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Delineation of groundwater potential zones with Analytic Hierarchy Process based geospatial modelling approach in metropolitan expanse

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ABSTRACT

Groundwater is a vital natural resource that is essential for the survival of humans and ecosystems alike. However, the depletion of the global water table has become a significant cause for concern. Hence, it is imperative that groundwater monitoring is managed in a systematic and sustainable way to ensure its long-term availability. Geospatial mapping is considered one of the most crucial tools in the field of subsurface water studies because it aids in finding, observing, and monitoring water levels in underground reservoirs. The purpose of this study is to classify the potential areas for groundwater use for agricultural development in the metropolitan district of Lahore in Punjab, Pakistan. To delineate groundwater potential areas, ten parameters are used including groundwater depth, geology, lineament density, slope, soil type, rainfall, drainage density, Topographic Wetness Index, land use/land cover and roughness. The weighted overlay technique is used to integrate the selected ten parameters for the delineation of groundwater potential zones. The contribution and influence of each parameter on groundwater recharge are considered, and potential groundwater recharge areas are classified into five classes ranging from very low to very high. Finally, the efficiency of the modeled groundwater potential zones is validated with the *in-situ* groundwater depth data from 40 wells distributed in the study area. The classification of recharge areas into distinct categories provides a useful framework for decision-making, enabling policymakers and stakeholders to prioritize areas for conservation and management based on their potential for groundwater recharge.

Keywords: Analytic Hierarchy Process; Groundwater potential zone; Weighted overlay analysis; Geographic Information System; Remote sensing

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1. Introduction

Groundwater is a crucial natural resource that plays a vital role in supporting economic growth and providing a reliable source of drinking water, both in rural and urban areas [1]. Water is critical for human life on the earth's surface [2], but freshwater accounts for only 2.5% of the total water on the planet, and only one-third of it is suitable for human consumption. Groundwater is a major source of fresh drinking water in residential areas [3]. It is necessary to keep track of groundwater resources to manage groundwater reduction crises and the effects of climate change on water resources [4]. Whereas Pakistan's total water resources have been declining over the years, from 5,000 m^3/capita in 1950 to 1,100 m^3 in 2005. This trend is expected to continue, with projections suggesting that by 2025, the per capita availability of water in Pakistan will further decline to 800 m^3 [5]. Hence, the identification of new potential groundwater zones is of utmost importance to meet the growing demands for water in Pakistan. The dwindling water resources have led to water shortages and increased competition for limited water supplies, particularly in areas where agriculture is the primary source of livelihoods. Whereas the identification of new groundwater resources can provide an opportunity to supplement existing water supplies and mitigate the impacts of water scarcity. The traditional methods used for the delineation of groundwater resources are expensive and laborious. But on the other hand, Remote Sensing and Geographic Information System (GIS) can be employed for the search of groundwater due to it functionality for drawing the groundwater recharge areas and can identify and differentiate several structures, including rocks, water, and vegetation [6].

In recent years, GIS tools have been integrated with Multi-Criteria Decision-Making (MCDM) analyses to support complex decision-making processes and Analytic Hierarchy Process (AHP) is one such MCDM technique that has been widely used in groundwater studies to evaluate the relative importance of various criteria and factors affecting groundwater potential and recharge [7]. These methods can be integrated into decision structure, appropriateness, and precision [8]. GIS and MCDM techniques have been used by various researchers to map groundwater recharge zones around the world [1,9]. Thus, the most used and integrated application of AHP technology is groundwater potential mapping and identifying suitable areas for artificial recharge [10,11]. Another advantage of the AHP technique is that it can be applied even when there is limited or insufficient availability of valid data [12]. A systematic AHP technique is applied to restrict the groundwater potential zone for the Uttar Pradesh region, India [13]. Similarly, Yeh et al. [14] employed AHP methodologies to calculate groundwater potentials by combining five contributing parameters: land cover/land use, lithology, slope, lineament density, and drainage density. The AHP is first proposed by Saaty [15] and is utilized to assign weights to each of the layers [16]. In the field of groundwater research, AHP is a basic tool to utilize MCDM procedures [17]. In this research the AHP modeling approach has been used with different parameters for groundwater potential zoning. In the light of applied methodology, the groundwater potential zone determination is assessed in evocative and technical.

1.1. Study area

Lahore is a significant city in Pakistan and is considered the commercial, cultural, and educational hub of the country as well as the country's second-largest metropolitan district by population and the provincial capital of the Punjab Province [18]. Lahore district lies between 31°16′ N to 31°41′ N and between 74°01′ E to 74°39′ E [19] covering an area of 1,772 km^2 (Fig. 1). The elevation is between 150 and 200 m above sea level. Lahore is geographically bordered by Kasur district to the south, Nankana district to the southwest, Sheikhupura district to the north and west, and India to the east. To the northwest, the city is delineated by the flowing waters of the River Ravi. Groundwater is a crucial source of water for most of the Lahore's population, which uses it for various purposes such as drinking, agriculture, and domestic activities. The rapid increase in population, urbanization, and industrialization has put tremendous pressure on the city's groundwater resources, leading to a decline in water quality and quantity. Therefore, it is imperative to conduct a comprehensive assessment of the city's groundwater situation and evaluate the present condition of groundwater resources across various areas within the metropolitan expanse.

2. Materials and methods

Remote sensing data with varying spectral, radiometric, and temporal resolutions can be used to provide precise, cost-effective, automatic, near-real-time information, even in the most remote locations on the planet [20]. The primary goal of this study is to use a multi-influencing factor approach to determine potential groundwater zones in the study area. Whereas, the research focus on the groundwater potential zone identification in metropolitan area. There for the research divided into the following steps (1) data gathered and generated, (2) applied multiple factors on data set using AHP modeling approach, (3) the groundwater potential indexed also applied and the hierarchy of all processes has also been showing in flow chart (Fig. 2).

