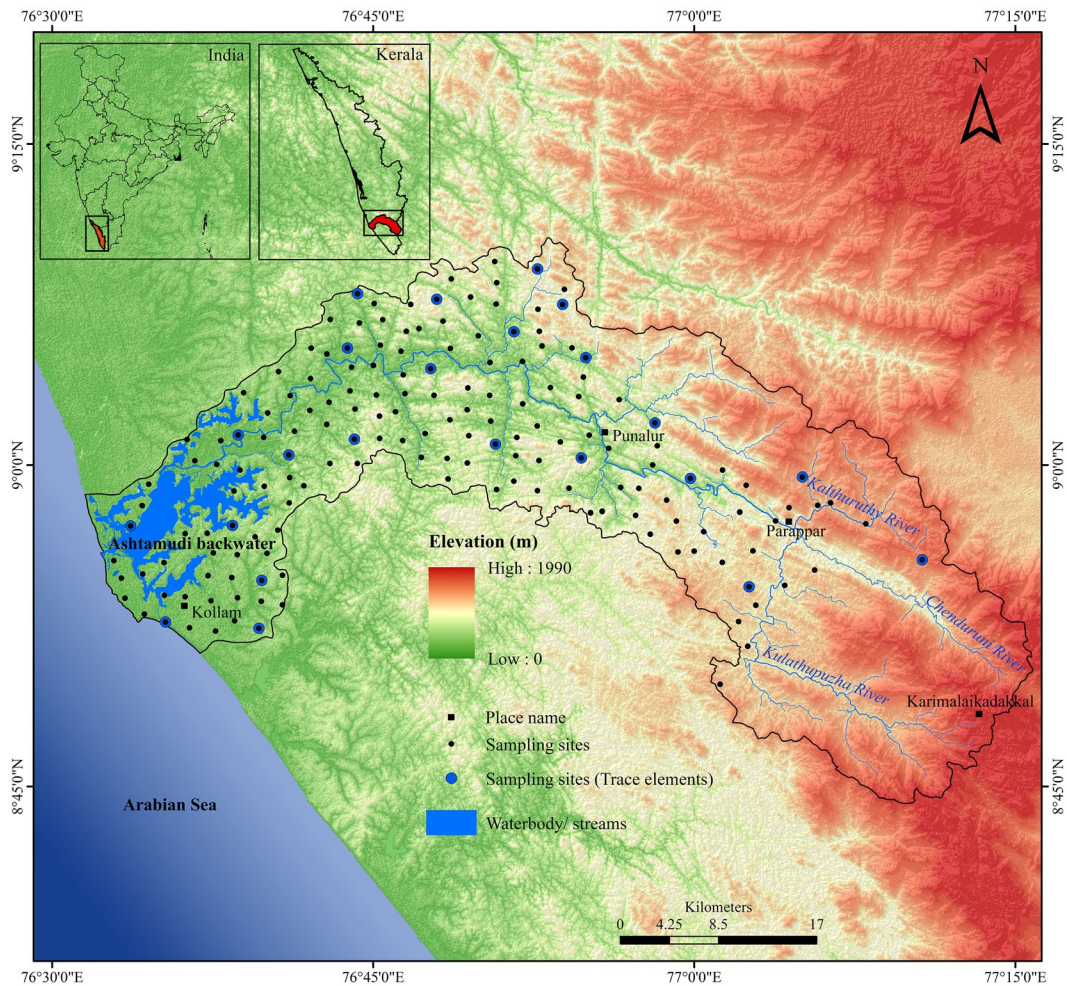


Fig. 2 The location map of the study area and well locations of water level monitoring and water sampling for major ion analysis are indicated by blue dots, overlaid over the SRTM

elevation model, and well locations of trace elements monitoring are indicated by larger dots

(Arulbalaji et al., 2019). The geological map of KRB was prepared from district geological resource maps (Scale 1:250,000) published by the Geological Survey of India (2006).

Geomorphology

Geomorphology represents the landforms and topography of an area and is one of the main factors used widely to delineate groundwater potential zones (Rajasekhar et al., 2019). The geomorphology map (scale 1:50,000) was obtained from Kerala State Remote Sensing and Environment Centre.

Lineament density

Lineaments are straight or nearly straight lines of landscapes, showing the rock basement architecture (Hobbs, 1904) and reflecting structural discontinuities in the subsurface. Lineaments can be caused by various geological features, including faults, fractures, and joints, and they can influence groundwater flow by providing preferential pathways for water movement. These are extensively spread over the Earth’s surface (Suganthi et al., 2013). The photo lineaments of the basin were visually interpreted and extracted from Landsat 8 OLI image with SRTM DEM (30 M).

Groundwater level fluctuation

The groundwater levels in 166 open wells (Fig. 3) were measured during pre- and post-monsoon of 2016 to assess the groundwater level fluctuations.

Hydrogeochemical parameters

The hydrogeochemical parameters such as pH and EC of the groundwater collected from these open wells during the same period were measured in the field using portable meters, and the concentrations of chloride, iron, and aluminium were assessed in the laboratory as per standard procedures (APHA, 1992 and Trivedy & Geol, 1986). Trace metals such as Fe and Al in the groundwater samples were analyzed using ICP-MS at the Central Laboratory for Instrumentation and Facilitation (CLIF), University of Kerala. Relative weights were assigned to these hydrogeochemical parameters, followed by their integration using the overlay method to categorize the basin into different zones with identical hydrochemical parameters.

Groundwater potential zonation and groundwater quality zonation

The relative importance of each geo-environmental factors and hydrogeochemical parameters was analyzed using the AHP matrix and was integrated to delineate the groundwater potential zones and groundwater quality zones in the basin. The relative ranking was done for each parameter based on expert opinion. A brief explanation of AHP and its applicability in groundwater studies are available in Achu et al. (2020b) and Aju et al (2021). Weights were assigned for each variable using analytical hierarchy analysis (AHP) followed by weighted overlay analysis to generate groundwater potential zones and groundwater quality zones using Eq. (1) (Saaty, 1990).

$$I = \sum_{i=1}^n F_i \times W_i, \tag{1}$$

where “I” denotes the groundwater potential and groundwater quality, “ F_i ” denotes the assessment rating of groundwater potential variables such as relative relief, land use/ land cover, drainage density, slope

