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Characterization of Groundwater Potential Zones from a Tropical River Basin, Southern Western Ghats, India

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Abstract

The increasing demands for groundwater resources and marked changes in climate over the years have imposed immense pressure on global groundwater resources. The present study has been undertaken to emphasize the expediency of remote sensing and geographic information system (GIS) to delineate the groundwater potential of a small tropical river basin of Kerala (India), *viz.*, Thuthapuzha River Basin. A total of 10 geo-environmental thematic layers such as Geology, Geomorphology, Drainage density, Rainfall, Soil, Slope, Topographic Position Index, Groundwater level and Curvature were prepared and studied for groundwater potential zone demarcation. Weights assigned to each class in all the thematic maps are based on their characteristics and water potential capacity through Weighed overlay method (WoM). The groundwater potential zone map subsequently obtained was classified into five classes-very high, high, moderate, low and very low. The study reveals that about 63% of the river basin is covered under a moderate groundwater potential zone. The low and high groundwater potential zones are observed at 27% and 9%, respectively. The area under very high and very low potential zones is recorded only in very limited areas (>1%) in the basin.

Keywords: Groundwater Potential Zone; Weighed Overlay Method (WoM); GIS; Thuthapuzha River; Kerala

Introduction

Groundwater is a vital natural resource that is stored in the subsurface geological formations of the earth's crust and supports human health, economic development and ecological diversity. Its occurrence, origin and movement depend on the geologic framework, such as lithology, thickness, structures and permeability of aquifers. It serves as a source of water for water supply, drinking, agricultural purposes and other developmental initiatives (Nampak *et al.,* 2014). Groundwater is a limited freshwater resource, and its distribution and occurrence are determined by anthropogenic and natural factors. It is essential for the ecosystem (Haihyvanshi, 2023; Oh *et al.,* 2011).

Groundwater serves as the major source of fresh water in most parts of the world with India being the largest user, with an annual consumption of 230 km^3 (*i.e.*, a quarter of global use) according to the world bank poverty report (http://www.worldbank.org). India is grouped under the water stress condition' by the Food and Agriculture Organization of the United Nations (AQUASTAT-FAO, 2013). This highlights the need for a better understanding of all available freshwater resources, particularly groundwater resources, as they constitute a major share of India's freshwater resources.

The groundwater development in the country is substantially less, compared to recharge, which is exemplified by the 1034 'over-exploited' blocks (*i.e.,* 15% of the total units), 253 'critical' units (4%), 681 'semi-critical' units (10%), and 96 'completely saline' units (1.5%) of the country based on the report by CGWB (Central Ground Water Board, 2017). Kerala has abundant rainfall and natural water sources but has the lowest per capita share of freshwater resources in India. This is due to the peculiar nature of the topography, which leads to increased surface runoff and low infiltration rate, leading to water scarcity. The Ministry of Environment and Forests, Government of India, predicted a decrease in water yield by up to 10% by 2030 due to climate change (Indian Network for Climate Change Assessment - INCCA).

The traditional approaches to delineating and mapping the groundwater potential zones are based on geophysical, geological and hydrogeological tools which are generally expensive and time-consuming (Asoka *et al.,* 2018; Mukherjee *et al.,* 2018; Senanayake *et al.,* 2016; Singh *et al.,* 2013). Geospatial tools are rapid and cost-effective in producing and modelling valuable data in geosciences (Adiat *et al.,* 2012; Moghaddam *et al.,* 2015; Oh *et al.,* 2011). Among the different methods, remote sensing and GIS constitute powerful tools that can be used for the fast assessment of natural resources. The method is cost-effective and can effectively be used for groundwater exploration (Bhatnagar *et al.,* 2023; Jha *et al.,* 2007) before going for expensive surveying techniques. A few studies have already been carried out on this perspective which reiterates the use of remote sensing and geographical information system (GIS) techniques for mapping groundwater potential zones in different parts of the earth (Venuprasad *et al.,* 2022; Yeh *et al.,* 2009).

