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Groundwater Potential Assessment in the Semarang-Demak Basin Using Geospatial and Multi-Criteria Analysis

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Abstract: Groundwater is a critical resource for meeting the increasing demands of urban, agricultural, and industrial sectors. However, overexploitation and contamination pose significant threats to its sustainability. This study aims to assess the groundwater potential zones (GWPZ) within the Semarang-Demak Groundwater Basin, a rapidly urbanizing region in Central Java, Indonesia, where clean water availability faces mounting challenges. A geospatial approach integrating Geographic Information Systems (GIS), Remote Sensing (RS), and the Analytical Hierarchy Process (AHP) was employed to identify and classify GWPZ. Key factors analyzed include geology, lithology, slope, soil type, drainage density, rainfall, geomorphology, and land use/land cover. The results delineate the basin into five classes of groundwater potential zones, ranging from very poor to very good, offering actionable insights into areas optimal for groundwater recharge and extraction. Validation using groundwater table measurements from 71 infiltration wells confirmed a significant correlation between predicted zones and observed water levels. The results showed that zones with very high groundwater potential are concentrated in the central part of the basin, primarily due to favorable conditions such as high rainfall, alluvial formations, and low drainage density. These findings provide actionable insights for stakeholders to implement targeted groundwater management strategies, ensuring sustainable water resource utilization in the face of growing urbanization and environmental pressures.

Keywords: Analytical Hierarchy Process (AHP), Geospatial Approach, Groundwater, Groundwater Potential Zone, Multi-Criteria Approach

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1. Introduction

Groundwater is vital for industrial, agricultural, and residential uses, but contamination and increasing demand threaten its sustainability (Alabdulkreem *et al.*, 2023). Groundwater extraction has significantly increased due to population growth, urbanization, and industrialization, leading to declines in quality and quantity in many regions (Gleeson *et al*., 2020). Overexploitation has resulted in severe depletion and quality degradation globally, affecting human populations and the environment (Jia *et al*., 2020).

Mapping GWPZ is crucial for sustainable water resource management, enabling informed decision-making regarding groundwater development and conservation. Recent studies have used Multi-Criteria Decision Analysis (MCDA), remote sensing, and GIS methodologies to delineate GWPZ, integrating key factors such as geology, slope, rainfall, land use/land cover, soil type, linear density, and drainage density shown in Table 1. (Ahirwar *et al*., 2021; Pande *et al*., 2021; Razi *et al*., 2024). The Analytical Hierarchy Process (AHP) is often used to assign weights to these parameters, aiding in classifying groundwater potential from very poor to very good (Razi *et al*., 2024). Validation techniques, including Receiver Operating Characteristic (ROC) analysis and well data, have shown high accuracy in mapping groundwater recharge zones (Pande *et al*., 2021). Remote sensing and GIS techniques, combined with satellite imagery such as Landsat and ASTER, enable the development of thematic maps that classify regions into different recharge potential zones (Ahirwar *et al*., 2021). Studies of groundwater potential in urban areas, utilizing advanced geospatial techniques and AHP, have proven crucial in ensuring environmental sustainability and water security.

As one of Indonesia's major urban areas, Semarang City faces significant challenges regarding clean water availability. Rapid population growth and urbanization have increased the demand for clean water, while surface water resources are limited and sometimes unreliable in quality (Pertiwi, 2017). As a result, groundwater has become a vital water source for Semarang's residents, but overuse without proper management could lead to groundwater table depletion, seawater intrusion, and contamination (Suprayogi *et al*., 2024). The trend of urban and rural populations in Central Java from 2010 to 2023 shows a significant shift toward urbanization. The proportion of the population living in urban areas steadily increased from 47.2% in 2010 to approximately 51.5% in 2023. This growth reflects the migration of people from rural to urban areas, likely driven by better economic opportunities, improved infrastructure, and easier access to public services in cities. Conversely, the percentage of the rural population declined from 52.8% in 2010 to around 48.5% in 2023 (BPS Central Java Province, 2019; Karra *et al*., 2021). This decrease is due to migration and the reclassification of some rural areas into urban zones due to infrastructure development and urban sprawl.

This study aims to assess the GWPZ within the Semarang-Demak Groundwater Basin, a rapidly urbanizing region in Central Java, Indonesia, where clean water availability faces mounting challenges. By integrating thematic spatial data, the study aims to inform sustainable groundwater management strategies in Semarang City, a rapidly urbanizing area facing water resource challenges due to population growth and urbanization.

2. Materials and Methods

2.1 Study Area

This study focuses on the Semarang-Demak Groundwater Basin (Figure 1) (Rifai, 2022), which is one of the essential groundwater basins in Central Java. The basin extends from Demak Regency in the north to Semarang City in the south, covering an area of approximately 1,000 km². The Semarang-Demak Basin is formed by alluvial deposits and folded sedimentary rocks, with varying topography, ranging from coastal lowlands to hills. This geomorphological diversity significantly influences groundwater potential in the region (Kurnianto, 2019).