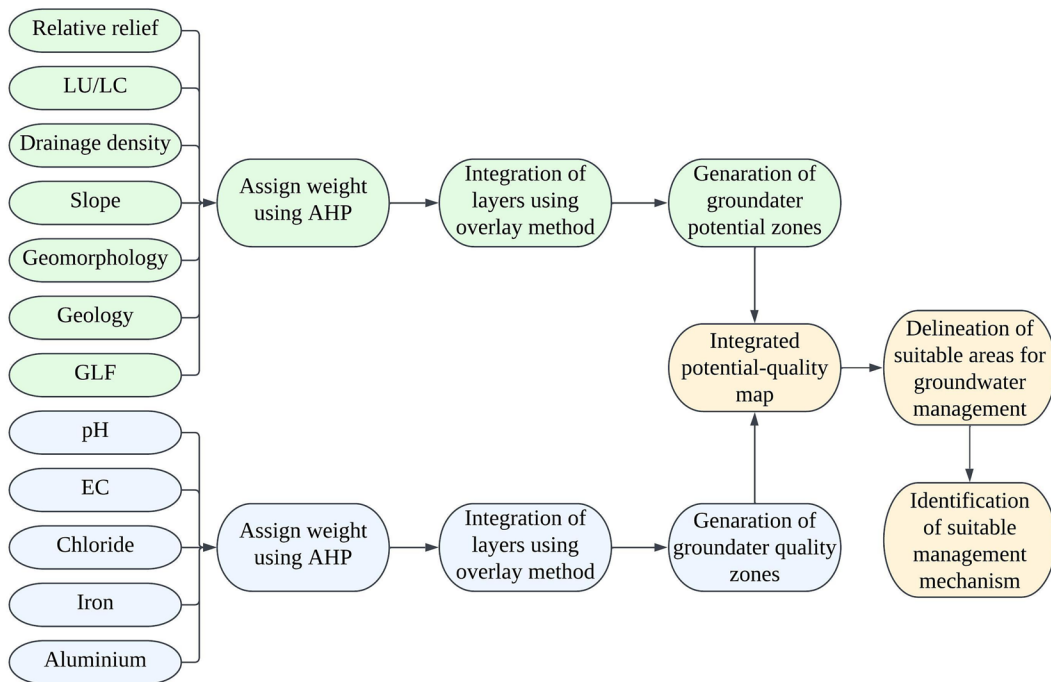


Fig. 3 The methodology adopted for the study

angle, geomorphology, geology, lineament density, groundwater level fluctuation, and groundwater quality variables such as pH, EC, Cl^- , Fe^{3+} , and Al^{3+} . The “ W_i ” indicates the corresponding weights given to each variable. The AHP weights used in the present study were derived based on the weightage of each parameter and expert judgments. The groundwater potential was validated using average groundwater yield data published by CGWB (2013).

An integrated groundwater potential-quality zonation map was prepared by overlying the groundwater potential and groundwater quality maps using GIS. The areas where groundwater management is necessary were delineated from the integrated map, and suitable management methods were proposed using a rule-based method (Achu et al., 2020a). Based on this, areas suitable for different recharge structures (injection wells, percolation ponds, roof water harvesting) were identified based on the terrain and hydrogeological conditions favorable for each recharge method (Achu et al., 2020a). Each criterion may have a specific threshold value that must be met for a site to be considered suitable. It can also help to minimize the potential for errors and subjective biases in the decision-making process.

Results and discussions

The areas requiring groundwater management were identified using the integrated groundwater potential and groundwater quality zonation by assigning relative weightage to the geo-environmental and groundwater quality parameters followed by their validation. The geo-environmental factors considered for evaluating groundwater potential in the basin are detailed in the following sub-sections.

Parameters of groundwater potential zonation

The groundwater potential zones in KRB were delineated by considering different geoenvironmental and hydrological parameters, which include relative relief, land use/land cover, drainage density, slope angle, geomorphology, geology, lineament density, and groundwater level fluctuation in KRB and are detailed in the following subheads.

Relative relief

The relative relief of KRB progressively decreases from 739.4 m/km^2 in the eastern mountainous regions to zero in the western coastal areas, as shown in Fig. 4a. Based on relative relief, the basin is reclassified as classes with very low ($< 100 \text{ m}/\text{km}^2$), low ($100\text{--}200 \text{ m}/\text{km}^2$), moderate ($200\text{--}400 \text{ m}/\text{km}^2$), and high ($> 400 \text{ m}/\text{km}^2$) relative relief, and the higher ranks were assigned to the classes with lower relative relief since the runoff will be slow in low relative relief areas, giving rainwater more time to infiltrate. The eastern and northeastern parts of the basin are characterized by considerably high relative relief and assigned low ranks.

Land use/land cover

Nearly 89% of the basin falls under the vegetated land category, of which 37% constitute plantations. The evergreen and semi-evergreen forests occupy 27% of the basin, mainly in the south-eastern parts (Fig. 4b). Both scrub forest/land and croplands occupy nearly 3% of the basin each, while the areas with urban built-up constitute nearly 5% of the basin. Barren rock exposures are significantly less in the basin. Water bodies are mainly dispersed along the coastal tracts occupying approximately 6% of the basin. Wetlands and forest plantations are favorable for the percolation of groundwater and were ranked higher, while built-up and double-crop areas are closely associated with low groundwater potential and were ranked lower.

Drainage density

The drainage density of KRB varies from 0 to 3.2 km/km^2 , and the spatial variation is shown in Fig. 4c. Higher drainage density is observed in the eastern parts of KRB, which gradually decreases towards the western parts. The basin is classified into four classes with very low ($> 0.5 \text{ km}/\text{km}^2$), low ($0.5\text{--}1 \text{ km}/\text{km}^2$), moderate ($1\text{--}2 \text{ km}/\text{km}^2$), and high ($> 2 \text{ km}/\text{km}^2$) drainage density. Areas with higher drainage density are characterized by less infiltration resulting in less groundwater potential. Subsequently, higher weightage is assigned to the area with low drainage density.

