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Groundwater potential zone mapping using geographic information systems and multi-influencing factors: A case study of the Kohat District, Khyber Pakhtunkhwa

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Groundwater is a vital component of life; without its identification, it is impossible to live. Therefore, identifying groundwater potential zones (GWPZs) is critical. For this purpose, the study area of the Kohat District was selected to identify GWPZs using the multi-influencing factors (MIF) approach. The Kohat area has a semi-arid to sub-humid subtropical climate and is classified as a sub-tropical, triple-season, semi-arid, sub-mountainous area. The geology, land use, soil, rainfall, lineament density, and drainage density are important parameters of ground water potential identification. The GWPZs were classified into five types: very poor, poor, good, high, and very high. We determined that 37.72% of the study area had high GWPZs, which were predominately in or near the northwest region of the study area, whereas 4.62% of the study area, in the southeast region, had very poor GWPZs. The water table data from the study varied due to different parameters used to identify the GWPZs. Our MIF results revealed that a large area of the Kohat District has good water potential. Still, due to topographic elevation changes, the groundwater potential has been limited in hilly areas. Our final results were compared with water level field data collected from different sources across the Kohat District.

KEYWORDS

GIS, land use, multi-influencing factors, weighted overlay, geology, groundwater potential

1 Introduction

Groundwater is an important abundant natural resource and is a very basic and constant source of water supply in all climatic regions worldwide (Konikow and Kendy, 2005). Overall, the planet has a stock of approximately 1.4 billion cubic kilometers of water, the vast majority of which (nearly 97%) is salt water in the oceans. Freshwater stocks are estimated to be around 35 million cubic kilometers in more limited areas. Groundwater is the most abundant source of irrigation in South Asia and North China (Shah, 2007). Pakistan is an agriculture-based country where groundwater is one of its dominant irrigation sources. The changing climate

scenario is slowly reducing river water flow, which has made groundwater a fundamental component of irrigation systems to certify food safety and commercial support (Khair et al., 2012). The demand for freshwater resources has increased significantly in recent years, due to rapid population growth, uneven spatiotemporal distribution of water resources, economic development, and changing climate, resulting in water scarcity in many parts of the world (Selvam et al., 2015). Groundwater resources are becoming increasingly important in a densely populated country (Bhuiyan et al., 2009). Groundwater is an important component of the hydrological system in subsurface geological formations (Ifediegwu, 2022). Groundwater occurrence and availability are

determined by the recharge process, which is influenced by factors such as physiography, lithological composition, drainage patterns, land use/land cover, drainage density, lineaments, soils, rainfall, and geology (Chatterjee and Dutta, 2022). In Pakistan, groundwater is the primary irrigation source that, at approximately 62 billion m³, makes up 40% yield water fulfillment (Hussain et al., 2011). Pakistan is a country loaded with glacial masses, waterways, streams, and trenches, yet is confronted with shortage of water. For example, at the hour of autonomy (i.e., in 1947), 5000 m³ of water was accessible for every Pakistani, which has now decreased to 1,000 m³, due to uncontrolled rapid population growth (Hussain et al., 2011).

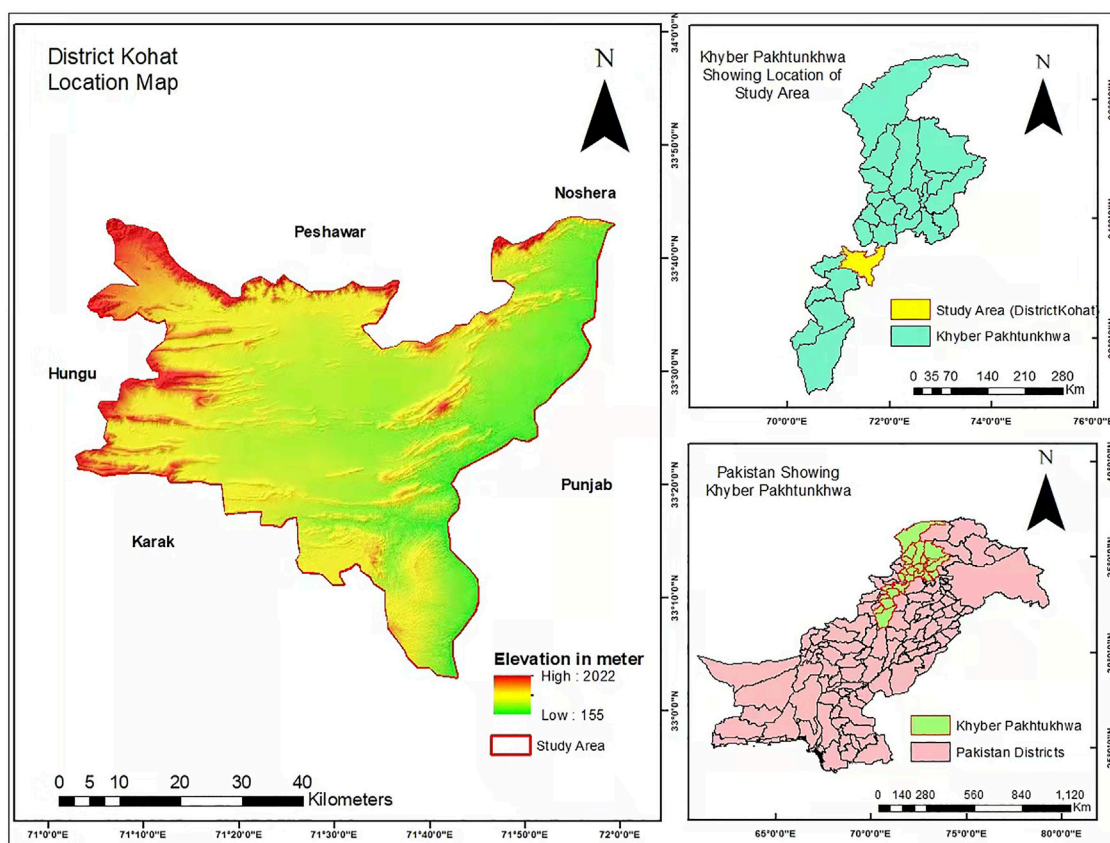


FIGURE 1 Kohat District area map.

TABLE 1 Dataset source and resolution.

Data	Spatial	Resolution (m)	Source
DEM(ASTER) slope, drainage density	Raster	30	https://earthexplorer.usgs.gov/
Landsat 8 OLI calculation of lineament density			EarthExplorer
Soil data			Directorate of Soil and Water Conservation and Directorate of Soil Survey of Khyber Pakhtunkhwa
Rainfall data			Pakistan Meteorological Department, Peshawar Region for the Province Khyber Pakhtunkhwa
Land use/land cover data			https://www.earthexplorer.usgs.gov/
Geology data			National Centre of Excellence in Geology, University of Peshawar (NCEG)

TABLE 2 Values of major, minor, and relative effects and proposed weights of influencing parameters.

Parameters	Major effects (A)	Minor effects (B)	Proposed relative effect (A + B)	Proposed weight of influencing parameter
Slope	2 + 2	1	5	16
Drainage density	2 + 2	1	5	16
Geology	2+ 2	1	5	12
Rainfall	2 + 2	1	5	16
Soil	2	1+0	3	06
Land use/land cover	2	1+1	4	25
Lineament density	2	1+0+0	3	09
			$\sum 30$	100

