

Research Article

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Assessment of groundwater potential zones using GIS and AHP techniques – A case study of the zone of influence of Kolubara Mining Basin

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Abstract: Groundwater forms through infiltration beneath the Earth's surface as it moves through various rock layers. Reliable and sustainable water supplies are predominantly sourced from underground sources, making them some of the most important natural resources. The aim of this study is to assess and identify potential groundwater zones using Geographic Information Systems, remote sensing, and multi-criteria analysis, specifically the Analytical Hierarchy Process (AHP), within the Kolubara Mining Basin influence zone in Serbia. This study considers factors such as rainfall, geology, slope, river network density, and land use/land cover. These factors were evaluated using the Saaty scale to determine their respective weights. Due to their higher weights, the AHP process revealed that precipitation and geology are the most influential factors in groundwater formation. Groundwater potential zones are categorized into five classes: very low, low, moderate, high, and very high. These results will enhance groundwater management at both regional and local levels and contribute to the future protection of this resource.

Keywords: groundwater potential zones, AHP, remote sensing, Kolubara MB, Serbia

1 Introduction

In contemporary conditions, characterized by the progressive depletion of surface water resources, groundwater has

become the primary source of fresh water for household, agricultural, and industrial needs, including drinking and technical water. The accelerated processes of industrialization and population growth directly impact the availability of groundwater [1]. Over time, this has led to the rapid and often uncontrolled exploitation of underground aquifers. This trend is particularly pronounced in arid and semi-arid regions, where average annual precipitation is low and the hydrological dependence of the local population on groundwater is notably high. In these areas, water from dug and deep wells is predominant, and often the sole source for irrigation, sanitation, and industrial purposes. The issue has a global dimension and is particularly acute during the summer, when agricultural activities significantly increase groundwater consumption for irrigation, often leading to unsustainable extraction. As a result, several problems arise, including a decline in groundwater levels, contamination due to agricultural practices, and a deterioration in water quality [2,3]. According to data by Taylor et al. [4], approximately 42% of all groundwater use worldwide is allocated to agricultural production. Groundwater is considered one of the vital elements of nature found in the voids of the earth and fills the pore space of soil beneath the water table [5–8]. As a dynamic resource, yet spatially and temporally limited, it is crucial for sustainable socio-economic development and the maintenance of hydrological stability. Groundwater serves as one of the most significant sources of water supply across all climate zones globally [9–12]. Its role in providing a reliable and continuous supply of drinking water in both urban and rural areas is of strategic importance, particularly in the context of climate change, increasing drought frequency, and growing water stress [13]. Effective management and spatial planning based on integrated hydrological analyses are vital for preserving both the quantitative and qualitative integrity of this resource. According to data from the food and agriculture organization of the United Nations [14], nearly 30% of global freshwater originates from groundwater sources, while only 0.3% is derived from surface waters, including lakes,

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reservoirs, and rivers [8,15]. The primary sources of groundwater are rainfall and snowmelt, which infiltrate through soil pores and percolate into aquifers [16]. As such, groundwater exploitation is regarded as a critical component of water resource management and planning strategies. The availability of groundwater is influenced by a range of geological, morphological, biological, and atmospheric factors, including lithology, topographic conditions, geological structures, climate, and soil type. However, groundwater movement is predominantly determined by the porosity, permeability, transmissivity, and storage capacity of the underlying rocks [17–21].

Groundwater located in Neogene and Quaternary sediments in Serbia constitutes a significant natural resource, widely distributed across the country, with approximately 75% of the population relying on these sources for various purposes [22]. Understanding groundwater dynamics, including flow regimes and storage capacity, is essential for the effective management of irrigation and land drainage systems. However, data on the quantity and utilization potential of groundwater in Serbia remain limited, and research in this area is still underdeveloped. According to the Jaroslav Černi Water Institute, only about 30% of the estimated 67 m³/s of available groundwater is currently being exploited [23]. Although this utilization rate is relatively low, excessive and uncontrolled extraction from the main aquifer, exceeding its natural recharge capacity, has led to a significant decline in piezometric levels in certain regions of Serbia [23].

Effectively addressing groundwater-related challenges requires a clear understanding of actual reserves and the extent to which these resources can be utilized for various purposes, including water supply, irrigation, and industrial use. Monitoring groundwater status is essential for assessing the capacity of existing sources and ensuring their long-term sustainability. By collecting and analyzing data, it is possible to evaluate the influence of both natural factors (e.g., precipitation, climate change) and anthropogenic activities (e.g., agricultural usage, urbanization) on groundwater levels, quality, and consumption [24,25]. Such information is critical for making timely, evidence-based decisions.

There are several approaches for assessing groundwater potential, considering the relevant factors. The applicable methods include geological, geophysical, and remote sensing techniques, which have been extensively studied by many scientists [26–30]. The efficiency of these methods varies; some are more effective, accurate, time-saving, and cost-efficient, while traditional methods tend to be more time-consuming and expensive [11,31,32]. Additionally, the integration of Geographic Information Systems (GIS) technologies and remote sensing methods allows for the analysis and storage of large volumes of geospatial data, enabling the precise delineation of

groundwater potential using various methodological approaches [8,21,32,33].

Based on contemporary research and new insights, policymakers at both the national and local levels can focus on developing sustainable management policies for this resource. One of the initial steps in this process is the identification and mapping of areas with potential for groundwater exploitation, which serves as the foundation for further planning and the implementation of sustainable usage strategies.

Although highly reliable, traditional methods for determining the location and characteristics of aquifers, such as exploratory drilling and stratigraphic analysis, are associated with high costs, lengthy procedures, and the need for specialized personnel [9,34,35]. Several studies have been conducted in the field of groundwater management, utilizing various multicriteria decision-making algorithms and machine learning techniques [20,31,36–38]. A wide range of research methods has been applied to groundwater potential mapping, including the Analytical Hierarchy Process (AHP), frequency ratio, and influencing factors [8,32,39–47]. Quantitative approaches include the AHP [48–51]. Additionally, other researchers have explored the logistic model tree, Dempster–Shafer model, certainty factor, logistic regression, random forest model, maximum entropy model, decision tree model, and artificial neural networks to enhance the delineation of groundwater potential [46,52–55].

Among contemporary methodologies, the AHP, when integrated with remote sensing and GIS, has proven to be an effective, reliable, and cost-efficient approach for the identification and mapping of groundwater potential [35,56–58].

The AHP is among the most widely utilized methods for delineating Groundwater potential zones (GWPZ), with its extensive application particularly attributed to its capacity for integration with GIS [32,41,59–61]. Originally developed in 1977 by Professor Thomas L. Saaty, AHP has found broad application in the field of natural resource management, where it is recognized as an effective tool for addressing complex decision-making problems [62].

The rapid advancement of digital technologies, particularly high-performance computing and the integration of remote sensing techniques with GIS, has enabled the development of advanced hydrological analyses that transcend the limitations of traditional methods. A prominent example is the delineation of GWPZ, which can now be accurately identified across a variety of geographic regions [22,63]. The use of GIS and remote sensing has largely supplanted conventional data collection methods, significantly improving data accessibility while reducing both the time and financial costs associated with research [22,64]. GIS tools facilitate the processing and analysis of large and complex spatial datasets, which is essential for establishing robust decision support systems in water resource management [11,65]. Furthermore, GIS

significantly enhances decision-making and planning processes by enabling efficient data input, manipulation, analysis, and long-term storage [66–75].