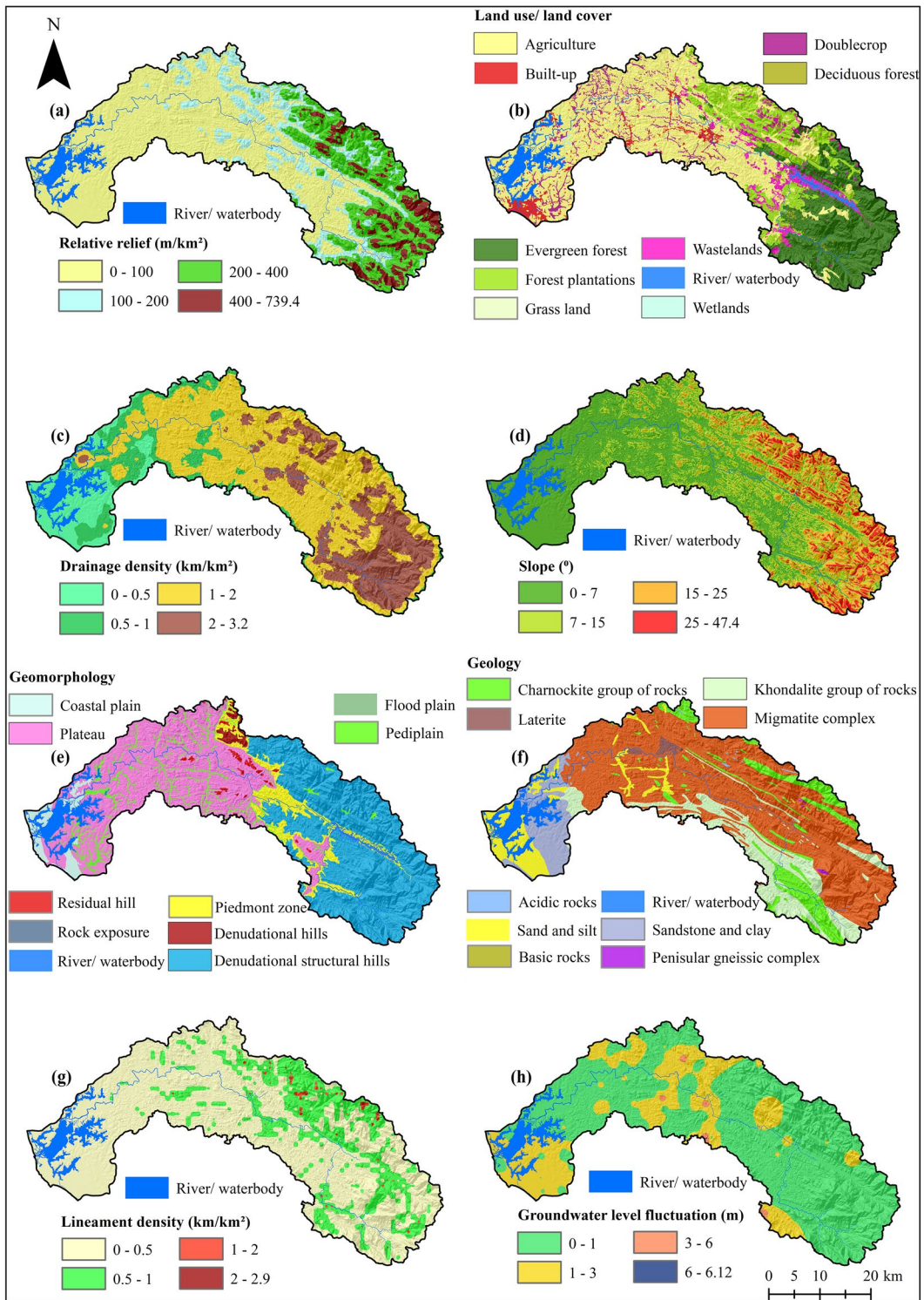


Fig. 4 Thematic maps of **a** relative relief, **b** land use/land cover, **c** drainage density, **d** slope angle, **e** geomorphology, **f** geology, **g** lineament density, and **h** groundwater level fluctuation

Slope angle

The slope angle of KRB varies from 0 to 47.43°, and the slope decreases progressively from the eastern mountainous regions to the western coastal areas. The spatial variation map of the slope angle in KRB is shown in Fig. 4d. Based on slope angle, the basin is classified into flat (<7°), moderate slope (7–15°), steep slope (15–25°), and very steep slope (>25°) classes. The majority of the basin is under the flat category, which is given a higher ranking since groundwater recharge occurs more rapidly in areas with flat/gentle slopes.

Geomorphology

The major geomorphological features in KRB include denudational structural hills along the eastern highlands and the lower lateritic plateaus distributed in the western parts, as shown in Fig. 4e. The north-eastern highlands of KRB constitutes patches of pediplains formed by the coalescence of pediments from the surrounding higher altitude areas. Weathered/buried pediplains with lateritic soils and alluvial sediments in the basin often follow the river channels. The central part of the river basin is characterized by widely scattered residual hills formed by peneplanation (Thornbury, 1990). The midlands are extensively covered by lower lateritic plateau, where the valleys are occupied mainly by croplands and paddy fields. The coastal plains in the lower reaches of the study area generally act as potential aquifers in the phreatic zone due to the presence of alluvial soils and coastal sediments. The high ranking is assigned for flood and coastal plains, and the low ranking is for residual and denudational hills.

Geology

About 85% of the total area of KRB is characterized by Precambrian crystalline rocks, as shown in Fig. 4f. Garnetiferous biotite gneiss and garnet-biotite gneiss are the most common rock types in the basin. These form a compact, foliated, and often fractured migmatite complex, rich in quartzo-feldspathic and mafic-minerals (Thampi, 1987). Charnockites and khondalites in the southeastern parts of the basin exhibit gneissosity (Aju et al., 2022). The occurrence of mylonites, formed by the shearing of rocks, is also reported in many places within the basin (Vikas,

2009). The primary porosity of crystalline rocks in the basin is very poor. However, secondary porosity plays a significant role in governing recharge in the basin. The hydrological importance of the rock is considered here for assigning rank. The characteristics such as types of rocks, origin, occurrence, and weathering are given due importance while assigning the weight. According to the rock characteristics, a high rank is assigned for sandstone and sand and laterite, and a low rank is assigned for acidic and basic rocks in the area.

Lineament density

The lineament density of KRB is estimated to vary from 0 to 2.9 km/km², as shown in Fig. 4g. Major and minor lineaments intertwine the study area with different dimensions, in which high fracture intensity is concentrated towards the northern central portion along the NW–SE to NNE–SSW trend, contributing nearly 50% of the total lineaments in the basin. Most lineaments are aligned along the river and stream courses, where the charnockite group and migmatite complex are the major rock types. Based on lineament density, KRB is classified into areas with low (<0.5 km/km²), moderate (0.5–1.5 km/km²), high (1.5–2 km/km²), and very high (>2 km/km²) lineament density. The low lineament density zone occupies a major part of the river basin. The lineaments are used as a geo-environmental variable in delineating groundwater potential zones in KRB as they represent the zones of faulting and fracturing and are well correlated with secondary porosity and permeability (Yeh et al., 2016). Higher ranks are assigned for areas with higher lineament density and low ranks for low-density classes.

Groundwater level fluctuation (GLF)

The groundwater levels in the monitoring wells show similar patterns during pre- and post-monsoon. The depth to the water level in KRB varies from 1.65 to 31.4 m with an average of 7.67 m during pre-monsoon and from 1.2 to 31.25 m with an average of 6.8 m during post-monsoon. The groundwater occurs at shallow depths towards the western parts and deeper depths towards the eastern side of the basin. The difference in groundwater levels in the monitoring wells during the pre- and post-monsoon periods is shown in

Fig. 4h. Based on the groundwater level fluctuation, KRB is classified into zones with low (< 1 m), moderate (1–3 m), high (3–6 m), and very high (> 6 m) groundwater levels. The areas with the least amount of groundwater level fluctuation throughout the pre- and post-monsoon periods are ranked higher because they are not influenced by groundwater level decline during the summer, indicating a high groundwater potential.

Relative importance of variables and groundwater potential zonation

The details of feature class divisions and the normalized eigenvectors of the geo-environmental factors used for AHP analysis are given in Table 1. Among the eight factors, the highest rating value is given to groundwater level fluctuation (0.0334), followed by lineament density (0.238) and geology (0.2000) while the lowest value is given to relative relief (0.022). Furthermore, weightages were assigned to the sub-classes of geo-environmental factors as given as supplementary material (Table 1). The numbers 1 to 10 in the Table represent the number of feature classes. Among the subcategories of relative relief, a relatively higher weightage of 0.4668 is given to the very low relative relief class, while the lowest weightage of 0.0953 is given to the high relative relief category. The highest weightages were assigned for the subcategories of each geo-environmental variable, such as water-logged areas with drainage density less than 0.5 km/km² (0.456), gently sloping areas with slopes less than 7° (0.516), flood plains (0.353), tertiary sediments of the Warkalli formation and the Quaternary deposits (0.320), regions having lineament density higher than 2.0 km/km² (0.567), and areas with groundwater level fluctuations less than 1 m (0.459). Similarly, the lowest weightage was assigned for geo-environmental subcategories such as built-up areas as well as steeply sloping areas with slopes greater than 25° (0.072), areas with higher density (0.0742), residual hills and denudational-structural hills, areas dominating with acidic and basic rocks (0.052), regions lineament density less than 0.5 km/km² (0.085), and areas with groundwater level fluctuation greater than 6 m (0.078).

The weights derived through the AHP method, as shown in the supplementary file Table 1, are used to classify the basin into zones of different

groundwater potential based on a natural junk classification scheme. The groundwater potential map of KRB is shown in Fig. 5, in which very high, high, moderate, and poor groundwater potential zones are demarcated with corresponding vertical lithological cross-sections.

