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Fuzzy TOPSIS-based geospatial framework for delineating groundwater potential zones in the Pune metropolitan catchment, western India

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ABSTRACT

Rapid urban expansion and increasing water demand place significant pressure on groundwater resources in metropolitan river basins. Although GIS-based multi-criteria decision-making (MCDM) approaches are widely used for groundwater potential mapping, their application in rapidly urbanizing basins requires improved handling of uncertainty and integration of hydro geological and anthropogenic factors. The objective of this study was to develop and apply a GIS-based Fuzzy-TOPSIS framework to identify and classify groundwater potential zones (GWPZ) in the Mula–Mutha catchment, western India, and to evaluate whether such an approach can provide spatially consistent prioritization for groundwater development in an urbanized basin. Six controlling factors – runoff, soil, slope, land use/land cover, groundwater level, and lithology – were integrated into a fuzzy membership structure to address uncertainty in parameter standardization. The weighted criteria were then ranked using the TOPSIS method to generate a groundwater potential indicator and spatial classification map. The results delineated three groundwater potential categories: low (28%), moderate (41%), and high (31%). High-potential zones are primarily associated with permeable lithological formations, gentle slopes, and favourable soil conditions, whereas low-potential zones correspond to urbanized or steep areas with limited infiltration capacity. The study achieved its objective by producing a spatially differentiated and internally consistent groundwater potential map for the entire catchment. The Fuzzy-TOPSIS framework successfully integrated heterogeneous environmental variables and generated a reproducible decision-support tool suitable for groundwater resource planning in urbanized basins.

Keywords: GIS, sustainability, environmental conservation, water resource management, urban studies

INTRODUCTION

Groundwater is one of the nation's most essential natural resources. Water supply systems in rapidly urbanising regions are increasingly strained by extreme weather events, demographic growth, and intensified domestic, industrial, and agricultural demand (USGS, 2025). In this context, groundwater represents a strategic resource for both human consumption and ecosystem stability. Globally, approximately 50% of the population relies on groundwater for drinking water, and nearly 40% of irrigated agriculture depends on it (USGS, 2025). An estimated 2.5 billion people use groundwater as a primary water source (USGS, 2025). Despite its renewable character under appropriate management, groundwater systems are highly sensitive to over-extraction, land-use change, and climate variability.

Urbanisation profoundly alters the hydrological cycle, modifying recharge processes, increasing impervious surfaces, and disrupting natural storage dynamics. These pressures are especially evident in semi-arid and monsoon-driven basins, where rainfall variability amplifies hydrological uncertainty. The Mula–Mutha river basin in Maharashtra, India, exemplifies such complexity. According to GSDA (2018), the basin possesses moderate to good natural groundwater potential controlled by geology, topography, and rainfall distribution. However, expanding urbanisation and anthropogenic pressures have significantly disturbed recharge mechanisms through surface sealing, altered drainage networks, and unsustainable abstraction (GSDA, 2018). Rainfall variability further complicates groundwater assessment, making spatially explicit evaluation essential.

Within this basin, Pune city illustrates the challenges of urban groundwater governance. Acwadam (2019) reported that Pune faces chronic water shortages due to unregulated bore-well extraction, limited recharge, weak regulatory enforcement, and urban–rural inequities. The city's spatial expansion (~400 km²) and a groundwater footprint of 354 mm indicate that nearly 46% of average annual rainfall would need to be effectively recharged to stabilise supplies (Acwadam, 2019). Seasonal groundwater fluctuations of 2–12 m below ground level highlight systemic instability. The World Bank (2022) therefore recommends integrated governance approaches that combine surface and groundwater management. Yet, recharge dynamics and spatial variability of groundwater potential in rapidly urbanising parts of Pune remain insufficiently quantified, limiting evidence-based planning.

International experience demonstrates that robust groundwater management depends on spatial modelling, uncertainty assessment, and locally adapted policy frameworks. For example, hydrological modelling in Miami-Dade County improved understanding of surface–groundwater interactions under sea-level rise scenarios (Hughes et al., 2015). GRACE satellite analyses supported regional storage estimation in the Mid-Atlantic United States (Xiao et al., 2015), while hydrogeological assessments in Northwest Cambodia quantified recharge under rapid demographic growth (Vouillamoz et al., 2016). In Cape Town, severe drought during 2015–2017 highlighted the need to incorporate underutilised groundwater into urban supply strategies (Olivier et al., 2019). Similarly, in Dhaka, statistical trend analyses revealed declining recharge and groundwater levels, prompting calls for policy reform (Moshfika et al., 2022).

Advances in geospatial modelling have further strengthened groundwater assessment. Multi-criteria decision analysis (MCDA), including AHP, FAHP, and TOPSIS, has been widely applied to delineate groundwater potential zones (Singha et al., 2021; Ray, 2025). Vulnerability mapping approaches such as DRASTIC integrate hydrogeological parameters within GIS frameworks to support sustainable management (Patel et al., 2022). More recently, hybrid techniques combining fuzzy logic, geographically weighted regression (GWR), remote sensing, and exploratory regression have demonstrated improved predictive performance and spatial sensitivity (Gao et al., 2025; Huishen et al., 2025; Chen et al., 2025). These approaches explicitly address uncertainty and spatial heterogeneity – two critical challenges in urban groundwater studies.

Despite these advances, significant knowledge gaps persist for the Mula–Mutha basin. First, existing assessments largely provide basin-scale or administrative summaries without integrating spatial variability, uncertainty, and decision-based weighting in a unified framework tailored to Pune's urban expansion. Second, the relative influence of hydrogeological, topographic, and land-use factors on groundwater potential under current urbanisation patterns remains insufficiently quantified. Third, there is limited validation of multi-criteria approaches in this basin to support operational planning and recharge prioritisation.

To address these gaps, the present study aims to develop and validate an integrated GIS-based fuzzy TOPSIS framework for delineating groundwater potential zones in the Mula–Mutha river basin, with a focus on Pune's urban and peri-urban areas. The study seeks to (i) quantify the spatial variability of groundwater potential using decision-based weighting of key controlling factors; (ii) evaluate how uncertainty-sensitive fuzzy logic improves classification robustness compared with conventional approaches; and (iii) generate a scientifically validated groundwater potential map to support recharge planning and sustainable extraction policies.

We hypothesise that: (1) groundwater potential in the basin exhibits significant spatial heterogeneity controlled primarily by lithology, slope, land use, and drainage characteristics; (2) integrating fuzzy logic with TOPSIS reduces ambiguity in factor weighting and improves predictive reliability; and (3) high-potential recharge zones are increasingly fragmented in rapidly urbanising sectors of Pune. By testing these hypotheses, this research aims to produce a transferable methodological framework and new spatial evidence to strengthen urban groundwater governance and long-term water security in monsoon-dependent basins. Details of groundwater potential studied for the Pune region are given in the Table 1.

ENVIRONMENTAL SETTINGS

Location of the study area.

The Mula-Mutha catchment is located on the Western Ghats' leeward flank (Sahayadri). Sahayadri is a rugged area with deep valleys and hill ranges that intersect and cross it. The foothills, or the denudational origin zone, are made up of a number of minor hills that extend from the Plateaux into valleys and enormous spurs. A sizable portion of the catchment is located in the Assured Rainfall Zone. The watershed is primarily composed of built-up and agricultural areas. The two main aquifers in the area are basalt and alluvium. There are two main aquifer systems in basalt and one shallow aquifer in alluvium that is restricted to riverbanks. The Deccan Trap is the region's main rock formation, composed of basalt that dates from the upper Cretaceous to the lower Eocene.

The Pune catchment demonstrates how topography influences the flow of groundwater. The Central Groundwater Board has conducted several studies in the district since 1964.

They consider both the present and future needs for water, supply, and demand. Figure 1 shows the location map of the study area. As of March 2013, the Pune catchment was classified as safe by the Ground Water Resources Estimate. However, regular groundwater studies are necessary to regulate flow and maintain stable water levels.

Groundwater scenario

Figure 2 shows that the Mula-Mutha catchment experiences considerable fluctuations in groundwater levels due to the influence of the Pune metropolitan area. Groundwater extraction has risen significantly, attributed to the peri-urban transformation, which involves incorporating villages on the outskirts into the Pune administrative boundary. The demand for groundwater in Pune city's peri-urban regions continues to grow daily (ACWADAM & PMC, 2022).

Well monitoring data indicate notable declines in groundwater levels during the pre-monsoon season, followed by an increase in the post-monsoon period due to rainwater recharge. Elevated groundwater levels, exceeding 16m below ground level, are recorded near Lonikalbhor, Rahu, and surrounding areas in the post-monsoon season, while levels drop below 2m below ground level near Kondhawale and Thakursai across the catchment. Figure 3 shows the village's falls under the Mula-Mutha catchment boundary. Figure 2 generated using well water level data collected from groundwater survey and department agency, Pune.

MATERIAL AND METHODOLOGY

Groundwater potential zone mapping was performed for the Mula-Mutha catchment using a geospatial-based fuzzy TOPSIS process. Groundwater potential delineation achieved though the important successive phases, creation of the geodatabase for the parameters influencing the groundwater potential of the region. Relative ranking to such parameters through the fuzzy TOPSIS ranking process and spatial and non-spatial data integration through the ArcGIS Pro software. Table 2 shows the comprehensive details of data and material used in this study.