2.1. Datasets

The satellite data is acquired from Landsat-8 satellite to extract the land use/land cover (LULC) of the study area. The Digital Elevation Model (DEM), Shuttle Radar Topographic Mission (SRTM), has also been used in this research with a spatial resolution of 30 m. For this research, all relevant data is obtained from several departments and sources as mentioned in Table 1. LULC and lineament density data are prepared from Landsat-8's Operational Land Imager (OLI) sensor. Geological data of the study area is collected from the Geological Survey of Pakistan, dated 2007. Soil data is obtained from the Water and Power Development Authority (WAPDA), Lahore and rainfall data for 2020 is acquired from Climatic Research Unit web portal (https://crudata.uea.ac.uk/cru/data/hrg/). DEM is used to calculate several topographic indicators, that is, slope, drainage density, Topographic Wetness Index (TWI), and roughness. Furthermore, the location of the tube well is collected from the Global Positioning System (GPS) based field survey to validate the result.

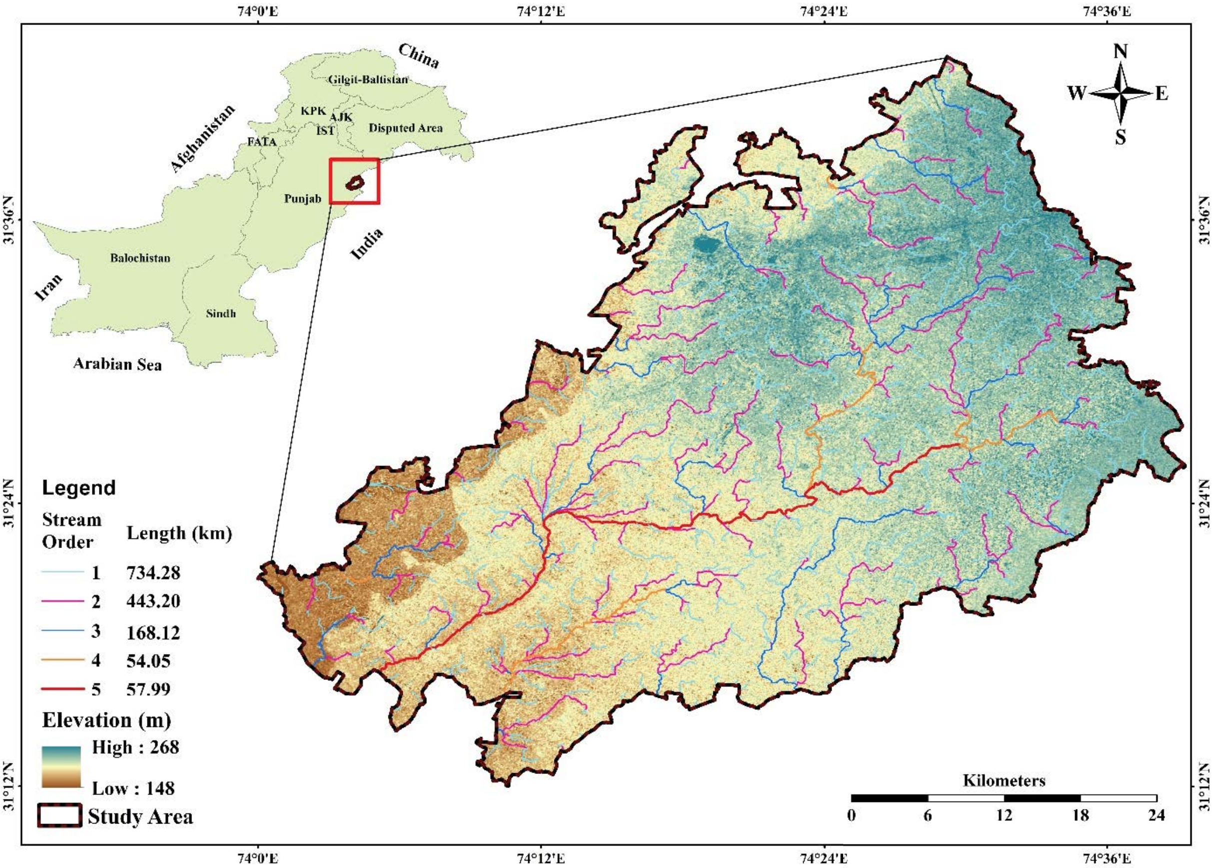

Fig. 1. Study area map of metropolitan.

Although, to classify Groundwater potential Zones (GWPZ), ten important input factors are chosen based on literature: groundwater depth, geology, lineament density, slope, soil types, LULC, rainfall, drainage density, TWI, and roughness. The parameter with a greater weight indicates a higher impact on groundwater, while the parameter with a lower weight suggests a lower impact. The weight for each layer is assigned according to a Saaty scale of relative importance (1–9). The process of assigning weights involves a review of several past studies, as well as incorporating the expertise of experts in the field. The detailed description of the data and its processing is shown in Fig. 2.

2.2. Analytical hierarchy process

Different indicators contribute differently to the incidence and recharge of groundwater [21]. One of the best techniques for decision making using a number of criteria is the AHP [22]. AHP is an analysis that considers how important the parameters are in relation to one another. This approach, which is dependent on a paired comparison, allows to analyze and evaluate issues that have both quantitative and qualitative components. AHP procedure starts with the identification and prioritization of various criteria, such as goals and other alternatives. As a first step, the hierarchy is created by identifying the elements as well as their relationships. The development of a priority scale in the analytical hierarchy process is based on the concept of measurement through paired comparisons of various aspects [23]. Because statistical measurements for a given weight consistency can be assessed and corrected as needed, AHP performs better than other approaches [24]. The hierarchy of the system is first established while utilizing AHP, and then the elements are analyzed and the consistency of the evaluation is verified. Each parameter is assigned a weight before being normalized. Thematic layers and their features are given weights on a scale of 1 to 9 based on how they might affect groundwater potential (Table 2). The normalized weights combined with the relative weight are determined using a pair-wise comparison matrix, including the thematic layers and their variables, to calculate their percentage of impact. By dividing every element in a comparison matrix column by the total of all the items in that column, they created the relative weight matrix. The total of the factors in each column of the relative weight matrix is equal to one. The pairwise comparison matrix of the groundwater thematic layer is obtained from AHP techniques (Table 3). Weights are normalized, and the weights for every layer are calculated by the eigenvector technique (Table 4).