Distinctive hydrogeological conditions, with an unconfined upper aquifer and a confined lower aquifer, characterize the Semarang-Demak Basin. The unconfined aquifer is near the ground surface, while the confined aquifer consists of lenses of sand and gravel covered by a layer of clay or sandy loam (Lo *et al*., 2022). Rainfall in this region is relatively high, with annual precipitation varying from 1500 to 3000 mm (BPS Central Java Province, 2019). The area experiences two distinct seasons: a dry season from April to September and a wet season from October to March. Heavy rainfall during the wet months contributes to groundwater recharge; however, uneven rainfall distribution can lead to significant fluctuations in groundwater levels, especially during the dry season (Lo *et al.*, 2021). Recent data from the Semarang Climatology Station for the year 2020 indicates monthly variations in precipitation, reflecting the seasonal patterns typical of the region. These hydrogeological characteristics, combined with the variability in rainfall distribution, underscore the importance of effective water resource management in the Semarang-Demak Basin to mitigate the impacts of seasonal fluctuations on groundwater levels.

2.2. Geological Factors Affecting Groundwater Potential Zones

Groundwater aquifers are classified by depth: very shallow (<5 m) and shallow (5–15 m) aquifers are vulnerable to contamination but suitable for small-scale uses. Medium-depth (15–30 m) and deep (30–60 m) aquifers are more stable and suited for larger-scale supplies, while very deep aquifers (>60 m) provide clean, reliable water for municipal and industrial needs but require significant investment (Olago, 2019).

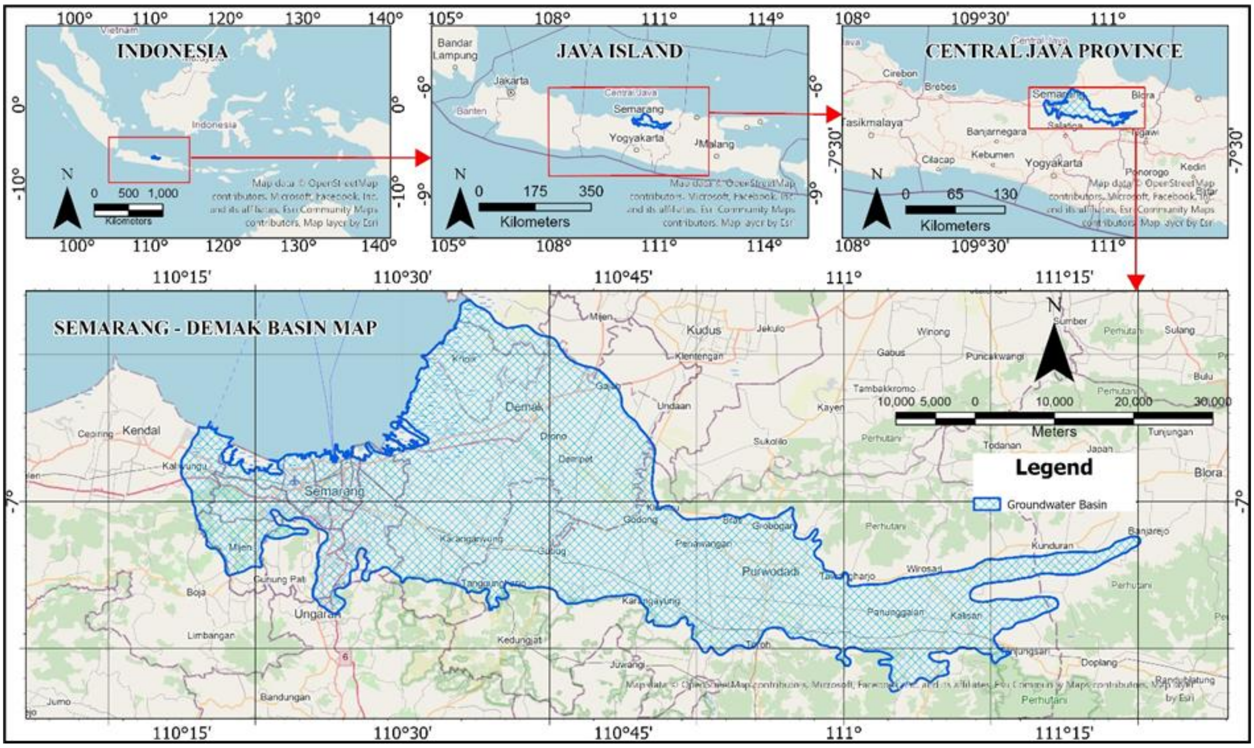

Figure 1. Map of the Study area, the Semarang-Demak Groundwater Basin, Indonesia

2.3. Groundwater Potential Parameters

Various geological, geomorphological, and environmental factors shape groundwater potential in the Semarang-Demak Basin. Alluvial formations exhibit the highest potential due to their porous and permeable nature, allowing significant groundwater storage and movement (Ardaneswari *et al.*, 2016; Kurnianto, 2019; Ridha & Darminto, 2016). Volcanic rocks, such as dense andesite, have lower potential because of limited permeability. The Kalibeng and Tambakromo formations demonstrate moderate potential, depending on sediment composition and stratigraphy. Other formations like Tuban and Mundu rely on porous layers to enhance groundwater potential (Figure 2a).

Geomorphology significantly affects groundwater potential (Figure 2b). Alluvial plain's extensive aquifer has the highest potential, while eroded mountainous regionsxhibit poor potential due to topsoil loss and reduced infiltration capacity (Ardaneswari *et al.*, 2016). Regarding lithology (Figure 2c), unconsolidated sediments such as gravel, sand, and clay contain significant groundwater potential thanks to their high porosity. Consolidated sediments offer varying potential (Trihatmoko *et al*., 2020), especially if fractures or more permeable materials are present. The base data for the soil classification in Fig 2d of present study has been obtained from Center for Research and Development of Agricultural Land Resources, Indonesia. The result of soil classification found that, the study area has three types of major soils such as gleisol, kambisol, mediteran, podsolik, regosol and other. Soil type is another critical factor (Pratama *et al*., 2018), with highly permeable regosol soils offering excellent water recharge, while saturated or acidic soils, like gleisol and podsolic, hinder infiltration.