Data collection

The data was gathered from various sources and processed within a GIS environment to develop the database. A 30-meter-resolution slope map was created from the Shuttle Radar Topography Mission (SRTM) digital elevation model

Table 1. Study of groundwater potential for Pune region

Sr. No	Study area	Year	Parameters
1	Pune District	Year 2018	Geology, Rainfall, Water level
2	Maharashtra State	Year 2023	Geology, Water level, Rainfall
3	ACWADAM	Year 2019	Geology, Water level, Rainfall

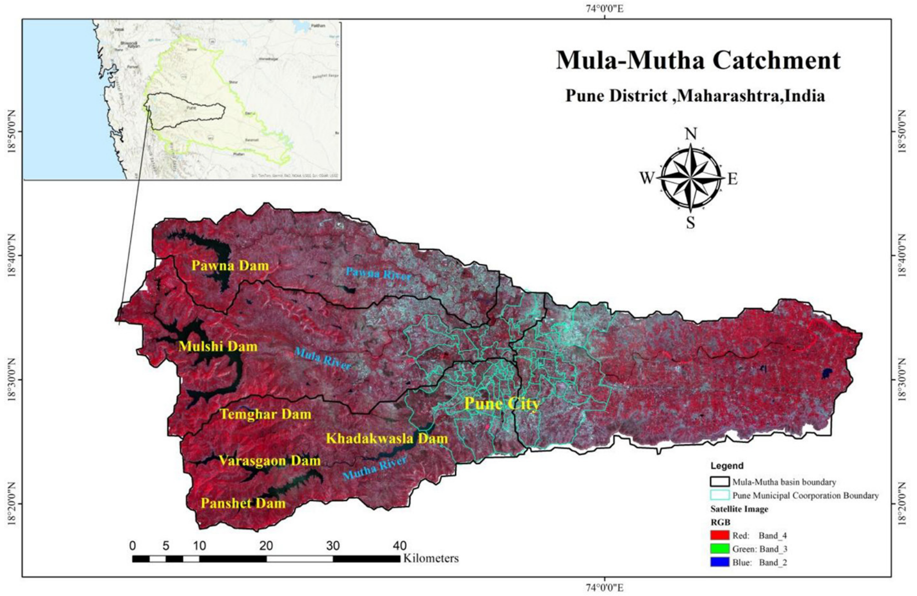

Figure 1. Location map

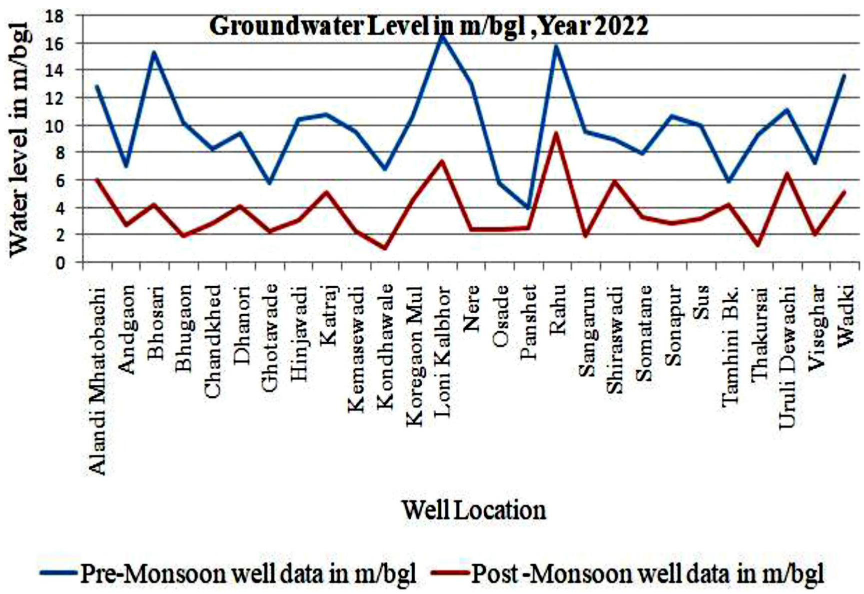

Figure 2. Groundwater fluctuations across the catchment

raster data downloaded from united state geological survey earth observation data achieve. A geology map at a scale of 1:50,000 vector data was downloaded for the study area from the Geological Survey of India, Bhukosh. A soil map sheet at a scale of 1:500,000 raster data were downloaded from European soil data centre. Soil data as per texture information digitised in ArcGIS Pro. A 10-meter-resolution land use and land cover layer was acquired from Sentinel 2 multispectral high-resolution data downloaded from the Environmental Systems Research Institute. The rainfall-runoff was computed using the Natural Resources Conservation Service, runoff technique using ArcGIS Pro software (Kamaraj et al., 2025; USDA-NRCS, 2009; Samal et al., 2025). A water level map was generated using well data from approximately 27 well (Table 3) monitoring station data collected by the Geological Survey and Department Agency, Pune (GSDA), and an interpolation technique was used to create a water level layer in ArcGIS Pro software. All these layers in raster format were re-projected to 10-meter resolution using the re-project tool set in ArcGIS Pro software and weights were assigned to each layer estimated by Fuzzy TOPSIS technique.

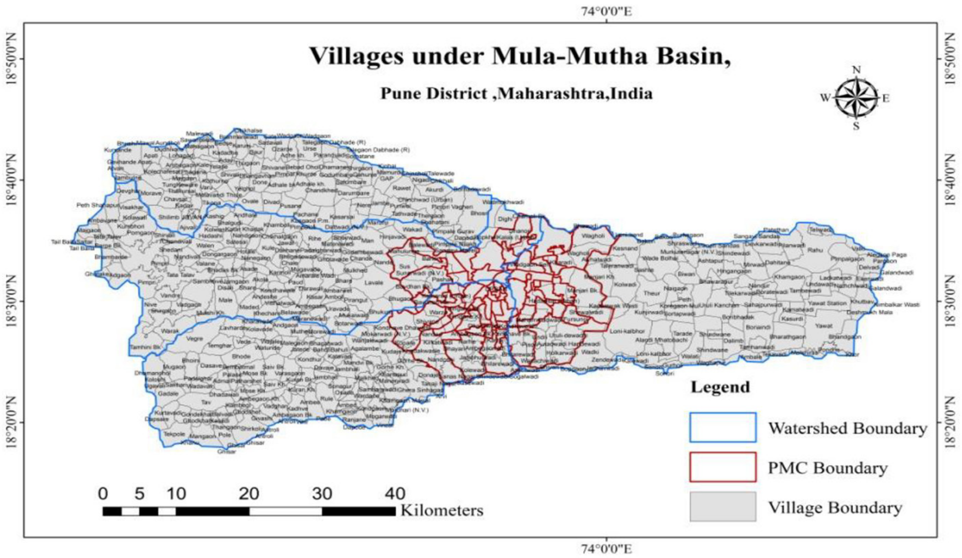

Figure 3. Village location map

Table 2. Details of data used in the study

Sr. No	Data	Details	Source
1	Digital elevation model	Digital elevation model, Shuttle Radar Topography Mission (SRTM), United state geological survey of India earth observation data archieve.	https://earthexplorer.usgs.gov/ Product Id:SRTM1N18E073V3 SRTM1N18E074V3
2	Land use land cover map	Sentinel 2 land use land cover map, ESRI (Environmental Systems Research Institute),	https://livingatlas.arcgis.com/ landcoverexplorer/#mapCenter=92.21745%2C26.42377%2C11.00&mode=step&timeExtent=2017%2C2024&year=2024 Product ID: 43Q_20220101-20230101 Product ID: 43Q_20220101-20230101
3	Geology map	Bhukosh, geological survey of India maps.	https://bhukosh.gsi.gov.in/Bhukosh/Public Layer Type ID:'1000000000000000' '4790739811998102' '4790739811999101' '4790739813994106' '4790739813995105' '4790739813996104' '4790739813997103' '4790739813998102' ' 4790739813999101'
4	Soil map	European soil data centre (ESDAC)	https://esdac.jrc.ec.europa.eu/content/maharashtra-soils-sheet-1 Resource type: National Soil Maps (EUDASM), Maps Maps & Documents Publisher: National Bureau of Soil Survey (NBSS) and Land Use Planning (LUP), Nagpur. Country: BD
5	Well water level data	Groundwater survey and department agency, Pune, well monitoring data. By filling out the data requisition application form of GSDA.	https://gsda.maharashtra.gov.in/en-guidelines/
6	Rainfall-runoff map	United States department of agriculture, natural resources conservation service, runoff technique.	https://directives.nrcs.usda.gov/sites/default/files2/1712930818/31754.pdf

Fuzzy TOPSIS mathematical model

All the GIS parameters runoff, soil, lithology, slope, land use land cover and water level reclassified and normalised in GIS software. Data transform to matrices and then aggregated fuzzy weight matrix, weighted normalize decision matrix then ideal solution calculated. All these steps are explained below. Figure 4 shows the methodology flow chart.

Data generation and standardization

Compile the decision-makers' subjective assessments of the weights' significance. Since not every operational process is Boolean, it is typically difficult to give precise values of priority while making decisions. Fuzzy numbers, such as trapezoidal or triangular fuzzy numbers, provide a means for evaluating preferences. Triangular fuzzy numbers are used in this study. Fuzzy numbers convey the ambiguity and imprecision present in human judgments by offering a range of values with corresponding degrees of membership.

All the components soil, slope, rainfall-runoff, water level, land use Landover, geology reclassified and then standardised. Then triangular Fuzzy scale applied to all components. Figure 5 shows the data processing. Table 3 shows the Pixel data used. Table 4 shows data standardization and Table 5 shows fuzzy scale and Table 6 shows applied scale to the parameters.

Generation of weight matrix

The relative importance of each criterion in the multicriteria decision-making process is represented by fuzzy significance coefficients or weights. It can be challenging to determine which factors are most important in multicriteria decision-making, as their importance fluctuates depending on the circumstances. Subjectivity is facilitated by fuzzy topics, allowing for thorough assessment. The preferred importance employed in this work is displayed in Table 5. The following formula uses the decision makers' subjective evaluations to determine the weights or fuzzy significance coefficients. Figure 6 shows the generation of weight matrix.