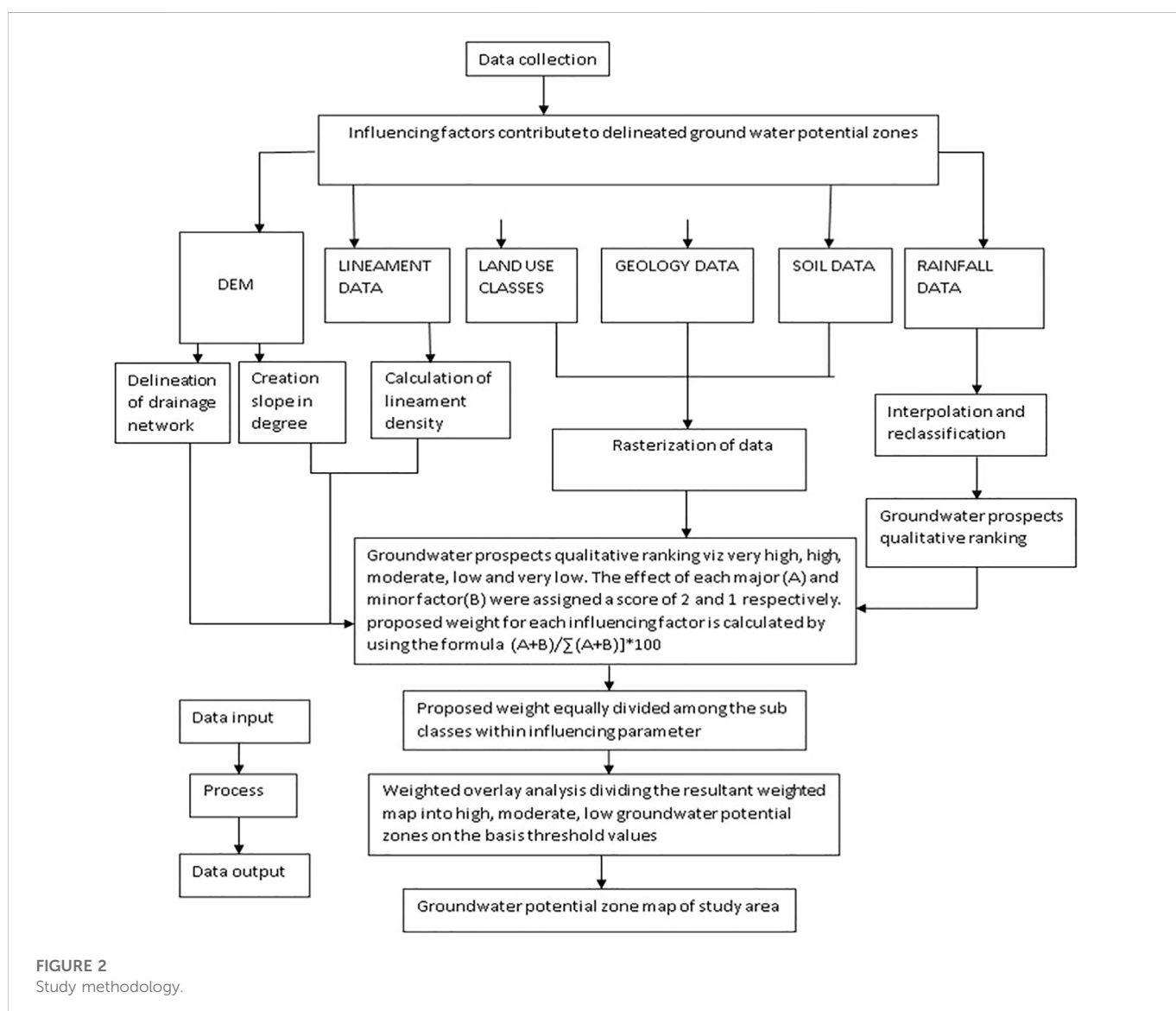


FIGURE 2 Study methodology.

In contrast to traditional methods, remote sensing and GIS make groundwater resource assessment time and cost-effective, rapid, and less labor-intensive (Thapa et al., 2017). Several researchers have applied GIS-based approaches to delineate groundwater potential

lineament, and hydro geomorphology, as well as groundwater level decline and its impact on regional subsidence, karst hazards, and groundwater pollution vulnerability (Thapa et al., 2017). Various factors play roles in delineating GWPZs (NARAYANAN and

TABLE 3 Details of parameters that influence groundwater potential.

Influencing parameter	Subclasses within influencing parameter	Ground prospects (qualitative ranks)	Proposed weight of each influencing parameter $[(A+B)/\sum(A+B)] * 100$	Groundwater prospects (quantitative score/rank; weight equally divided among the subclasses within influencing parameters)
Slope in degree	00–5.78	Very high	16	16
	5.78–13.5	High	16	12
	13.50–23.14	Good	16	08
	23.14–35.03	Low	16	04
	35.03–81.97	Very low	16	01
Drainage density in km/sq.km	1.08–1.61	Very high	16	16
	1.61–1.86	High	16	12
	1.86–2.11	Good	16	08
	2.11–2.38	Low	16	04
	2.38–3.08	Very low	16	01
Geology	Sedimentary rock	High	16	16
Rainfall in mm	13–281	Very high	16	16
	281–577	High	16	12
	577–604	Good	16	08
	604–629	Low	16	04
	629–663	Very low	16	01
Soil	Morainic material	High	06	06

VENUGOPAL, 2021), including amounts of rainfall, lithology, soil texture, slope, elevation, and distribution of water table depth (Magesh et al., 2012), slope, elevation (Magesh et al., 2011), drainage systems (Thapa et al., 2017), and groundwater table distribution (Arkoprovo et al., 2012).

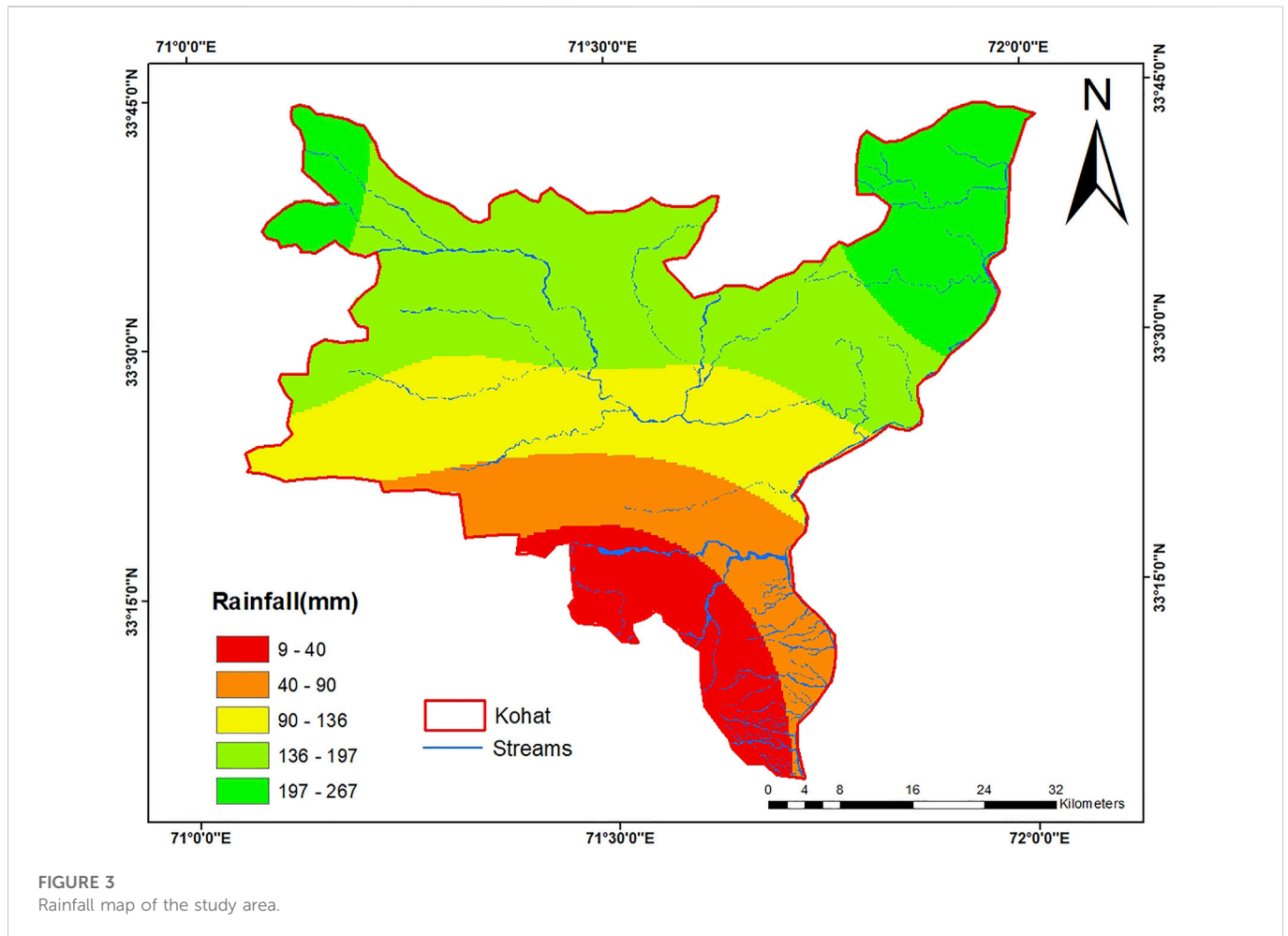
Recently, various methods have been used to protect groundwater (Magesh et al., 2011) and reservoirs, including geospatial, seismic, geological, hydrogeological, and geophysical methods (Magesh et al., 2012). Use of a combination of remote sensing (RS), GIS, and the multi-influencing factors (MIF) technique is one of the most common, dependable, and cost-effective approaches for groundwater identification and assessment of recharge and storage (Moodley et al., 2022). Several studies have used GIS and RS with multi-criteria decision-making analysis (MCDMA) to detect GWPZs (Taloor et al., 2020). Researchers have used various techniques, such as frequency (Razandi et al., 2015), multi-criteria decision evaluation (MCDE) (Thapa et al., 2017), artificial neural networks (ANN) (Lee et al., 2012), random forest modeling (Zabihi et al., 2016), logistic regression modeling (Pourtaghi and Pourghasemi, 2014), and the analytic hierarchy process (AHP) (Rahmati et al., 2015). The major drawbacks of bivariate and multivariate statistical methods are that assumptions are made before investigation, and they are sensitive to outliers (Thapa et al., 2017). For delineating GWPZs in this context, MIF was a simple, reliable, and effective method (Selvam et al., 2016).

Thus, we aimed to use the MIF method to identify and assess GWPZs in the Kohat District, Pakistan. Here, the integration of GIS

and RS data plays an important role in characterization of high and low GWPZs in the study area. The main objectives of this study were: 1) to evaluate the capacity of the MIF method in potential groundwater assessment, 2) to assess several parameters influencing the groundwater potential of the study area, and 3) to cross-validate the derived groundwater potential site results with tube well/borehole data.

1.1 Overview of study area

Our research study was conducted in the Kohat District (Figure 1), a medium-sized city located in the southern part of Khyber Pakhtunkhwa, Pakistan. The district's population is more than 562,644, according to the Khyber Pakhtunkhwa survey report. The Kohat Plateau consists of a heavily deformed and structurally elevated thrust sheet. The Kohat District spans from the latitude of 33° 35'0.24" N and a longitude of 71.25'59.59" E or 33.58° and 71.43°, respectively. The altitude of the study area is about 1,607 feet, and the water table in the area ranges from 40 to 50 m in depth. Kohat coordinates with the Afghanistan borders: 128.4 km SE of Jalalabad Nangarhar, Afghanistan. It is a mountainous area located east of the Indus River and has a few spread patches of plains. There are three major water reservoirs in the area: Tanda Dam, Gandiali Dam, and Kandar Dam. The study area is



divided into three geological domains; the Peshawar Basin in the north, the Kotal ranges in the center, and the Kohat sub-basin south of the Main Boundary Thrust (MBT). Kohat Province of the upper Indus Basin constitutes the western part of the Himalayan fold and thrust belt, resulting from the ongoing collision between the Indian and Asian plates. The upper Indus Basin is divided into two areas: the Potwar Plateau to the east of the Indus River and the Kohat Plateau west of the Indus River. Several outcrops of Lockhart and Kohat Limestone in the Kohat District are found along the Indus Highway, the Kohat Pindi Road, and Kohat–Hangu Road. All these limestones belong to the Kohat Formation, representing the top of the Eocene sequence within the Kohat Plateau.