Calculation of the consistency ratio (CR) involves a number of steps. First, the principal Eigenvalue (λ) and second, the consistency index (CI) is considered from the Eq. (1). λ_{max} denotes a function for the matrix deviation from consistency [25]. A pairwise matrix is consistent only when

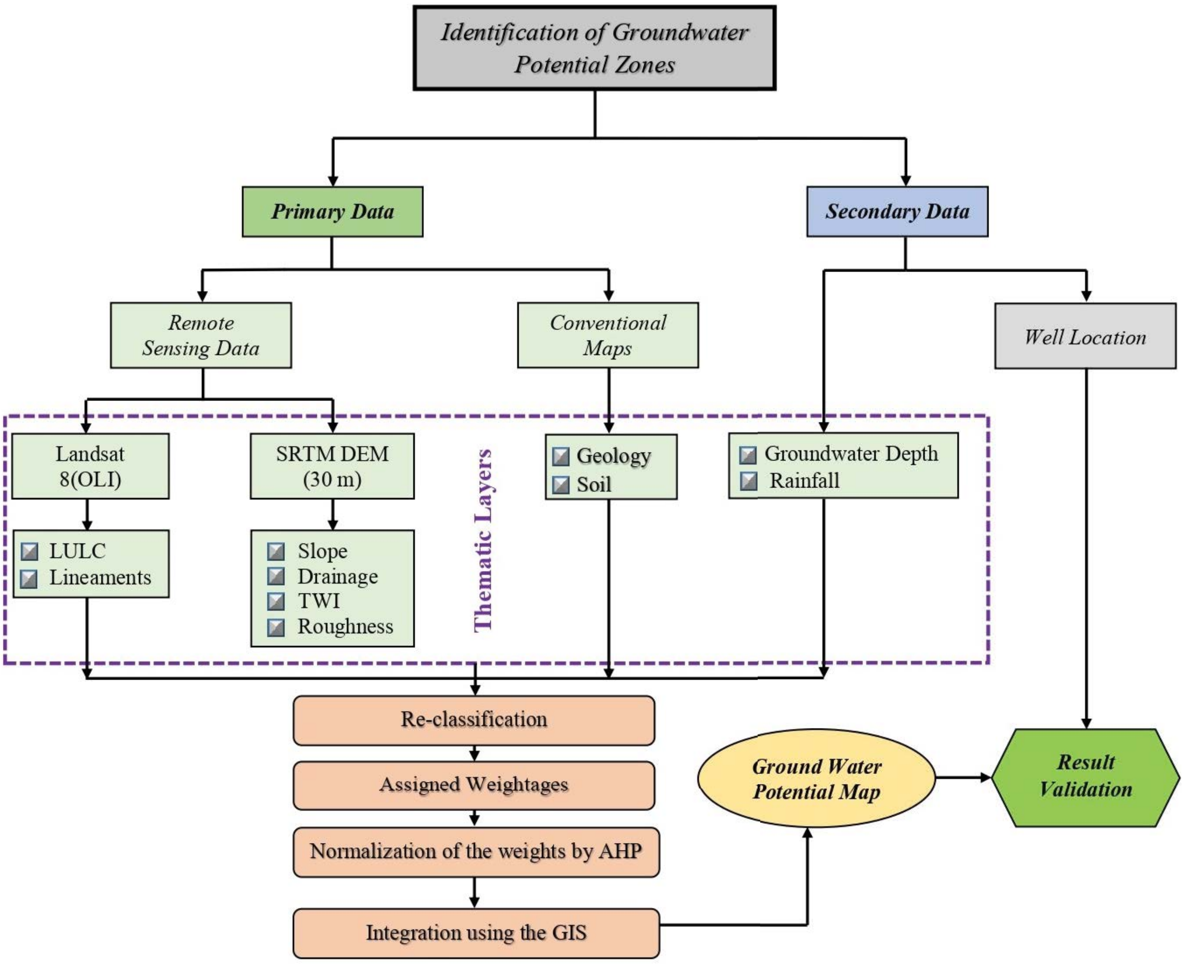

Fig. 2. Overview of the methodological framework.

Table 1
Datasets used for the extraction of required thematic layers

S. No.	Data	Source
1	Landsat-8	United State Geological Survey (https://earthexplorer.usgs.gov)
2	DEM (SRTM)	
3	Slope	Derived from DEM
4	Drainage density	
5	Topographic Wetness Index	
6	Roughness	
7	Groundwater depth	Mahmood et al. [3]
8	Lineament density	Derived from Landsat-8
9	Geology	Geological Survey of Pakistan
10	Soil	WAPDA, Lahore, Pakistan
11	Rainfall	Climatic Research Unit (https://crudata.uea.ac.uk/cru/data/hrg/)
12	Tube well locations	Field survey

λ_{max} is equal to or more than the number of thematic layers examined; otherwise, a new matrix will be generated [26]. Normalized weights are verified for consistency by calculating the consistency ratio [27].

$$\text{CI} = \frac{\left(\lambda_{max} - n\right)}{\left(n-1\right)} \tag{1}$$

where n indicates the total number of thematic layers used.

λmax = 10.37
CI = (10.37–10)/(10–1) = 0.041
CR = CI/RI, where RI is a random consistency index value
CR = 0.041/1.49 = 0.02

If CR value is less than 0.1, the weight is acceptable. If the value is greater than 0.1, then re-evaluation of the comparison matrix is required. If CR value is equal to 0, it refers that the matrix is good for further analysis. These ten factors are input into GIS software, where relative scores and weights are assigned to the corresponding thematic raster's [28]. To calculate the GWPZ map, all 10 layers, after assigning ranks and weights, are integrated.

Table 3 displays the normalized weights of every thematic layer and their corresponding total weight. The maximum weight shows the most important parameter/thematic layer, and the minimum weightage denotes the least important parameter.