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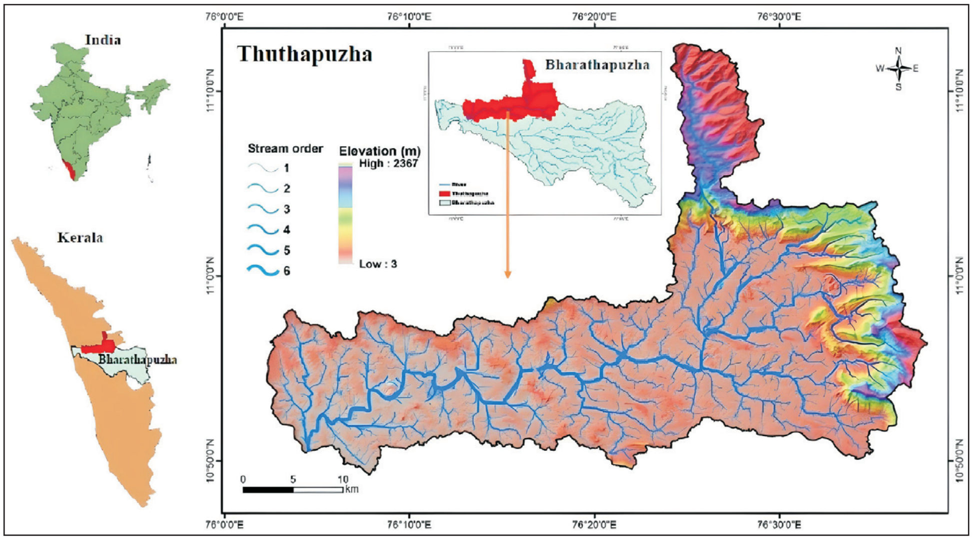

Fig. 1. Drainage and location map of the Thuthapuzha River Basin

In the present study, of several methods available for determining interclass/Intermap dependency, a probability-weighted approach has been adopted that permits a linear combination of probability weights of each thematic map (Wt) and different categories of derived thematic maps have been assigned scores (Wi), based on their capacity to hold groundwater (Arulbalaji *et al.,* 2019). The spatial analyst extension of Arc GIS 10.2 was used for converting the features to raster and also for the final analysis. In this method, the total weights of the final integrated map were derived as the sum or product of the weights assigned to the different layers according to their suitability. The Thuthapuzha River basin is a small catchment river basin from the Southern Western Ghats in India. It provides freshwater to many developmental centres in the Malappuram and Palakkad districts of Kerala and is the lifeline of a large agriculture-dependent population (Manjula and Warrier, 2019). The people in the area are heavily dependent on groundwater resources for their domestic and agricultural/horticultural requirements. The main objective of the study is to delineate, identify and map the groundwater potential zone of the Thuthapuzha River Basin as an example of sustainable water resource development and planning.

Study area

The present study has been conducted in a small, tropical river basin that spread in one of the densely populated areas on the western flank of Southern Western Ghats (Fig.1). This area faces rapid growth in population and economic development according to the census report 2011 by the Government of India. Thuthapuzha River located within the Malappuram and Palakkad districts of Kerala is a west-flowing river system, and it is experiencing a humid and tropical climate. The river has a length of 63 km and a basin area of 1107 km^2. Thuthapuha is a sub-basin of the second largest river basin of Kerala, *i.e.* Barathapuzha River (Manjula and Warrier, 2019). Thuthapuzha has four tributaries draining into it, namely Kuntipuzha, Nellipuzha, Kanhirapuzha and Thuppanadpuzha. The reservoir is built across Kanhirapuzha and serves as a source of water for irrigation. The river is in the sixth order and exhibits a dendritic drainage pattern. The average annual discharge is 1750 MCM (Manjula and Warrier, 2019) and the Silent Valley Reserve Forest is located at the north-eastern corner of the basin. The annual rainfall ranges from 1526 to 3102 mm, which is higher than the average annual rainfall (1822 mm) of the entire Bharathapuzha River Basin and the average annual rainfall (2817 mm) of Kerala state.