2 Materials and methods

2.1 Data collection

GWPZ assessment requires vast spatial data, which was collected from different sources. First, the digital elevation model (ASTER 30 m), with basic data required for calculating slope and drainage density, was downloaded from earthexplorer.usgs.gov. Landsat 8 OLI imagery was also downloaded from

EarthExplorer to calculate lineament density. The soil data were requested from the Directorate of Soil and Water Conservation and the Directorate of Soil Survey of Khyber Pakhtunkhwa. The data were provided in a raster format, which was then georeferenced and digitized in ArcMap 10.5. The rainfall data were collected from the Pakistan Meteorological Department, Peshawar Region, Khyber Pakhtunkhwa. As the Karak District does not have meteorological observatories, the data available for all provinces were interpolated using inverse distance weighting (IDW). Land use/land cover data from 2018 were requested from the Forest Management Center Peshawar. The geology data were requested from the National Centre of Excellence in Geology, University of Peshawar. All data were then converted from raster to vector format by digitization. The details of all the processes are discussed in the following Methodology section. Dataset details are provided in [Table 1](#).

2.2 Methodology

In this study, various types of data were used to delineate GWPZs. A digital elevation model (DEM) with 30 m resolution was obtained using Shuttle Radar Topography Mission (SRTM) data combined with ArcGIS and RS to prepare the thematic layers. With

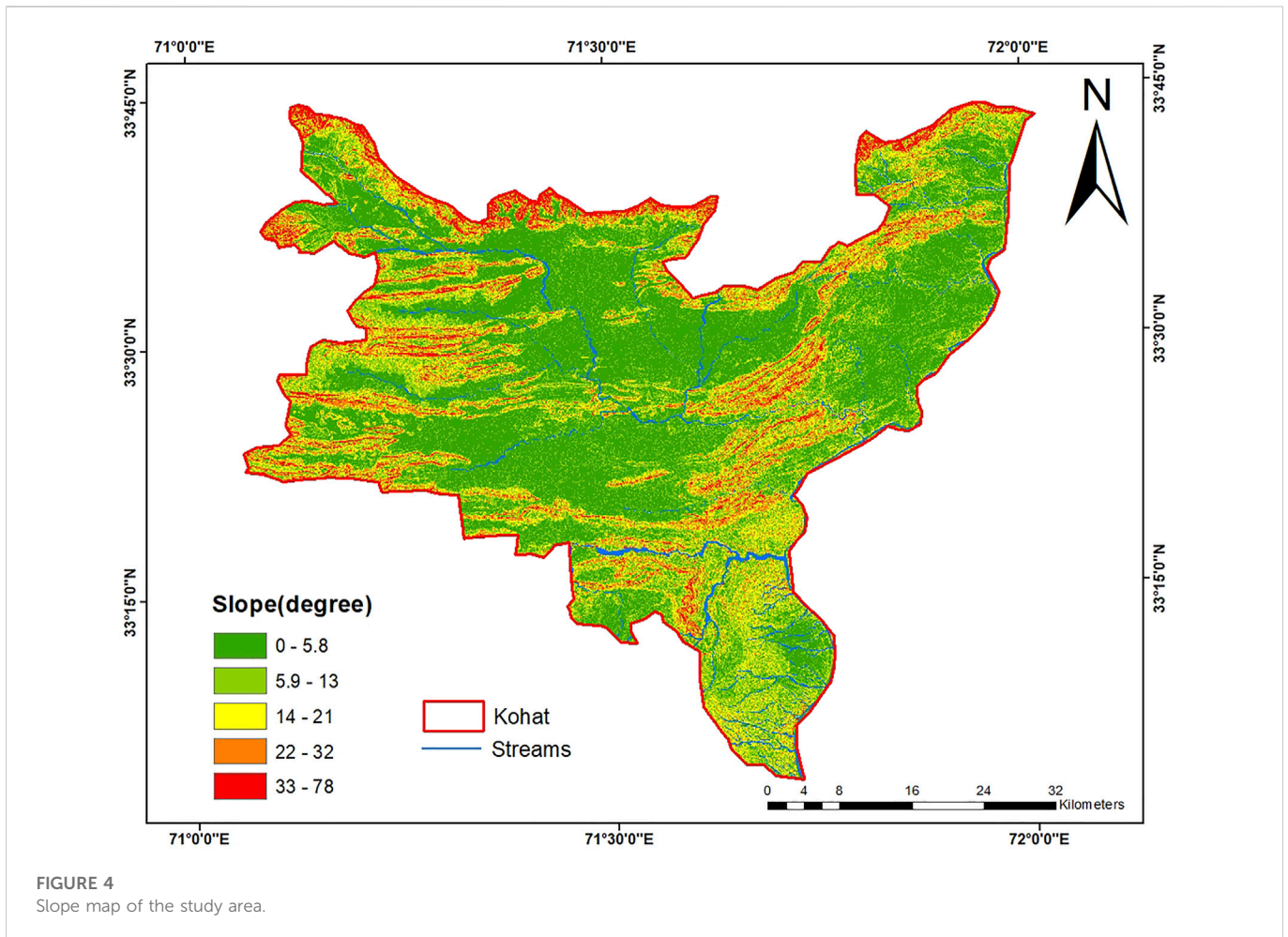


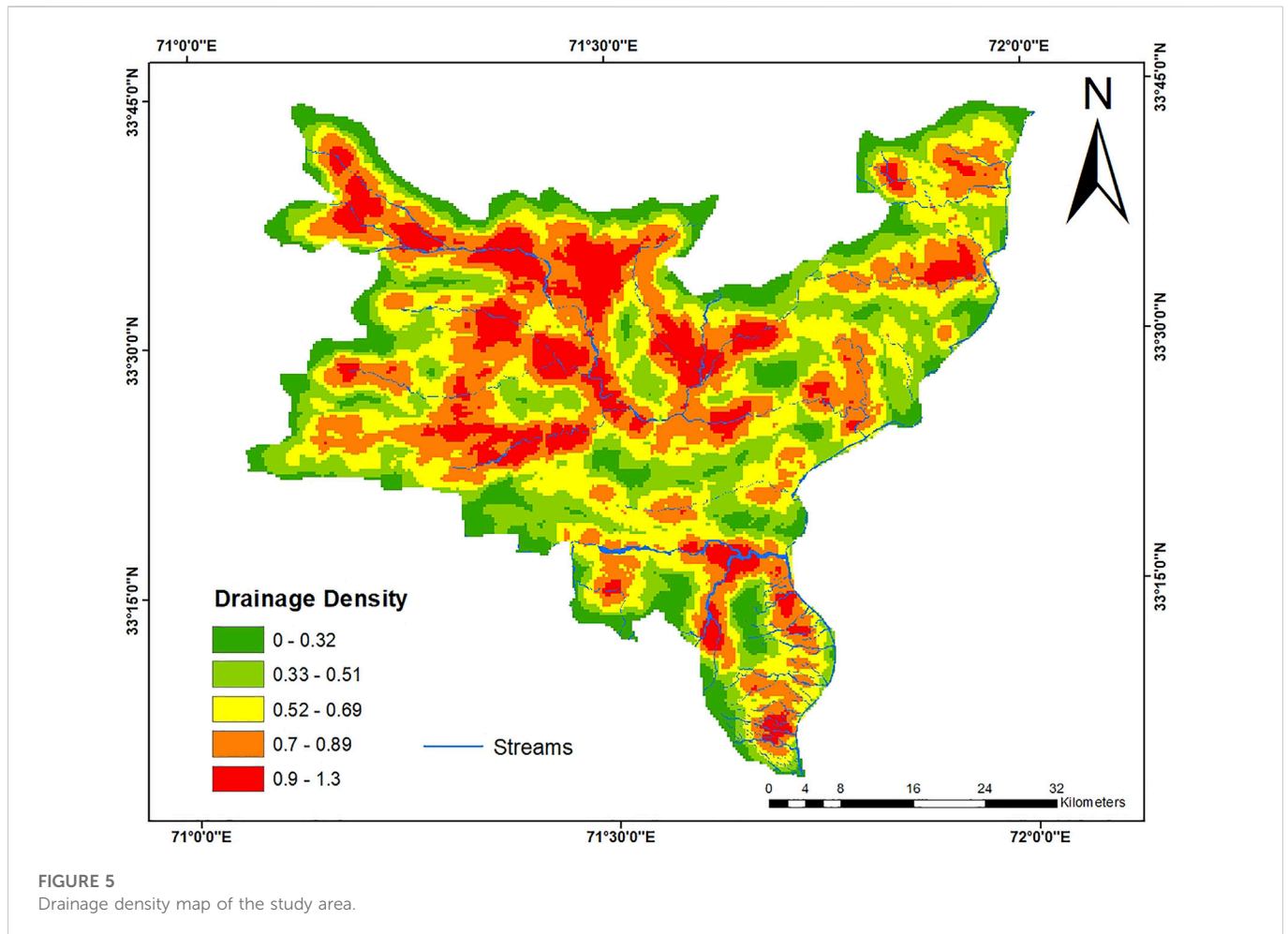
FIGURE 4 Slope map of the study area.

the help of MIF modeling, ground water potential was calculated. GWPZs were determined using MIF models, which also explain relevant factors. The methodology involved four main steps. The first step was a literature search to identify parameters that impact groundwater potential. The probability of locating groundwater in a specific region varies depending on parameters that influence the revival of groundwater aquifers. Some of the factors currently utilized in the assessment of groundwater potential include land use/land cover, precipitation, slope, drainage density, geology, lineament density, and soil condition of the catchment (Nasir et al., 2018).