Very high and high groundwater potential zones occupy nearly 50% of the study area. Nearly 425.2 km² area is characterized by very high groundwater potential, which covers nearly 26.5% of the total area of the basin. However, the very high potential zones are randomly distributed over the study area. The high, moderate, and poor groundwater potential zones cover approximately 400 km², 395.5 km², and 394.7 km², respectively.

Poor groundwater potential zones are spatially distributed towards the eastern parts of KRB, whereas the very high groundwater potential zones are distributed towards the western parts, as shown in Fig. 5. The groundwater potential map of KRB depicts that significant factors controlling the occurrence of groundwater towards the western parts of the basin include relative relief, drainage density, slope, geomorphology, geology, and lineament density especially, due to the dominance of “very high” groundwater potential zones with very low relative relief, drainage density, and slope. Also, these areas are characterized by lateritic plateaus with Quaternary to Recent alluvial deposits such as sandstone, clay, sand, and silt. “Poor” groundwater potential zones are located in the eastern and northeastern parts, where the relative relief and drainage density are moderate to high. These steeply sloping areas are dominated by crystalline rocks such as migmatite, charnockite, and khondalite group of rocks. In spite of the high to very high lineament density, the highly steep slopes and moderate to high drainage density in this area have resulted in minimal recharge and increased surface runoff. High and moderate groundwater potential zones are randomly distributed over the central parts of the basin. The groundwater potentials of many of the other river basins in Kerala including Muvatupuzha River basin (Dinesh Kumar et al., 2007), Ithikara River basin (Nair et al., 2017; Preeja et al., 2011), Meenachil River basin (Vijith, 2007), and Kuttiyadi River basin (Swetha et al., 2017) are also reported to be higher towards the western parts and lower towards the eastern parts.

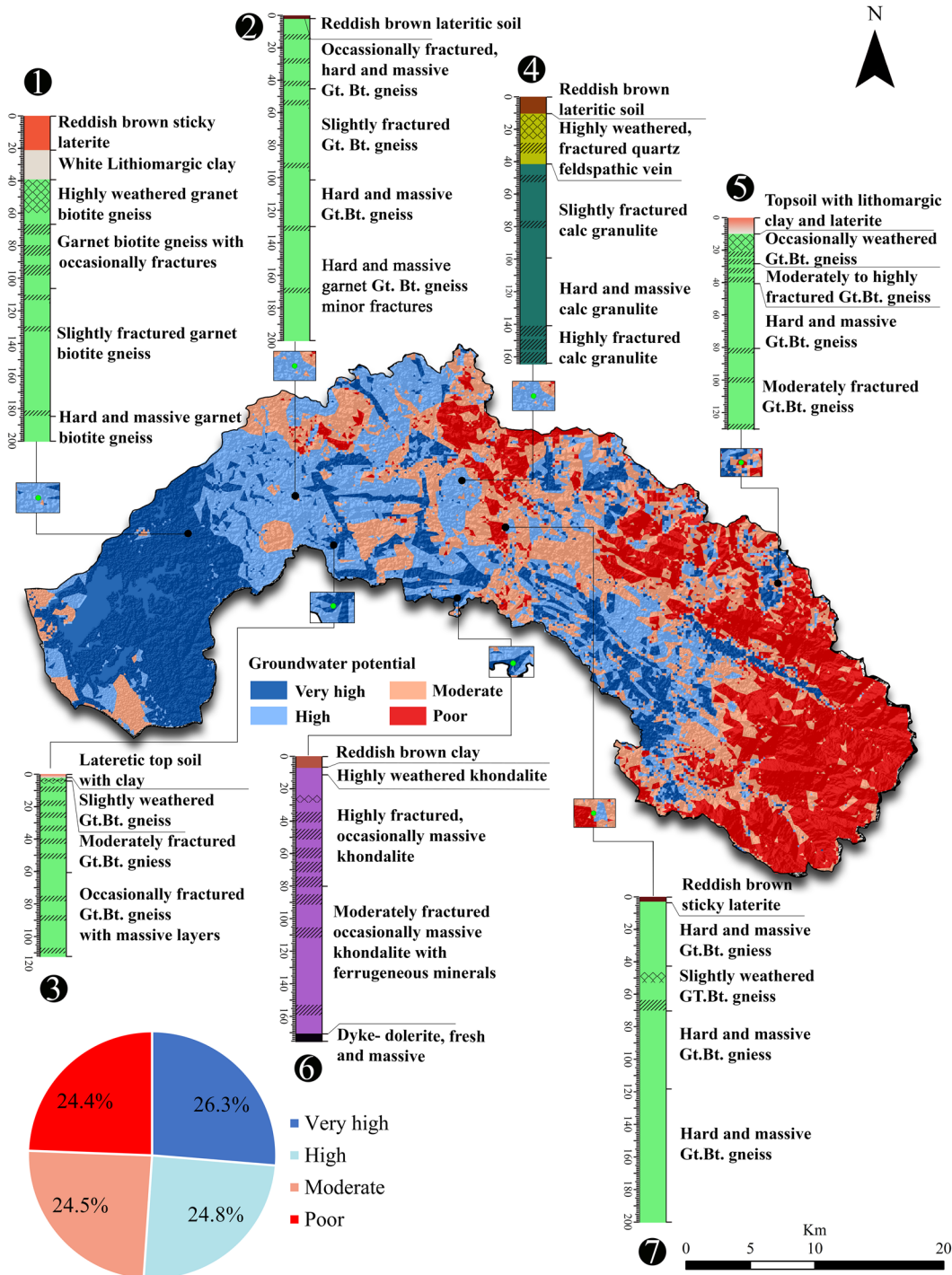


Fig. 5 Groundwater potential zones of KRB with CGWB observation wells and its vertical lithological cross-sections

Validation of groundwater potential with well yields

Well yield is used as an effective parameter to validate the groundwater potential of river basins (Achu et al., 2020b). Well yield data is used to validate the AHP-derived groundwater potential in the Upper Cauvery River basin, India (Basavarajappa et al., 2016), Wabe Shebele River basin, Ethiopia (Guduru & Jilo, 2022), Dak Lak Province, Vietnam (Nguyen et al., 2020), and Mehran region, Iran (Rahmati et al., 2016). In the present study, the estimated groundwater potential is correlated with the lithologies and corresponding well yield data (CGWB, 2019), as shown in Fig. 5. The lithologies numbered 1 to 6 are embedded on the groundwater potential map. The lithologies 1 and 3 are characterized by very low groundwater discharge (0.33 l/s), while litholog 4 is dried up. Similarly, the groundwater discharge of lithologies 2, 5, and 6 are 15.2 l/s, 4.5 l/s, and 11.04 l/s, respectively, as shown in Table 1. The very high and high groundwater potential zones are characterized by comparably higher groundwater discharge except at location 1 (0.33 l/s), while the moderate and poor groundwater potential zones have very less discharge. The major rock type in these areas is garnet-biotite gneiss except at location 2, where calc-granulite and quartz feldspathic veins cross through the area. Due to the high weathering and the abundance of secondary fractures, the quartzo-feldspathic veins may act as aquifers, allowing higher discharge in wells at locations 2, 5, and 6. The deeper and longer groundwater flow paths and high groundwater discharge in weathered or fractured formations in hard rock aquifers were also reported by (Comte et al., 2019; Mpofo et al., 2020; Patiño-Rojas et al., 2021).