Methodology

Geospatial techniques were applied in this paper to delineate the groundwater potential zones of the Thuthapuzha river basin using knowledge-based factor analysis of a total of 10 layers of information of the area such as geology, geomorphology, drainage density, lineaments, rainfall, soil, roughness, slope, curvature groundwater level and topographic position index (TPI) (Table 1). The ASTER-DEM 30-meter resolution data from the United States Geological Survey (USGS) were used to delineate the Thuthapuzha river basin boundary (Oh *et al.,* 2011) with the support of a hydrology tool in Arc GIS software of version 10.2. The Indian Remote Sensing Linear Imaging Self Scanning Sensor 3 (IRS LISS-III) (24-meter spatial resolution) geo-coded false-color composite satellite data were used (Arunbose *et al.,* 2021; Aykut, 2021; Githinji *et al.,* 2022) for the preparation of geomorphology. The visual interpretation techniques were employed to define the geomorphology map using satellite data developed using GIS software (National Remote Sensing Agency, 2005). The published map of geology and soil atlas were collected and digitized from the Geological Survey of India (GSI) and the National Bureau of Soil Survey, respectively. The slope, curvature and roughness were generated from (Shuttle Radar Topography Mission) SRTM data (Chandrasekar and Prince, 2012; Kumar *et al.,* 2016). For the study, rainfall data were obtained from Indian Meteorological Department (https://mausam.imd.gov.in/imd_latest/contents/index_rainfall_state_new.php). An inverse distance weighted (IDW) interpolation tool was used for generating the spatial distribution of rainfall and groundwater levels (Nair *et al.,* 2017; Palanisamy, 2016). Based on automatic extraction methods, Drainage and lineaments were extracted from SRTM and IRS LISS-III data respectively. From the drainage data, the density was prepared using line density in the spatial analyst tool in GIS software. For the study, the topographic wetness index (TWI) was prepared based on the "TOPMODEL"

Table 1: Categorization of factors influencing the Groundwater Potential Zones

Factor	Assigned weight	Domain of effect	Rank
Geology (GG)	8	Basic Rocks	3
		Charnockite group of rocks	3
		High-grade metasedimentary rocks	4
		Khondalite group of rocks	4
		Laterite	7
		Migmatite Complex	4
		Pegmatite/Aplite/Quartz vein	5
		Peninsular gneissic complex	3
		Sand and Silt	8
Geomorphology (GM)	7	Denudational hills	3
		Denudational structural hills	2
		Flood Plain	7
		Valley	8
		Piedmont zone	5
		Lateritic Plateau	5
		Residual hill	4
		Rock exposure	2
		Structural hills	2
		Water bodies	9
LULC	7	Agriculture plantation	5
		Barren rock	2
		Built-up (cities/towns/villages)	2
		Agriculture land	6
		Deciduous forest	4
		Evergreen forest	7
		Forest plantations	5
		Grassland	4
		Land with scrub	4
		Marshy/Swampy	8
		River/ Water bodies	9
		Land without scrub	4
Soil	6	1	8
		2 (Refer to Table 2 for details)	7
		3	7
		4	8
		5	6
		6	4
		7	3
		8	2
Drainage Density	4	Very Low (0.159-4.62)	8
		Low (4.62-7.21)	6
		Moderate (7.21-9.58)	4
		High (9.58-12.24)	3
		Very High (12.24-18.5)	2
Slope	5	Flat (0-6.6)	8
		Gentle (6.6-13.5)	6
		Moderate (13.5-22.7)	4
		Steep (22.7-34.5)	3
		Very Steep (34.5-73.4)	2
Rainfall	5	1526-1842	2
		1842-2157	3
		2157-2472	4
		2472-2787	5
		2787-3102	6
Groundwater Level	5	2.4-6.5	8
		6.5-13.5	6
		13.5-22.7	4
		22.7-34.5	3
		34.5-73.4	2
TPI	3	(-)210.7- (-)36.6	6
		(-)36.6- (-)4.25	5
		(-)4.25-26.1	4
		26.1-78.7	3
		78.7-305.4	2
Curvature	3	(-) 23.3 - (-) 1.9	2
		(-) 1.9 - (-) 0.76	3
		(-) 0.76 - 0.24	4
		0.24 -1.74	5
		1.74 - 19.3	6

index (Nagarajan and Singh, 2009). The topographic position index (TPI) was prepared based on the Jenness algorithm (Jenness, 2006). For the study, groundwater levels were obtained from India Water Resources Information System (https://indiawris.gov.in/wris/#/groundwater). The Ground Water Potential Zone (GWPZ) of Thuthapuzha was generated by integrating all ten layers using the weighted overlay analysis method in the GIS platform. The thematic maps of all these layers were reclassified using the natural breaks classification method. Each thematic map was assigned a rank depending on its influence on the groundwater development on a total scale of 100 and different features of each layer were assigned weightage on a scale of 0 to 9 (Kumar *et al.,* 2016). The final GWPZ was classified into very low, low, moderate, high and very high parameters (Arulbalaji *et al.,* 2019; Palanisamy, 2016).