Rainfall plays a vital role in recharging groundwater (Figure 2e). High-rainfall areas generally have excellent potential, primarily when supported by suitable geological and soil conditions (Kurniawan *et al*., 2023).

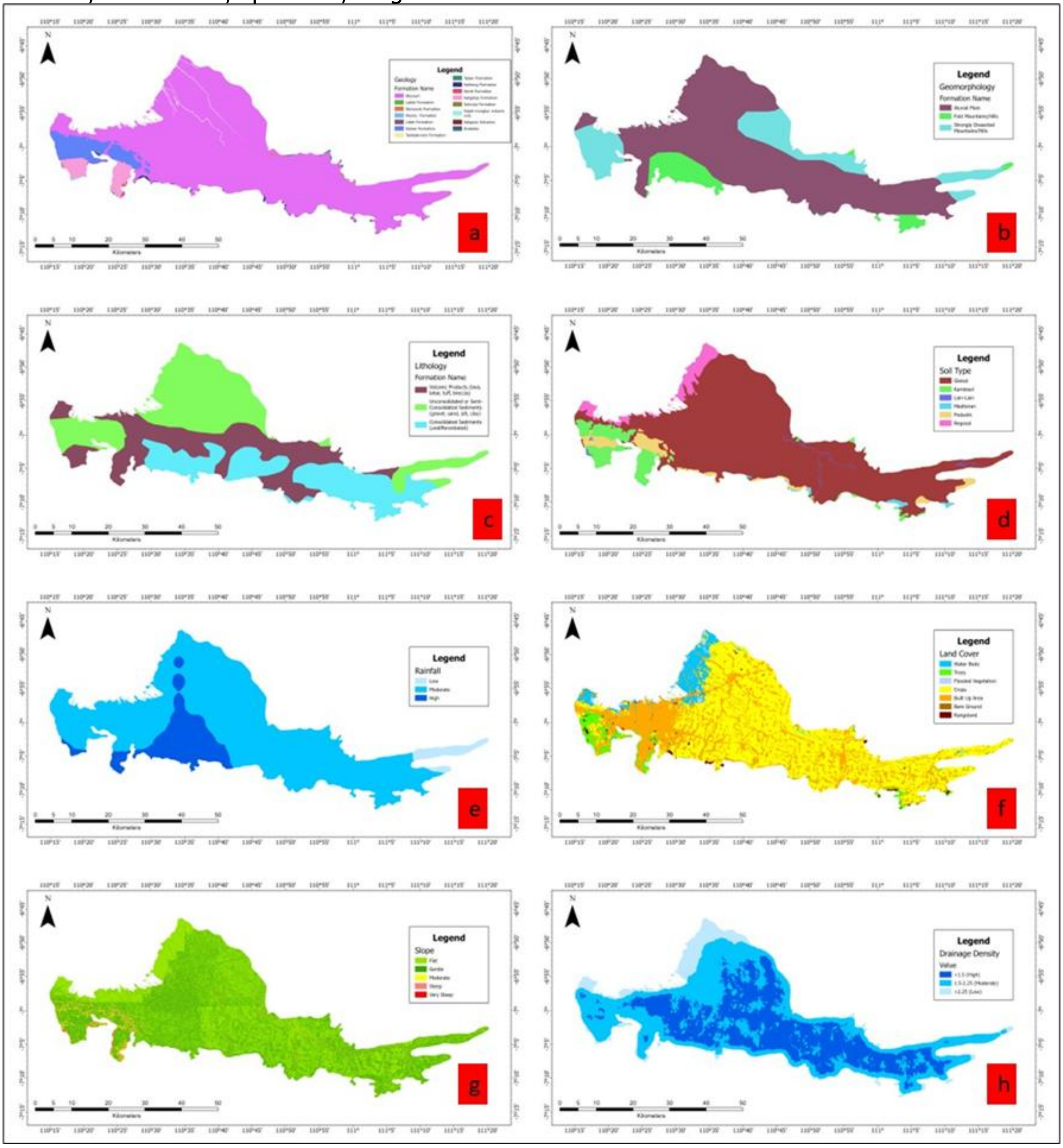

Figure 2. Potential Groundwater Parameter Map of the Semarang-Demak Groundwater Basin (GWB): (a) Geology; (b) Geomorphology; (c) Lithology; (d) Soil Type; (e) Rainfall; (f) Land Cover; (g) Slope Gradient; (h) Drainage Density.

The Sentinel 2 satellite image has been used for the study to find out the land cover of study area. The supervised classification method has been used with level – 2A classification. The result of the study found the study area covered by seven different classes such as water body, trees, flooded area, crops, built-up area, bareground and rangeland (Figure 2f) (Karra *et al.*, 2021). Forested and vegetated areas offer moderate to high potential due to better infiltration, while urbanized or impervious surfaces limit groundwater recharge (Fakhrudin & Daruati, 2017). The slope gradient further determines recharge potential (Figure 2g), with flat to gentle slopes enabling more water percolation into the ground, whereas steep slopes reduce infiltration due to rapid runoff (Darwis & Sc, 2018). The drainage system of the study area is shown in Fig. 2h. The drainage pattern was extracted directly from DEMNAS (8x8m). Then, the coordinates of the center of each grid were used to prepare the surface drainage density map by IDW interpolation technique (Rahmati *et al.*, 2015). Regions with low drainage density provide better infiltration opportunities, as slower water flow allows for more excellent percolation.