Wj1, Wj2, and Wj3 are fuzzy significance coefficients or weights that are computed as

$$Wj_{1=\frac{min}{k}}\{wj1^k\} \tag{1}$$

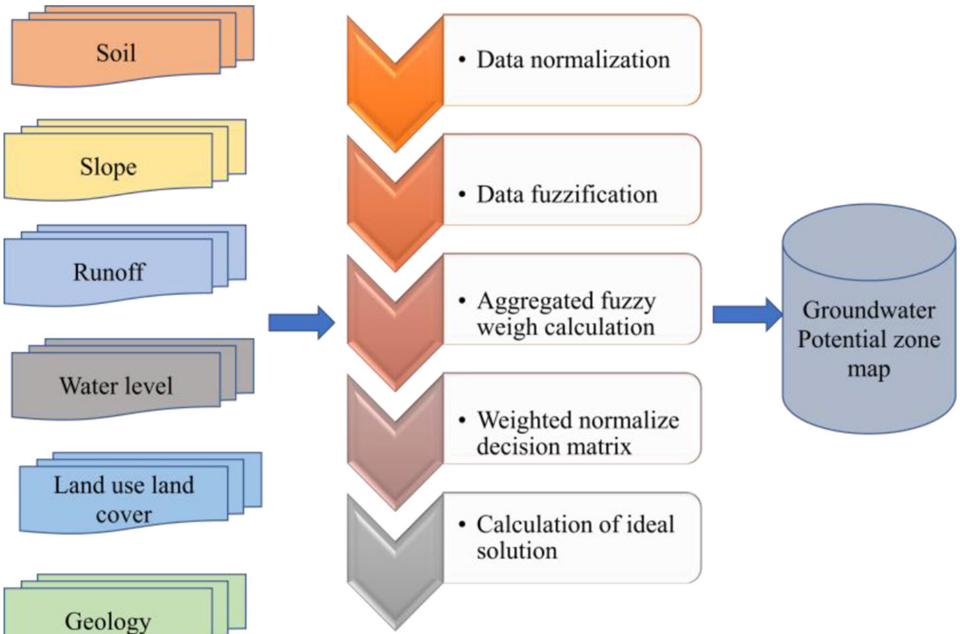

Figure 4. Methodology flow chart

Table 3. Reclassified pixel data count

Categories	Categorical pixel counts				
Rainfall-Runoff	7470324	674085	5898793	8333063	6016673
Soil	13322491	3973550	2991385	4417033	5093830
Lithology	2608	8538	24319	23312	17019
Slop	341	7944	117688	563014	2560248
LULC	1429236	7107135	3479104	8651574	8028444
Well	35825	14499	12952	4711	1430

Table 4. Data standardization

Categories	Categorical pixel values				
Soil	1.000	0.298	0.225	0.332	0.382
Lithology	0.107	0.351	1.000	0.959	0.700
Well	1.000	0.405	0.362	0.132	0.040
Rainfall-Runoff	0.896	0.081	0.708	1.000	0.722
Slop	0.000	0.003	0.046	0.220	1.000
LULC	0.165	0.821	0.402	1.000	0.928

Table 5. Triangular fuzzy scale

Importance	Symbol	Fuzzy weight
Very high	VH	(0.7,0.9,0.1)
Very low	VL	(0,0.1,0.3)
High	H	(0.5,0.7,0.9)
Low	L	(0.1,0.3,0.5)
Medium	M	(0.3,0.5,0.7)
Extremely low	EL	(0,0,0.1)
Extremely high	EH	(0.9,1,1)

Source: Zadeh 1965

$$Wj_{2}=\frac{\sum_{k=1}^{K} wj_2{}^\wedge k}{k} \quad (2)$$

$$Wj_{3}=\frac{max}{k}\{wj_{3^k}\} \quad (3)$$

where: k = 1,…, K are the decision makers and j = 1,..., n are the criteria, then aggregate fuzzy triangular number created.

$$\mu A(x) = \begin{Bmatrix} 0 \\ (x-1/(m-1)) \\ (\mu - x/(\mu - m)) \end{Bmatrix} \quad 0 \quad \begin{matrix} x < 1 \\ 1 \le x \le m \\ 1 \le x \le \mu \\ x > \mu \end{matrix} \quad (4)$$

where: $\mu_{A(x):} X[0,1]$ is the membership function of A and $\mu_{A(x)}$ is the degree of membership of x in A. $\mu A(x)$ can take any value between [0,1], capturing partial membership of x in fuzzy set A.

According to Madi et al., a fuzzy number M is a convex normal fuzzy set M of the real line R such that – there exists exactly one x_0 ∈ R with μ_M (x_0)=1(x_0is called mean value of M) and μ_M(x) is piecewise continuous.

There are several different types of fuzzy numbers, such as bell-shaped fuzzy numbers, trapezoidal fuzzy numbers, and triangular fuzzy numbers (TFN). Due to its ease of use and computational simplicity, the TFN is the most commonly utilized. Three real numbers (l, m, and n) make up the triplet TFN. Table 7 shows the weight matrix.

Generation of the fuzzy weighted decision matrices

Create the matrix of decisions as indicated below. GIS software is used to standardize data so that all components are on the same scale. Figure 7 shows the Fuzzy weighted decision matrix.

Let D = x_{ij} be a decision matrix where $_{ij}$ ∈ R.

$$D = \begin{matrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{matrix} \quad (5)$$

Table 6. Applied triangular fuzzy scales

Categories	Decision Maker 1	Decision Maker 2	Decision Maker 3
Soil	L	M	M
Lithology	M	VH	H
Well	L	H	VH
CN	M	EH	EH
Slop	H	H	EH
LULC	L	M	M

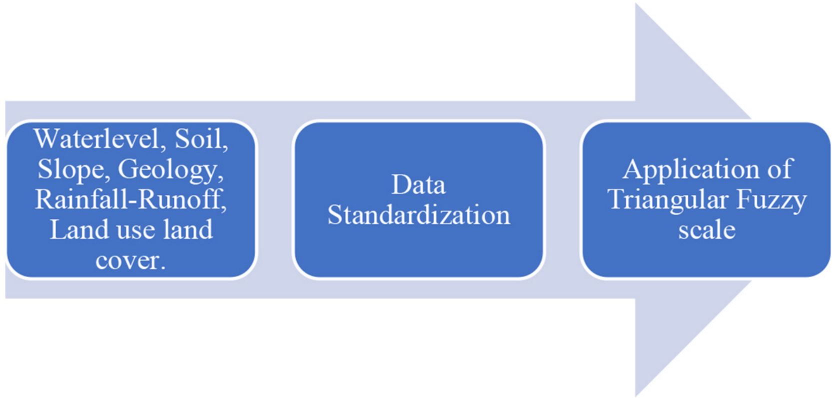

Figure 5. Data processing

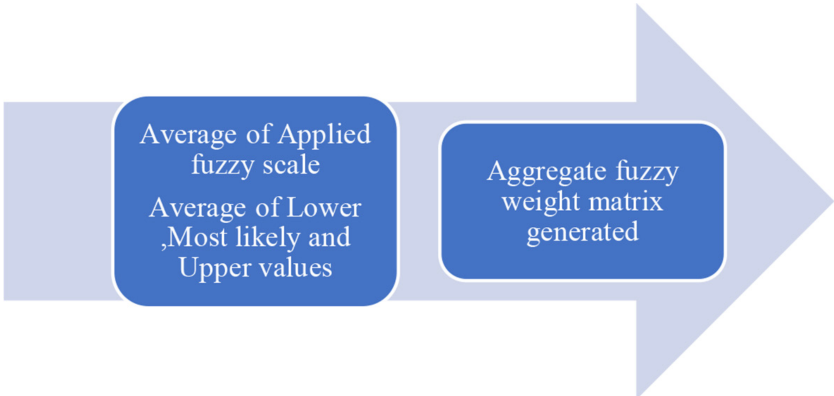

Figure 6. Fuzzy weight matrix

Table 7. Weight matrix

L-FW	M-FW	U-FW
0.23	0.43	0.63
0.43	0.63	0.83
0.17	0.37	0.57
0.57	0.73	0.87
0.57	0.73	0.87
0.23	0.43	0.63

Normalised decision matrix formed for standardization of all components used in this study. Table 7 shows the same.

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{6}$$

The normalized decision matrix is multiplied by the relevant fuzzy weight to create a fuzzy weighted decision matrix. It is crucial for producing fuzzy negative ideal solutions (FNIS) and fuzzy positive ideal solutions (FPIS) (Table 8).

$$\bar{D} = \begin{matrix} \tilde{N}_{11} & \tilde{N}_{12} & \cdots & \tilde{N}_{1n} \\ \tilde{N}_{21} & \tilde{N}_{22} & \cdots & \tilde{N}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{N}_{m1} & \tilde{N}_{m2} & \cdots & \tilde{N}_{mn} \end{matrix} \tag{7}$$

where: $\tilde{N} = (w_{j1}, N_{ij}, w_{j2}, N_{ij}, w_{j3}, N_{ij})$ where, $I = 1 \ldots\ldots m$ and $j = 1, \ldots., n$

Creation of ideal solution

To facilitate the ranking of alternatives in the Fuzzy TOPSIS approach, the following formula is used to calculate the distances to the fuzzy positive ideal solution (FPIS) and the fuzzy negative ideal solution (FNIS).

FPIS represents the ideal solution where each criterion achieves its maximum possible performance value. Represents the least desirable solution where each criterion achieves its minimum possible performance value for each criterion from all the alternatives. Fuzzy positive ideal solution (FPIS) and FNIS coordinates:

$$\tilde{A}_J^{+} = Max\tilde{N}_{ij}\Big|_j \in B \quad Min\tilde{N}_{ij}\Big|_j \in C \tag{8}$$

where: $i = 1,\dots, m$.

$$\tilde{A}_J^{-} = Max\tilde{N}_{ij}\Big|_j \in B \quad Min\tilde{N}_{ij}\Big|_j \in C \tag{9}$$

where: $i = 1,\dots, m$.

Euclidean distance helps measure how close or far each alternative is from the best and worst possible scenarios, which is essential for effectively ranking the alternatives in multicriteria decision-making. Distance from FPIS indicates how close an alternative is to the best possible performance across all criteria. Euclidean distance from the FNIS indicates how far an alternative is from the worst possible performance. Figure 8 shows Ideal solution process.