2.3. Groundwater potential index

Groundwater Potential Index (GWPI) is defined as the relative weights obtained from AHP techniques (Table 5) assigned to every thematic layer to calculate the cumulative weight of the respective thematic layer.

Table 2
Random index values [29]

No.	Random index value
1	0
2	0
3	0.58
4	0.9
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

Eq. (2) is utilized to calculate the groundwater potential map [30].

$$\begin{aligned} \text{GWPI} = &\left(\text{GWwGWr}\right)+\left(\text{GEwGEr}\right)+\left(\text{LDwLDr}\right)\\ &+\left(\text{SLwSLr}\right)+\left(\text{SOwSOr}\right)+\left(\text{LUwLUr}\right)\\ &+\left(\text{DDwDDr}\right)+\left(\text{RFwRFr}\right)\\ &+\left(\text{TWIwTWIr}\right)+\left(\text{ROwROr}\right) \end{aligned} \tag{2}$$

where GWPI (groundwater potential index), GW (groundwater depth), GE (geology), LD (lineament density), SL (slope), SO (soil types), LU (land use and land cover), DD (drainage density), RF (rainfall), TWI, RO (roughness), w (weightage), and r (rank) are used with abbreviations [31]. Depending on the range of GWPI values, GWPZ in an area that can be classified into five categories.

3. Results and discussion

In this research groundwater potential in the metropolitan expanse of Lahore district is estimated with the help of different datasets and AHP. Results against each thematic layer/parameter is discussed as follows. This study will also be helped in Lahore for sustainable water management under the used criteria. It has great potential to eliminate the area where groundwater issues exist under the following indicators results as discussed below in detail. Moreover, for the future implication regarding potential zoning of groundwater its much beneficent in agricultural practices.

3.1. Depth to water table

Fig. 3 shows that depression is greater in urban areas. The level of aquifers is decreasing because of high levels of water consumption due to population growth. As reported in many studies, there is a zone of depression around the Shadman zone [2] in the study area. This refers that the inner city of our study area has low GWPZ due to the high depth of the water table. Similarly, as the water table is higher in the suburbs of the study area, the groundwater potential is greater. For the calculation of water table depth, the required data is obtained from the work of Mahmood et al.

Table 3
Pair-wise comparison matrix of 10 thematic layers

	Groundwater depth	Geology	Lineament density	Slope	Soil types	LULC	Drainage density	Rainfall	TWI	Roughness
Groundwater depth	1	2	2	3	4	5	6	7	8	9
Geology	1/2	1	2	2	3	4	5	6	7	8
Lineament density	1/2	1/2	1	2	2	3	4	5	6	7
Slope	1/3	1/2	1/2	1	2	2	3	4	5	6
Soil types	1/4	1/3	1/2	1/2	1	2	2	3	4	5
LULC	1/5	1/4	1/3	1/2	1/2	1	2	2	3	4
Drainage density	1/6	1/5	1/4	1/3	1/2	1/2	1	2	2	3
Rainfall	1/7	1/6	1/5	1/4	1/3	1/2	1/2	1	2	2
TWI	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1/2	1	2
Roughness	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1/2	1

Table 4
Calculation of normalized weights for 10 thematic layers

	Groundwater depth	Geology	Lineament density	Slope	Soil types	LULC	Drainage density	Rainfall	TWI	Roughness	Weight	Influence (%)
Groundwater depth	0.300	0.322	0.282	0.302	0.290	0.269	0.247	0.226	0.208	0.191	0.264	26.4
Geology	0.150	0.322	0.282	0.201	0.218	0.215	0.205	0.194	0.182	0.170	0.214	21.4
Lineament density	0.150	0.080	0.141	0.201	0.145	0.161	0.164	0.161	0.156	0.149	0.151	15.1
Slope	0.100	0.080	0.070	0.101	0.145	0.108	0.123	0.129	0.130	0.128	0.111	11.1
Soil types	0.075	0.054	0.070	0.050	0.073	0.108	0.082	0.097	0.104	0.106	0.082	8.2
LULC	0.060	0.040	0.047	0.050	0.036	0.054	0.082	0.065	0.078	0.085	0.060	6.0
Drainage density	0.050	0.032	0.035	0.034	0.036	0.027	0.041	0.065	0.052	0.064	0.044	4.4
Rainfall	0.043	0.027	0.028	0.025	0.024	0.027	0.021	0.032	0.052	0.043	0.032	3.2
TWI	0.038	0.023	0.023	0.020	0.018	0.018	0.021	0.016	0.026	0.043	0.025	2.5
Roughness	0.033	0.020	0.020	0.017	0.015	0.013	0.014	0.016	0.013	0.021	0.018	1.8
Sum	1	1	1	1	1	1	1	1	1	1	1	100

Table 5
List of parameters and Analytic Hierarchy Process weight and ranking

Parameter	Weight	Influence (%)	Sub-criteria	Score	Area (km^2)
Groundwater depth (m)	0.264	26.4	<6.9	9	207.58
			6.9–10.8	8	289.83
			10.8–14.7	7	566.56
			14.7–18.6	6	145.54
			18.6–22.5	5	46.6
			22.5–26.4	4	72.39
			26.4–30.3	3	79.48
			30.3–34.2	2	175.16
			34.2–38.1	2	111.65
			>40	1	45.73
Geology	0.214	21.4	Unconsolidated sand, and silty sand	2	100.35
			Unconsolidated sand, silt and loam	4	12.51
			Sand, silty sand and loamy clay	5	163.47
			Loamy clay and silt	7	395.43
			Silty clay, clay and silt	9	53.34
			Unconsolidated sand, and silty sand	2	100.35
Lineament density (km/km^2)	0.151	15.1	Very low (0–0.93)	1	303.17
			Low (0.94–1.72)	3	421.91
			Moderate (1.73–2.46)	5	508.95
			High (2.47–3.34)	7	378.24
			Very high (3.35–5.49)	9	126.38
Slope (°)	0.111	11.1	Very low (0–2)	9	613.34
			Low (3–4)	7	636.82
			Moderate (5–6)	5	368.63
			High (7–10)	3	100.81
			Very high (11–44)	1	11.4
Soil types	0.082	8.2	Sandy loam	5	140.75
			Loamy	7	174.25
			Clay loam	4	1093.46
			Silty clay loam	2	332.16