Eight factors were analyzed using GIS to map GWPZ, including slope, drainage density, land cover, rainfall, soil type, lithology, geomorphology, and geological formations (Table 1). These spatial data layers were integrated to identify zones with varying groundwater recharge and storage capacities, aiding in sustainable water resource management.

Table 1. Geospatial Data in this Research

No.	Data	Format	Scale/cell size	Source
1.	DEMNAS	Raster	Cell Size 8 m	Geospatial Information Agency
2.	Geology	Tabular/GIS	1: 50.000	Ministry of Energy and Mineral Resources (ESDM)
3.	Geomorphology	Vector (Polygon)	1: 50.000	Ministry of Energy and Mineral Resources
4.	Litology	Vector (Polygon)	1: 50.000	Ministry of Energy and Mineral Resources
5.	Soil Type	Vector (Polygon)	1: 50.000	Center for Research and Development of Agricultural Land Resources
6.	Rainfall	Tabular/GIS	1: 50.000	Central Java Statistics Agency
7.	Land Cover	Raster	Cell Size 10 m	Sentinel-2
8.	Drainage Density	Raster	Cell Size 8 m	Geospatial Information Agency

2.4. Methods

This study employs a geospatial approach that relies on compiling Remote Sensing data (Widyaningrum *et al.*, 2021) and GIS to prepare GWPZ maps (Danso & Ma, 2023). In predicting GWPZ, AHP can be used to integrate multiple parameters that influence groundwater availability and potential (Arulbalaji *et al.*, 2019). Eight controlling parameters were used to delineate the GWPZ: geology, slope gradient, drainage density, rainfall, lithology, soil type, geomorphology, and land cover. The spatial analysis results of these parameters were tested using the AHP method with normalized weights (Riyandi *et al.*, 2019) to evaluate GWPZ in the Semarang-Demak Groundwater Basin (GWB) area (Figure 3).