Numerous significant studies worldwide have focused on identifying GWPZ through the application of remote sensing technologies and GIS for water resource assessment. These investigations encompass a range of geographic regions, including the Central Eastern Desert in Egypt [76], the Burdur region in Turkey [77], Ghana [64], the Maknassy Basin in Tunisia [60], and the Kurdistan region in Iran [41]. The integration of remote sensing and GIS enables the accurate mapping and evaluation of GWPZ, adapted to the diverse climatic and geological conditions specific to each area. Furthermore, Ferozur et al. [78] conducted a similar study in the arid regions of Bangladesh, utilizing a remote sensing and GIS-based approach to delineate groundwater potential. Their findings underscore the effectiveness of this methodological framework in drought-prone areas, offering critical insights for sustainable water resource management. In Europe, similar studies have been conducted in and around the region of Serbia [1,22,24,79], employing remote sensing and GIS techniques to assess groundwater potential zones under varying climatic and geological conditions.

The objective of this study is to evaluate and delineate GWPZ within the influence area of the Kolubara Mining Basin (MB) through the application of GIS-based spatial analysis techniques, specifically the Weighted Overlay (WO) method and the AHP. This integrative approach is designed to support the sustainable management of groundwater resources by enabling more efficient and targeted exploration and utilization. The study addresses three key research questions: (1) Which areas within the Kolubara MB are most suitable for sustainable groundwater exploitation? (2) What are the most influential environmental and geological factors affecting groundwater potential in the region? and (3) How effectively can the integration of GIS-based WO and AHP methods support the delineation of GWPZ under conditions of intensive land use and climatic stress? By addressing these questions, the research aims to establish a scientifically robust foundation for evidence-based decision-making and contribute to the long-term planning and management of groundwater resources in the region.

2 Methods

2.1 Study area

The research area lies within the zone influenced by the Kolubara MB, located approximately 60 km southwest of

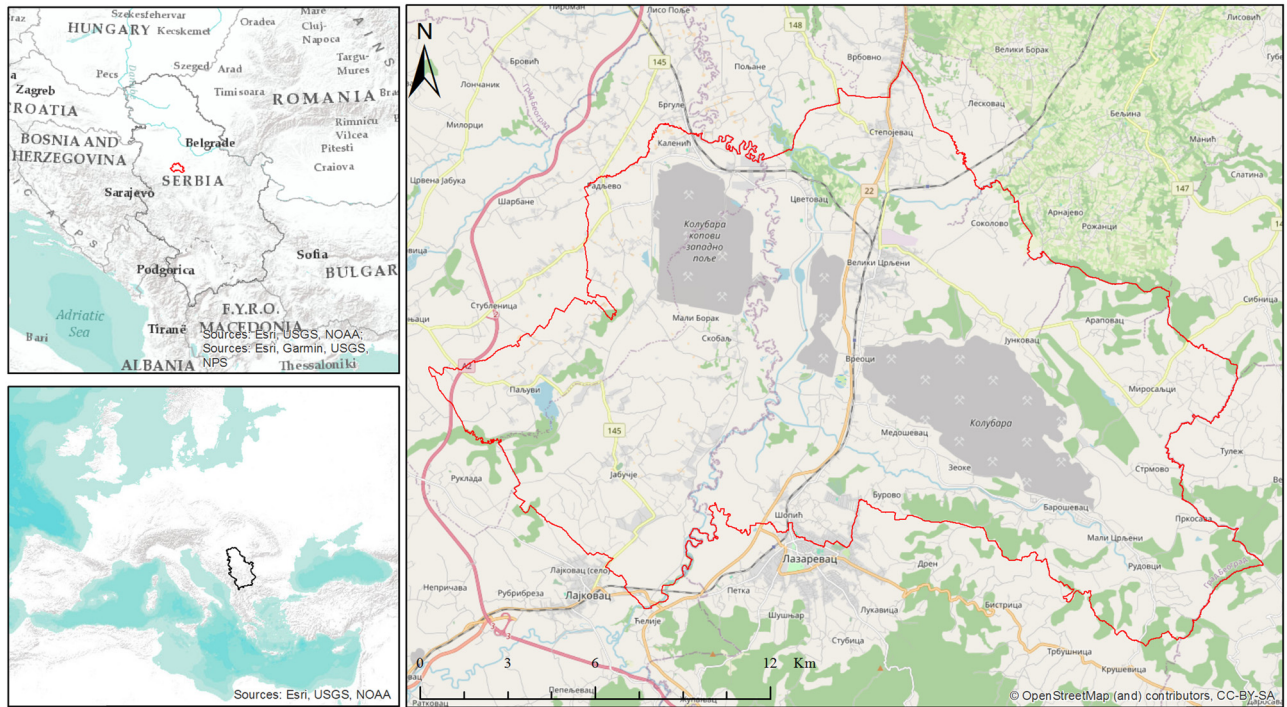
Belgrade and spanning around 600 km². The region experienced significant mining and industrial expansion during the latter half of the twentieth century. The designated zone of influence, encompassing 301.29 km², was delineated based on areas affected by lignite extraction. The study area is located between 44°21'19"N and 44°32'07"N latitude, and 20°05'45"E and 20°27'21"E longitude. Lignite, a combustible sedimentary rock of organic origin, serves as a key energy resource in this area.

Geographically, the terrain is defined by gently rolling alluvial plains along the Kolubara River and its tributaries, including the Tamnava, Peštan, and Turija rivers. The basin itself is divided into eastern and western sectors. While the eastern section has been fully surveyed and developed, recent exploration and mining activities have increasingly targeted the western portion [80]. Most active extraction operations are concentrated in the municipality of Lazarevac, with additional, though less intensive, activity occurring in Lajkovac and Ub (Figure 1).

The region's rich natural resources, particularly lignite coal, combined with advantageous geographic and environmental conditions, have driven its industrial growth. However, this development has had adverse environmental consequences. Extensive coal mining has led to significant landscape alteration, repurposing of agricultural land, and a shift in the workforce from traditional farming to mining and industrial jobs. These changes have increased ecological vulnerability in the area [81].

As mining operations continue to expand across multiple open-pit sites, the local population has experienced displacement, often relocating within nearby settlements or adjacent zones linked to Kolubara MB. Socio-demographic changes, triggered by economic shifts and population movement, have compounded the strain on the region's natural resources. The environmental repercussions include deforestation, soil and water contamination, and further land conversion to support new residential developments and infrastructure projects [81–84].

The spatial development of lignite basins has been the subject of analysis by researchers in neighboring countries and beyond [67,81,85–89]. In Serbia, lignite – a type of fossil fuel – plays a central role in the national energy system, particularly in the generation of electricity through thermal power plants. As outlined in the Republic of Serbia's Energy Sector Development Strategy up to 2025, with forecasts extending to 2030, and corroborated by various scholarly sources, lignite with a low degree of carbonization constitutes the country's most substantial geological energy resource [90]. Presently, coal fuels approximately 88% of Serbia's electricity production [91]. In contrast, the combined energy potential from alternative reserves, including hydropower,



Legend

- Republic of Serbia
- Zone of influence of Kolubara Mining Basin

Figure 1: Geographical location of the influence zone of Kolubara MB [81].