Table 5 (Continued)

Table 5

Parameter	Weight	Influence (%)	Sub-criteria	Score	Area (km^2)
LULC	0.060	6.0	Built up	1	810.95
			Barren land	3	19.65
			Vegetation	7	902.18
			Water	9	7.82
Drainage density (km/km^2)	0.044	4.4	Very low (0–48)	9	224.76
			Low (49–96)	7	493.58
			Moderate (97–145)	5	550.33
			High (146–193)	3	367.46
			Very high (194–241)	1	102.96
Rainfall (mm)	0.032	3.2	Very low (657–696)	1	249.36
			Low (697–726)	3	247.76
			Moderate (732–751)	5	335.36
			High (7252–774)	7	669.59
			Very high (775–821)	9	237.9
TWI	0.025	2.5	Very low (–8.09—3.91)	1	817.38
			Low (–3.9—1.66)	3	389.03
			Moderate (–1.65—0.59)	5	327.72
			High (0.6–3.56)	7	156.6
			Very high (3.57–12.4)	9	40.24
Roughness	0.018	1.8	Very High (0.11–0.36)	9	170.14
			High (0.37–0.47)	7	489.87
			Moderate (0.48–0.56)	5	641.91
			Low (0.57–0.67)	3	373.11
			Very low (0.68–0.89)	1	71.64

[3]. The shallow water table is given a high ranking because the water depth is lower. The depth > 40 m is assigned a lower rating because the water depth is very high, and all other in-between values are ranked accordingly.

3.2. Geology

Geological formation influences the existence and distribution of groundwater in any region. A geological map obtained from the Geological Survey of Pakistan (developed in 2007) is digitized and reclassified into 6 geological types: (1) silty clay, clay and silt, (2) loamy clay and silt, (3) silt and silty clay, (4) sand, silty sand and loamy clay, (5) unconsolidated sand, and silty sand, and (6) unconsolidated sand, silt and loam. These geological types are used to define different geological units within the study area.

3.2.1. Lineament density

Lineaments are organized into curvilinear or linear features. They can be identified from satellite imagery by their linear placement [32]. Linear is a region of cracks and faults that increases secondary porosity [33]. An automatic lineament extraction process is used to obtain Lineaments of the study area from Landsat-8 satellite image [34]. Lineament is used in mineral exploration [35], geothermal resources [36], soil erosion studies [37], and for the identification of GWPZ [38,39]. Lineaments are extracted from Landsat-8 images using Geomatica software suite. Lineaments are saved as vector format. Lineament density map was prepared using line density tool in ArcGIS software suite. Lineament density maps are reclassified into five categories: very low (0.93), low (0.94–1.72), moderate (1.73–2.46), high (2.47–3.34), and very high (3.35–5.49). High lineament density is assigned to high weight, and low lineament density is assigned to low weight [40].

3.3. Slope

The slope is a particularly important topographic feature that indicates how the ground surface is shaped and gives vital information about the geological composition at a various spatial scale [41]. Slope, especially in mountainous regions, is one of the regulatory elements for GW recharge [42]. In this research slope map is generated using SRTM DEM in ArcGIS software suite [43,44]. The study area's slope is divided into five different categories: very low slope (0°–2°), low slope (3°–4°), moderate slope (5°–6°), high slope (7°–10°), and very high slope (11°–44°). Very high slopes provide less recharge because water obtained from rain flows quickly down a steep slope during the rainy season. Groundwater recharge is generally high in flat sloping areas, whereas infiltration is low in steep areas [9,45].

3.4. Soil

Soil hydraulic properties are critical in the movement of surface water through the soil to the water table [46]. Soil