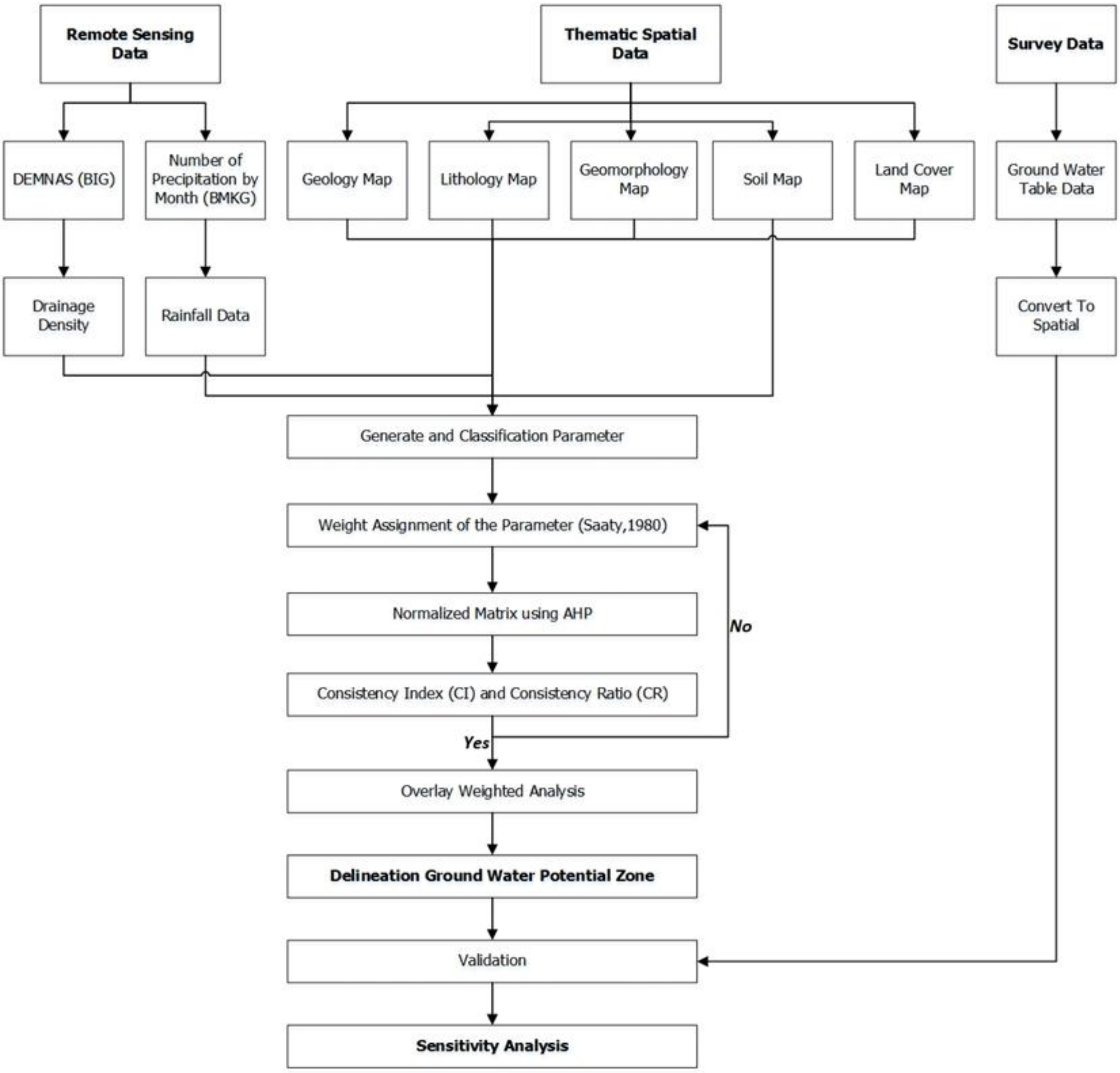

Figure 2. Flowchart diagram of the Groundwater Potential Zone Identification in the Semarang-Demak Groundwater Basin, Central Jawa, Indonesia

The groundwater potential index (GWPI) is a dimensionless index value that expresses the potential of groundwater (equal 1) in a specific area. It can be calculated using the equation below:

$$\mathrm{GWPI} = \sum_{w=1}^{m} \sum_{j=1}^{n} (\mathrm{Wj} \times \mathrm{Xi}) \qquad \text{.... (1)}$$

where Wj is the normalized weight of the j-th parameter, Xi refers to the class weight of the i-th parameter, m represents the number of parameters, and n represents the number of classes for a specific parameter. For each grid, the GWPI (equation 2) is calculated using the following equation:

$$\mathrm{GWPI} = \mathrm{GeaGeb} + \mathrm{LiaLib} + \mathrm{GeoaGeob} + \mathrm{SlaSlb} + \mathrm{RaaRab} + \mathrm{LCaLCb} + \mathrm{StaStb} + \mathrm{DDaDDb} \qquad \text{.... (2)}$$

where Ge=Geology; Li=Lithology; Geo=Geomorphology; Sl=Slope; Ra=Rainfall; LC= Landcover; St=Soil Type; DD=Drainage Density. The parameter weight is denoted by "a," while the subclass weight is denoted by "b."

In this study, the AHP was employed to determine the relative importance of various factors influencing groundwater potential, assigning weights to each parameter (Saaty, 2004). Scoring was then applied to classify these parameters into categories based on their characteristics, with higher scores indicating greater groundwater potential. For instance, flat slopes, low drainage density, permeable soils, and high rainfall were scored higher due to their positive contributions to groundwater recharge (Ridha & Darminto, 2016); these scores range from 1 (low potential) to 5 (high potential), ensuring consistent evaluation across parameters. These weights and scores were integrated into a spatial analysis using the Weighted Overlay tool in ArcGIS Pro. This tool combines reclassified spatial data layers according to their scores and weights, derived from AHP, to produce a comprehensive groundwater potential map (Tešić *et al.*, 2020). Parameters such as geomorphology, lithology, soil type, rainfall, slope, drainage density, and land cover were analyzed in detail to capture their individual and combined impacts (Suja Rose & Krishnan, 2009; Ramu, 2014). The result is a visually intuitive and data-driven representation of groundwater potential zones, offering valuable insights for resource management and environmental planning (Ardiyanto *et al.*, 2022).

3. Result

3.1. Variable Weighting

3.1.1. Pairwise Comparison Matrix

Priorities were assigned on a scale of one to eight points for each pair of layers. For example, lithology is considered more important than rainfall for groundwater potential and was thus assigned a value of 2 (Table 2).

The eigenvector expresses the order of influence of the layers on groundwater potential. The normalized primary eigenvector (NPE) in this study was calculated using an Excel sheet created by the researchers (Table 2).

Table 2. Pairwise Comparison Matrix for AHP-based GWPZ

	Ge	**Li**	**Geo**	**Sl**	**Ra**	**LC**	**St**	**DD**	**NPE**
Ge	1	1	1 1/4	3	2	4	5	5	22.80%
Li	1	1	1	3	2	4	5	5	22.24%
Geo	4/5	1	1	2	1 1/4	3 2/3	4 1/2	4 1/2	18.50%
Sl	1/3	1/3	1/2	1	1	2 2/5	3 2/3	3 2/3	10.96%
Ra	1/2	1/2	4/5	1	1	1 5/9	3 2/3	4	12.18%
LC	1/4	1/4	1/4	2/5	2/3	1	1 1/4	2 2/5	5.84%
St	1/5	1/5	2/9	1/4	1/4	4/5	1	1 5/9	4.10%
DD	1/5	1/5	2/9	1/4	1/4	2/5	2/3	1	3.38%
Total	4.28	4.48	5.24	10.90	8.42	17.82	24.75	27.12	100%

Ge = Geology; Li = Lithology; Geo = Geomorphology; Sl = Slope; Ra = Rainfall; LC = Landcover; St = Soil Type; DD = Drainage Density; NPE = Normalized Principal Eigenvector

3.1.2. Matrix Consistency Value

This study calculated the consistency index (CI) value of 0.02 based on the eigenvector value of 8.14 (Table 3). The random index (RI) value for eight parameters in this study is 1.41 (Table 4). Therefore, the consistency ratio (CR) is calculated as follows:

$$\mathrm{CR} = \frac{0.02}{1.41} = 0.0138 = 1.38\%$$

Since the resulting CR value is 1.38% (less than 10%), the process can proceed to the weighted overlay, integrating all parameters to produce the groundwater potential map for the Semarang-Demak Groundwater Basin.