All these parameters were used to study the groundwater potential in the Kohat District. In the second step, we assigned a score and weight for each parameter to generate subclasses within each parameter affecting the GWPZ. The subclasses with major effects on groundwater recharge (A) had a score of 2, and the subclasses with minor effects (B) had a score of 1. The subclasses with no effect on groundwater recharge had a score of zero. The total of both the major and minor (A + B) effect scores was calculated to determine the relative effect (Table 2). This relative effect was then used to calculate the weight of each influencing parameter (Deepa et al., 2016) $[(A+B)/\sum (A+B)] * 100$. Using this formula, we calculated the weight of each parameter. A is the major subclass effect and B is the minor subclass effect within the seven influencing

parameters. The weight designated for each influencing parameter was distributed equally, which allowed ranking of each subclass, as shown in Table 2.

In the third step, we prepared maps of all seven parameters and reclassified them in ArcMap 10.5. Each map shows its effect in influencing parameters of groundwater, expressed in numerical values. In step four, we integrated all seven parameters using weighted overlay analysis and categories in five classes: very high, high, good, poor, and very poor GWPZ. The AHP is the most commonly used and well-known GIS-based method for delineating GWPZs. This method helps integrate all thematic layers. The probability of the presence of groundwater in a specific region fluctuates depending on different parameters that impact the revival of groundwater aquifers. Some of the factors currently utilized in the assessment of groundwater potential include land use/land cover, geology, slope, drainage density, lineament density, soil, and rainfall. For each parameter, thematic maps were prepared to examine the study area's groundwater potential, and all of these parameters were used to study the groundwater potential in the Kohat District. These thematic layers were combined, and a groundwater potential map was prepared in ArcGIS software. The thematic layers are defined briefly below. To validate the final map of weighted overlay analysis, we conducted a field survey to collect ground truth water



well data to identify the groundwater levels of the study area. We collected 150 well data measurements from different regions of the study area with different water levels at each point. We categorized these data into five classes: 43 wells had water level up to 35 m, which is near the Earth's surface and considered as having very high groundwater potential, 39 wells had groundwater level up to 69 m, which indicated high potential zones, 50 wells had water level up to 105 m, which showed good groundwater potential, 12 wells had groundwater level up to 132 m, which indicated poor GWPZs, and five wells contained groundwater level up to 210 m, which indicates a very poor water table and therefore was considered to have very poor groundwater potential. A diagram of the full study methodology is shown in Figure 2. We overlaid all of these well data points in the final weighted overlay analysis, which validated the final results map.

3 Results and discussion

There are several parameters that influence groundwater potential in an area. Therefore, various thematic layers of different parameters were generated to evaluate the study area for GWPZs (Table 3). The details of different parameters are provided below.

3.1 Rainfall

Rainfall is an important parameter in delineating groundwater potential and is a major hydrological source of stored groundwater (Andualem and Demeke, 2019). The higher the rainfall intensity, the higher the groundwater recharge, and *vice versa* (Das and Mukhopadhyay, 2020). With the help of rainfall, we can regulate the instability of groundwater (Agarwal et al., 2013). The GWPZ perceptively alters the infiltration rate, which is controlled by precipitation dispersal and slope gradient (Selvam et al., 2016). From the surrounding relief, dunes, and waves in the rainy season, more than 10% of the 420 mm/year average annual rain fall recharge is predictable (Zghibi et al., 2016). High-intensity, short-duration rain leads to less infiltration and more surface runoff; low intensity, long-duration rain leads to high infiltration and less surface runoff (Ibrahim-Bathis and Ahmed, 2016). For high groundwater potential, high intensity rainfall is favorable and has high priority. Due to climatic variation, the amount of rainfall is not constant in the region (Adiat et al., 2012). Figure 3 shows rainfall data. The rainfall map indicates five main classes, ranging from 9 to 267 mm. In the first class, the values range from 9 to 40 mm, showing minimum rainfall in the region, and indicating areas that are very poor GWPZs. Similarly, the second class shows poor GWPZs, the third class shows good

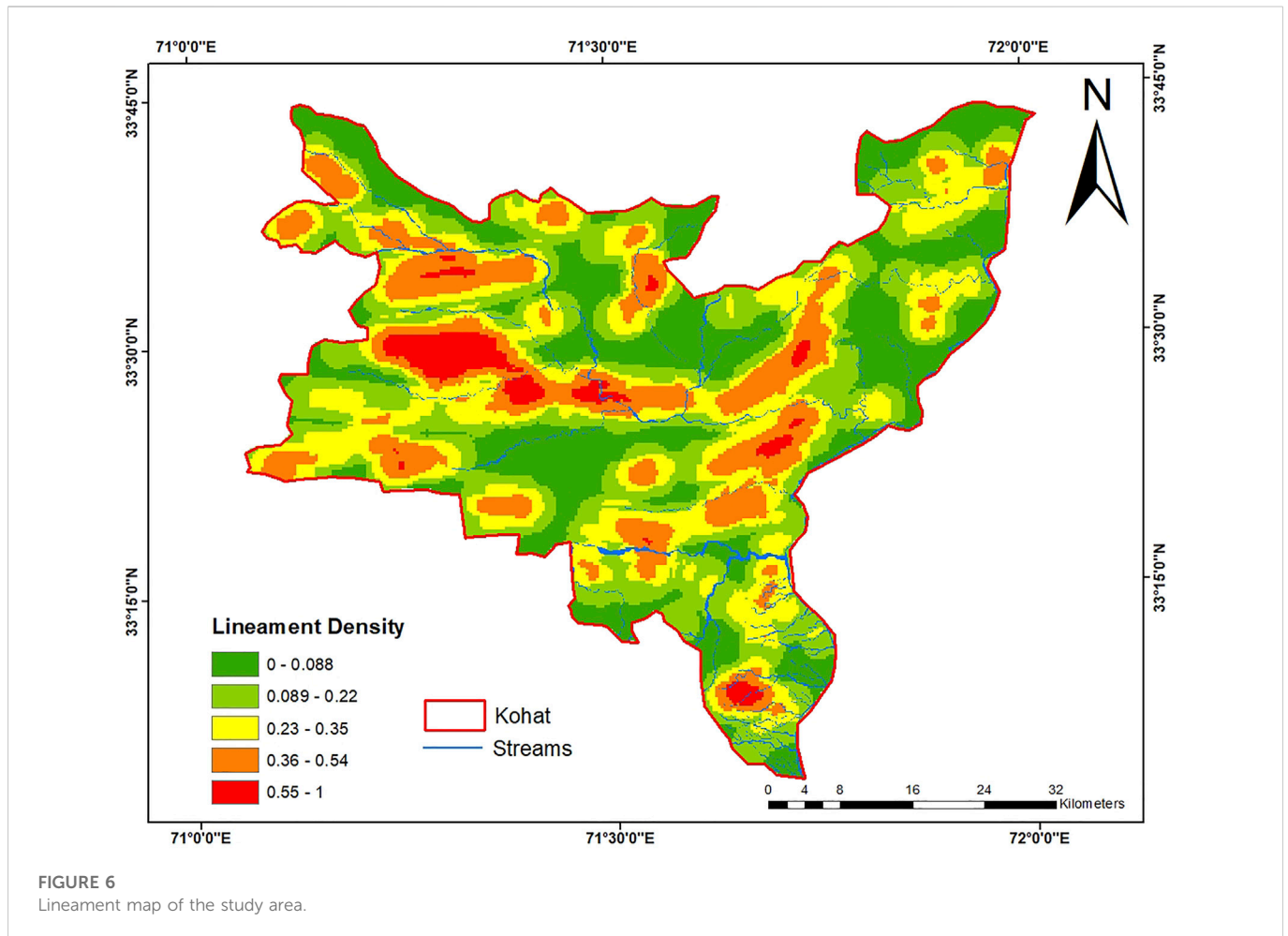


FIGURE 6
Lineament map of the study area.

GWPZs, the fourth class shows high GWPZs, and the fifth class shows very high GWPZs.

3.2 Slope

Slope plays an important role in water infiltration and runoff (Tweed et al., 2007). It is a characteristic of local and regional relief, which is an important factor that influences water retention, the intensity of infiltration, aquifer recharge, and groundwater movement (Cai and Offerdinger, 2016). The infiltration rate will be lower when the slope of the ground is high, due to a large amount of runoff in the area (Rajasekhar et al., 2019). The slope is directly proportional to surface runoff and inversely proportional to the purification and infiltration rate of surface water (Das and Pal, 2019). The rate of infiltration and surface runoff is highly influenced by the slope of the surface (Singh et al., 2013). Figure 4 shows slope data. Slope data were organized into five classes ranging from 0–78°. In the first class, the value ranges from 0–5.8, which shows a gentle slope in that region, indicating a very suitable zone for ground water potential; for classes with increased slope, the greater the slope, the lower the ground water potential.