The Euclidean distances of each alternative from the fuzzy positive and negative ideal values are shown in Table 9.

$$\text{as } S_i^{+} = \sum_{j=1}^{n} d\left(\tilde{N}_{ij}, \widetilde{A_j^{+}}\right) \quad i= 1,\dots,m; j = 1,\dots,n \tag{10}$$

$$S_i^{-} = \sum_{j=1}^{n} d\left(\tilde{N}_{ij}, \widetilde{A_j^{-}}\right) \quad i= 1,\dots, m ; j = 1,\dots,n \tag{11}$$

The distance between two fuzzy numbers, denoted by d (.,.), is determined by

$$d(\tilde{A}, \tilde{B}) = \sqrt{\frac{1}{3}[(a_l - b_l)^2 + (a_m - b_m)^2 + (a_u - b_u)^2]} \tag{12}$$

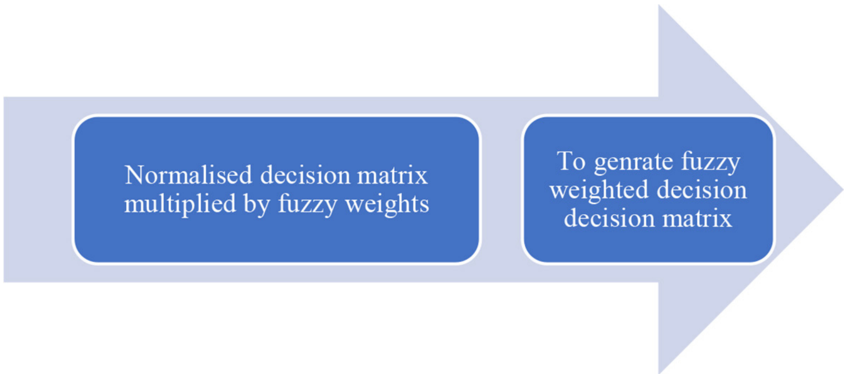

Figure 7. Fuzzy weighted decision matrix

Table 8. Fuzzy weighted decision matrices

Soil			Lithology			Well		
0.2333	0.4333	0.6333	0.1491	0.2088	0.169	0.0973	0.1422	0.1123
0.025	0.0465	0.0679	0.1755	0.2458	0.1989	0.4333	0.6333	0.5
0.4333	0.4333	0.6333	0.2024	0.2833	0.2293	0.1567	0.229	0.1808
0.2092	0.3885	0.5678	0.0404	0.0566	0.0458	0.3067	0.4483	0.3539
0.00003	0.0001	0.0001	0.0016	0.0022	0.0018	0.0199	0.0291	0.023
0.385	0.0716	0.1046	0.4107	0.575	0.4655	0.1743	0.2547	0.2011
Runoff			Slope			LULC		
0.2321	0.2763	0.2984	0.21	0.2652	0.3094	0.0892	0.1657	0.2422
0.671	0.7988	0.8627	0.6071	0.7669	0.8947	0.1633	0.3033	0.4432
0.0921	0.1096	0.1184	0.0833	0.1052	0.1227	0.0093	0.0173	0.0253
0.7	0.8333	0.9	0.6333	0.8	0.9333	0.1685	0.3129	0.4573
0.1539	0.1833	0.1979	0.1393	0.1759	0.2052	0.2333	0.4333	0.6333
0.7	0.8333	0.9	0.6333	0.8	0.9333	0.2165	0.4021	0.5877

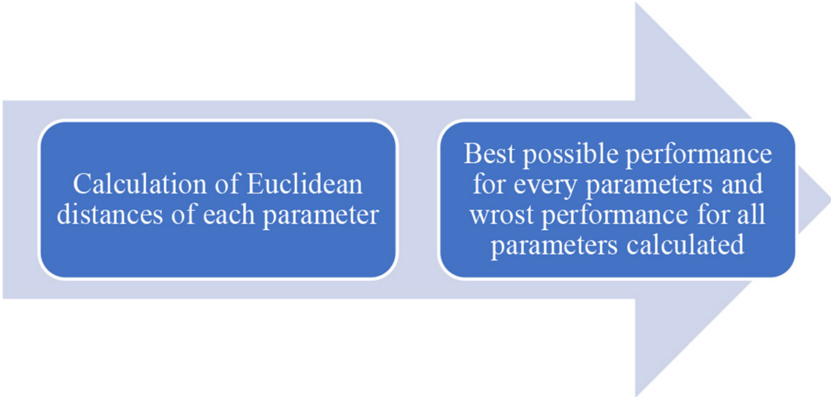

Figure 8. Ideal solution

Table 9. Ideal solutions

Fuzzy ideal positive solution (FPIS)	Fuzzy negative ideal solution (FNIS)
1.3181	2.0977
2.3805	0.9669
0.5855	2.7606
2.4496	0.9401
2.0872	1.2589
2.5634	0.7849

Table 10. Closeness of coefficient

Parameters	Coefficients	Ranking
Soil	0.614	2
Lithology	0.289	4
Well,/Water level	0.825	1
Rainfall-Runoff	0.277	5
Slope	0.376	3
LULC	0.234	6

Determination of closeness of coefficient

Fuzzy positive $\boldsymbol{S_i^+}$ formula is used to determine the closeness coefficient (CCi) of the alternatives, which is then sorted in descending order (Kore et al., 2017; Mijalkovski et al., 2023). This indicates how close an option is to the FPIS and how far away it is from the FNIS. The best option is indicated by the alternative with the highest proximity coefficient, which can be used to rank the alternatives. The alternatives' order is displayed in Table 10. Figure 9 shows the final weights estimation.

Since ambiguity and subjective data are widespread in groundwater potential assessment, fuzzy TOPSIS was chosen over other Multicriteria decision making (MCDM) approaches because of its superior accuracy in managing these types of data. Figure 10 shows the influence of the parameters to identify groundwater potential zones.

RESULTS AND DISCUSSION

The potential groundwater zones rely on all six parametric layers included in the research,

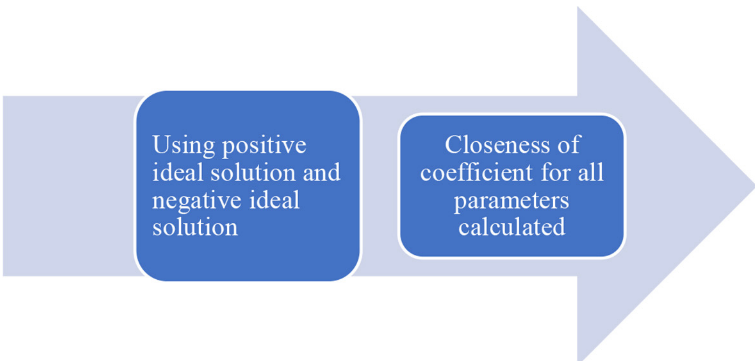

Figure 9. Final weights estimation

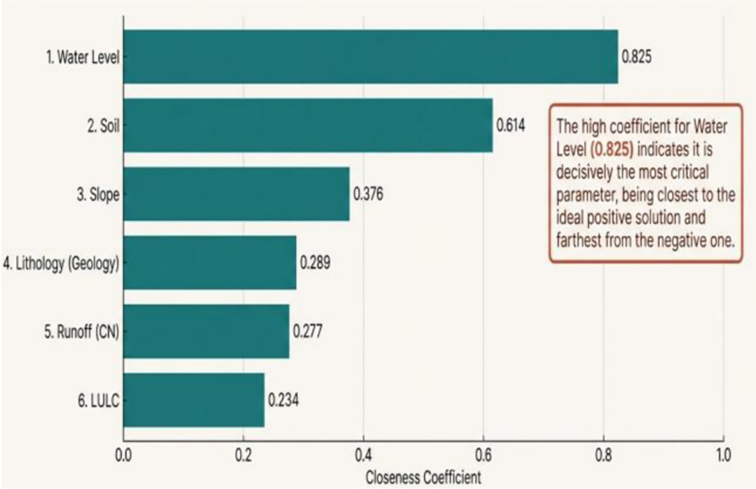

Figure 10. Ideal criteria's to identify potential zones

Table 11. List of parameters and Fuzzy-Topsis ratings and weights

Parameters	Range	Rating	Weights
Lithology	Mahabaleshwar	0.107	0.289
	Purandhargarh	0.351	
	Indrayani	1	
	Karla	0.959	
	Diveghat	0.7	
Slope	≥ 41	0.001	0.376
	31 to 40	0.003	
	21 to 30	0.046	
	11 to 20	0.22	
	0 to 10	1	
Rainfall-Runoff	0.97 to 0.98	0.896	0.277
	0.99 to 0.99	0.081	
	0.98 to 0.99	0.708	
	0.96 to 0.97	1	
	0.98 to 0.98	0.722	
Landuse-LandCover	Water	0.165	0.234
	Builtup	0.821	
	Dense vegetation	0.402	
	Sparse vegetation	1	
	Agricultural	0.928	
Soil	Fine,Calcariosu,iso-hyperthermic	1	0.614
	Loamy,mixed,iso-hyperthermic,Lithic ustorthens	0.298	
	Clay-montmorillonitic,calcareous,iso-hyperthermic	0.225	
	Impervious areas	0.332	
	Veryfine,montmorillonitic,iso-hyperthermic	0.382	
Well Water Level	≥ 8	1	0.825
	6 to 7	0.405	
	5 to 6	0.362	
	3 to 4	0.132	
	1 to 2	0.04	

both directly and indirectly. The relationship between each layer and its impact on the others was assessed using the Fuzzy TOPSIS technique, and suitable weights were assigned for the overlay procedure in the ArcGIS Pro software (Forootan, 2025; Aouragh et al., 2016). Table 11 shows the parameter wise estimated weights.

As multiple parameters were used in this study, which have proven that groundwater potential is associated with all 6 parameters, however, estimated weights reveal that water level has a greater impact due to a different type of aquifer system composed of deccan basalt trap, shallow/unconfined aquifers, and deeper/confined aquifers. After that Soil texture plays an important role in the water infiltration process. Soil with permeability percolates water to downwards and recharge the aquifer, and increase the groundwater level. Slope is also one of the influential topographic factors that affect the groundwater potential. Gentle or flat slope, slow runoff, which leads to more infiltration and a high groundwater level (Forootan, 2025; Aouragh et al., 2016). Lithology is important in terms of the physical characteristics of rock that govern rock porosity and groundwater occurrence. The Deccan Trap in Pune contains basalt, so groundwater is stored only in fractured or weathered rock. Rainfall-runoff and groundwater level show an inverse relationship. Moderate runoff shows good infiltration and a high groundwater level. In case of land use land cover, sparse vegetation and agriculture field have good potential of groundwater as soil is more exposed and due to permeability water can easily infiltrate raised groundwater level. Compared to forests, due to high evapotranspiration, deep-rooted trees may take up significant groundwater (Burayu et al., 2025; Saranya and Saravanan, 2020).