Results and Discussion

Geology

Geology plays a vital role in the occurrence and distribution of groundwater (Yeh *et al.,* 2009). The published geology map of the study area from the (DRM, 1995) was used for delineating nine geological units. The major portion of the basin is covered by a charnockite group of rocks and migmatite complex (441 and 437 km^2, respectively) followed by basic rocks of 108 km^2, peninsular gneissic complex for 103 km^2, sand and silt (sedimentary deposits) 9.9 km^2, high-grade metasedimentary rocks for 6.8 km^2 and Khondalite Group of rocks for 1.9 km^2. Unconsolidated sedimentary and fractured granitoid rocks were more favourable for groundwater movement and accumulation than massive rocks (Guru *et al.,* 2017). The region structurally composed of Precambrian - Charnokite, hornblende biotite gneiss, garnet biotite gneiss, are the hard rock present as the base. Geologically more favourable groundwater prominence in the study area is sand, silt, and laterite. The characteristics of rocks, origin and occurrence, and weathering are taken into account when assigning weight. High weight is assigned for sedimentary formation, low weight for basic rocks, charnockite group, high-grade for the metasedimentary rocks, khondalite group, migmatite complex, and peninsular gneiss. Pegmatite/ Aplite/ Quartz vein and laterite formations are very rare in the study area.

Geomorphology

Geomorphology gives information about the distribution of various landform features as well as processes like temperature changes, geochemical reactions, movement of water, freezing and thawing and so on (Thapa *et al.,* 2017). The geomorphic features of the study area are denudational hills (5 km^2), denudational structural hills (270 km^2), flood plain (7 km^2), valleys (170 km^2), piedmont zone (314 km^2), plateau (320 km^2), residual hill (5 km^2), rock exposure (2 km^2), structural hills (7 km^2) and water bodies (9 km^2). The valley and Piedmont zone areas are associated with agricultural land, which has a good to moderate GWPZ (Thapa *et al.,* 2017). The high weights were assigned for valleys, water bodies, flood plain and the Piedmont zone followed by denudational hills and structural hills.

Drainage Density

The drainage networks depend on the lithology and it provides an index of the infiltration rate. Drainage density is an inverse function of permeability, so it is an important parameter in evaluating the GWPZ (Nair *et al.,* 2017). Drainage density is the total length of all the rivers in a drainage basin divided by the total area of the drainage basin (Yeh *et al.,* 2009). Low drainage density offers more groundwater potential than high drainage density, as it has a higher infiltration rate. The drainage density was reclassified and categorized into five classes such as very low (0.159-4.62 km/km^2), low (4.62-7.21 km/km^2), moderate (7.21 -9.58 km/km^2), High (9.58-12.24 km/km^2) and Very high (12.24-18.50 km/km^2). For groundwater, potential zonation high weightages were assigned for low density and low weightages were assigned for high density.

Slope

The slope of the surface is an important factor in determining the nature of geologic and geodynamic processes at a regional scale, such as surface runoff and infiltration (Thapa *et al.,* 2017). The slope gradient is directly involved in the infiltration of rainfall and larger slopes produce a smaller recharge because the water flows rapidly down a steep slope during rainfall, so it does not have sufficient time to infiltrate the surface and recharge the saturated zone (Yeh *et al.,* 2009). The slope values were reclassified and categorized into five classes such as flat (0 - 6.6), gentle (6.6 - 13.5), medium (13.5 - 22.7), steep (22.7 - 34.5) and very steep (34.5 - 73.4).

Soil

Soil types play an important role in the amount of water that can infiltrate into the subsurface formations and hence influence groundwater recharge (Ibrahim-Bathis and Ahmed, 2016). The soil texture and hydraulic characteristics are the main factors considered for the estimation of the rate of infiltration. The details of the soil categories identified in the basin as per the scheme of the National Bureau of Soil Survey (NBSS) and Land Use Planning (LUP), India are summarized in (Table 2).

Rainfall

The Thuthapuzha River receives the majority of its hydrological input from rainfall, which also has the greatest impact on the study area's groundwater. According to an analysis of rainfall data from 2016, the annual range ranged from 1526 to 3102 mm. The amount and length of rainfall have an impact on infiltration. Rainfall intensity and duration have an impact on infiltration, with heavy rain lasting just a short time (Ibrahim-Bathis and Ahmed, 2016).