Parameters of groundwater quality zonation

The groundwater quality zones in KRB were delineated by considering different hydrogeochemical parameters, which include pH, EC, and the concentrations, occurrence, and distributions of Cl^- , Fe^{2+} , and Al^- in KRB and are detailed in the following subheads.

pH

The pH of the groundwater in KRB varies from 3.66 to 7.49. Based on the pH of groundwater, KRB has been divided into areas with highly acidic (<4.5),

Table 1 Location-wise groundwater discharge and predicted groundwater potential

Well locations	Discharge (l/s)	Groundwater potential
1	0.33	High
2	15.2	High
3	0.33	Moderate
4	0	Poor
5	4.5	Very high
6	11.04	Very high

moderately acidic (4.5 to 5.5), slightly acidic (5.5 to 6.5), and slightly acidic to slightly basic (>6.5) waters, and the spatial distribution of these categories is shown in Fig. 6a. Groundwater near the Kallada River mouth is characterized by comparatively higher pH due to the mixing of colloidal particles in river mouth with the seawater and the subsequent reduction in the acidity of water in the nearby vicinity (Chithra et al., 2022). Extremely high and low pH may harm human consumption (Ricolfi et al., 2020). Groundwater with a pH close to “7” is considered better for drinking, and hence, a higher rank is assigned to the “slightly acidic to slightly basic” category in the AHP analysis (Nguyen et al., 2021).

Electrical conductivity (EC)

The EC of groundwater in KRB varies from 41 to 851 $\mu\text{S}/\text{cm}$, and the spatial variation of EC is shown in Fig. 6b. Based on the EC of groundwater, KRB has been divided into class 1 with $\text{EC} < 100 \mu\text{S}/\text{cm}$, class 2 with EC between 100 and 200 $\mu\text{S}/\text{cm}$, class 3 with EC between 200 and 300 $\mu\text{S}/\text{cm}$, class 4 with EC between 300 and 400 $\mu\text{S}/\text{cm}$, class 5 with EC between 400 and 500 $\mu\text{S}/\text{cm}$, class 6 with EC between 500 and 600 $\mu\text{S}/\text{cm}$, and class 7 with $\text{EC} > 600 \mu\text{S}/\text{cm}$. The majority of the central and eastern parts of KRB are characterized by comparatively lower EC values (<300 $\mu\text{S}/\text{cm}$), whereas the western parts, towards the coastal areas, are characterized by higher EC (>500). The spatial variation of EC suggests the occurrence of distinct hydrogeochemical processes in the basin. Crystalline rocks on the eastern parts of the basin favor lesser dissolution, while the western parts favor the mixing of groundwater with lake water/seawater, which is also reported by Chithra et al. (2022).

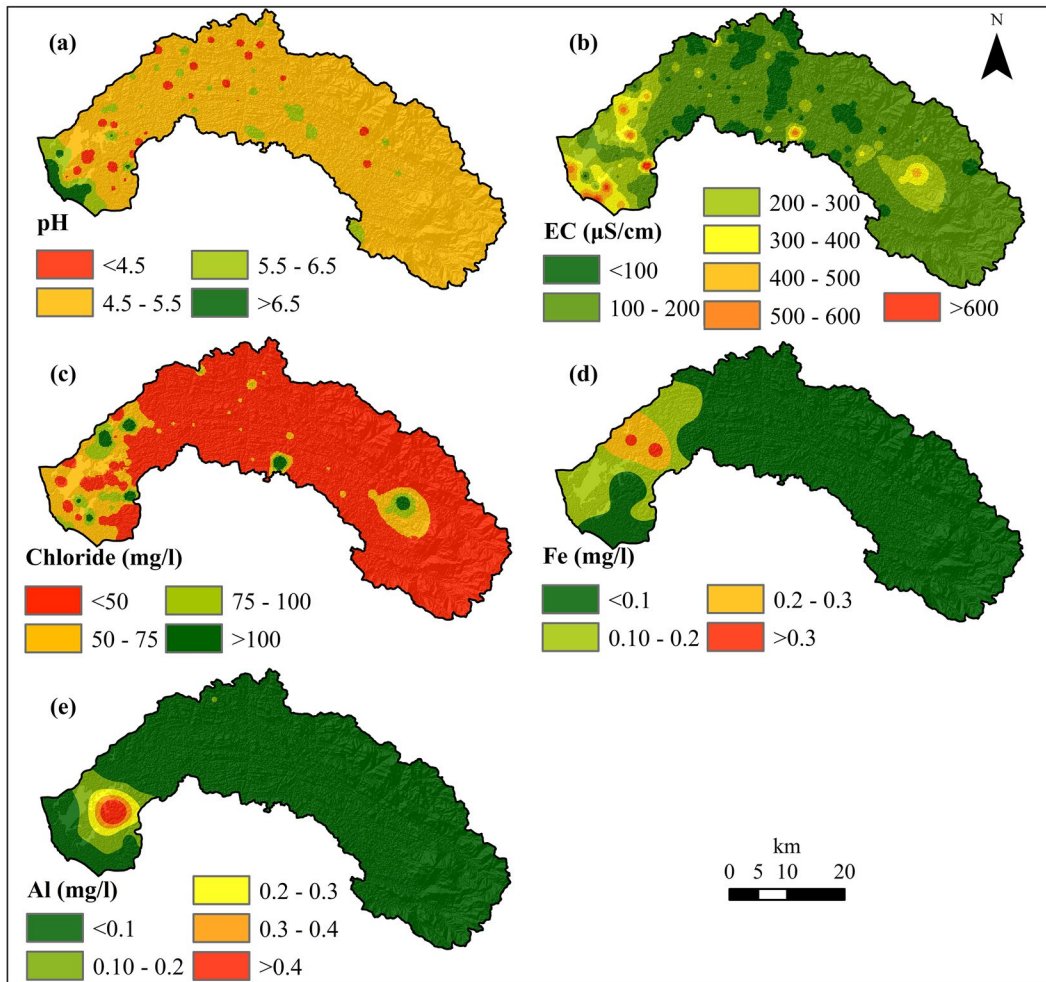


Fig. 6 Thematic maps of the distribution of different subcategories of groundwater quality parameters such as **a** pH, **b** EC, **c** Cl, **d** Fe, and **e** Al

As groundwater with EC permissible for drinking purposes is less in the area, “class 1” is assigned the highest rank in the AHP analysis.

Chloride

Natural and anthropogenic sources, including chemical fertilizers, landfill leachates, irrigation drainage, and seawater intrusion, mainly influence the chloride concentration in groundwater along coastal areas. The chloride concentration in KRB varies from 7.1 to 204 mg/l. Its spatial variation is shown in Fig. 6c. Based on this, the basin is classified into areas with very low ($Cl^- < 50$ mg/l), low (50–75 mg/l), moderate (75–100 mg/l), and high ($Cl^- > 100$ mg/l)

Cl^- concentration as shown in Fig. 5c. Majority of the central and eastern parts of KRB are characterized by groundwater with very less chloride concentration. In contrast, groundwater towards the western parts, in and around the river mouth, falls under the moderate to high category due to the mixing of lake water/ seawater (Chithra et al., 2022). As the desired chloride concentration for drinking purposes is less as per the drinking water standards, a higher rank is given to the “very low” category.