3.3 Drainage density

A key indicator of the hydrological landscape is drainage density, which determines the infiltration and underlying lithology (Murmu et al., 2019). Drainage density is the ratio of the length of all the streams and the aggregate area of the drainage basin (Avtar et al., 2011). Due to the high probability of groundwater recharge, areas with lower drainage density generally have higher groundwater potential (Andualem and Demeke, 2019). Areas with high drainage density generally have low potential for groundwater recharge due to high runoff rate (Thomas et al., 2017). Drainage density is an important parameter in evaluating the distribution of the groundwater potential of an area (Harinarayana et al., 2000). Drainage density plays an important role in groundwater accessibility and contamination (Ganapuram et al., 2009). Drainage density is inversely related to permeability (Chowdhury et al., 2009). Figure 5 shows drainage density data. The drainage density data were organized into five classes, with values ranging from 0 to 1.3. In the first class, the values range from 0–0.32, indicating high drainage density and low ground water potential. In classes with increased values, indicating lower drainage density, the lower the drainage density, the higher the ground water potential.

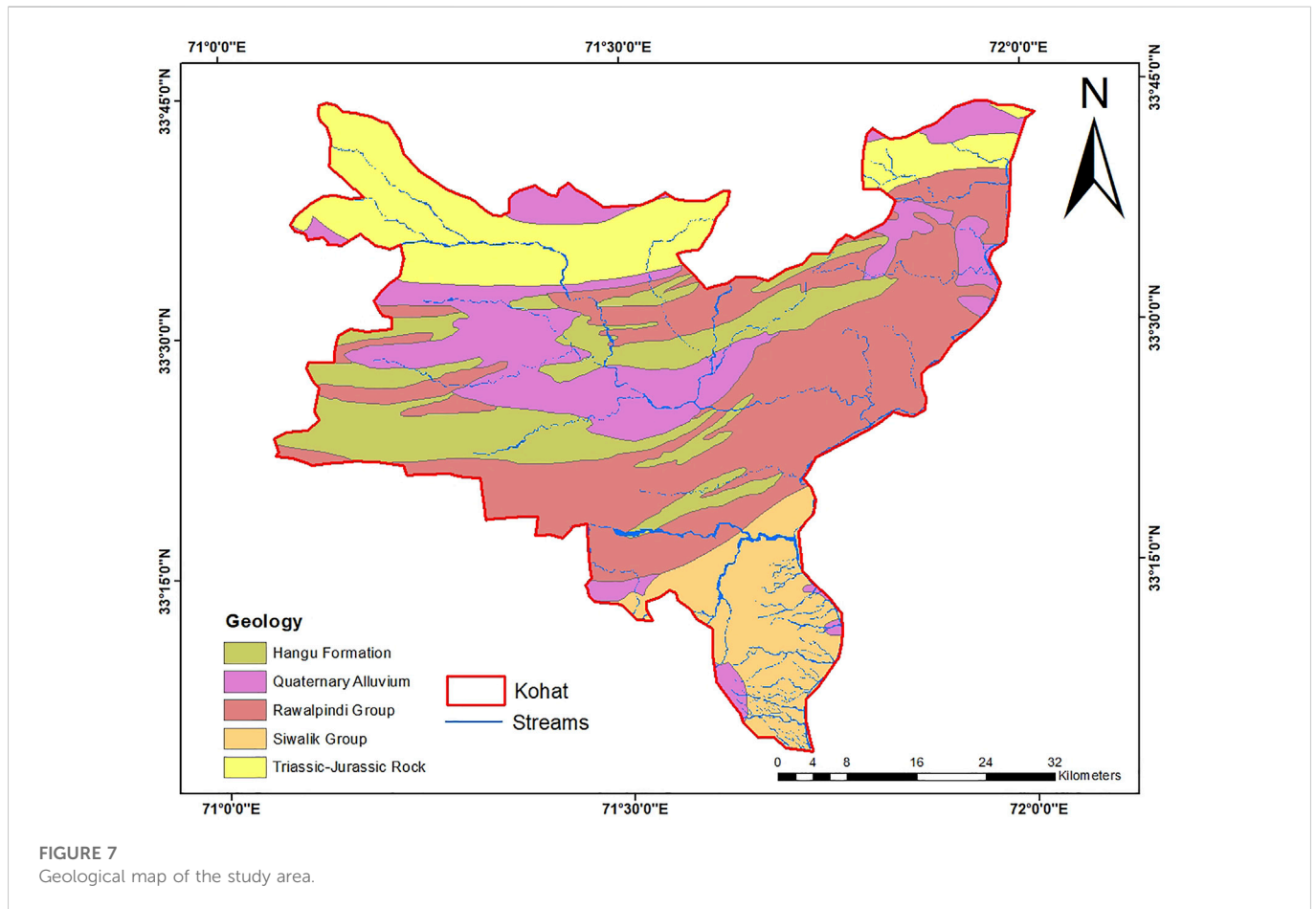


FIGURE 7
Geological map of the study area.

3.4 Lineament density

Lineaments are linear or wavy features and can be recognized from satellite images due to their linear positioning (Nampak et al., 2014). Lineaments and their connections play an important role in crystalline rock in terms of incidence and movement of groundwater resources (Prasad et al., 2008). The occurrence of fractures, cracks, and lineaments controls the rate of flow and movement of groundwater in the solid rock by secondary porosity (Murmu et al., 2019). High lineament density areas favor GWPZs due to high infiltration rate (Srivastava et al., 2012). Lineaments are the “lines in the landscape” visible at the Earth’s surface as important features (Kumar et al., 2014). Figure 6 shows lineament density data. We organized lineament density into five classes, with values ranging from 0 to 1. In the first class, the values range from 0 to 0.8, which indicate high lineament density and suggest very suitable zones with high ground water potential. In classes with increased values, indicating lower lineament density, the lower the lineament density, the lower the ground water potential.

3.5 Geology

Geological structures play a significant role in controlling the quantity and quality of groundwater (Aneesh and Deka, 2015).

Geological settings play an important role in the existence and circulation of groundwater in any landscape (Yeh et al., 2016). Unconsolidated sedimentary and fractured crystalline rock is more favorable for groundwater movement and storage related to massive rock types (Murmu, 2023). Geological structure plays a significant role in prediction of GWPZs (Biswas et al., 2020). Geological factors affect the porosity and permeability of subsurface rocks (Rahmati et al., 2015). Higher porosity and permeability lead to greater groundwater storage and yields. Almost all the rocks exposed in our research area were sedimentary rocks; we weighted them highly, indicating and inferring high ground water potential, as shown in Figure 7.

3.6 Land use/land cover

Land use/land cover is an important aspect in recognizing GWPZs (Abrar et al., 2021). Built-up areas inhibit the subsurface infiltration of groundwater. Thus, areas with vegetation cover have higher groundwater potential (Adewumi and Anifowose, 2017). Land use/land cover gives information about groundwater, infiltration, surface water, and soil moisture and shows groundwater conditions (Rajaveni et al., 2017). Land use/land cover is disturbing groundwater recharge, existence, and availability (Selvam et al., 2016). Land use/land cover is divided into four major classes: class 1 indicates urban areas, which are

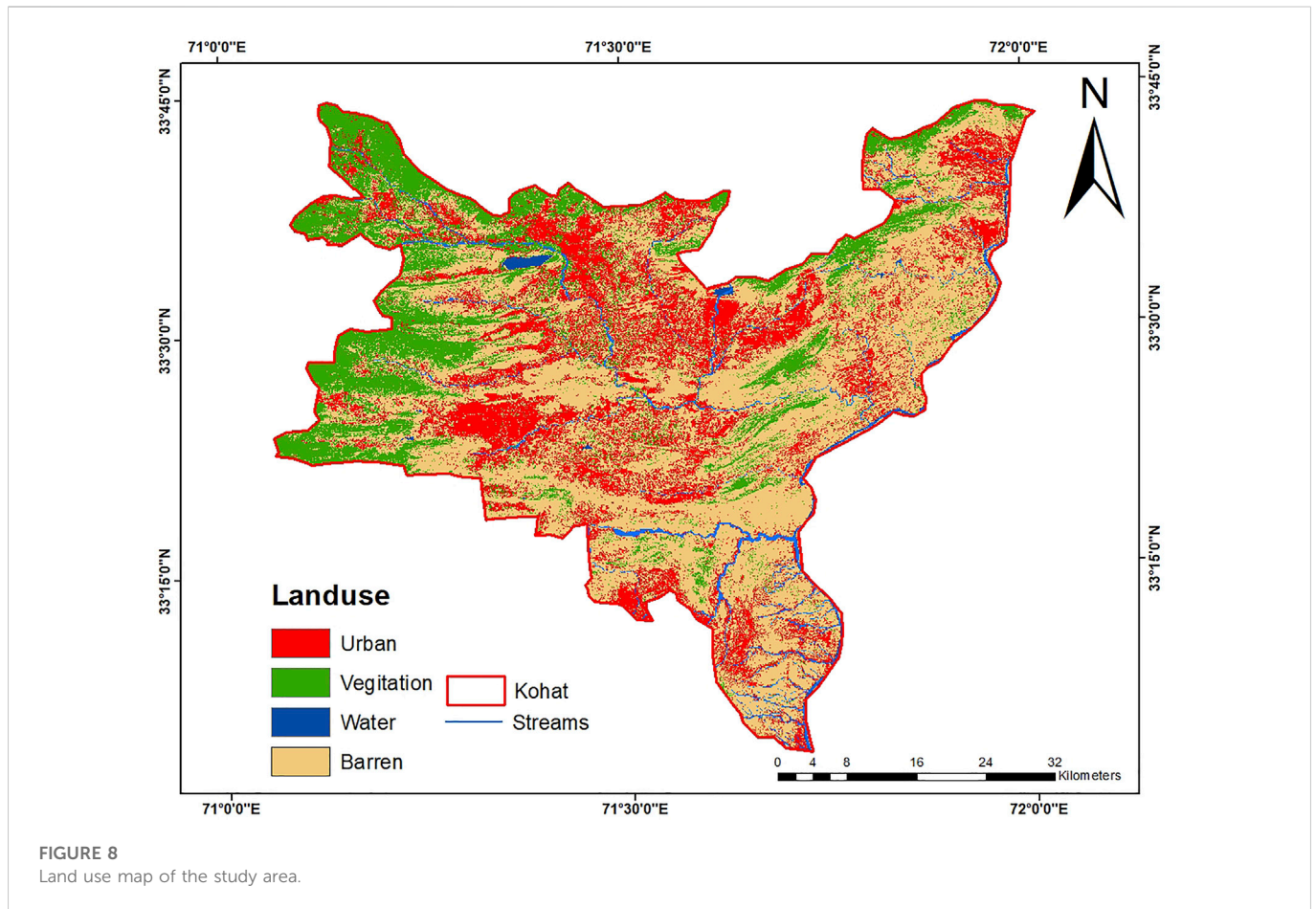


FIGURE 8
Land use map of the study area.

associated with poor ground water potential; class 2 indicates vegetation, which is associated with good ground water potential; class 3 indicates water bodies, which are associated with very high ground water potential; and class 4 indicates barren lands, which are associated with high ground water potential (Figure 8).