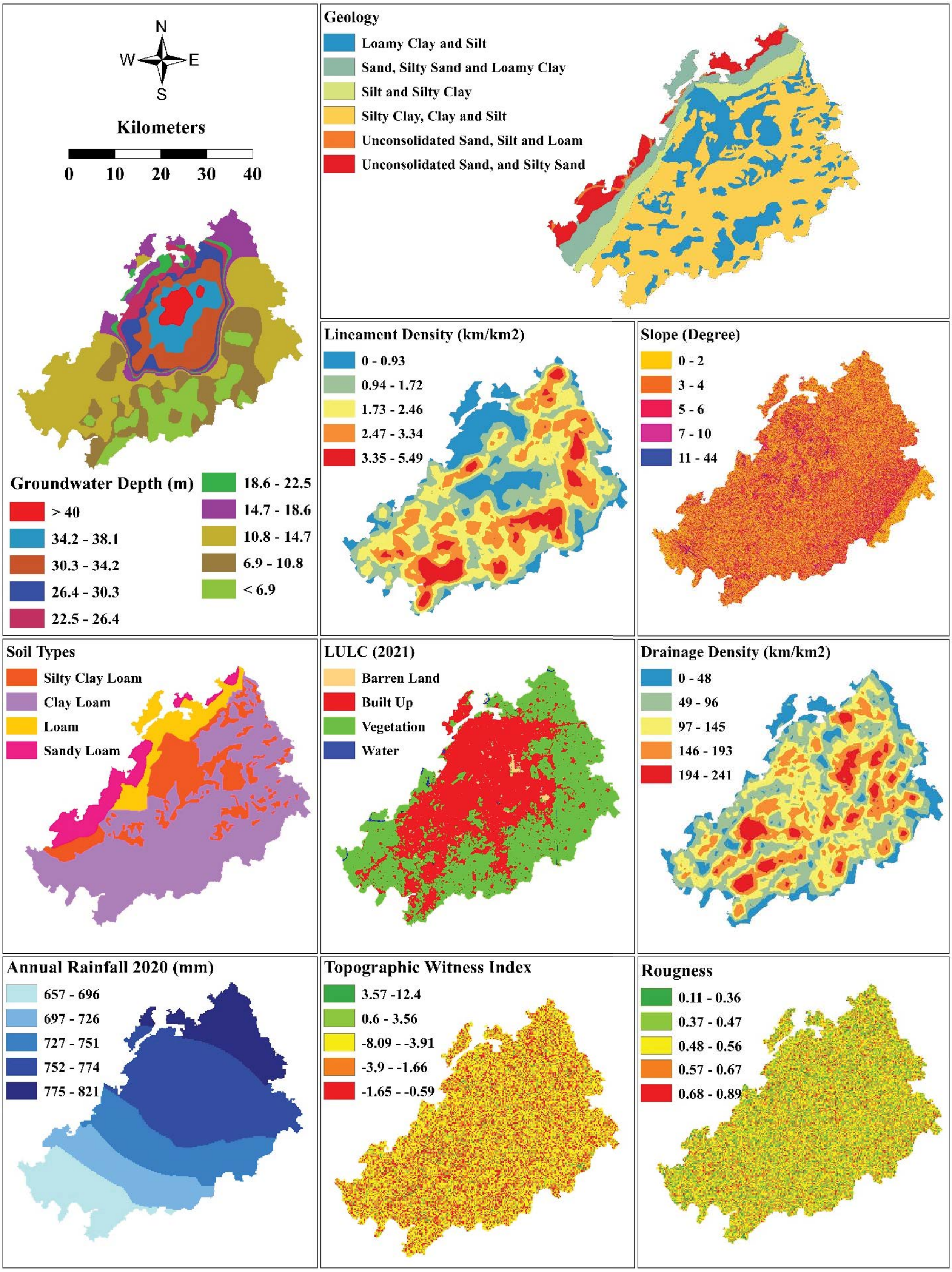

Fig. 3. Representation of comprehensive thematic layers of Lahore.

is the top layer on earth and acts as a filtration medium for water to penetrate. Water-holding capacity depends on the type of soil as well as the ability to access it. If an area has highly permeable soils, it has more potential to store groundwater than areas of soil with low porosity. The soil map of the study area is obtained from the WAPDA in Lahore, which reflects the four classes of soil types. Clay loam is found in 62.50% of the total area, and 19.03% of the area has silty clay loam. The loam is found to cover 9.27% of the district of Lahore. Sandy loam is found to cover 5.98% of the study area. The soil weight is assigned according to the penetration rate [47].

3.5. Land use/land cover

LULC provide critical information on soil moisture, infiltration, surface water, groundwater, and so on [33]. "Land use" determines how people use land, while "land cover" represents how land is covered by physical features [10,48]. LULC has a significant effect on groundwater recharge [49]. Supervised image classification techniques are used to derive LULC maps using Landsat-8 image as input. We used supervised image classification technique as it has higher accuracy than unsupervised image classification technique [50]. Four different types of LULC are extracted from the study area: vegetation, built-up, barren land, and water. Water bodies and vegetation assigned very high weightage as it tends to support more groundwater potential. The built-up and barren land represent the moderate and low classes regarding groundwater potential, paying for penetration as compared to surface runoff [51] and according to [52], water has a high infiltration rate.

3.6. Drainage density

The drainage density is an important measure of the linear scale of the topography and the channels' proximity to each other [53]. It is the result of the interaction of the factors controlling surface runoff [54] and indicates the closeness of the spacing between channels and surface features [55]. It is a very important element in calculating the groundwater potential [7]. Drainage density is calculated using SRTM DEM at 30 m resolution. About 33.43% of the entire study area is composed of low and very low drainage density, as it is primarily a plain area. Only 34.29% of the study area has a moderate drainage density while 24.15% has a high drainage density. Only 8.13% of the total study area constitutes a very high drainage density. Factors such as land use, geology, topography, and geomorphology affect drainage density [56]. The maximum drainage density value means the highest chance of runoff, which ultimately results in less purification. The area that has a high drainage density is assigned lower ranking, while the area that has a low drainage density is assigned higher ranking.

3.7. Rainfall

Rainfall is an important factor in the water cycle and is a crucial source of water input for hydrology [7]. Sufficient rainfall is essential to increase the groundwater potential of any region [57] and rainfall is a key source of groundwater recharge [58]. For the year 2020, annual mean rainfall data is obtained from the Climatic Research Unit (https://crudata.uea.ac.uk/cru/data/hrg/). Rainfall is not constant everywhere due to climate change in the region [59]. The annual rainfall in the study area for 2020 ranged from 657 to 821 mm. The rainfall map is generated using inverse distance-weighted interpolation technique in ArcGIS software suite. The map is categorized into five classes based on literature. The rainfall map shows that the upper and central parts of the study area received more rainfall, ranging from 752 to 821 mm, and thus a high weight is assigned to these regions. The lower part of the study area received only 657 to 751 mm and is, hence, assigned low weight.

3.8. Topographic Wetness Index

TWI is used to calculate the topographic control of the hydrologic process and reflect potential groundwater infiltration due to topography [60]. TWI is prepared using the runoff model (TOPModel) to stimulate the hydrologic flow of water across the watershed [61].

$$\mathrm{TWI} = \ln\left(\frac{\alpha}{\tan\beta}\right) \tag{3}$$

α = upslope; β = slope of a topographic gradient. The TWI of the study area varies from –1.65 to 12.4. Based on literature, TWI values are reclassified into five classes, such as (–1.65 – –0.59), (–3.9 – –1.66), (–8.09 – –3.91), (0.6 – 3.56), and (3.57 – 12.4). The TWI has the great importance to the assignee of weights.

3.9. Roughness

The roughness index represents the height of the elevation difference between adjacent cells of DEM [61]. The roughness index describes the undulation of the terrain, the higher the roughness, the higher the undulation, and vice versa. The hilly areas are characteristic of the mountainous region, and the terrain is changing from rugged to flat and flat terrain over the long term due to the process of erosion [47]. The roughness values are categorized into five classes with the help of literature, as (0.111–0.367), (0.368–0.371), (0.472–0.566), (0.567–0.669), and (0.67–0.889). High roughness is assigned to a high weight, and low roughness is assigned to a low weight to enhance the quality of the results.