Iron

Concentrations of iron in groundwater in the basin vary from 0.018 to 0.33 mg/l, and its spatial map is

shown in Fig. 6d. Based on this, KRB has been classified into areas with very low ($\text{Fe}^{3+} < 0.1$ mg/l), low (0.1–0.2 mg/l), moderate (0.2–0.3 mg/l), and high ($\text{Fe}^{3+} > 0.3$ mg/l) iron concentrations in groundwater. Groundwater under the “high” category is mainly distributed over the central west portion of the basin, towards the river mouth. Though the concentrations of Fe^{3+} in groundwater are mostly below the permissible limits within the basin, Fe^{3+} is given weightage, as iron is a major geogenic pollutant in Kerala, mainly leaching from the lateritic soil, which functions as a cap formation covering numerous crystalline rocks, particularly in the midlands. The areas with high leaching capabilities are not suitable for implementing conventional aquifer recharge methods except for direct well recharging. These adverse impacts of the interaction between formation materials and infiltrating water on the hydrochemistry of the area need to be considered during groundwater management as most of the recharge structures site-specific (Raicy & Elango, 2020).

Aluminium

Aluminium in groundwater is mainly derived from the weathering of rock-forming minerals such as feldspars, anorthite, albite, mica, and bauxite and is also leached to groundwater from laterites. Aluminium concentrations in groundwater in the basin vary from 0.013 to 0.61 mg/l. Based on the aluminium concentrations in groundwater, the basin is classified into areas with very low ($\text{Al}^{3+} < 0.1$ mg/l), low (0.1–0.2 mg/l), moderate (0.2–0.3 mg/l), high (0.3–0.4 mg/l), and very high ($\text{Al}^{3+} > 0.4$ mg/l) concentrations of aluminium in groundwater. The spatial distribution of these five classes in KRB is shown in Fig. 6e. The “very high” category is distributed in the central west portion of the area, near the river mouth. The consumption of groundwater with high concentrations of aluminium may cause neurological hazards and disorders in humans (Wang et al., 2016); lower ranks were assigned to the “very high” category in the AHP analysis.

Relative importance of variables and groundwater quality zonation

The groundwater quality zones were delineated by generating the AHP matrix using the above groundwater quality parameters, as shown in Table 2. Among the five groundwater quality parameters, the

highest rating is assigned to pH (0.3600), followed by the same rating given to (0.2190) EC and Cl^- , while lower ratings are assigned to trace elements such as Fe^{3+} (0.1229) and Al^{3+} (0.0792).

Further, the sub-classes of hydrogeochemical parameters were given weightages as part of the delineation of groundwater quality zones, and the details are given in supplementary Table 2. The groundwater falling under the $\text{pH} > 6.5$ category is assigned relatively higher weightage (0.4402) and that falling under the $\text{pH} < 4.5$ category is given the lowest rating (0.0791). Similarly, groundwater with $\text{EC} < 100$ is assigned the highest weightages (0.3501) and that with $\text{EC} > 600$ is assigned the lowest rating (0.0247). Also, a higher rating is given to $\text{Cl}^- < 50$ category of groundwater samples (0.4832) and a lower rating to $\text{Cl}^- > 100$ category (0.0882). Among the trace minerals, higher ratings were given to areas with $\text{Fe}^{3+} < 0.1$ (0.4668) and $\text{Al}^{3+} < 0.10$ category zones (0.2835), whereas lower ratings were given to $\text{Fe}^{3+} > 0.30$ category zones (0.0953) and areas with $\text{Al}^{3+} < 0.6$ (0.0435).

Furthermore, the groundwater quality zonation maps were generated using the weights derived through the AHP method (Fig. 7). The basin is categorized into different groundwater quality zones based on a natural junk classification scheme and is demarcated in the groundwater quality zonation map as shown in Fig. 7. The major categories include excellent, good, moderate, and poor, occupying 26.82%, 66%, 2.32%, and 4.71% of the total area of the basin. Poor groundwater quality zones characterize the western coastal zones in the basin, while the eastern parts are mostly characterized by “good” water quality zones. Similarly, the central and west central areas are mainly characterized by “excellent” water quality, while the areas between the poor and excellent water quality zones constitute groundwater with moderate quality.

The regional groundwater quality of an area is influenced by several factors, including topography, slope, geology, and land use. The relation between these parameters and the type of groundwater quality zones of the area was analyzed to understand the influence of each factor on groundwater quality. Figure 8 demonstrates that the geology of KRB has less impact on the overall groundwater quality of the basin, as the various groundwater quality zones are evenly dispersed among diverse rock types.

However, the sandy and silty formations occupy most areas of the “poor” groundwater quality zones, especially along the coastal zones in the western parts of KRB (Fig. 4f), which could have resulted from the prevailing estuarine environment, as well as the urban settlements and domestic wastes in the coastal zones.

Similarly, the types of groundwater quality zones were relatively compared with the slope of the terrain to provide a clear understanding of the control of slope on groundwater recharge mechanisms, which is shown in Fig. 9. The volume of recharge induced by the high rainfall is large and is often accelerated by the flat/gentle sloping topography of

Table 2 AHP matrix used for the delineation of groundwater quality zones

Themes	Feature class	[1]	[2]	[3]	[4]	[5]	[6]	[7]	Normalized eigenvector
pH	> 6.5	1							0.44
	6.5–5.5	1/2	1						0.35
	5.5–4.5	1/3	1/4	1					0.13
	< 4.5	1/4	1/5	1/2	1				0.08
	CR: 0.056								
EC (µS/cm)	< 100	1							0.35
	100–200	1/2	1						0.24
	200–300	1/3	1/2	1					0.20
	300–400	1/4	1/3	1/3	1				0.09
	400–500	1/6	1/5	1/5	1/2	1			0.06
	500–600	1/7	1/6	1/7	1/3	1/2	1		0.04
	> 600	1/8	1/7	1/8	1/4	1/4	1/2	1	0.02
		CR: 0.040							
Cl⁻ (mg/l)	< 50	1							0.48
	50–75	1/2	1						0.27
	75–100	1/3	1/2	1					0.16
	> 100	1/5	1/3	1/2	1				0.09
	CR: 0.006								
Fe³⁺ (mg/l)	< 0.10	1							0.47
	0.10–0.20	1/2	1						0.28
	0.20–0.30	1/3	1/2	1					0.16
	> 0.30	1/4	1/3	1/2	1				0.10
	CR: 0.013								
Al³⁺ (mg/l)	< 0.10	1							0.28
	0.10–0.20	1/2	1						0.22
	0.20–0.40	1/3	1/2	1					0.18
	0.40–0.60	1/4	1/3	1/2	1				0.09
	> 0.60	1/5	1/4	1/3	1/2	1			0.07
	CR: 0.035								
Themes	pH	1							0.36
	Ec (µS/cm)	1/2	1						0.22
	Cl ⁻ (mg/l)	1/2	1	1					0.22
	Fe ³⁺ (mg/l)	1/3	1/2	1/2	1				0.12
	Al ³⁺ (mg/l)	1/3	1/3	1/3	1/2	1			0.07
		CR: 0.017							