3.7 Soil

Soil plays a key role in the spatial distinction of groundwater recharge (Mehra et al., 2016). The groundwater table is primarily recharged by infiltration, several drainage systems, and adjacent water channels (Mokadem et al., 2018). The study of soil is an important factor in delineating groundwater recharge potential. Groundwater recharge depends upon factors such as water holding capacity, soil thickness, porosity, and runoff (Doke et al., 2021). Soil plays an important role in groundwater recharge, as recharge is dependent upon the water penetrating the ground (Nag et al., 2022). Soil texture has a great impact on the availability of groundwater in an area. Figure 9 shows soil data, which indicate three types of soil: gravel soils contain gravel and have high permeability, which contributes to high ground water potential; shallow, loamy soil has good ground water potential; and pure loamy soil has very poor ground water potential.

3.8 Groundwater potential zones by MIF

The systematic analysis of weighted parameters using MIF techniques produced a suitable GWPZ map in raster format, using the raster calculator module in the ArcGIS 10.5 environment, by integrating all the maps (Figure 10). The map sequence adopted in this study was 1) lineament density, 2) rainfall, 3) lithology, 4) slope degree, and 5) drainage density.

According to the quintile method, the MIF values were classified into five GWPZ groups: very high, high, good, poor, and very poor (Figure 11). Our analysis demonstrated that only 21% (122 km²/sq.km) of the study area exhibited poor ground water potential, with nearly all located in the northern half of the study area. Most of the regions under investigation (326 km²/sq.km) showed good to excellent groundwater potential (southern-central regions and a small part of the northern half). About 24% (141 km²/sq.km) of the area was classified as having good groundwater potential (most regions of the northern half and some regions of the southern half). The presence of excellent to good ground water potential resulting from groundwater potential mapping in the aforementioned regions may pertain to the presence of high lineament density, high rainfall, limestone as the dominant lithology, slope degree of lower than 30°, and low drainage density in these regions. The presence of these features in the study area increase the chance of infiltration and storage of groundwater. Due to the occurrence of significant rainfall, this effect will be greater. In contrast, good to poor GWPZs are

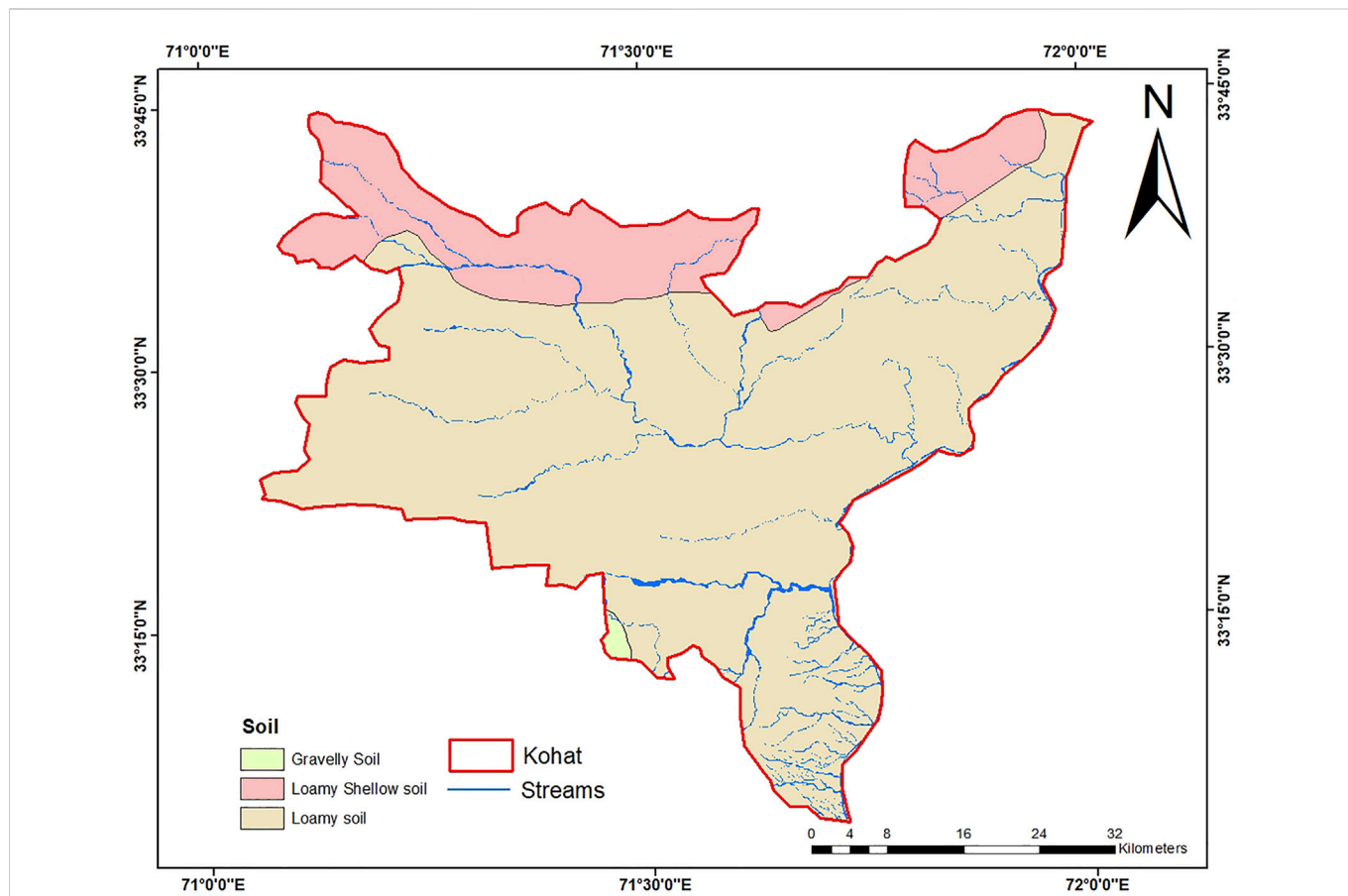


FIGURE 9
Soil map of the study area.