Description of parameters influencing the Potential groundwater occurrence

Geology

The catchment includes the Indrayani, Karla, Diveghat, Purandar, and Mahabaleshwar formations shown in the Figure 11. The Indrayani Formation features dense, massive, porphyritic basalt. The fine-grained groundmass holds phenocrysts. Geochemically, the Indrayani is part of the Khandala Formation, which is itself part of the Lonavala sub-group. Its lava flows are joined and heavily worn, found in low-lying plains, and they create moderate to adequate aquifers. The eastern catchment primarily consists of the Indrayani Formation, which covers areas such as Bhosari, Dhanori, Shiraswadi, Koregaon Mul, Wadki, and Lonikalbhor. These areas show high water levels. Compound lava flows with pahoehoe characteristics comprise the Karla Formation, which transitions into the Bushe Formation based on its geochemical features. These flows are aphyric or sparsely

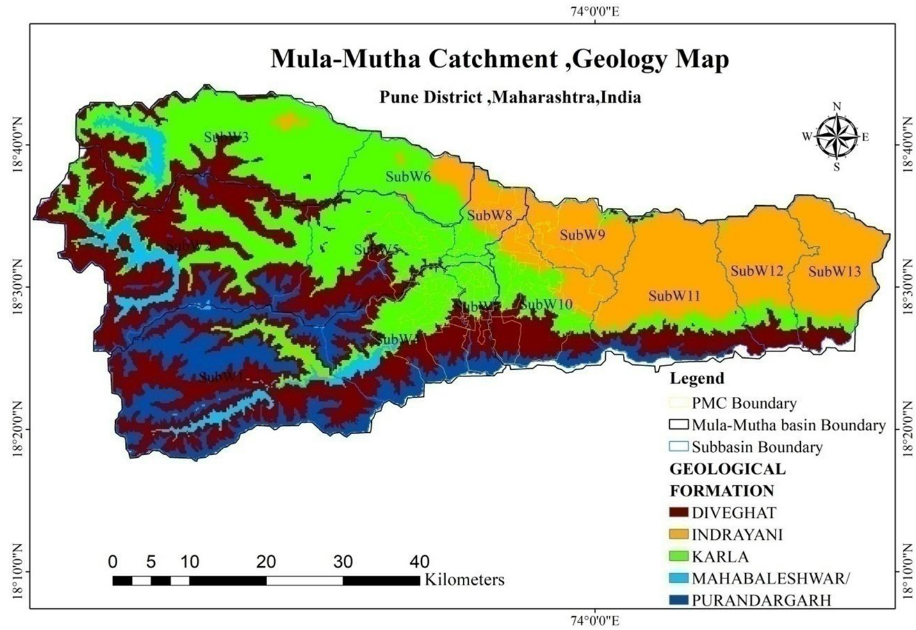

Figure 11. Geology map

plagioclase phyric in composition. While plagioclase is almost nonexistent in the flows, they are marked by coarse-grained, altered amygdaloidal basalt. According to groundwater theory, the transition creates moderate to appropriate aquifers, mainly found on low-lying, level plains.

Water level

The basalt units under Pune differ in thickness, ranging from a few meters to hundreds of meters. The vesicular amygdaloidal basalt in the research area is worn. It shows parallel and sub-parallel sheet seams due to overburden deterioration. As a result, these basalts have better hydraulic conductivity than compacted basalts. Fracturing is common in the study area. Closely spaced, sub-vertical fractures are visible along zones that have distinct patterns. These fractures help raise the basin's water level. Figure 12 displays a water level map.

Building on the water level map shown in Figure 7, groundwater levels are moderate to high (3.15 to 10.5 m below ground level) at Chandkhed, Nere, Hinjavadi, Ghotavade, Sus, and Kondhawale Falls. On the hills and slopes, the Diveghat Formation, which overlies the Karla Formation, is visible. Groundwater levels vary from 4 meters below ground level at the west side of the basin near Panshet, to 16.55 meters below ground level near Loni Kalbhor, on the eastern side of the catchment. This indicates that the aquifers at higher elevations, represented by the hillocks and ridges, particularly in the south and west, have lower groundwater levels.

Further examination of the formations reveals that vesicular, plagioclase basalt with a medium-grained groundmass is present in the lava flows of this formation. Since these lava flows occur on mountainous terrain, they have limited groundwater potential from a hydrogeological perspective. This formation, which includes Thakursai, Visaghar, and Osade, has low groundwater levels, ranging from 2 to 8 m below ground level (bgl).

Soil

Weathering basalt depends on the climate. Therefore, brown soil is common in the west of the basin, where it is coarser and shallower than black soil. Soils here, classified as types B and D, have moderate infiltration. Conversely, the east has high porosity and excellent to moderate infiltration. Near Dhanori, Shiraswadi, Shindewadi, Koregaon Mul, and Rahu, soils change from sandy loam to clay loam. Figure13 shows the map of soil distribution in the area.

Rainfall runoff

In the western part of the catchment, specifically around Sangarun, Bhugaon, Ghotavade, and Chandkhed areas, the excellent clay Loam mixed soil indicates high rainfall runoff. Due to this, it has moderate potential for groundwater. The middle portion of the catchment

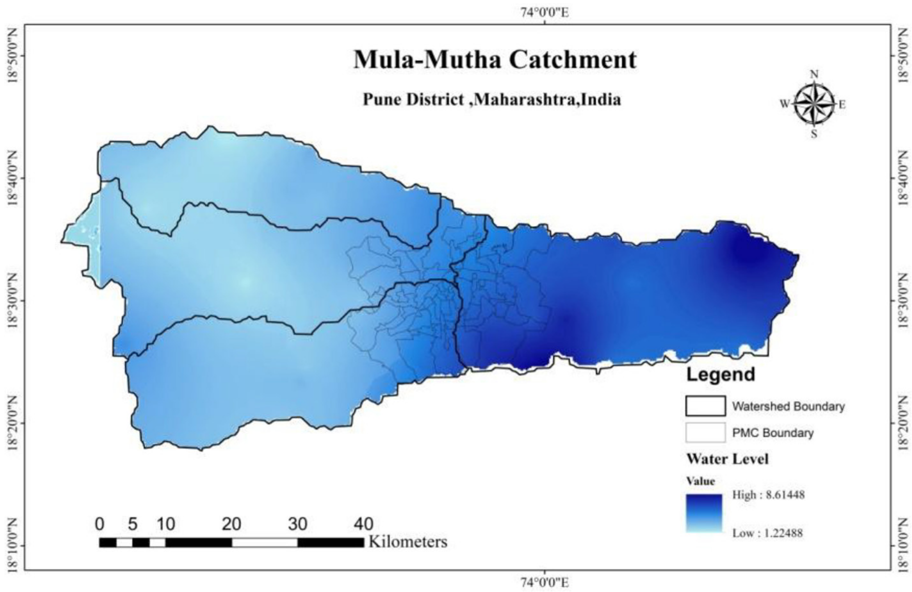

Figure 12. Water level map

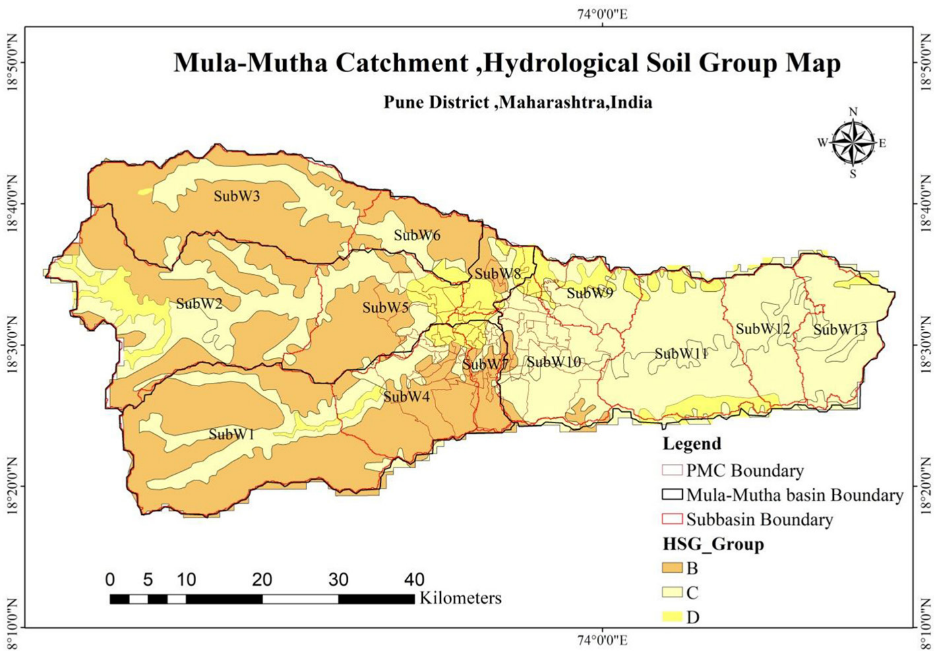

Figure 13. Hydrological soil group map

exhibits an impervious surface due to the presence of Pune City, resulting in high runoff from rainfall. This area also has moderate to good groundwater potential due to the region's aquifer system. The eastern part of the basin, Dhanori, Shiraswadi, Shindewadi, Koregaon Mul, and Rahu, shows moderate runoff potential and good groundwater potential. Figure 14 shows rainfall runoff across the catchment.