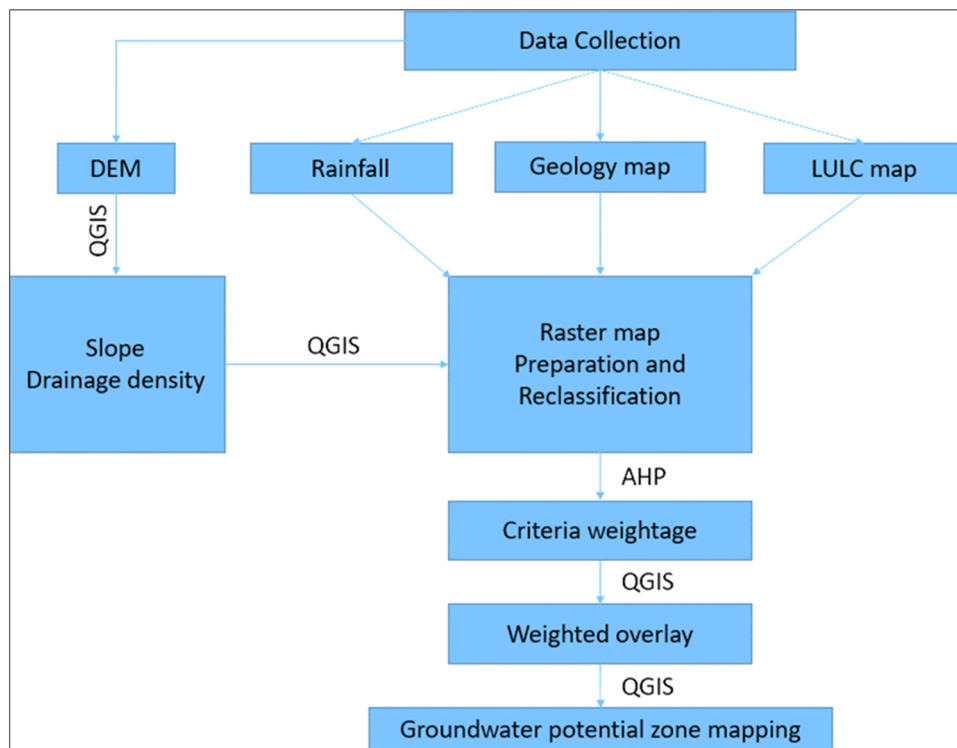


Figure 2: Flowchart describing the methodology.

smaller coal deposits, and oil shale, is projected to contribute no more than 10% to total energy output [81,91].

The influence zone of the Kolubara MB, in addition to active mining areas, is largely comprised of agricultural land that depends on groundwater resources. The region's continental climate is marked by hot, dry summers and, in recent years, relatively mild winters. These climatic conditions underscore the need for targeted groundwater management strategies to mitigate the impacts of drought. It is therefore crucial to systematically identify areas with potential for the development of new groundwater sources. The initial phase of this planning process centers on the mapping of groundwater potential.

2.2 Data acquisition and integration into a GIS

GIS and remote sensing techniques were employed to delineate GWPZ through the application of the AHP. The AHP was employed to assess thematic maps and their associated characteristics based on their relative importance to groundwater occurrence. A total of five thematic layers were generated for model development, including rainfall, geology, slope, drainage density, and land use/land cover (LULC). Each thematic layer was assigned a relative weight based on expert judgment and supported by existing literature. The complete methodological framework is presented in Figure 2.

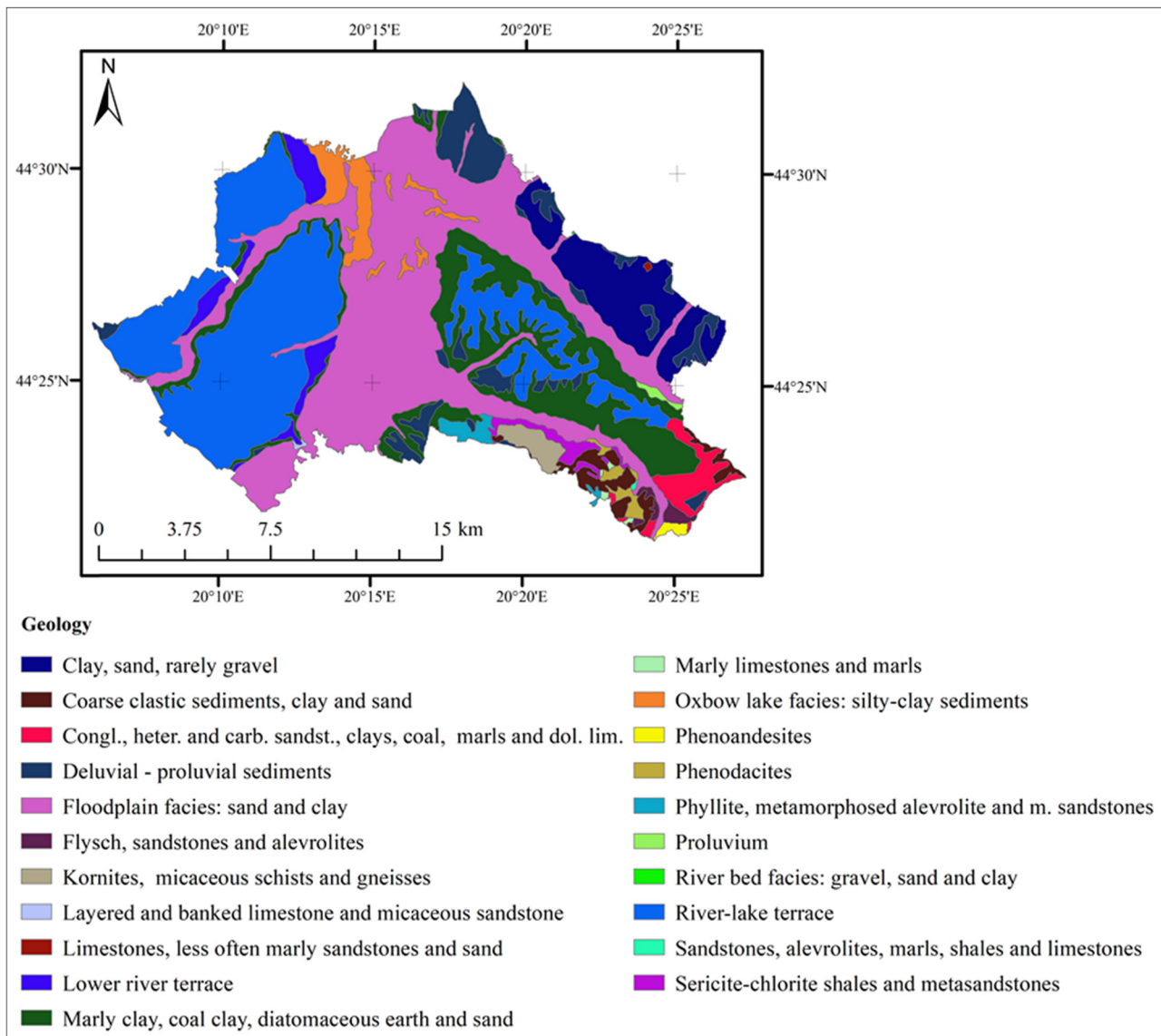


Figure 3: Geological map of the zone of the influence of Kolubara MB [81].