3.10. Groundwater potential zones

GIS and remote sensing are commonly used globally to identify groundwater potential zones [62]. Proper weight distribution is the main factor in getting the right results [63]. As the variety of layers increases, the accuracy of the result also increases [64]. The most common features used to identify GWPZ are geology, land-use land cover, slope, LD, soils, and drainage density [65]. The accuracy of potential zone map depends on how accurately the weights of each layer are assigned [66]. Many researchers use some of the approaches to provide precise weight to the layer, including AHP technique [1,67,68]. The groundwater potential map is prepared with GIS-based AHP techniques (Fig. 4)

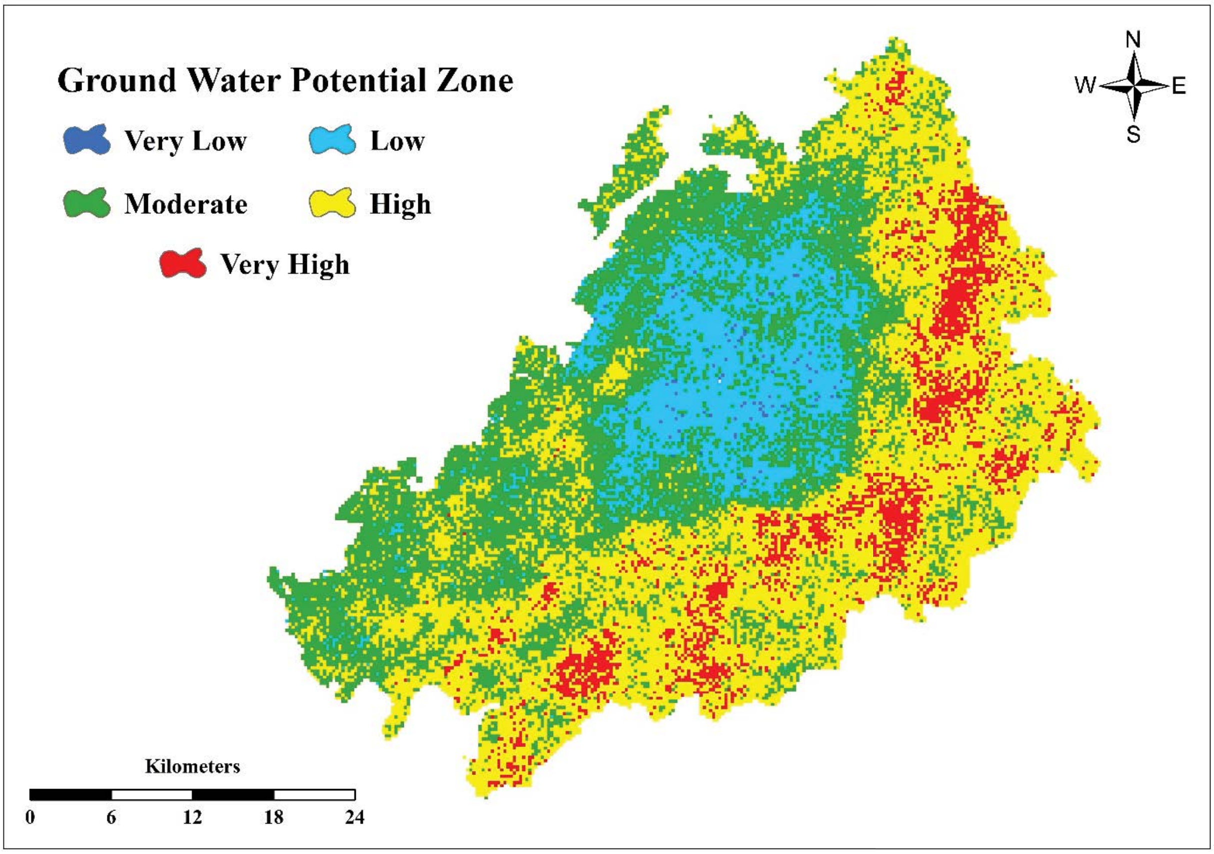

Fig. 4. Groundwater potential zone map.

According to overlay analysis, the GWPI map is classified into five groundwater potential zones: very low (15.49%), low (24.36%), moderate (32.52%), high (26.63%), and very high (1%), respectively (Table 6). The very high groundwater potential zone (Fig. 4) is located on the district's northeast and east-southeast sides. The names of the union council are: Ghawind, Jaman, Barki, Minahala Kalan, Shahzada, Jodhu Dheer, Jia Bagga, Ariyan, Heir, Pandoke, and Kahna Nau. Moreover, the central part of the Lahore district, because of its high drainage density and high slope with low absorptivity, falls into very poor groundwater potential zones.

Table 6
Classification and area of groundwater potential zones

Classification	Area (km^2)	Area (%)
Very low	264.87	15.49
Low	416.61	24.36
Moderate	556.08	32.52
High	455.45	26.63
Very high	17.17	1

3.11. Validation of groundwater potential map

Field verification is a very important modeling process. Without field verification, the GIS model has no scientific importance [69]. For field verification, compare the groundwater depth with the groundwater potential zone map obtained from AHP techniques [70–73]. It is established that the AHP technique can be used as a simple testing tool for the valuation of groundwater potential [74,75], said that AHP techniques are very useful for complex analysis and the results of current research has been validating the research conducted in study area regarding groundwater contamination by Mahmood et al. [3]. A survey is conducted to determine the depth of the water table throughout the district. The coordinates of several wells (including hand pump and tube wells) are gathered using the GPS, and their depth in meters is recorded. The water depth ranges from 6.9 m to more than 42 m, according to the survey. Based on the tube well depth, wells are divided into four classes for better validation: shallow (6–15 m), moderate (16–22 m), high (23–34 m), and deep (35–42 m). The groundwater depth data is overlaid on top of the groundwater potential zones layer. The cross-verification method is used to calculate the accuracy of weighted overlay results. According to the depth of wells in the Lahore district. The groundwater potential is high in those regions where the table is moderately shallow. A few areas (Ghawind, Jaman, Barki, Minahala Kalan, Shahzada, Jodhu Dheer, Jia Bagga, Ariyan, Heir, Pandoke, and Kahna Nau) have very high groundwater potential due to their low water tables, and other areas like the inner city of Lahore (Data Darbar-Peer Maki, Lohari Gate, Bhati Gate, Shahi Qilla, Gulberg III, Canal Park) have very poor groundwater