Curvature is a quantitative expression of the nature of the surface profile and it can be concave upward or convex upward profiles (Nair *et al.,* 2017). Water slows down and accumulates in convex and concave profiles. Curvature ranges of the study area varied from (-) 23.3 to19.3 and were reclassified into five categories such as -23.3 to -1.9, -1.9 to -0.76, -0.76 to 0.24, 0.24 to 1.74 and 1.74 to 19.3. The highest weights are assigned for high curvature values and vice versa.

Topographic Position Index

The topographic position index (TPI) is an algorithm increasingly used to measure topographic slope positions and automate landform classifications (De Reu *et al.,* 2013). Many physical processes such as a hilltop, valley bottom, exposed ridges, flat plain, and upper and lower slope actions on the landscape are correlated with the topographic position index. TPI was calculated using the following formula:

$$\mathrm{TPI_i} = \mathrm{M_0} - \sum_{n-1} \mathrm{M_n}/n$$

Where Mo is the elevation of the model point under evaluation, Mn is the elevation of Grid, and n- is the total number of surrounding points employed in the evaluation (Jenness, 2006). TPI ranges varied from 305 to (-) 210.7 and was reclassified into five categories such as -210.7 to -36.6, -36.6 to -4.25, -4.25 to 26.1, 26.1 to 78.7 and 78.7 to 305.4. TPI values zero indicate the flat ground surface. The high weights are assigned for low TPI values and vice versa (Fig. 2).

Table 2: Soil type and characteristics of the Thuthapuzha River Basin

Index	Description	Type
1	Very deep, moderately well-drained, clayey soils with the moderately shallow water table in nearly level narrow valleys with slight erosion: associated with very deep imperfectly drained, clayey soils with moderately shallow water table or nearly level lands.	• Fine mixed, Typic dystropets • Fine mixed, Typic tropaquepts
2	Very deep, well-drained, gravelly clay soils with moderate surface gravelliness on moderately steeply sloping laterite mounds, with moderate erosion: associated with deep, well-drained gravelly clay soils on gentle slopes.	• Clayey - skeletal, kaolinitic, ustoxic humitropepts • Clayey- skeletal, Kalolinitic, ustic haplohumults
3	Deep, well-drained, gravelly clay soils with moderate surface gravelliness and ironstone layer at 100 to 150 cm on gently sloping midland laterites, with moderate erosion: associated with laterite outcrops.	• Clayey - skeletal, kaolinitic, ustic haplohumults • Ironstone
4	Very deep, imperfectly drained, loamy soils with the moderately shallow water table in nearly level broad valleys of Palghat Gap, with slight erosion: associated with moderately deep, well-drained gravelly loam soils with coherent materials at 75 to 100 cm on gentle slopes, moderately eroded.	• Fine - loamy, mixed, aquic ustropepts • Fine - loamy, mixed, typic, haplustalfs.
5	Very deep, well-drained, clayey soils on gently sloping low hills with isolated hillocks, with moderate erosion: associated with deep well-drained, gravelly clay soils on moderately steep slopes	• Fine, mixed, ustic humitropepts. • Clayey, mixed, ustic palehumlts
6	Very deep, well-drained, gravelly clay soils with strong surface gravelliness on moderately sloping medium hills with thin vegetation, with moderate erosion: associated with rock outcrops.	• Clayey, mixed, ustic palehumults • Rock land
7	Very deep, well-drained, clayey soils on moderately steeply sloping high hills with this vegetation with moderate erosion: associated with rock outcrops.	• Clayey mixed, ustic palehumults • Rock land
8	Moderately deep, well-drained, moderately calcareous, gravelly loam soils with moderate surface gravelliness on gently sloping foothills and valleys, with moderate erosion associated with moderately shallow, somewhat excessively drained, gravelly clay soils with strong surface gravelliness and coherent material at 50 to 75 cm on moderate slopes, severely eroded.	• Loamy-skeletal, mixed typic ustropepts • Clayey - skeletal, mixed, Typic ustropepts.