GWPZ were delineated through the superimposition of all relevant thematic layers using the WO technique, as described by Waikar and Nilawar [92], with spatial analysis tools implemented in the QGIS 3.34.5 LTR software environment.

These data were utilized to develop thematic layers relevant to the assessment of groundwater potential. Among the key factors in identifying areas with groundwater potential is the lithological composition of the terrain. The porosity and permeability of geological materials directly influence the direction and intensity of subsurface flow, as well as the accumulation of groundwater [8,32,93].

The Kolubara MB represents one of the largest Neogene sedimentary basins in Serbia, primarily composed of lacustrine and fluvial sediments, with extensive deposits of clay, marl, sandstone, and lignite. These sediments were deposited during the Miocene and Pliocene epochs within a tectonically active environment, resulting in complex stratification and heterogeneity of the subsurface [94].

The dominant lithological units in the basin include alternating layers of poorly cemented sandstone, siltstone, claystone, and lignite seams, which collectively influence groundwater movement and storage. Due to the variable grain size and composition, these formations exhibit moderate to low permeability, although local sandy and gravelly horizons may act as confined or semi-confined aquifers. The lignite seams, although extensive, are considered aquitards due to their low permeability. The spatial distribution of lithofacies reveals zones with differing groundwater recharge potential, where sandy and alluvial sediments are more favorable for infiltration, while clay-rich layers inhibit vertical water movement.

Geological data were updated based on the basic geological map of Serbia, Obrenovac sheet (scale 1:100,000), originally compiled by the Federal Geological Institute in 1979 [94]. The map was subsequently digitized and geologically classified for further analysis using the QGIS software package (Figure 3 and Table 1).

The geological structure of the study area plays a critical role in controlling the formation and spatial distribution of groundwater. More than 60% of the study area is composed of Tertiary and Quaternary sediments, including river and lacustrine terraces and floodplain facies, primarily consisting of sands and sandy clays. These lithologies generally exhibit favorable hydrogeological properties. As indicated on the geological map, these deposits are predominantly distributed across the central and western portions of the study area.

The southeastern part of the study area is underlain by magmatic rocks, which are characterized by low primary

Table 1: Geological composition of the investigated area

Type of rock	Surface (km ²)	%
Deluvial-proluvial sediments	18.29	6.07
River bed facies: gravel, sand, and clay	0.01	0.004
Oxbow lake facies: silty-clay sediments	8.38	2.78
Floodplain facies: sand and clay	96.38	31.99
Phenoandesites	0.61	0.20
Phenodacites	1.63	0.54
Phyllite, metamorphosed alevrolite and metamorphosed sandstones	2.05	0.68
Flysch, sandstones and alevrolites	1.38	0.46
Clay, sand, rarely gravel	22.24	7.38
Coarse clastic sediments, clay, and sand	5.59	1.85
Conglomerates, heterogeneous and carbonaceous sandstone, clays, coal, marls, and dolomitic limestones	5.67	1.88
Kornites, micaceous schists, and gneisses	2.97	0.99
Limestones, less often marly sandstones, and sand	0.10	0.03
Marly clay, coal clay, diatomaceous earth, and sand	42.06	13.30
Marly limestones and marls	0.29	0.10
Lower river terrace	7.33	2.43
Sandstones, alevrolites, marls, shales, and limestones	0.07	0.02
Proluvium	0.55	0.18
River-lake terrace	82.78	29.13
Sericite-chlorite shales and metasandstones	2.78	0.92
Layered and banked limestone and micaceous sandstone	0.14	0.05
Total	301.29	100

permeability. As a result, these zones exhibit limited potential for groundwater infiltration and storage, indicating a generally low hydrogeological potential. Magmatic formations typically function as poor aquifers due to their compact structure; however, if significantly fractured or weathered, their permeability may locally increase, allowing for limited groundwater flow and accumulation.

The slope map was derived from the SRTM Digital Elevation Model (DEM) obtained from the official platform of the United States Geological Survey (USGS). The dataset, labeled as DEM USGS 1arcSec, has a spatial resolution of approximately 30 m. Using the SLOPE function in QGIS, slope values were calculated and expressed in degrees. For analytical purposes, the resulting slope layer was classified into five categories according to the degree of steepness, enabling its integration as a thematic layer in the GIS-based analysis.

Terrain slope and drainage density represent key morphometric factors that directly influence surface runoff and infiltration patterns, and consequently, the formation

of groundwater. Numerous studies have emphasized their critical role in controlling hydrological processes, particularly in the context of evaluating groundwater accumulation potential [32,95]. Steep slopes are associated with increased surface runoff, heightened erosion, and reduced infiltration capacity, whereas areas with gentle slopes are more conducive to infiltration processes due to prolonged surface water retention. In the studied area, gentle slopes (0°–5°) predominantly occur in the influence zone of Koluvara MB, covering approximately 80% of the total area. Slopes ranging from 5° to 15° are present on about 19% of the analyzed area, primarily in the central and eastern regions. The smallest proportion of the area, approximately 1%, is characterized by steep slopes (15°–39°), which are mainly located in the southeastern part of the study area (Figure 4 and Table 2).

The LULC map was constructed using data from the CORINE Land Cover 2018 program (<https://land.copernicus.eu/en>). Land cover and its spatial distribution play a crucial role in groundwater infiltration processes. Vegetated areas, including forests and green spaces, facilitate higher infiltration rates, whereas urbanized regions reduce groundwater recharge and increase surface runoff. In this study, a land cover map was developed through an analysis of the CORINE Land Cover 2018 dataset, obtained from the official Copernicus platform. Land classification was conducted using the QGIS software tool.

The final land cover map comprises 15 major categories: broad-leaved forest, complex cultivation patterns, coniferous forest, construction sites, discontinuous urban

Table 2: Angles of slope of the terrain

Slope (°)	Surface (km ²)	%
0–2	154.91	51.41
2–5	86.90	28.84
5–15	57.79	19.18
15–35	1.69	0.57
35–39	0.003	0.001
Total	301.29	100

fabric, dump sites, industrial or commercial units, land principally occupied by agriculture, mineral extraction sites, mixed forest, non-irrigated arable land, pastures, transitional woodland-shrub, water bodies, and watercourses (Figure 5). The results indicate that the predominant land use within the study area is agricultural, covering approximately 70% of the total surface. This is followed by mineral extraction sites (10%) and transitional woodland-shrub, as shown in Table 3. Urban areas are primarily located along the periphery of surface mining zones. Water bodies occupy a relatively small portion of the area. Forested areas, agricultural land, grasslands, and sparsely vegetated regions significantly contribute to increased infiltration and the recharge of groundwater resources.