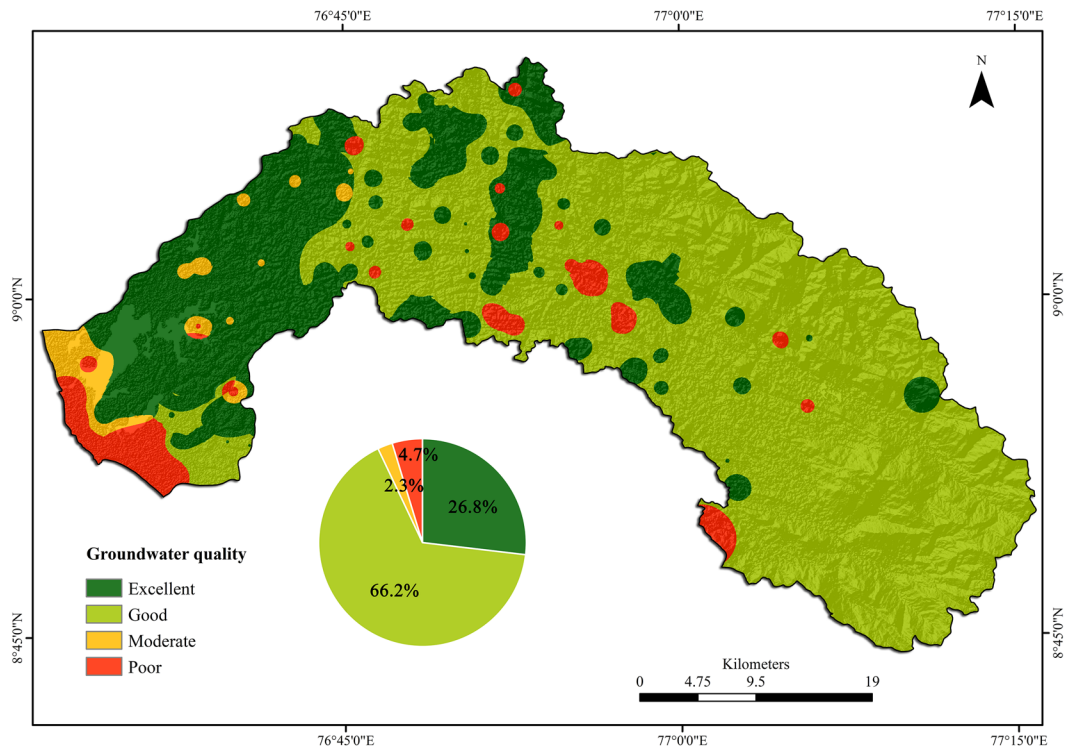


Fig. 7 Groundwater quality zones of KRB

the area which ultimately impacts the groundwater quality of the basin.

Integrated groundwater potential-quality zonation

The groundwater potential zones and the groundwater quality zones were integrated to generate the groundwater potential-quality zones of KRB, and the map is shown in Fig. 10. Based on the proportions of groundwater potential and quality, the basin is categorized into 16 classes. The “poor groundwater potential with good groundwater quality” class occupies the majority of the river basin, especially towards the central and eastern regions, while the “poor groundwater potential with moderate groundwater quality” class occupies the least area of the basin. Similarly, the “very high groundwater potential with excellent groundwater quality” class occupies nearly 204 km² and is mainly distributed in the west-central parts, a few kilometers east of the coastline. The coastal zones are mainly characterized by the “moderate groundwater potential with moderate to poor groundwater quality” class. The areas occupying moderate groundwater potential

with moderate groundwater quality to poor groundwater potential with poor groundwater quality categories

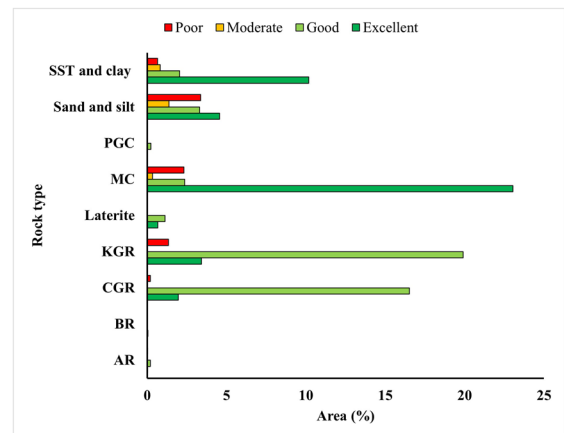


Fig. 8 The areas of groundwater quality zones in different geological formations such as sandstone, peninsular gneissic complex, migmatitic complex, khondalite group of rocks, charnockitic group of rocks, basic rocks, and acidic rocks, represented by SST, PGC, MC, KGR, CGR, BR, and AR, respectively

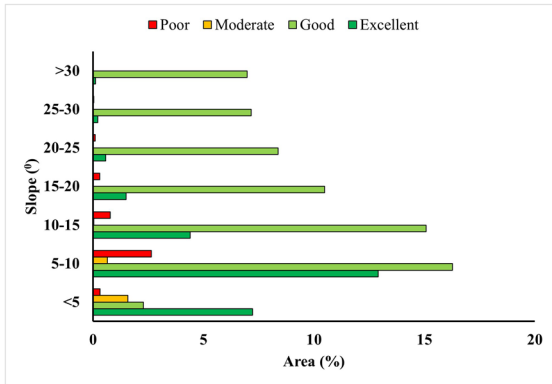


Fig. 9 The slopes and areas of respective groundwater quality zones

cover an area of 868 km², where groundwater management is necessary for the sustainable development of groundwater resources. Hence, suitable management strategies were proposed to develop the groundwater resources of the area both quantitatively and qualitatively. The proposed areas for groundwater management in KRB are shown in Fig. 11.

Groundwater management in KRB

The selection of suitable groundwater management methods and the sites of their implementation need detailed preliminary investigations as these methods are highly site-specific (Dillon, 2005). For