Table 3. Results of Eigenvector Value Calculation (λ_{max})

	Column Sums (Row 9 of Table 2)	**Eigenvector (Row 10 of Table 2)**	**Parameter Rank (1) x (2)**
	(1)	**(2)**	**(3)**
Ge	4.28	0.23	0.98
Li	4.48	0.22	1.00
Geo	5.24	0.19	0.97
Sl	10.90	0.11	1.19
Ra	8.42	0.12	1.03
LC	17.82	0.06	1.04
St	24.75	0.04	1.01
DD	27.12	0.03	0.92
		Sum (λmax)	8.14

Ge = Geology; Li = Lithology; Geo = Geomorphology; Sl = Slope;
Ra = Rainfall; LC = Landcover; St = Soil Type; DD = Drainage Density

Table 4. Index Ratio (RI) for Scores of n Parameters

N	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0.58	0.89	1.12	1.24	1.32	1.41	1.45	1.49

3.1.3. Parameter Weighting Values

The variable weighting analysis using AHP yielded the following weights for each variable: geology scored 22.80, lithology scored 22.20, and geomorphology scored 18.50. The slope was weighted at 11, rainfall at 12.20, soil type at 4.10, and drainage density at 3.40. These results indicate that each variable significantly contributes to understanding groundwater potential in the study area. Geology provides critical insights into the subsurface structure that influences the distribution and types of aquifers.

Lithology is critical in determining porosity and permeability, which affect groundwater storage capacity. Geomorphology helps determine landforms and surface features that influence water flow and infiltration. Combining these parameters allows for identifying areas with the highest groundwater potential, which is the primary goal of this research (Table 5).

Table 5. Parameter Classification for Identifying GWP

Factor (Unit)	**Class**	**Parameter Weight**	**Class Rank**
Geology	Andesite	22.80%	1
	Kaligesic Volcanics		1
	Gajah mungkur volcanic rock		1
	Tuban Formation		2
	Wonocolo Formation		2
	Mundu Formation		2
	Lidah Formation		2
	Selorejo Formation		2
	Kaligetas Formation		2
	Damar Formation		2
	Tambakromo Formation		3
	Kerek Formation		3
	Ledok Formation		3
	Kalibeng Formation		4
	Aluvial		5

Factor (Unit)	**Class**	**Parameter Weight**	**Class Rank**
Lithology	Unconsolidated or Semi-consolidated Sediments (Gravel, Sand, Silt, Clay)	22.20%	1
	Consolidated Sediments (undifferentiated)		3
	volcanic eruption (lava, lahars, tuff, breccia)		5
Geomorphology	Strongly Eroded Mountains/Hills	18.50%	1
	Folded Mountains/Hills		3
	Alluvial Plain (Dataran Aluvial)		5
Slope	Flat (0-3.98)	11.00%	1
	Gentle (2.98-8.37)		2
	Moderate (8.37-14.95)		3
	Steep (14.95-24.32)		4
	Very Steep (>24.32)		5
Rainfall	Low (< 1900 mm /years)	12.20%	1
	Moderate (1900-2000 mm /years)		3
	High (>2000 mm /years)		5
Landcover	Built Up Area	5.80%	1
	Bare Ground		2
	Rangeland		3
	Crops		4
	Trees		5
	Flooded Vegetation		5
	Water Body		5
Soil Type	Podsolik	4.10%	1
	Mediteran		2
	Gleisol		3
	Kambisol		4
	Regosol		5
Drainage Density	Low (0-250m)	3.40%	1
	Moderate (250-500m)		3
	High (more than 500m)		5

3.2. Groundwater Potential Zones

This study shows the distribution of area based on the Groundwater Potential Zone (GWPZ) classification in a specific region, with a total area of 185,479.3 hectares. Of the total area, the "Very Poor" zone encompasses 1,084.665 hectares, equivalent to approximately 0.6% of the total area, indicating that only a small portion of this area has very low groundwater potential. Furthermore, the "Poor" zone, with an area of 11,074.16 hectares, accounts for about 6.0%, suggesting that although it is larger, water resources still have limited potential. The "Moderate" classification dominates with an area of 34,899.25 hectares, which makes up approximately 18.8%, reflecting better conditions for groundwater management.

The "Good" zone has the largest area at 107,214.8 hectares, contributing approximately 57.8% of the total, indicating a significant potential for water resource availability. Lastly, the "Very Good" zone, covering 31,206.4 hectares, accounts for around 16.8%, showing the presence of areas with very good quality for groundwater. Thus, the GWPZ area distribution provides a clear picture of groundwater potential spread in the region, highlighting the need for resource management focus on areas with better potential.