Three main climate types can be identified in the Republic of Serbia: continental, moderately continental, and modified Mediterranean [96,97]. Although the influence of moisture and heat from the surrounding seas is partially obstructed by mountain ranges, increased precipitation

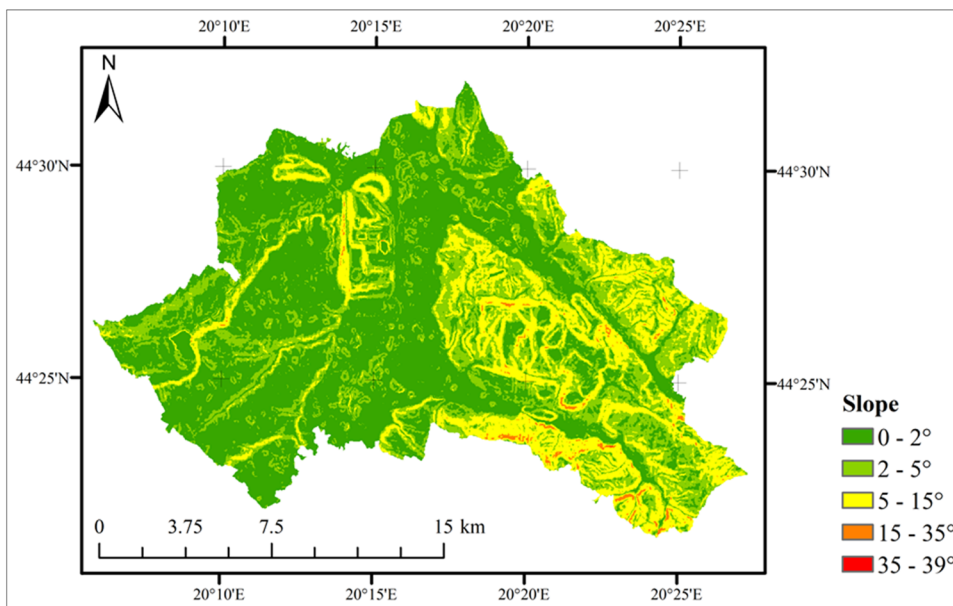


Figure 4: Spatial arrangement of the slope of the terrain of the studied area [81].

remains prominent in the western parts of Central Serbia. The Carpathian Basin in the north facilitates the penetration of polar air masses into Central Serbia during the winter months. In contrast, during the summer, hot air currents from the Sahara affect the region's climatic conditions [97]. According to the Köppen climate classification, the climate of Central Serbia falls within the Dfa/Cfa categories, indicating either a cold winter without a dry season and a hot summer, or a temperate climate without a dry season and a warm summer [97–99].

The average annual air temperature in Central Serbia for the period 1949–2015 was 10.07°C, while the total annual precipitation averaged 685.3 mm [97]. In their comprehensive analysis of Central Serbia's climatic characteristics, Radaković *et al.* [97] examined average monthly air temperature and precipitation data from 26 meteorological stations. These data were essential for calculating monthly, seasonal, and annual aridity indices over 66 years. According to the De Martonne climate classification, five, three, and four climate types were identified at the monthly, seasonal, and annual levels, respectively. Winter was found to be extremely humid, while spring and autumn were also classified as humid, and summer exhibited semi-humid characteristics. The authors applied the annual Pinna Combined Index to identify humid and semi-humid climates with Mediterranean vegetation. The results indicated no significant trend in aridity change in Central Serbia over the study period.

Precipitation data for this study were obtained from the WorldClim version 2.1 database, which provides high-

Table 3: Purpose of land use

LULC	Surface (km ²)	%
Built-up area	19.85	6.59
Open pits	29.17	9.68
Agriculture area	195.02	64.74
Forest	54.21	18.00
Water bodies	3.05	1.01
Total	301.29	100

resolution global climate layers (<https://www.worldclim.org/>). Specifically, monthly precipitation data (variable *prec*) at a spatial resolution of 30 arc-seconds (approximately 1 km²) for the period 1970–2000 were used. WorldClim 2.1 integrates data from a global network of weather stations, applying advanced spatial interpolation techniques to generate continuous and standardized climate surfaces. This dataset is widely utilized in ecological, hydrological, and environmental research due to its fine spatial resolution, long-term temporal coverage, and global extent. The selected precipitation data offer reliable estimates of historical rainfall patterns, serving as a critical input for climate-related analyses and modelling.

Precipitation is one of the most important factors influencing groundwater recharge [32,100]. Based on the available data, a map of average annual precipitation for the study area was created in raster format and processed using QGIS software (Figure 6). Analysis of the map indicates that the central, southern, and western parts of the area receive slightly higher amounts of precipitation

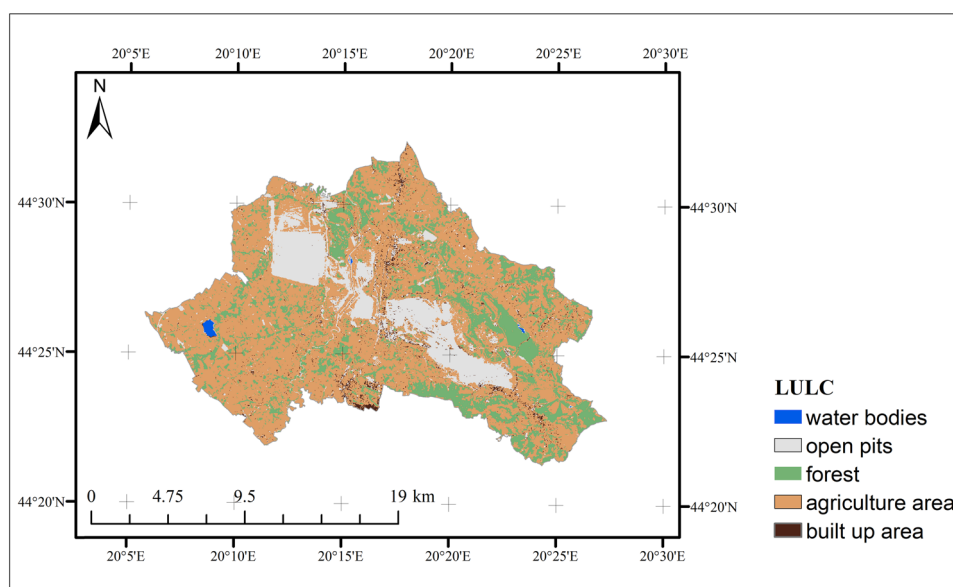


Figure 5: Display of areas for different purposes of land use.