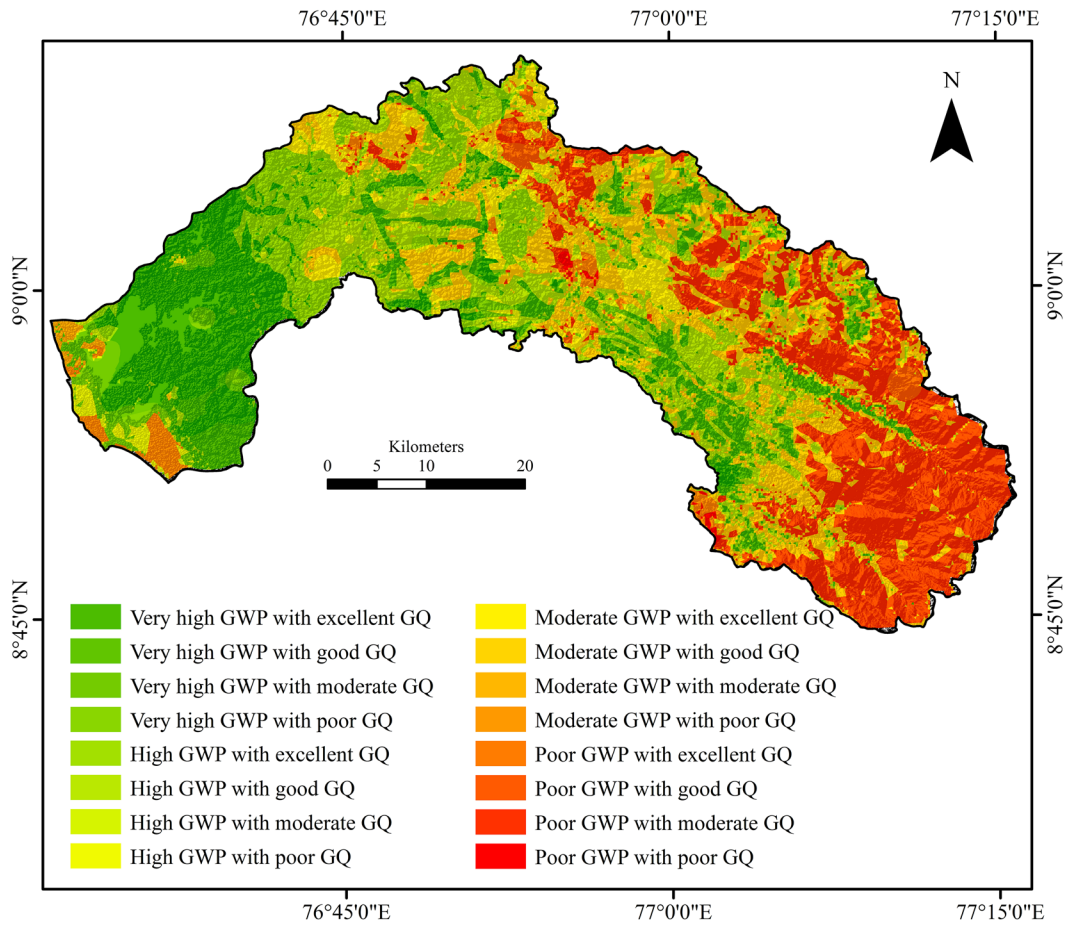


Fig. 10 Integrated groundwater potential-quality map representing the combination of different categories of groundwater potential and groundwater quality

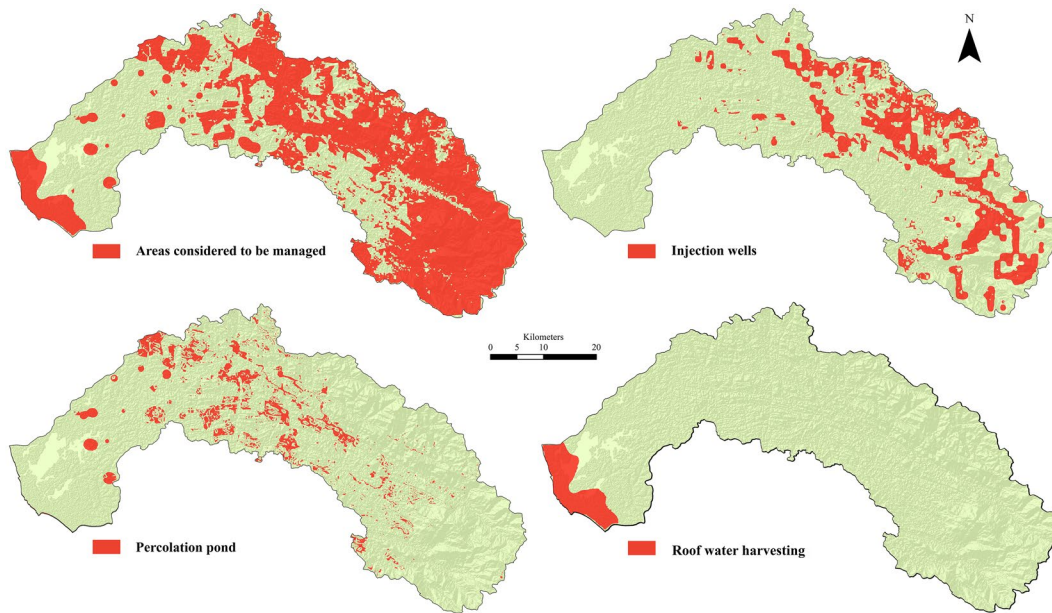


Fig. 11 The areas proposed for groundwater management in KRB and those for effective implementation of injection wells, percolation ponds, and roof water harvesting

example, the areas with high lineament density are best suitable for the implementation of injection wells, which can bypass the upper impermeable strata and directly recharge the excess water into the aquifers. These structures are often constructed in deep groundwater, and the overlying targeted aquifers are characterized by less permeable formations (Achu et al., 2020b). Similarly, recharge pits are effective at the intersections of lineaments and at zones with distinct lineament features (CGWB, 2007). Moreover, aquifers in areas with low drainage density and gentle slopes (from 0 to 5°) can also be replenished effectively using percolation ponds by collecting the surface runoff from the surrounding area (CGWB, 2007). In contrast, regions with high drainage are best suitable for implementing rainwater harvesting structures (Mugo & Odera, 2019). Based on these criteria, the areas suitable for the construction of injection wells, percolation ponds, and rainwater harvesting in KRB were delineated, and the maps are shown in Fig. 11. The percolation ponds are suitable recharge method in the central parts of the basin while injection wells are suitable in the eastern parts of the basin. However, recharge structures are not advisable along coastal areas due to the shallow groundwater levels,

where roof water harvesting methods are best suitable to conserve rainwater.

Conclusion

In the present study, an integrated groundwater potential-groundwater quality analysis is carried out in the Kallada River basin to demarcate areas where groundwater management is necessary for sustainable development and to locate suitable sites to effectively implement the site-specific recharge structures. The groundwater potential zones and groundwater quality zones were delineated using GIS techniques and the AHP method by considering eight geo-environmental factors viz., relative relief, land use/land cover, drainage density, slope angle, geomorphology, geology, lineament density, and groundwater level fluctuation and five hydrogeochemical parameters viz., pH, EC, and the concentrations of Cl^- , Fe^{3+} , and Al^{3+} . Based on the groundwater potential zonation, very high groundwater potential zones occupy most of the basin, covering an area of 425.2 km², followed consecutively by high, moderate, and poor groundwater potential zones covering areas of 400 km², 395.5 km², and 394.7 km², respectively. The areas falling

under the high groundwater potential category are mostly located in the lower catchments, while areas falling under the poor groundwater potential category are distributed in the eastern parts of the basin. The groundwater quality zonation of KRB shows that the majority of the basin is occupied by good groundwater quality zones, accounting for 66% of the total area of the basin, followed by excellent, poor, and moderate groundwater quality zones, respectively, covering 26.82%, 4.71%, and 2.32% of the total area of the basin areas. The slope of the terrain is the dominant controlling factor of groundwater potential and groundwater quality of KRB. Based on the integrated groundwater potential-quality zonation, areas with moderate groundwater potential and moderate to poor groundwater quality dominate the basin and cover an 868 km². This category is the most suitable area for constructing site-specific groundwater management structures. The central and eastern parts were found to be suitable for constructing percolation ponds and injection wells, respectively, for achieving maximum performance of the structure. Also, coastal areas are found to be unsuitable for the implementation of recharge structures due to shallow groundwater levels. This integrated approach, considering the groundwater potential and quality, helps policymakers develop and implement the most suitable management strategies with maximum performance. It can also be applied for similar geo-environmental and hydrogeochemical conditions to demarcate the areas where groundwater recharge is essential for sustainable water resource development.

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Author contribution Aju C D: conceptualization, methodology, data analysis, and manuscript writing; A L Achu: methodology, data analysis, and manuscript writing; Pranav Prakash: data analysis; Rajesh Reghunath: manuscript correction and reviewing; Raicy M C: manuscript correction and reviewing.

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Availability of data and materials Data will be available upon a direct request to corresponding author.

Declarations

Competing interests The authors declare no competing interests.

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