Slope

Figures 15 show slope maps. The watershed is urbanized, with dense vegetation in the western part of the catchment, which is surrounded by hills with steep slopes of nearly 51%. In contrast, the Tahmini area of the Mulshi region, where Mulshi Dam is located, shows less potential for groundwater. Additionally, the catchment features more than four damsPawana, Panshet,

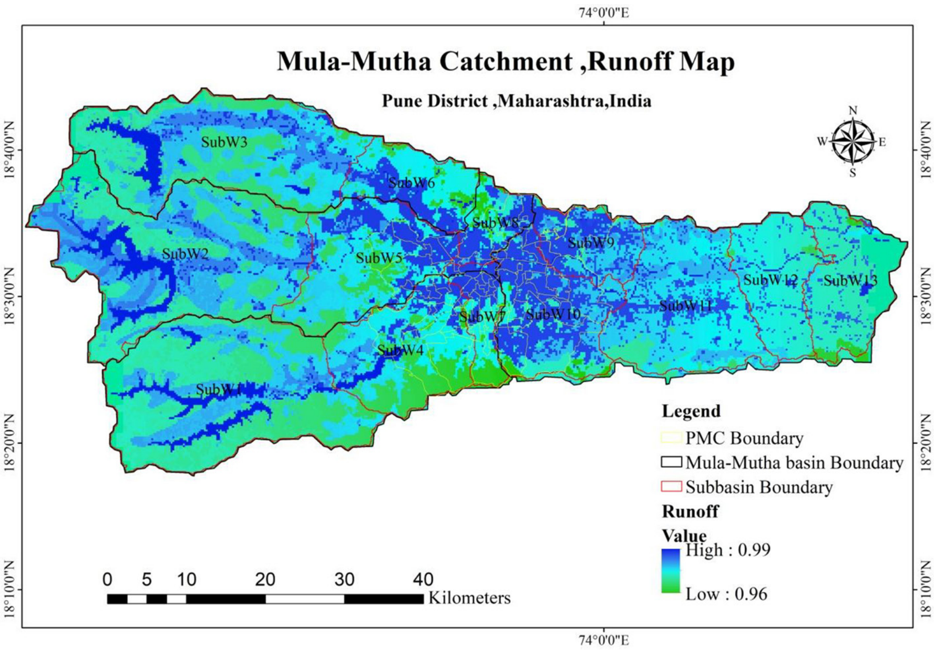

Figure 14. Rainfall runoff map

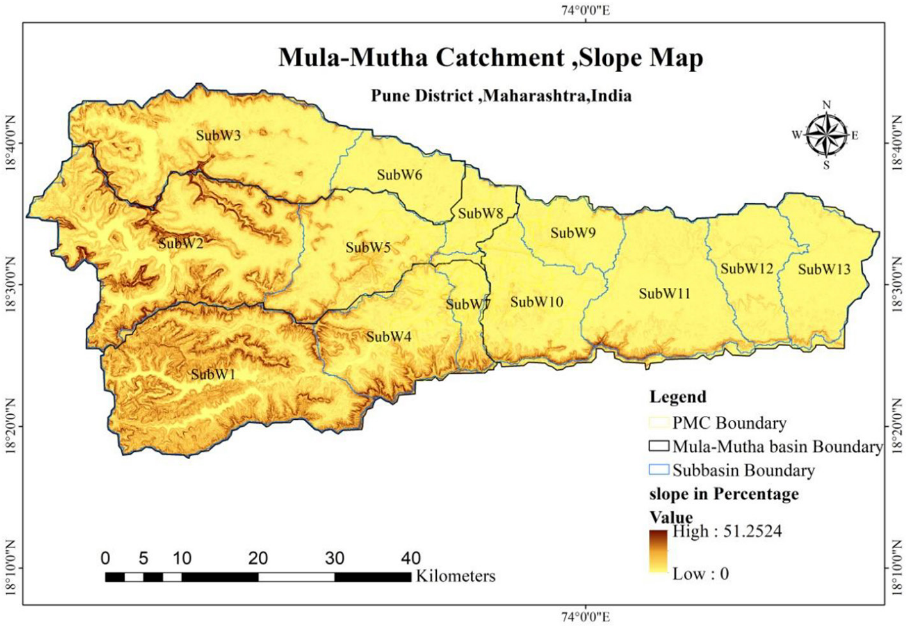

Figure 15. Slope map

Varasgaon, and Khadakwaslalocated on gentle to moderate slopes (10–25%) on the west side of the basin. Meanwhile, the eastern region of the sub-basin, where the topography is relatively flat and the slope is less (0 to 10%), shows excellent potential for groundwater.

Land use land cover

The western side of the watershed, covered with forest, demonstrates lower groundwater potential due to other governing factors. The hilly areas, characterized by sparse vegetation, exhibit moderate groundwater potential. The middle portion of the catchment, dominated by built-up areas associated with the city of Pune, maintains moderate to good groundwater potential due to the presence of the aquifer system. The eastern section of the basin, marked by numerous agricultural patches, indicates high groundwater potential. Figure 16 shows the land use land cover map.

Delineation of groundwater potential zones

Fuzzy TOPSIS improves the trustworthiness of outcomes by processing inaccurate expert assessments using fuzzy logic. Moreover, through the use of the proximity coefficient, it becomes possible to rank alternatives more precisely by considering both ideal and non-ideal solutions. Fuzzy TOPSIS improves accuracy by preserving uncertainty throughout the decision space and enhances reliability by reducing sensitivity to subjective judgment errors. Fuzzification, weighting, and distance calculationsare performed using fuzzy arithmetic proves to be more accurate and reliable for complex, real-world decision-making scenarios. This approach is illustrated in Figure 17, and Figure 18 shows a groundwater potential map and their percentage respectively.

The current study reveals that groundwater behaviour is influenced by topography. Figure 17 shows possible spatial variations in groundwater potential. The soil is very deep and well-drained, loamy, and composed of the Diveghat and Purandar geological formations, which have a lower groundwater potential. In the western part of the catchment is the upper region of the Pawna, Mula, and Mutha sub-watersheds. This region receives heavy rainfall (average is over 400 mm). Steep slopes (more than 45%), reduced infiltration, and dense vegetation result in lower water levels, about 2 meters below ground level. Approximately 28% of the area is clearly characterized by lower groundwater potential (Figure 18).

The lower region (Southern part) of the sub-watershed of Pawna, Mula, and Mutha, namely the sub-watershed, receives a moderate amount of rainfall (Average >300 mm) and generates sufficient runoff. The area exhibits a mix of land use and land cover types, including agricultural patches, sparse vegetation, and built-up areas, which reduces infiltration. The slope is gentle (10 to 25%) in this region, which is responsible for

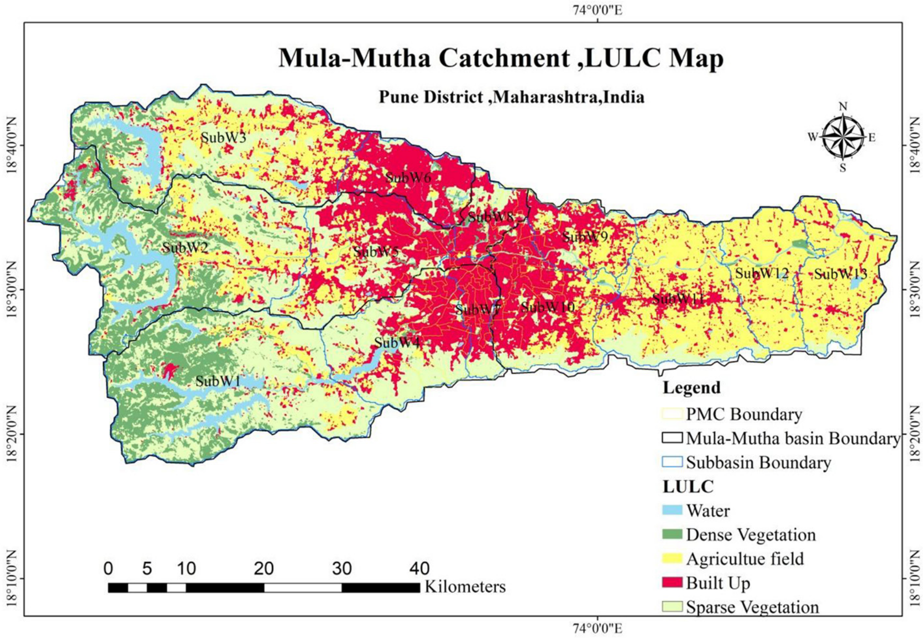

Figure 16. Land use land cover map

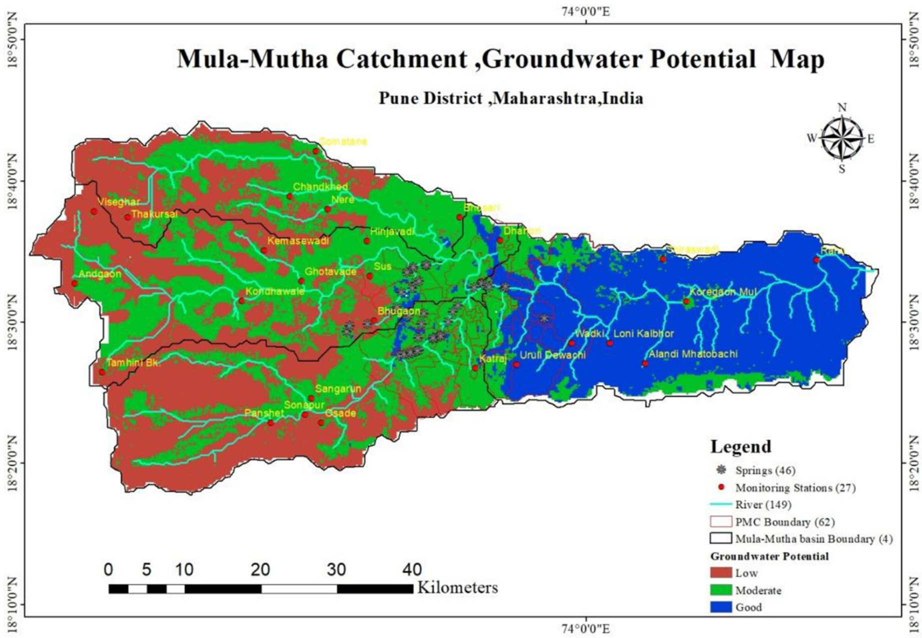

Figure 17. Groundwater potential maps

the moderate velocity of the water and reduced resistance to flow. Additionally, the basin exhibits Karla's geological formation, characterized by a moderate to strong aquifer system. As a result, the area's water level is also within a suitable range, from 8m to 10m, and has a moderate potential for groundwater, covering an area of approximately 41%. This part of the basin lies within the administrative boundary of Pune city, characterized by a good distribution of natural springs that discharge regularly into the aquifer system, indicating a high groundwater potential. However, the outskirts and patches of the city, as well as many peri-urban villages, face water issues that affect their day-to-day survival. Water supply authorities need to consider other available resources, such as groundwater, to meet the region's water demand.