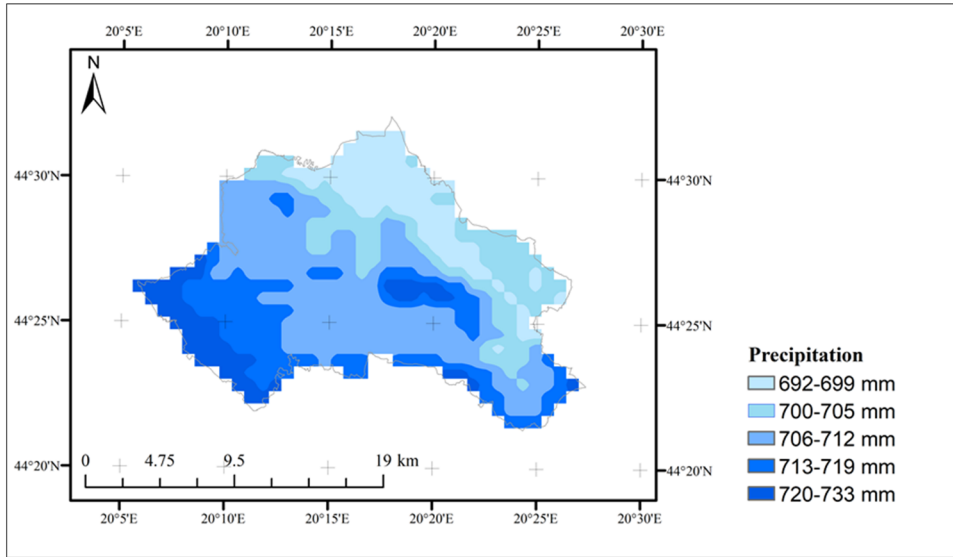


Figure 6: The precipitation schedule in the area of influence of the Kolubara MB (data retrieved from the platform WorldClim.com, date of retrieval December 12, 2024).

compared to the northern and eastern regions. Annual precipitation ranges from 692 to 733 mm, making it a key contributor to groundwater replenishment in the region.

Drainage density was also derived from the DEM using the Line Density tool within the spatial analysis tools of the GIS software.

Drainage density is a critical hydrological parameter for assessing surface runoff and groundwater infiltration

potential. A high drainage density typically indicates increased surface runoff and limited conditions for infiltration, whereas a low drainage density is associated with a greater capacity for water retention and infiltration into subsurface layers [8,101,102].

Based on the results, a thematic map of drainage density was created, with values classified into five categories (Figure 7 and Table 4), and subsequently resampled for more precise spatial representation.

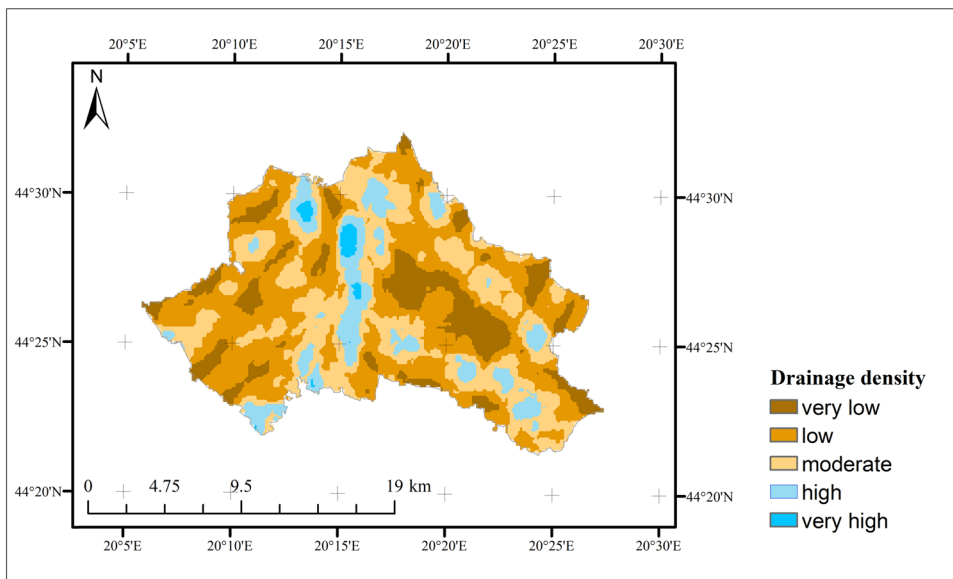


Figure 7: The drainage density in the area of influence of Kolubara MB.

Table 4: Drainage density classes in the study area

Drainage density class	Surface (km ²)	%
Very low	45.67	15.16
Low	129.51	42.99
Moderate	90.91	30.17
High	31.80	10.55
Very high	3.40	1.13
Total	301.29	100

2.3 AHP

For multi-criteria analysis, the AHP was applied, along with the development of a composite (synthesis) map. This method, developed by Saaty [103,104], aims to quantitatively structure decision-making by establishing a hierarchy of criteria based on their relative importance [8,105,106]. Effective application of the AHP method and the assignment of weight coefficients requires familiarity with the study area, as well as an understanding of the relevant environmental processes and physical principles, to construct a well-founded and meaningful hierarchy of prioritized criteria [107–109].

A key feature of the AHP method is the incorporation of subjective judgment in determining the weights assigned to each criterion [110]. This subjectivity is informed by prior research and empirical findings within the field. In this context, expert judgment regarding the relative importance of natural conditions can, paradoxically, contribute to a more objective and context-sensitive representation of the results. The primary rationale for employing the AHP method lies in its ability to assign differentiated coefficients to individual parameters-emphasizing those with the greatest influence while appropriately down-weighting less significant factors.

According to Hosseinali and Alesheikh [111], the AHP comprises several phases: defining objectives, determining criteria, performing pairwise comparisons of factors, constructing a matrix, determining the relative weights of factors using eigenvalue techniques, calculating the

consistency ratio, and ultimately making the final decision. The significance of each factor is assessed through pairwise comparisons, utilizing a scale from 1 (indicating equal importance of factors) to 9 (indicating one factor is significantly more important than the other), as outlined in Table 5 [103]. The values corresponding to each factor have been provided in Table 6.

The normalized pairwise comparison matrix is obtained by dividing each cell by the total of its respective column. The normalized weights for each factor are then calculated as the average of the values in each row, as shown in Table 7.

Once the weights have been assigned, it is necessary to calculate the consistency of the matrix; the consistency ratio is assessed using the following equation developed by Saaty [104].

$$CR = \frac{CI}{RCI},$$

where CR represents the consistency ratio, CI is the consistency index, and RI is the random index obtained from a table provided by Saaty [104]. The value of RI depends on the number of criteria in the analysis, and in this study, it is 1.12. The CI is calculated using the following equation:

$$CI = \frac{(\lambda_{\max} - n)}{(n - 1)},$$

Table 6: Pairwise comparison matrix between all factors for AHP model

Factors	Factors				
	Rainfall	Geology	Drainage density	Slope	LULC
Rainfall	1	5	9	7	9
Geology	0.2	1	7	3	5
Drainage density	0.11	0.14	1	3	1
Slope	0.14	0.33	0.33	1	1
LULC	0.11	0.2	1	1	1
Sum	1.56	6.67	18.33	15	17

Table 5: Saaty's scale of relative importance [103]

Weights	Importance	Explanation
1	Equally important	Two elements contribute equally to the objective
3	Weakly important	Experience and judgment slightly favor one element over another
5	Fairly important	Experience and judgment strongly favor one element over another
7	Strongly important	An element is favored very strongly over another; its dominance is evident.
9	Absolutely important	The evidence favoring one element over another is of the highest possible order
2, 4, 6, 8	Intermediate values	Used to express compromises between the above values

Table 7: Normalized pairwise comparison matrix and weights of each factor

Factors	Factors					Weights
	Rainfall	Geology	Drainage density	Slope	LULC	
Rainfall	0.64	0.75	0.49	0.47	0.53	0.58
Geology	0.13	0.15	0.38	0.20	0.29	0.23
Drainage density	0.07	0.02	0.05	0.20	0.06	0.08
Slope	0.09	0.05	0.02	0.07	0.06	0.06
LULC	0.07	0.03	0.05	0.07	0.06	0.06
Sum	1.000	1.000	1.000	1.000	1.000	1.000

where λ_{\max} is the principal eigenvalue of the matrix, calculated from the matrix itself, and in this study, it is 5.4. Additionally, n represents the number of factors considered for assessing groundwater potential, which is 5. The value of the CI is 0.1. According to Saaty and Malczewski [104,112], the CR should be less than 0.1. If CR exceeds 0.1, the pairwise comparison matrix must be readjusted by assigning new values to the factors [113]. In this study, the CR was found to be 0.089, which is below 0.1, thereby confirming the consistency of the matrix.