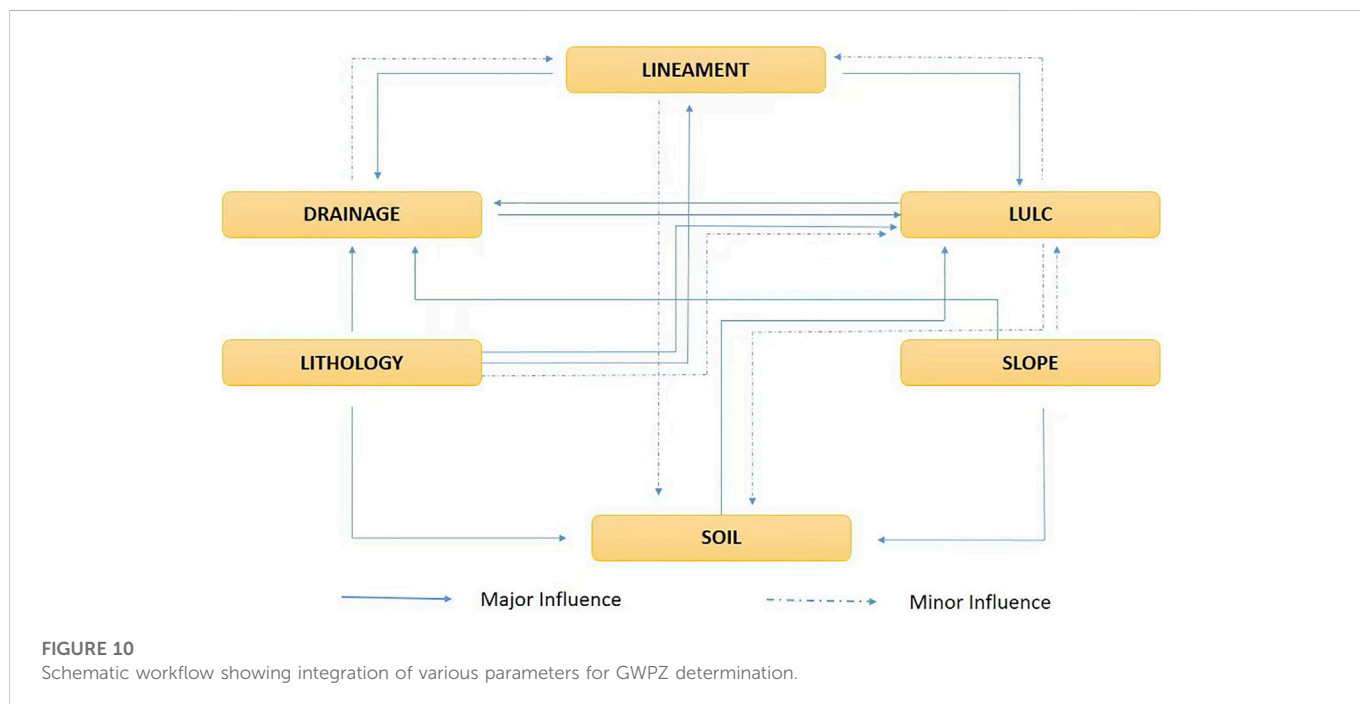
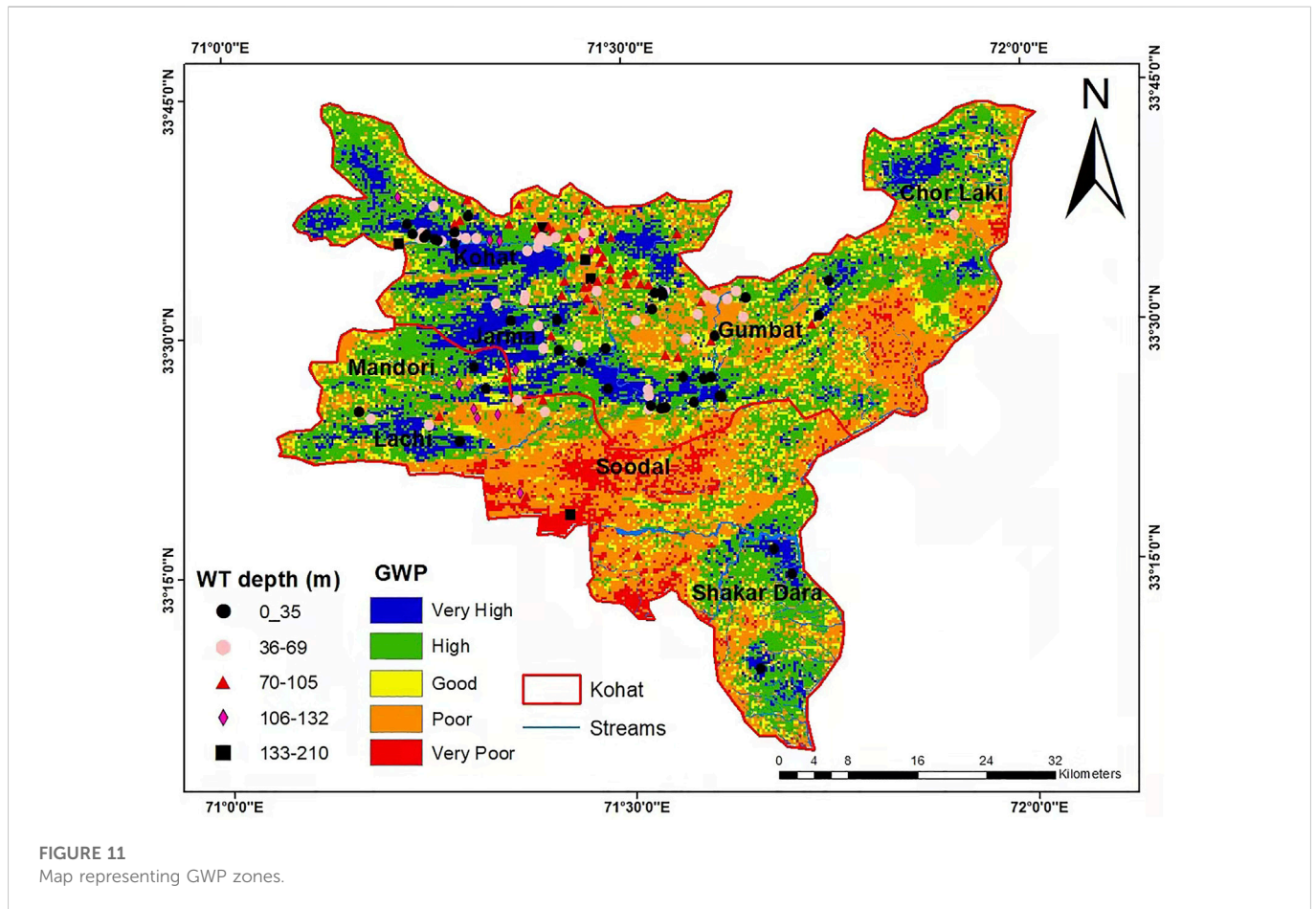


FIGURE 10
Schematic workflow showing integration of various parameters for GWPZ determination.



characterized by good to low lineament density, low rainfall, shale and marl and shale and limestone lithology, slope degree of more than 30°, and high drainage density. Therefore, there is less capacity for groundwater infiltration, and more rainfall is expected to flow through surface runoff. The GWPZ mapping can be useful for hydrologists in detecting new zones of potential groundwater (Shekhar and Pandey, 2015).

Overall, the study area included up to 2,952.40 km/sq.km, with the spatial extent of the GWPZs distributed in five classes. Therefore, we determined the area covered by each zone class and demonstrated that very high GWPZs covered 398.96 km/sq.km, high GWPZs covered 1,113.791 km/sq.km, good GWPZs covered 370.97 km/sq.km, poor GWPZs covered 932.2 km/sq.km, and very poor GWPZs covered 136.48 km/sq.km.

3.9 Validation of results

In the absence of a validation process, models do not have scientific significance (Remondo et al., 2003). The location and existence of springs and their catchment areas, along with sinkholes in the study area, were used to validate groundwater potential (Figure 10). To verify the study results, water depth/water table data from 150 wells were collected along with their global positioning system (GPS) location. The results from MIF were then validated by conducting a field survey of the groundwater table.

During the survey, field samples were collected by using a groundwater table indicator and a handheld GPS device for geotagging. The results were compiled on a detailed questionnaire designed for the field investigation. The GPS coordinates were recorded on the questionnaire and *via* the GPS receiver. The coordinates from the receiver were transferred in GPX format using EasyGPS software. The Data Interoperability tool in ArcGIS was used to convert the GPX format data into a shape file. The groundwater table data were spatially joined to the shape file using the Join and Relate tool.

The groundwater potential results determined using MIF modeling were then overlaid with the collected field data to validate the results (Table 4). The water table in the study area ranged from 35 to 210 m. The wells were divided into five groups. The delineated GWPZ data were overlaid with the good data from the field study. The overlay analysis revealed that most wells with high and medium groundwater depths were well within the very high and high GWPZs.

3.10 Accuracy assessment by using confusing matrix

After obtaining the land use/land cover classification results, accuracy assessments were carried out. For that purpose, the user, producer, and overall accuracy matrix were run to assess accuracy.

TABLE 4 Water table depth at various locations in the study area.

S. No	District	Tehsil	Latitude	Longitude	Total depth of bore hole
1	Kohat	Kohat	33.567,938	71.481,608	275
2	Kohat	Kohat	33.566,868	71.481,542	260
3	Kohat	Kohat	33.573,419	71.469,324	260
4	Kohat	Kohat	33.578,797	71.473,145	250
5	Kohat	Kohat	33.587,935	71.479,102	300
6	Kohat	Kohat	33.589,212	71.478,148	285
7	Kohat	Kohat	33.584,382	71.480,665	300
8	Kohat	Kohat	33.58749	71.466,622	180
9	Kohat	Kohat	33.555,277	71.480,907	190
10	Kohat	Kohat	33.601,005	71.565,853	120
11	Kohat	Kohat	33.563,745	71.51179	240
12	Kohat	Kohat	33.539,208	71.537,441	232
13	Kohat	Kohat	33.539,743	71.53624	260
14	Kohat	Kohat	33.517,932	71.567,627	260
15	Kohat	Kohat	33.490,485	71.574,398	220
16	Kohat	Kohat	33.465,202	71.609,718	171
17	Kohat	Gumbat	33.521,917	71.610,873	116
18	Kohat	Gumbat	33.524,153	71.61115	129
19	Kohat	Gumbat	33.526,808	71.616,015	300
20	Kohat	Gumbat	33.536,802	71.61798	280
21	Kohat	Gumbat	33.525,312	71.61578	210
22	Kohat	Kohat	33.49576	71.603,233	210
23	Kohat	Kohat	33.5205	71.586,948	171
24	Kohat	Gumbat	33.598,957	71.977,103	145
25	Kohat	Gumbat	33.467,517	71.619,818	179
26	Kohat	Gumbat	33.467,052	71.61882	176
27	Kohat	Gumbat	33.468,397	71.618,418	210
28	Kohat	Gumbat	33.467,447	71.61836	160
29	Kohat	Gumbat	33.514,665	71.615,962	180
30	Kohat	Gumbat	33.513,605	71.613,868	200
31	Kohat	Gumbat	33.51335	71.615,092	220
32	Kohat	Gumbat	33.514,162	71.61508	150
33	Kohat	Gumbat	33.503,713	71.732,002	300
34	Kohat	Kohat	33.47417	71.548,372	200
35	Kohat	Kohat	33.474,415	71.556,848	180
36	Kohat	Kohat	33.472,473	71.563,165	100
37	Kohat	Kohat	33.549,695	71.518,373	250
38	Kohat	Kohat	33.550,395	71.50083	311
39	Kohat	Kohat	33.559,933	71.501,223	258

(Continued on following page)

TABLE 4 (Continued) Water table depth at various locations in the study area.