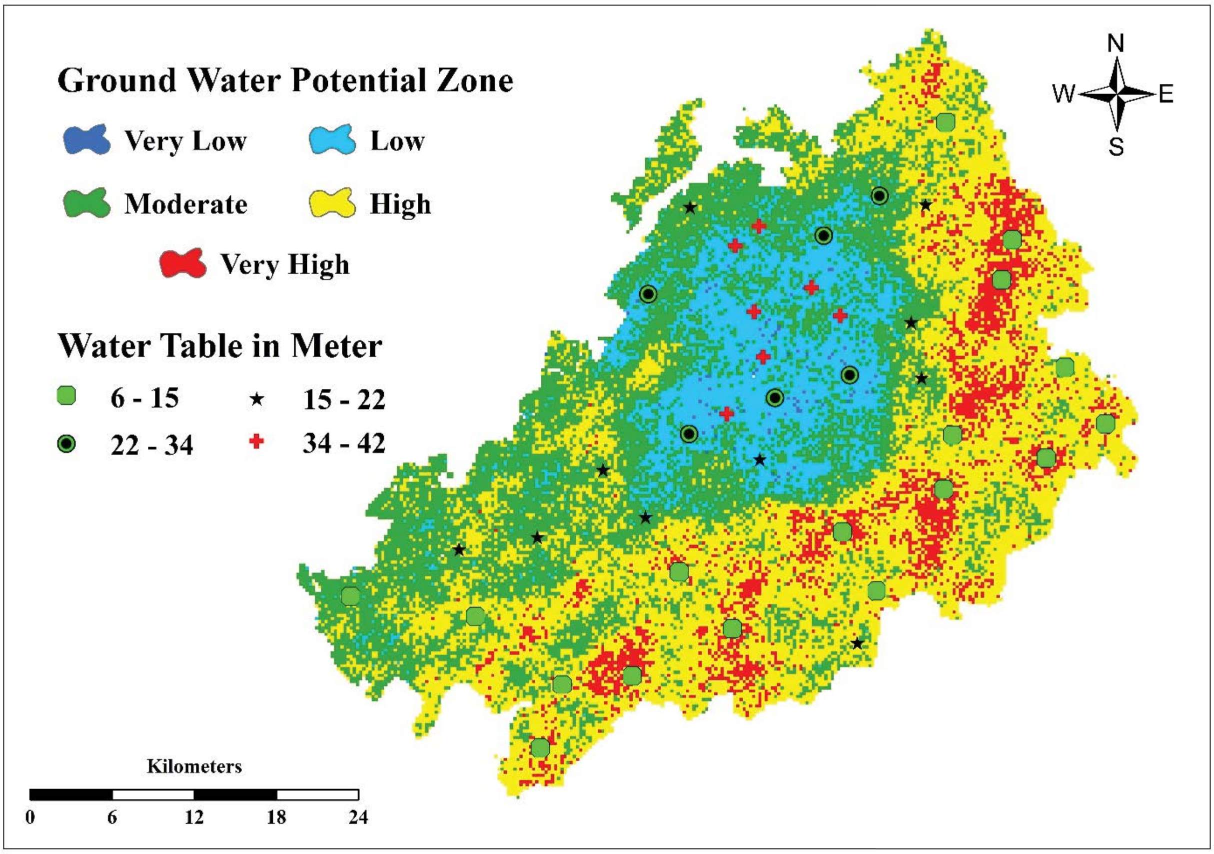

Fig. 5. Validation of groundwater potential zones map.

potential because of the high depth of the table. Overlay analysis has shown that many tube wells with shallow or moderate groundwater depths have high groundwater potential zones (Fig. 5). Hence, effective water management and planning are required because of the current worldwide water deficit. Accurately predicting and responding to the current status of crucial resources is the first step in effectively planning the use of water resources. Particularly in areas with limited water resources, groundwater is a significant source of water [76]. The uncertainty of groundwater availability is high; therefore, assessment of GWPZ is essential. Effective groundwater resource management and conservation planning face a critical problem in the mapping of GWP.

This research can also be useful in agricultural practices to overcome the issues in agricultural perspective. This study somehow depends upon the satellite and field observations data and if the satellite data will be used with high spatial resolution with rich field observations/samples then it may helpful in more precise findings and beneficent for other fields, that is, sustainable water management and agricultural practices as well.

4. Conclusions

Groundwater potential zone identification is very big problem these day in dense population areas. In this study, various parameters are used to delineate groundwater potential zones in Lahore, Pakistan. These parameters included groundwater depth, geology, lineament density, slope, soil types, land use and land cover, rainfall, drainage density, TWI, and roughness map. To prepare the maps, topographic maps, conventional data, and satellite images are used, and the AHP technique is employed to provide weights to each thematic and its associated classes. The study found that very high potential zones are typically located on the northeastern and southeast side of the study area, while low potential zones are found in the central part of Lahore. The groundwater potential map produced by the study is based on the integration of all thematic layers using GIS. The study also used existing tube-well data to confirm the potential zones, and the predicted map produced in the investigation matched over 80% of the field data. The study found that only 1% of the study area has a perfect zone for groundwater potential, while 26.63% has a high zone, 32.52% has a moderate zone, 24.36% has a low zone, and 15.49% has a very low zone for groundwater potential. The study concludes that the methods used to delineate groundwater potential areas in Lahore are cost-effective and time efficient. The findings of this study can be useful for promoting comprehensive groundwater exploration and recharge management. Moreover, the approach used in this research is transferable to other contexts where groundwater utilization is important.

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Competing interests

There is no competing conflict of interest.

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