Moving eastward within the catchment, in the eastern part of the Mula-Mutha basin, at the confluence of the Mula and Mutha rivers, a dense

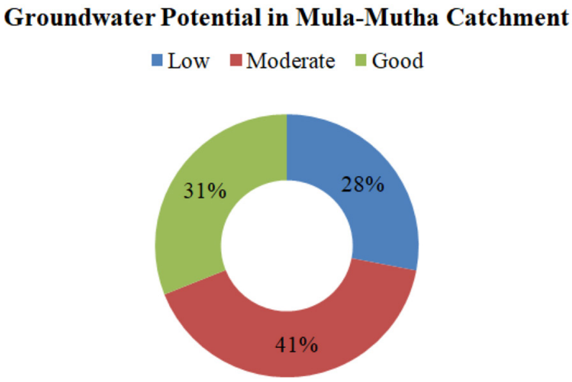

Figure 18. Groundwater potential in percentage

population is found due to the presence of the city of Pune. Here, the slope is very gentle and almost flat. Impervious surfaces cause the basin to generate a high amount of runoff. Indrayani and Karla are the geological formations present, and the soil is slightly deep, well-drained, fine, and calcareous, making for good groundwater potential. Gravitational forces downstream result in a high water level (10 m/bgl to 12 m/bgl). Clusters of natural springs are also found here. 31% of the area has good groundwater potential. The Mula-Mutha sub-watershed has high groundwater potential due to its flat terrain. Most of the area is characterized by the Indrayani formation, which features a high water table above 12 m bgl and a sound aquifer system. Large areas are dedicated to agriculture due to the availability of groundwater irrigation. Water moves on the surface for a long time because the terrain is flat. Fine, calcareous soil and slightly deep drains increase infiltration in the east. Clayey soil and shallow drains can retain more water, helping the groundwater system. The aquifers in this area have good groundwater potential, high transmissivity, and a well-developed joint network, resulting in higher storage coefficients. This part of the basin lies at the edge of rural and urban areas of Pune city. Many water distribution issues occur between institutions. Even in areas with excellent groundwater potential, water scarcity persists due to a lack of transparency and an inadequate framework for groundwater management.

The Mula-Mutha basin groundwater system has two hydrogeological formations. The first type has a lower compact basalt unit (a dense, hard volcanic rock) and an upper vesicular amygdaloidal basalt unit (a lighter volcanic rock with cavities). Groundwater mainly enters through sheet joints (horizontal fractures) in the upper and lower vesicular amygdaloidal basalt and through sub-vertical joints in the compact basalt. These formations are usually in riverbeds.

Another formation is made up of a lower vesicular amygdaloidal basalt unit and an upper compact basalt unit. The primary inflow zones are sheet joints in the upper part of the vesicular amygdaloidal basalt and sub-vertical joints in the compact basalt. This formation is found in highland areas and gentle hill slopes, including Vadgaon, Kharadi, Viman Nagar, Bavdhan, and Kondhawa Bk., in both the east and west parts of Pune city.

The groundwater potential map and study components indicate that hills, hilltops, and slopes are significant areas for managing and replenishing groundwater. Foothill and riverside patches, which are lower-lying areas near the base of slopes or adjacent to rivers, are especially suitable for groundwater recharge at the aquifer level, where the potential for replenishment is good.The ridge between Kothrud and Pashan, including the MIT College Ridge, ARAI Hill, VetalTekdi, Chatushringi, and Bavdhan, is crucial for groundwater replenishment. The Range Hills and Aundh-Baner-Pashan ridge also have strong recharge areas. Another recharge zone is in the uplands, moving from the river toward Viman Nagar near Pune Airport.

The study shows that a groundwater map can help protect natural recharge zones. It also supports soil and water conservation for aquifer protection for household's water supply.

Validation of the results

Validation of was performed for the output groundwater potential zone map using a performance metric to evaluate the accuracy. An area under the curve (AUC) of 0.77 is observed in the groundwater potential output map which is validated with well monitoring stations, as shown in Figure 20. Probability is displayed using the area under the curve. Strong statistical correlation of 0.7 is also observed between water level data and groundwater potential zone map Figure 21 shows the same. Figure 19 shows ground data used for validation. It is revealed that the basin has sufficient groundwater for the integrated surface and groundwater supply to meet household requirement.

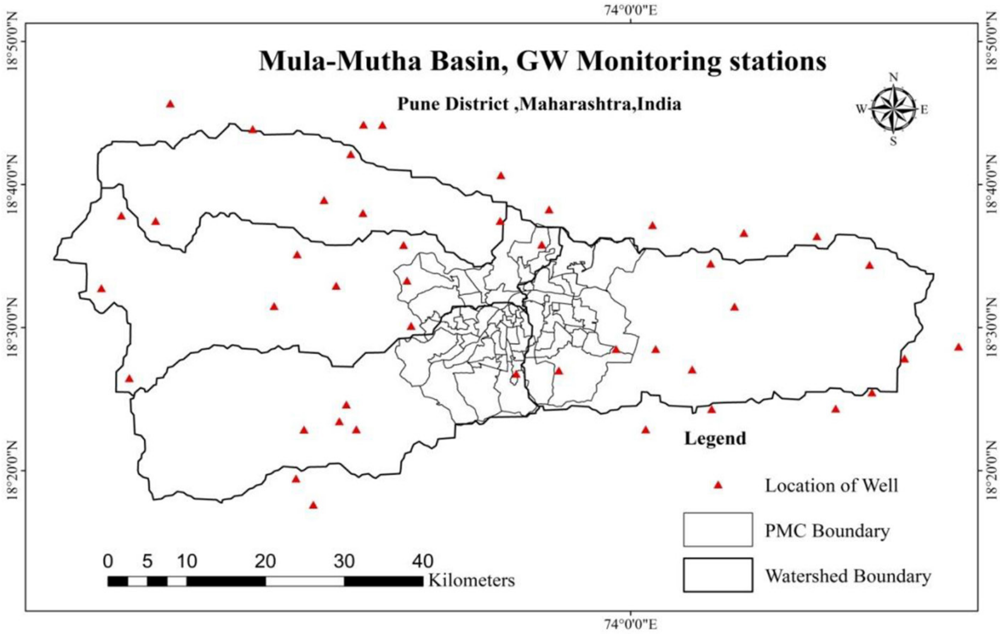

Figure 19. Well monitoring stations

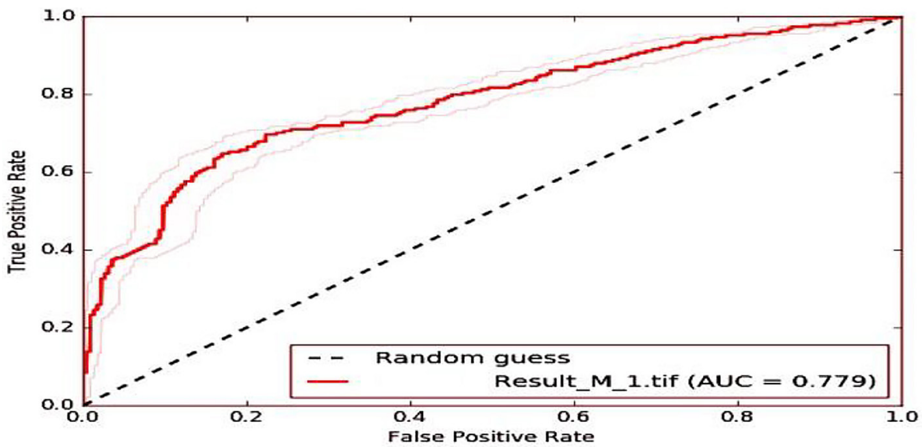

Figure 20. Area under curve for validation

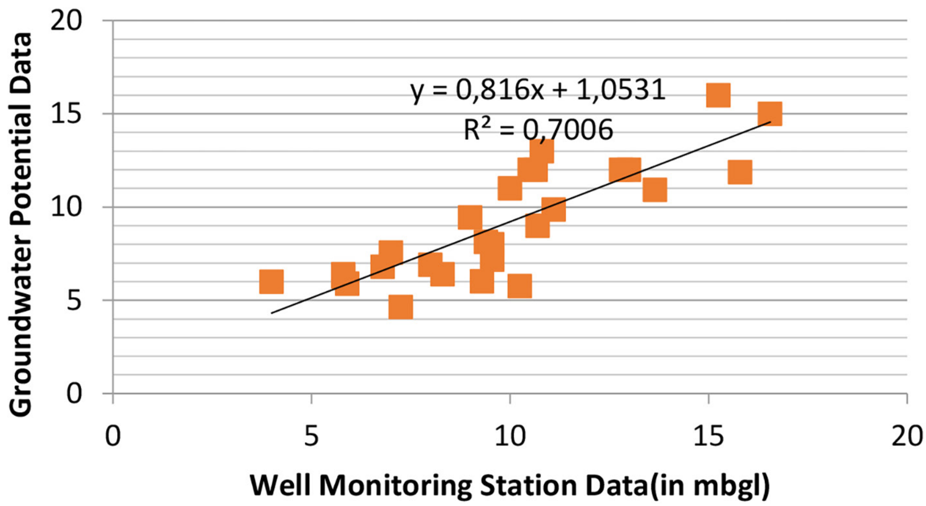

Figure 21. Correlation of groundwater potential map and well data

CONCLUSIONS

The study was conducted using the six factors that affect groundwater potential. These spatial factors are integrated with fuzzy TOPSIS weights in the ArcGIS Pro environment. The predicted groundwater potential delineation using this technique indicated that 31% of the area has good groundwater potential, 41% has moderate potential, and 28% has low potential across the Pune catchment. This confirmed that water level, soil, slope, geology, rainfall-runoff, and land use and land cover have a significant impact on the spatial variability of groundwater potential.