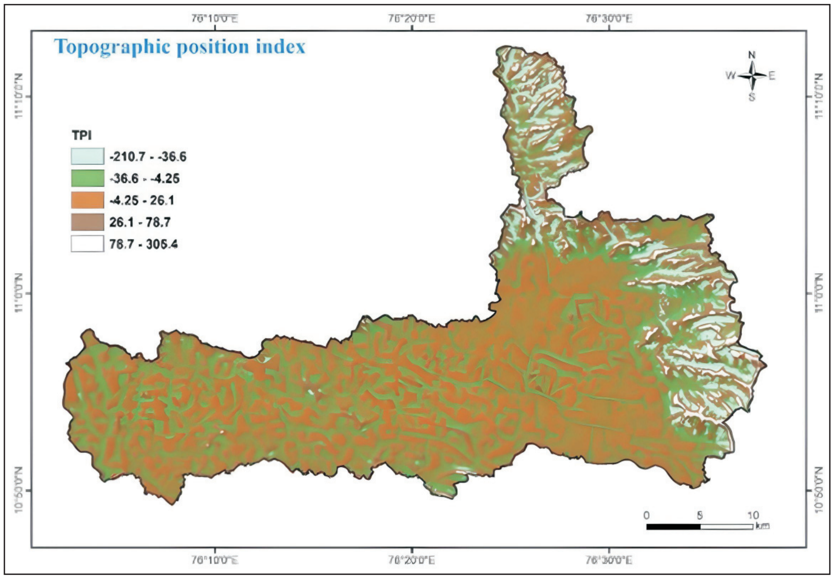

Fig. 2. Topographic position index map of the study area

Groundwater Level

Groundwater level indicates the elevation of the atmospheric pressure of the aquifer (Nair *et al.,* 2017). The groundwater level data of the observation wells of the year 2013 for local changes and 2017 data for the district reference (Central Ground Water Board, 2017)are used in this study.The groundwater fluctuation yielded the average annual groundwater recharge in Thuthapuzha varying from 2.4 to 23 m. These groundwater level values indicate the actual groundwater variations in different parts of the watershed. Based on these groundwater levels, the area can be divided into five zones: (i) 2.4 to 6.5 m; (ii) 6.5 to 10.6 m; (iii) 10.6 to 14.8 m; (iv) 14.8 to 18.9 m; and (v) 18.9 to 23m (Fig. 3).

Groundwater Potential Zones (GWPZ)

In the past 4 to 5 decades, the recharge of groundwater has been reduced due to numerous anthropogenic activities as well as skewed development (Arulbalaji *et al.,* 2019). The groundwater potential of the Thuthapuzha River Basin is essential for planning and sustainable development. It can be divided into hard rock aquifers, laterite aquifers and valley fills/alluvium, which are composed of sand, silt and clay in the coastal plains and valleys of the basin. This data is essential for corrective measures to improve groundwater recharge processes.Laterite is a potential aquifer in the basin, overlying both crystallines and Tertiary and Quaternary sediments. The groundwater availability is not uniform in space and time, so a detailed and accurate assessment is needed.

The parameters that are considered here are geology, geomorphology, lineament density, drainage density, soil, slope, rainfall, TPI, groundwater level, curvature and roughness. The weighted overlay method has been applied to generate the groundwater potential zones in the Thuthapuzha River basin. The resulting map is divided into very high, high, moderate, low and