All factors were initially classified into appropriate subclasses and ranked based on their impact on groundwater-related activities. To ensure comparability among subclasses, the ranks were normalized. Normalization was carried out by dividing each rank by the total sum of all ranks, thereby obtaining the relative weight of each factor within the subclass, as presented in Table 8. Subsequently, the GWPZ were delineated by applying the following equation, which was implemented using the raster calculator.

$$\text{GWPI} = \sum_{i=1}^a \cdot \sum_{j=1}^b \cdot (W_i \times X_j),$$

where GWPI is the groundwater potential index, W_i is the weight of the i th theme, X_j is the weight of the j th features, a is the total number of themes, and b is the total number of features in a theme. According to GWPI, the final GWPZ map was classified as very poor, poor, moderate, good, and very good.

3 Results and discussion

In this study, five key thematic layers influencing groundwater potential were considered. Using the AHP, a suitability map was generated and subsequently classified into five categories: very low, low, moderate, high, and very high (Figure 8 and Table 9).

The zone with moderate potential for groundwater constitutes the largest portion of the study area, accounting

for 45.28% of the total surface and primarily occupying the central part of the region. The northern section is characterized by poor groundwater potential, encompassing 33.26% of the area. In contrast, zones with good groundwater potential cover 18.88% of the territory and are predominantly located in the southern, central, and eastern parts of the study area.

Surface coal mining operations require extensive land drainage as part of their extraction process. Significant volumes of groundwater are pumped out, resulting in a lowered water table. This water, typically discharged as mine water into nearby watercourses, currently represents an underutilized resource. In the future, it may serve additional purposes, offering potential for more efficient and sustainable resource management.

The continual expansion of surface mines has necessitated increasingly sophisticated approaches to groundwater management. In the vicinity of the Kolubara MB mining complex, several municipal water supply systems have been established to provide potable water to settlements located near the mining operations. These systems were developed in response to the depletion of household wells, thereby resolving issues related to the regular supply of drinking water.

Given the ongoing process of mine expansion and the opening of new pits, there is an urgent need to adopt a more systematic and long-term strategy for groundwater management in the region. Such an approach would not only address current environmental and hydrological challenges but also support sustainable development and resource utilization in the broader area.

Within the lignite deposit and the broader impact zone of the Kolubara MB, characterized by sandy and gravelly sediments of Tertiary and Quaternary origin, the following hydrogeological collectors have been identified: overburden (or surficial) aquifers (present in alluvial sands and gravels, terrace gravels and sands, as well as upper Pontian sands), interlayer aquifers, and basal aquifers. These aquifer layers are, in many cases, separated by

Table 8: Assigned normalized weights and rates for all factors and sub-classes

No	Factors	Sub-classes	Rating	Normalized rates	Weights
1	Rainfall	692–699	1	0.07	0.58
		700–705	2	0.13	
		706–712	3	0.20	
		713–719	4	0.27	
		720–733	5	0.33	
2	Geology	Deluvial-proluvial sediments	2	0.04	0.23
		River bed facies: gravel, sand, and clay	5	0.10	
		Oxbow lake facies: silty-clay sediments	1	0.02	
		Floodplain facies: sand and clay	2	0.04	
		Lower river terrace	3	0.06	
		Proluvium	3	0.06	
		Clay, sand, rarely gravel	2	0.04	
		Coarse clastic sediments, clay, and sand	3	0.06	
		Conglomerates, heterogeneous and carbonaceous sandstone, clays, coal, marls, and dolomitic limestones	2	0.04	
		Phenoandesites	3	0.06	
		Phenodacites	3	0.06	
		Limestones, less often marly sandstones, and sand	4	0.08	
		Marly clay, coal clay, diatomaceous earth, and sand	1	0.02	
		River-lake terrace	5	0.10	
		Flysch, sandstones, and alevrolites	1	0.02	
		Marly limestones, and marls	1	0.02	
		Sandstones, alevrolites, marls, shales, and limestones	2	0.04	
Layered and banked limestone and micaceous sandstone	3	0.06			
Phyllite, metamorphosed alevrolite, and metamorphosed sandstones	2	0.04			
Kornites, micaceous schists, and gneisses	1	0.02			
Sericite-chlorite shales and metasandstones	1	0.02			
3	Drainage density	Very low	5	0.33	0.08
		Low	4	0.27	
		Moderate	3	0.20	
		High	2	0.13	
		Very high	1	0.07	
4	Slope	0–2	5	0.33	0.06
		2–5	4	0.27	
		5–15	3	0.20	
		15–35	2	0.13	
		35–39	1	0.07	
5	LULC	Water bodies	5	0.33	0.06
		Open pits	2	0.13	
		Forest	4	0.27	
		Agriculture area	3	0.20	
		Built-up area	1	0.07	

coal seams and Pontian clays, which act as natural hydrogeological barriers or confining layers.

Although the direct application of the AHP model within the Kolubara MB has not been widely documented, similar methods, such as Fuzzy AHP, have been successfully employed in nearby regions. For instance, a study conducted in the municipality of Titel utilized GIS and Fuzzy AHP techniques to identify zones with high groundwater potential, taking into account factors such as geomorphology, soil type, and drainage density [22].

The use of hydrogeological modelling to assess the impact of flooding on groundwater regimes in mining basins, such as the Kolubara MB, can significantly enhance risk assessment and water resource management [23]. The objective of this study conducted by Polomčić *et al.*, was to evaluate the influence of historical flood events on the groundwater regime within the Kolubara MB. The authors employed a hydrogeological model to analyze changes in groundwater levels caused by flooding across different periods. Particular attention was given to identifying key