By validation of the groundwater potential map with well data, it is observed that GIS-based Fuzzy TOPSIS techniques constitute a powerful framework that explicitly distinguishes between benefit and cost criteria during normalization, ensuring that higher normalized values consistently reflect variations in groundwater. Systematically incorporating uncertainty and variability in both criteria weights and decision matrix values, thereby reducing the influence of individual subjectivity on the final ranking to provide the best solution and significantly supporting the hypothesis.

Urban growth and human activities in the Mula-Mutha basin increase pressure on groundwater resources. Groundwater potential map plays a vital role in meeting the population's water needs and for regularised recharge strategies as a core requirement for sustainable water management. Groundwater potential zone maps provide a scientific basis for integrating groundwater into Pune's urban and peri-urban water supply system and policy reformation.

REFERENCES

1. ACWADAM. (2019). *Urban groundwater management: Pune city pilot initiative*. Advanced Center for Water Resources Development and Management (ACWADAM). https://www.acwadam.in/
2. Advanced Center for Water Resources Development and Management (ACWADAM) & Pune Municipal Corporation. (2022). *Unravelling Pune's aquifers: Framework for groundwater management and governance*. https://www.acwadam.in/
3. Advanced Center for Water Resources Development and Management (ACWADAM) & Pune Municipal Corporation. (2022). *Unravelling Pune's aquifers: Framework for groundwater management and governance*. https://www.acwadam.in/
4. Aouragh, M. H., Essahlaoui, A., El Ouali, A., El Hmaidi, A., Kamel, S. (2016). Groundwater potential of Middle Atlas plateaus, Morocco, using fuzzy logic approach, GIS and remote sensing. *Geomatics, Natural Hazards and Risk, 8*(2), 194–206. https://doi.org/10.1080/19475705.2016.1181676
5. Bogale, A. (2021). Morphometric analysis of a drainage basin using geographical information system in Gilgel Abay watershed, Lake Tana Basin, upper Blue Nile Basin, Ethiopia. *Applied Water Science*, *11*(7), 122.
6. Burayu, D. G., Karuppannan, S., Shuniye, G. (2025). Geospatial mapping of groundwater potential zones using multi-criteria decision analysis and GIS fuzzy logic in Dabus Sub-Basin, western Ethiopia. *Quaternary Science Advances, 18*, 100275. https://doi.org/10.1016/j.qsa.2025.100275.
7. Chen, M., Zhang, S., Liu, S., Li, M., Zhang, T., Wu, T., Bu, X. (2025). Mapping the groundwater potential zones in mountainous areas of Southern China using GIS, AHP, and fuzzy AHP. *Scientific Reports, 15,* 17159. https://doi.org/10.1038/s41598-025-62024-5
8. Choudhari, P. P., Nigam, G. K., Singh, S. K., Thakur, S. (2018). Morphometric based prioritization of watershed for groundwater potential of Mula river basin, Maharashtra, India. *Geology, Ecology, and Landscapes*, *2*(4), 256–267.
9. Forootan, E. (2025). The integrated fuzzy AHP and fuzzy logic techniques for mapping and prioritizing groundwater potential zone based on water quality. *Environmental Monitoring and Assessment, 197*, 698. https://doi.org/10.1007/s10661-025-XXXXX
10. Gao, J., Alasgah, A. A., Ahmad, I., Nahas, F., Dar, M. A., Zelenakova, M., Sisay, M., Zewdu, G. S. (2025). Integration of fuzzy logic and geographic weighted regression modeling for enhanced groundwater potential mapping using remote sensing and GIS. *Environmental Sciences Europe, 37,* 135. https://doi.org/[insert DOI]
11. Gao, L., Connor, J. D., Dillon, P. (2014). The economics of groundwater replenishment for reliable urban water supply. *Water*, *6*(6), 1662–1670.
12. Groundwater Surveys and Development Agency (GSDA). (2018). *Groundwater information Pune district report (2017–2018)*. Government of Maharashtra, Water Supply and Sanitation Department. https://gsda.maharashtra.gov.in/
13. Guug, S. S., Abdul-Ganiyu, S., Kasei, R. A. (2020). Application of SWAT hydrological model for assessing water availability at the Sherigu catchment of Ghana and Southern Burkina Faso. *HydroResearch*, *3*, 124–133.
14. Horton, R. E. (1932). Drainage basin characteristics. *Transactions, American Geophysical Union, 13*(1), 350–361. https://doi.org/10.1029/TR013i001p00350
15. Horton, R. E. (1945). Erosional development of streams and their drainage basins: Hydrophysical

approach to quantitative morphology. *Geological Society of America Bulletin, 56*(3), 275–370. https://doi.org/10.1130/0016-7606(1945)56[275:EDOSAT]2.0.CO;2

16. https://waterdata.usgs.gov/nwis/gw
17. https://www.usgs.gov/mission-areas/water-resources
18. Hughes, J. D., Langevin, C. D., White, J. T. (2015). MODFLOW-based coupled surface water routing and groundwater-flow simulation. *Groundwater*, *53*(3), 452–463.
19. Hybel, A. M., Godskesen, B., Rygaard, M. (2015). Selection of spatial scale for assessing impacts of groundwater-based water supply on freshwater resources. *Journal of environmental management*, *160*, 90–97.
20. Jeihouni, M., Toomanian, A., Mansourian, A. (2020). Decision tree-based data mining and rule induction for identifying high quality groundwater zones to water supply management: a novel hybrid use of data mining and GIS. *Water Resources Management*, *34*, 139–154.
21. Kamaraj, P., Subramani, D., Kucher, D. E., Aslam, M., Said, Y., Tariq, A. (2025). Rainfall-runoff estimation for groundwater enhancement through remote sensing and GIS-based geostatistical model. *Hydrological Processes, 39*(6), e70180. https://doi.org/10.1002/hyp.70180
22. Kore, N. B., Ravi, K., Patil, S. B. (2017). A simplified description of fuzzy TOPSIS method for multi criteria decision making. *International Research Journal of Engineering and Technology (IRJET)*, *4*(5), 2047–2050.
23. Mijalkovski, S., Peltecki, D., Despodov, Z., Mirakovski, D., Adjiski, V., & Doneva, N. (2023). Application of the Fuzzy TOPSIS method for selecting an underground mining method. *Acta Montanistica-Slovaca*, *28*(2), 465–478.
24. Moshfika, M., Biswas, S., Mondal, M. S. (2022). Assessing groundwater level declination in Dhaka city and identifying adaptation options for sustainable water supply. *Sustainability*, *14*(3), 1518.
25. Muralitharan, J., Palanivel, K. (2019). Sub-watershed wise runoff modeling using drainage morphometric analysis in Karur District, Tamil Nadu, India through remote sensing and GIS techniques. *Journal of Remote Sensing & GIS*, *10*(1), 1–9. https://www.researchgate.net/publication/334207432
26. Olivier, D. W., Xu, Y. (2019). Making effective use of groundwater to avoid another water supply crisis in Cape Town, South Africa. *Hydrogeology Journal*, *27*(3), 823–826.
27. Patel, P., Mehta, D., Sharma, N. (2022). A review on the application of the DRASTIC method in the assessment of groundwater vulnerability. *Water Supply*, *22*(5), 5190–5205.
28. Radulović, M., Brdar, S., Mesaroš, M., Lukić, T., Savić, S., Basarin, B.,..., Pavić, D. (2022). Assessment of groundwater potential zones using GIS and fuzzy AHP techniques – A case study of the Titel Municipality (Northern Serbia). *ISPRS International Journal of Geo-Information*, *11*(4), 257.
29. Ray, S. K. (2025). Unveiling groundwater gems: A GIS-powered fusion of AHP and TOPSIS for mapping groundwater potential zones. *Groundwater for Sustainable Development, 25,* 101431. https://doi.org/10.1016/j.gsd.2025.101431
30. Samal, P., Swain, P. C., Samantaray, S. (2025). Assessment of runoff using GIS based SCS-CN approach on Badanadi sub watershed of Rushikulya basin. *Proceedings of the Indian National Science Academy.* https://doi.org/10.1007/s43538-025-00505-z
31. Saranya, T., Saravanan, S. (2020). Groundwater potential zone mapping using analytical hierarchy process (AHP) and GIS for Kancheepuram District, Tamilnadu, India. *SN Applied Sciences, 6*, 1105–1122. https://doi.org/10.1007/s42452-020-2913-5
32. SChumm, S. A.(1956). Evolution of drainage systems & slopes in Badlands at Perth, New Jersey. *Bulletin of the Geological Society of America, 67*(5), 597–646. https://doi.org/10.1130/0016-7606(1956)67[597:EODSAS]2.0.CO;2
33. Singha, S., Das, P., Singha, S. S. (2021). A fuzzy geospatial approach for delineation of groundwater potential zones in Raipur district, India. *Groundwater for sustainable development*, *12*, 100529.
34. U.S. Geological Survey. (2025). *Water data for the Nation*.
35. U.S. Geological Survey. (2025). *Water resources mission area.*
36. United States Department of Agriculture, Natural Resources Conservation Service. (2009). *Chapter 2: Estimating runoff volume and peak discharge*. In *Part 650 engineering field handbook* (National engineering handbook). USDA.
37. Vouillamoz, J. M., Valois, R., Lun, S., Caron, D., Arnout, L. (2016). Can groundwater secure drinking-water supply and supplementary irrigation in new settlements of North-West Cambodia? *Hydrogeology journal*, *24*(1), 195.
38. World Bank. (2025 *Water*. https://www.worldbank.org/en/topic/watersupply
39. Xiao, R., He, X., Zhang, Y., Ferreira, V. G., Chang, L. (2015). Monitoring groundwater variations from satellite gravimetry and hydrological models: A comparison with in-situ measurements in the mid-atlantic region of the United States. *Remote Sensing*, *7*(1), 686–703.
40. Zhu, H., Alasgah, A. A., Ahmad, I., Dar, M. A., Zelenakova, M., Sisay, M., Zewdu, G. S., Youssef, Y. M. (2025). Exploring groundwater potential: Combining GIS techniques with OLS, GWR, and exploratory regression. *Journal of Hydrology: Regional Studies*, *61*, 102564. https://doi.org/10.1016/j.ejrh.2025.102564