S. No	District	Tehsil	Latitude	Longitude	Total depth of bore hole
40	Kohat	Kohat	33.56075	71.50328	271
41	Kohat	Kohat	33.537,467	71.546,778	150
42	Kohat	Kohat	33.539,775	71.545,347	230
43	Kohat	Kohat	33.54063	71.549,095	260
44	Kohat	Kohat	33.549,212	71.529,433	200
45	Kohat	Kohat	33.598,603	71.224,147	106
46	Kohat	Kohat	33.636,528	71.20749	258
47	Kohat	Kohat	33.602,927	71.250,063	150
48	Kohat	Kohat	33.602,413	71.242,118	190
49	Kohat	Kohat	33.602,363	71.243,973	150
50	Kohat	Kohat	33.600,675	71.263,582	300
51	Kohat	Kohat	33.607,838	71.246,853	180
52	Kohat	Kohat	33.621,358	71.188,745	300
53	Kohat	Kohat	33.605,467	71.253,907	120
54	Kohat	Kohat	33.599,443	71.26655	80
55	Kohat	Kohat	33.635,097	71.262,161	175
56	Kohat	Kohat	33.620,738	71.294,975	250
57	Kohat	Kohat	33.607,725	71.287,405	240
58	Kohat	Kohat	33.60045	71.314,977	245
59	Kohat	Kohat	33.61974	71.294,417	205
60	Kohat	Kohat	33.605,073	71.413,857	270
61	Kohat	Kohat	33.603,457	71.417,537	250
62	Kohat	Kohat	33.600,245	71.413,875	226
63	Kohat	Kohat	33.596,738	71.404,043	271
64	Kohat	Kohat	33.602,925	71.393,255	340
65	Kohat	Kohat	33.601,408	71.384,842	300
66	Kohat	Kohat	33.600,295	71.395,823	250
67	Kohat	Kohat	33.596,065	71.392,445	295
68	Kohat	Kohat	33.610,458	71.397,577	280
69	Kohat	Kohat	33.595,999	71.392,482	280
70	Kohat	Kohat	33.586,805	71.3785	160
71	Kohat	Kohat	33.592,445	71.353,788	250
72	Kohat	Kohat	33.589,958	71.355,542	292
73	Kohat	Kohat	33.597,493	71.33408	168
74	Kohat	Kohat	33.598,672	71.331,653	185
75	Kohat	Kohat	33.597,178	71.343,925	229
76	Kohat	Kohat	33.592,092	71.370,467	250
77	Kohat	Kohat	33.599,333	71.366,418	330
78	Kohat	Kohat	33.601,277	71.300,067	180

(Continued on following page)

TABLE 4 (Continued) Water table depth at various locations in the study area.

S. No	District	Tehsil	Latitude	Longitude	Total depth of bore hole
79	Kohat	Kohat	33.601,304	71.301,662	163
80	Kohat	Kohat	33.607,455	71.288,098	160
81	Kohat	Kohat	33.598,587	71.271,595	151
82	Kohat	Kohat	33.595,417	71.287,198	180
83	Kohat	Kohat	33.603,813	71.290,713	170
84	Kohat	Kohat	33.556,712	71.42558	268
85	Kohat	Kohat	33.603,603	71.449,922	280
86	Kohat	Kohat	33.558,473	71.449,383	280
87	Kohat	Kohat	33.589,591	71.391,392	165
88	Kohat	Kohat	33.554,387	71.462,475	270
89	Kohat	Kohat	33.574,521	71.430,839	400
90	Kohat	Kohat	33.432,228	71.525,793	150
91	Kohat	Kohat	33.438,387	71.524,092	170
92	Kohat	Kohat	33.41859	71.54115	30
93	Kohat	Kohat	33.41842	71.52519	175
94	Kohat	Kohat	33.511	71.61468	300
95	Kohat	Lachi	33.424,469	71.58253	28
96	Kohat	Lachi	33.496,274	71.497,064	293
97	Kohat	Lachi	33.5112	71.51263	306
98	Kohat	Lachi	33.52403	71.46006	276
99	Kohat	Lachi	33.4904	71.41953	170
100	Kohat	Lachi	33.48847	71.4289	300
101	Kohat	Lachi	33.45748	71.36636	150
102	Kohat	Lachi	33.4842	71.39565	152
103	Kohat	Lachi	33.48645	71.43885	300
104	Kohat	Lachi	33.41872	71.32223	270
105	Kohat	Lachi	33.42253	71.30653	290
106	Kohat	Lachi	33.41914	71.32249	392
107	Kohat	Lachi	33.416,347	71.26395	210
108	Kohat	Lachi	33.40647	71.25052	75
109	Kohat	Lachi	33.41426	71.17778	120
110	Kohat	Lachi	33.42235	71.1639	28
111	Kohat	Lachi	33.42238	71.1636	30
112	Kohat	Lachi	33.42373	71.36423	410
113	Kohat	Lachi	33.42215	71.36264	220
114	Kohat	Lachi	33.42067	71.36269	155
115	Kohat	Lachi	33.42187	71.3654	262
116	Kohat	Lachi	33.42197	71.3644	260
117	Kohat	Lachi	33.53777	71.46597	300

(Continued on following page)

TABLE 4 (Continued) Water table depth at various locations in the study area.

S. No	District	Tehsil	Latitude	Longitude	Total depth of bore hole
118	Kohat	Lachi	33.54265	71.46365	247
119	Kohat	Lachi	33.43059	71.39362	300
120	Kohat	Lachi	33.268,223	71.495,925	40
121	Kohat	Lachi	33.266,516	71.485,195	130
122	Kohat	Lachi	33.237,603	71.487,517	30
123	Kohat	Lachi	33.236,175	71.487,582	35
124	Kohat	Lachi	33.318,148	71.371,847	420
125	Kohat	Lachi	33.318,148	71.371,847	398
126	Kohat	Lachi	33.303,144	71.385,116	21
127	Kohat	Lachi	33.303,144	71.385,116	25
128	Kohat	Lachi	33.31538	71.432,669	270
129	Kohat	Lachi	33.53172	71.33751	240
130	Kohat	Lachi	33.5395	71.37427	230
131	Kohat	Lachi	33.53534	71.37292	200
132	Kohat	Lachi	33.5353	71.37292	288
133	Kohat	Lachi	33.5353	71.37291	280
134	Kohat	Lachi	33.54018	71.419,787	232
135	Kohat	Lachi	33.5353	71.37291	295
137	Kohat	Lachi	33.378,862	71.44439	24
138	Kohat	Lachi	33.55365	71.45255	216
139	Kohat	Lachi	33.55201	71.4527	280
140	Kohat	Lachi	33.421,718	71.528,245	30
141	Kohat	Lachi	33.419,157	71.546,047	28
142	Kohat	Lachi	33.448,977	71.289,198	30
143	Kohat	Lachi	33.448,977	71.289,198	180
144	Kohat	Lachi	33.448,865	71.278,617	27
145	Kohat	Lachi	33.455,257	71.35087	120
146	Kohat	Lachi	33.513,601	71.413,886	272
147	Kohat	Lachi	33.507,825	71.389,057	160
148	Kohat	Lachi	33.503,808	71.387,181	170
149	Kohat	Lachi	33.5111	71.38234	125
150	Kohat	Lachi	33.5111	71.38234	80

TABLE 5 Accuracy assessment of land use map.

Class name	User accuracy (%)	Producer accuracy (%)	Overall accuracy (%)
Urban area	71	100	88
Vegetation	85	100	
Water bodies	100	100	
Barren land	100	72	

User accuracy was obtained by dividing all correctly classified cells by total reference points. For this study, reference points were taken from Google Earth. Producer accuracy was also obtained by dividing the total cells with correct land use/land cover classification by total ground truth pixels; to obtain overall accuracy, correctly classified cells were divided by all pixels (Table 5).

4 Conclusion

We used the MIF method to investigate GWPZs in the Kohat District, Pakistan. For this purpose, various datasets were collected from different sources and processed using the ArcMap 10.5 spatial analysis tool. Several influencing parameters were then selected from the study area, such as land use/land cover, rainfall, slope, drainage density, geology, lineament density, and soil. These parameters were weighted based on their importance in evaluating GWPZs in the study area. The GWPZs were classified as very poor, poor, good, high, and very high. Our results revealed that out of an area of 2,952.40 km² area, 4.62% of the area were very poor GWPZs, 31.57% were poor GWPZs, 12.57% were good GWPZs, 37.72% were high GWPZs, and 13.51% were very high GWPZs. Data from a total of 150 wells with GPS-specified locations were collected to verify the study results. In the study area, the water table ranged from 35 to 210 m, and the GWPZ data overlaid with well data revealed that most wells with high and medium groundwater depths were well within the very high and high GWPZs.

In this study, the MIF method was useful in evaluating potential groundwater zones in the study area by utilizing the RS dataset. However, due to the limited availability of the dataset for suitable parameter selection, there were limitations affecting our results. Therefore, future study with selection of more parameters and their integration with machine learning prediction models will help further delineate GWPZs in the study area. The findings of this investigation may be helpful in development of compelling strategies for manageable groundwater asset advancement.

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Data availability statement

The original contributions presented in the study are included in the article/supplementary material, and further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization, HF and ZK; methodology, ZK; software, FI; validation, HF, RK, and ZK; formal analysis, IK and RA; investigation, HF and ET; resources, FI; data curation, HF; writing—original draft preparation, HF; writing—review and editing, ZK, HF, and RH; visualization, FI; supervision, ZK; project administration, RK, IK, and ET; funding acquisition, HF. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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