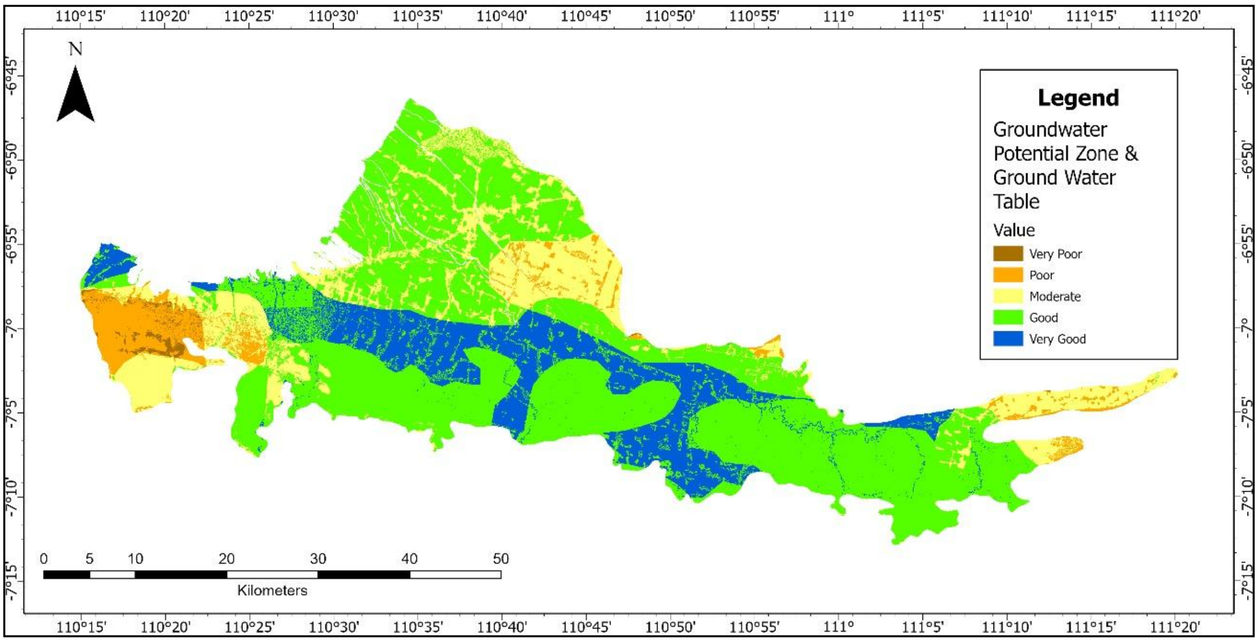

Figure 4. Groundwater Potential Zone Map of Semarang-Demak Groundwater Basin

Table 6. Groundwater Potential Zone Areas in Semarang-Demak Groundwater Basin

No.	Class Zone GWPZ	Area (Ha)
1.	Very Poor	1,084.665
2.	Poor	11,074.160
3.	Moderate	34,899.250
4.	Good	107,214.800
5.	Very Good	31,206.400
Total		185,479.300

3.3. Validation of Groundwater Potential Zone Identification

This study demonstrates the distribution of area based on the GWPZ classification in a specific region, totaling 185,479.3 hectares. Within this area, the "Very Poor" zone encompasses 1,084.665 hectares, approximately 0.6% of the total, indicating a minimal portion with very low groundwater potential. The "Poor" zone, covering 11,074.16 hectares, accounts for about 6.0%, suggesting limited water resource potential despite its larger area. The "Moderate" classification occupies 34,899.25 hectares, representing roughly 18.8%, indicating better conditions for groundwater management. The largest area is in the "Good" zone at 107,214.8 hectares, contributing approximately 57.8% of the total, highlighting significant potential for water resource availability. Lastly, the "Very Good" zone, at 31,206.4 hectares, accounts for around 16.8%, reflecting very high groundwater quality areas. Thus, the GWPZ area distribution provides a clear understanding of the groundwater potential in the region, emphasizing the need for focused resource management in higher potential areas.7.

The accuracy analysis between Groundwater Level and Groundwater Potential indicates a relatively good level of congruence, with a percentage reaching approximately 73.24%. Out of 72 locations analyzed, 52 show alignment between groundwater level and potential categories based on validation results. However, it is worth noting that among the measurement points examined, 63% exhibited low or very low groundwater potential, 30% fell within the moderate category, and only 7% showed good potential. While there is high congruence, particularly at locations classified as "Good" and "Moderate," where shallow groundwater levels correlate with good potential, several locations categorized as "Poor" and "Very Poor" demonstrate less optimal alignment.