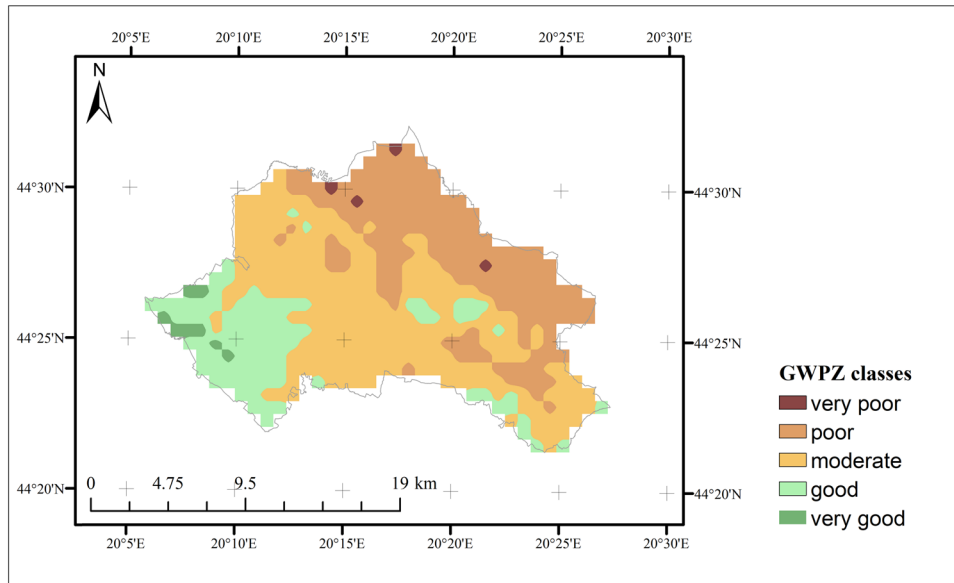


Figure 8: The groundwater potential maps for zone impact Kolubara MB, by AHP model.

Table 9: Areas of different zones of groundwater potential

Zone	Surface (km ²)	%
Very poor	2.50	0.86
Poor	96.91	33.26
Moderate	131.92	45.28
Good	55.02	18.88
Very good	5.00	1.72
Total	291.35	100

factors influencing groundwater dynamics, including geological formations, hydraulic conductivity of the strata, and natural processes of aquifer recharge and discharge. This research provides valuable insights into the effects of flooding on hydrogeological systems in mining regions. The findings can serve as a foundation for developing water resource management strategies in the context of mining activities, especially regarding groundwater level control and the prevention of adverse impacts on mining operations.

In the study by Ketkat et al. [114], the authors assessed the groundwater potential in the Zaafarana region of Egypt using an integrated approach that combines the AHP, GIS, and remote sensing techniques. The objective of the research was to evaluate GWPZ through a multi-criteria decision-making framework that incorporated morphometric analysis, AHP modelling, and thematic spatial layers.

The results revealed significant spatial variability in morphometric characteristics influencing groundwater

recharge and flow potential. The AHP model effectively delineated areas with high, moderate, and low groundwater potential, offering valuable insights for targeted exploration and sustainable water resource management. The sensitivity analysis confirmed the model's robustness, as slight variations in parameter weights had minimal impact on the delineated GWPZ.

These studies underscore the value of applying multi-criteria decision-making methods in hydrogeological analyses, particularly in regions characterized by complex hydrological conditions. For the Kolubara MB, the application of the AHP model could significantly enhance the accuracy of groundwater potential assessments, which is essential for sustainable water resource management and effective planning of mining activities.

4 Conclusion

Groundwater is an essential renewable resource whose utilization is increasingly rising due to rapid population growth and the growing demand for water across various sectors, including food production, industrial processes, and domestic consumption. Furthermore, anthropogenic activities within agricultural practices significantly affect the dynamics of groundwater. These activities contribute to the depletion of groundwater reservoirs, which may lead to critical issues regarding water supply.

A comprehensive understanding of groundwater potential is a crucial factor for the effective planning and

sustainable development of water resource management in a specific area. Accurate assessment of groundwater potential enables the formulation of more targeted strategies for the conservation and rational use of this valuable resource. Such information is vital for the design and implementation of appropriate infrastructure and corrective measures that aim to enhance groundwater recharge processes, thereby ensuring the sustainable use and protection of the resource for the future.

Groundwater potential mapping has been conducted for decades using various traditional methods, as well as contemporary approaches based on remote sensing technologies. The integration of remote sensing and GIS has significantly streamlined this process, making it more efficient and cost-effective, while also reducing time consumption. Within the GIS environment, various modelling techniques are employed, which can be either spatial (based on geographical data) or non-spatial (statistical) in nature, all aiming to accurately assess groundwater potential. The accuracy of these methods may vary, depending on the approach and data utilized.

The reliability of the AHP model in determining groundwater potential is largely dependent on the accurate assignment of weights and ranks to each factor, class, and subclass considered in the analysis. For the model results to be precise, it is crucial to thoroughly examine and fully comprehend all the factors influencing groundwater distribution. Additionally, it is important to account for the specific characteristics of the study area, including its geographical, geological, and hydrological attributes, as these directly impact the accuracy and reliability of the AHP model outcomes.

Despite the numerous advantages offered by the integration of remote sensing, GIS, and AHP models in assessing groundwater potential, several limitations can affect the accuracy, reliability, and applicability of the outcomes. One of the primary limitations of the AHP method is the subjective nature of weight and rank assignment to the various thematic layers and classes (e.g., land use, soil type, slope, geology). The results are highly sensitive to these weightings, which are often based on expert opinion or literature values rather than empirical data. This subjectivity introduces bias and potential inconsistency. Remote sensing and GIS analyses rely heavily on secondary data, including satellite imagery and spatial datasets. The resolution and quality of these data can vary significantly, influencing the precision of the GWPZ. Coarse-resolution datasets may fail to capture micro-level variations in terrain, land use, or hydrology, an important consideration in areas with complex geology or small-scale hydrological features. Groundwater systems are dynamic and

influenced by temporal changes such as seasonal variation, climate change, and human interventions (e.g., over-pumping or recharge projects). However, groundwater potential maps produced through remote sensing and GIS are typically static snapshots that do not reflect temporal fluctuations. This limits their long-term reliability unless updated frequently with new data and analysis. Although the AHP-GIS approach is efficient, it often lacks adequate field validation (ground-truthing). Without sufficient hydrogeological surveys, borewell data, or geophysical investigations, the output remains largely theoretical. This gap may lead to misclassification of GWPZ, particularly in heterogeneous terrains where subsurface conditions can differ significantly over short distances. The AHP-based model generally incorporates a set of predefined parameters (e.g., rainfall, slope, land use) assumed to influence groundwater availability. However, groundwater occurrence is controlled by complex interactions among geological, structural, and hydrological factors, many of which are difficult to quantify or include in spatial models. This simplification may overlook critical subsurface features, such as fractures or aquitards, that are not visible in satellite imagery. The outcomes of an AHP-GIS model are often specific to the study area due to regional differences in geology, topography, climate, and land use. As such, the same model configuration or weightings may not be directly transferable to other regions, limiting the general applicability of the findings without significant recalibration. Remote sensing and GIS techniques can only infer the potential for groundwater presence based on surface indicators. They cannot directly assess aquifer properties such as porosity, permeability, or transmissivity, which are critical for understanding actual water availability and sustainability. This restricts their utility in detailed hydrogeological studies needed for water extraction planning.

The findings of this study offer valuable guidance for the relevant authorities in efficiently planning the management of groundwater resources, including aspects such as distribution, utilization, consumption, and artificial recharge. However, to enhance the accuracy of these findings, they should be complemented by further field investigations and additional relevant analyses. Such follow-up studies would enable more precise mapping of groundwater potential at a finer geographical scale, such as small municipalities and villages, thus providing reliable data that could inform and improve water resource management strategies.

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