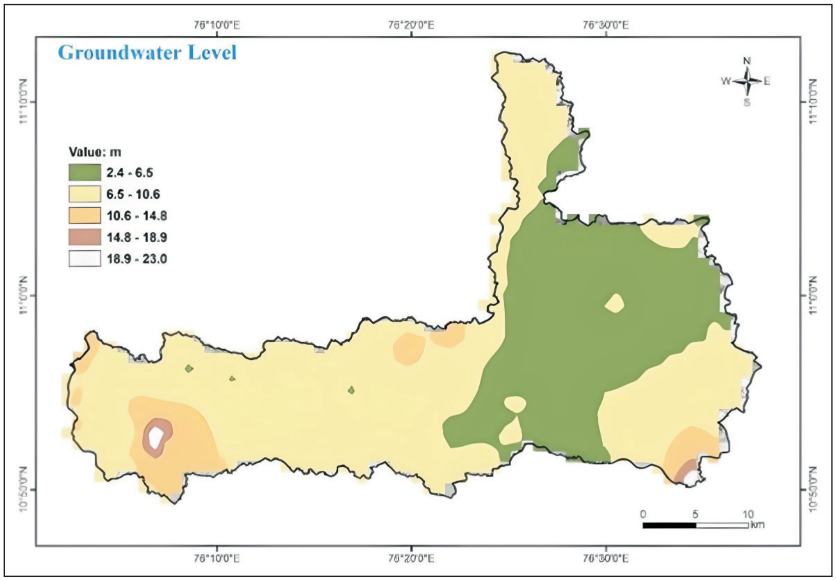

Fig. 3. Groundwater level map of the study area

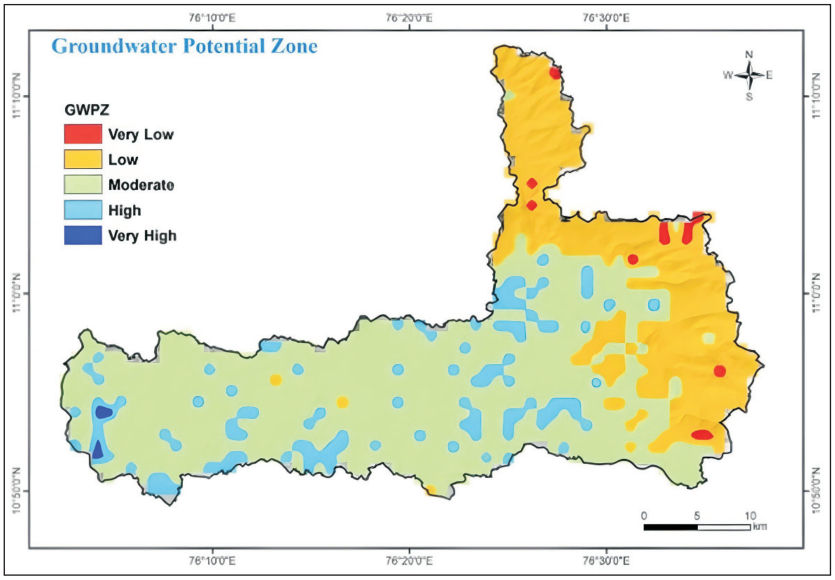

Fig. 4. Groundwater potential zone map of the study area

very low groundwater potential zones and the aerial spread of these categories are 5 km^2, 95m^2, 699m^2, 298 and 10 km^2, respectively (Fig. 4).

As seen from the figure, very high and high groundwater potential zones occur mainly in midland and lowland regions. Very high and high groundwater potential zones are confined generally to high rainfall regions which in turn have high infiltration potential. Substantially over the valleys and areas of high drainage density, moderate groundwater potential zones occur (Arulbalaji *et al.,* 2019). The low and very low groundwater potential zones occur in the denudational structural hills, migmatite complex, steep slope, high drainage density and reserved forests. The weighted overlay analysis using GIS that delineates the groundwater potential zones is a useful tool for river basin-based planning and development in tropical and sub-tropical regions with varied geoenvironmental settings.

Conclusions

The present study is an attempt to delineate the groundwater potential zones using the weighted overlay analysis method in the GIS platform by assigning weight to different classes in each theme depending on their relative contribution to groundwater potential in a small humid tropical river basin in South India - the Thuthapuzha River Basin, which is located in an elevated continental margin, mainly, in the western side of southern Western Ghats. A total of 10 thematic layers such as Geology, Geomorphology, Soil, Rainfall, Lineament Density, Drainage Density, Slope gradient, TPI, Roughness, groundwater level and Curvature were used in this study to delineate the groundwater potential zones. According to the final output map, the study area could be classified into five distinct groundwater potential zones such as very high, high, moderate, low and poor. Very high and high groundwater potential zones are predominantly located in the lower catchment as well as the middle reaches of the river basin. Low and very low groundwater potential zones are present in the migmatite complex formation of the river basin. A moderate groundwater potential zone spreads over the catchment area and covers 63% of the study area. High and low groundwater potential zones cover an area of 9% and 27%, respectively. Very high and very low groundwater potential zones in the study area together account for less than 1%. The GWPZ identified in the Thuthapuzha River Basin reveals that very high and high GWPZs cover only 9.5% of the watershed, which in turn reiterates the need for alternate water management strategies to meet the water requirements of the area. This research provides insight into the proper planning and management of groundwater in the urban and agricultural zones. Since, the study area is covered by agricultural land, this study will help to improve the irrigation facility and develop the agricultural productivity of the area.

Authors' Contributions

SS: Writing-Original Draft of Manuscript, Software Handling, Investigation. **AKS:** Methodology, Supervision and Reviewing. **SS:** Editing, Investigation and Reviewing.

Conflict of Interest

The authors declare that they have no competing interests.

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