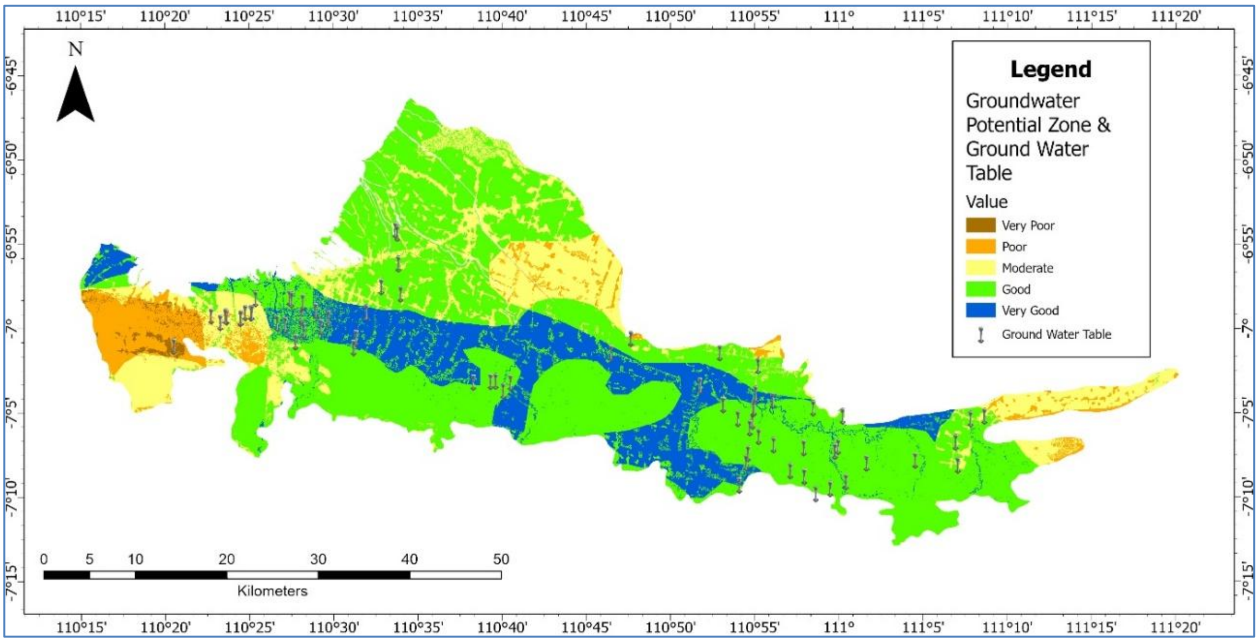

Figure 5. Overlay Groundwater Table on Groundwater Potential Zone Map of Semarang-Demak Groundwater Basin

Table 7. Validation of Groundwater Potential Zone Identification with Water Table Data

Groundwater Potential	**Groundwater Level**	**Average depth (m)**	**Number of Locations**
Very Poor	Very Deep	-84.91	12
Poor	Deep	-25.57	10
Poor	Shallow	-3.81	15
Moderate	Deep	-39.46	14
Moderate	Shallow	-1.49	23
Good	Shallow	-0.45	12
Good	Very Deep	-44.75	2

4. Discussion

High-potential groundwater zones were primarily concentrated in the central and southwest regions, where favorable conditions such as unconsolidated sediments, high rainfall, and low slopes were prevalent. This finding aligns with the observations of Achu *et al*. (2020), who identified lithology, lineament density, and geomorphology as critical factors influencing groundwater recharge and occurrence. Furthermore, it supports the findings of Kawara *et al*. (2024), who emphasized the importance of lineament density, slope, rainfall, and drainage density in their GWPZ analyses.

The study underscores the interplay of geological, hydrological, and anthropogenic factors in shaping groundwater potential. The central zones have very good potential and provide essential recharge areas critical for sustaining groundwater resources in Semarang and Demak. These insights can guide policymakers and stakeholders in prioritizing conservation efforts and optimizing groundwater extraction to mitigate overexploitation risks. Additionally, identifying low-potential zones highlights areas where alternative water supply strategies may be necessary, such as rainwater harvesting or managed aquifer recharge.

While the study effectively combines GIS, remote sensing, and AHP, some limitations exist. First, the accuracy of the GWPZ map depends on the resolution and quality of spatial data, which may not capture micro-level variations. Second, the validation covered only

71 locations, which might not fully represent the basin's heterogeneity. Future research could enhance validation by incorporating more extensive field data and employing advanced machine learning algorithms for GWPZ prediction.

4. Conclusion

This study highlights the importance of mapping Groundwater Potential Zones (GWPZ) for sustainable water resource management in rapidly urbanizing regions like the Semarang-Demak Groundwater Basin. By employing advanced geospatial techniques and the AHP, the study integrates key parameters such as geology, geomorphology, slope, and rainfall to delineate areas with varying groundwater potential, with a total area of 185,479.3 hectares. The "Very Poor" zone covers 1,084.665 hectares (0.6% of the total area), indicating minimal groundwater potential. The "Poor" zone, spanning 11,074.16 hectares (6.0%), also has limited potential. The "Moderate" zone, comprising 34,899.25 hectares (18.8%), reflects improved conditions for groundwater management. The "Good" zone, the largest at 107,214.8 hectares (57.8%), demonstrates significant groundwater potential, while the "Very Good" zone, at 31,206.4 hectares (16.8%), highlights areas of excellent groundwater quality.

The results show that zones with very high groundwater potential are concentrated in the central part of the basin, primarily due to favorable conditions such as high rainfall, alluvial formations, and low drainage density. Conversely, low and very low groundwater potential zones are found in the south and eastern regions, characterized by less favorable geological and topographical factors. Validation using groundwater table data from infiltration wells confirms the reliability of the GWPZ map, with significant compatibility observed in many locations. These findings provide actionable insights for stakeholders to implement targeted groundwater management strategies, ensuring sustainable water resource utilization in the face of growing urbanization and environmental pressures. Future research should incorporate dynamic parameters such as climate variability and human-induced land use changes to refine the models further and enhance their predictive capabilities.

Data availability statement

The data used in this research consists of primary and secondary data. The primary data were collected from field measurements conducted by the Agency for Energy and Mineral Resources (ESDM), Central Java Province, in 2023. The secondary data were obtained from official Indonesian government institutions, including the Ministry of Energy and Mineral Resources, Geospatial Information Agency (BIG), and the Indonesian Geological Agency. The rainfall data were sourced from CHIRPS, which can be accessed via the website chc.ucsb.edu.

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Author Contribution

RAo conducted the investigation, formal analysis of the literature review and preparation of the manuscript, **DR, BHS, A, EGAS, WH, RP** were involved in conceptualization as well as reviewed the manuscript. All the authors read and approved the final manuscript.

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