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Groundwater Potential Mapping (GWPM) using Analytical Hierarchy Process (AHP) in Bengkulu City, Indonesia

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Original scientific paper

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Abstract

Rapid urbanization and industrial expansion have led to heightened water demand. Groundwater plays a crucial role in urban settings for sanitation, drinking water, and agriculture. This research seeks to assess groundwater potential in Bengkulu City, Indonesia, employing the Analytical Hierarchy Process (AHP). The study incorporates eight primary factors: lineament density, drainage density, precipitation, geomorphology, geology, slope, land cover, and elevation. A multicollinearity test confirmed the absence of multicollinearity among these parameters. The pairwise comparison matrix produced a consistency ratio of 0.098 (9.8%), indicating acceptable consistency in parameter comparisons. Overlay-weighted linear combination (WLC) analysis categorized the groundwater potential into five levels: very high (2.9% or 3.83 km^2), high (50.9% or 67.47 km^2), moderate (35.2% or 46.71 km^2), low (5.2% or 6.88 km^2), and very low (5.8% or 7.64 km^2). The AHP model yielded strong performance metrics, including a ROC value of 0.89, accuracy of 0.81, MAE of 0.19, RMSE of 0.43, Kappa of 0.62, precision of 0.86, recall of 0.80, and an F1-score of 0.83. Precipitation, lineament density, and drainage density were the key factors affecting groundwater potential. This study shows that the AHP method is highly effective for mapping groundwater potential, especially in urban areas like Bengkulu City. The results can assist in making informed decisions regarding well drilling for drinking water, agricultural purposes, and artificial recharge projects, contributing to sustainable groundwater management in the region.

Keywords:
AHP, Bengkulu City, GIS, groundwater potential zone

1. Introduction

Urbanization has grown rapidly across all regions of Indonesia, with the urbanization rate reaching 57.9% in 2022 and projected to rise to 77.1% by 2045 (**Giyarsih et al., 2023**), including in Bengkulu City. The rate of urbanization of Bengkulu City has increased significantly, with 41,000 villagers relocating to the city between 2019 and mid-2023 (**URL 3**). This rising urbanization necessitates the accelerated development of infrastructure to meet the growing population's needs. Previous research has indicated that population growth impacts water availability (**McDonald et al., 2014; McGrane, 2016; Lo et al., 2021**). Water, often referred to as a panacea for life, is one of the most critical natural resources for survival. It plays a crucial role in daily activities and economic development (**Zewdie et al., 2024**). Recent research confirms that freshwater scarcity is one of the most pressing challenges for cities globally. This crisis is driven by several complex environmental issues, including (i) deforestation causing climate change, (ii) droughts and water pollution from industrial waste, and (iii) rapid urbanization. According to **URL 1**, 15.36% of households in Bengkulu City lack access to clean water. Furthermore, **URL 2** reveals that the primary water sources for households in Bengkulu City are wells/drilled wells (36.13%), bottled water (1.21%), PDAM water (6.35%), rainwater reservoirs (0.02%), and other sources (56.29%).

Rapid population growth and urbanization have increased the demand for groundwater, necessitating an effective methodology to comprehensively map groundwater availability, including in Bengkulu City (see **Figure 1**). Micro-scale studies on groundwater in Bengkulu City have been conducted using methods such as verti-

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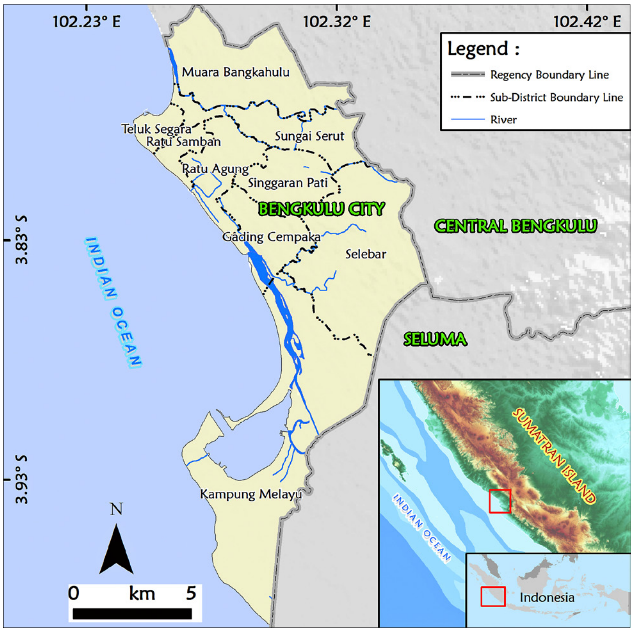

Figure 1. Study area in the World Geodetic System 1984 (WGS-1984) reference system

cal electrical sounding in Kandang Limun Village (**Nuraini et al., 2022**), overlay techniques (**Prabowo et al., 2022**), 1-D Multichannel Analysis of Surface Waves (MASW) and 2-D resistivity tomography in Lempuing Village (**Angglena et al., 2022**), and vertical electrical sounding in the Kampung Melayu District (**Syaputri et al., 2024**). However, these studies are limited to the village or sub-district scale and do not fully incorporate other key parameters that influence groundwater conditions. Groundwater availability is influenced by recharge processes, which are affected by urbanization, land-use changes, agricultural practices, and long-term soil changes (**Saha et al., 2024**). Understanding subsurface groundwater conditions is critical for developing sustainable management strategies to address the increasing demand for this crucial resource. Despite the limitations of traditional methods like water-witching, geobotanical indicators, and dowsing – which have questionable accuracy – these methods are still commonly used. Geological and geophysical methods, while accurate, are often time-consuming and costly (**Zewdie et al., 2024**) and may overlook key groundwater parameters (**Maizi et al., 2023; Kom et al., 2024**). Researchers have highlighted the effectiveness of Multi-Criteria Decision-Making Analysis (MCDMA) in identifying groundwater potential zones (**Allafta et al., 2021; Roy et al., 2022; Diriba et al., 2024**). The MCDMA method, particularly the Analytical Hierarchy Process (AHP), is known for its simplicity, efficiency, and reliability (**Zewdie et al., 2024; Aju et al., 2021**)

The AHP method is widely used for groundwater potential mapping (GWPM) due to its non-invasive nature, cost-effectiveness, robustness, and high efficiency (**Zewdie et al., 2024; Sikakwe et al., 2024; Saha et al., 2024; Kom et al., 2024**). It generates reliable data over large areas in a relatively short time and at a low cost (**Zewdie et al., 2024**). This method helps narrow down target areas before conducting detailed geophysical, geological, and hydrogeological surveys. This study applies the AHP method by analyzing eight parameters – geomorphology, geology, lineament density, elevation, drainage density, precipitation, slope, and land cover – to map groundwater potential zones (GWPM) in Bengkulu City, Indonesia. Situated along the western coast of Sumatra Island, this region exhibits significant diversity in land cover, geomorphology, slope, and precipitation, making the use of AHP a novel and efficient approach for identifying groundwater potential. The results of this modelling will provide valuable insight for government agencies, local communities, and water resource managers, which will aid in formulating more effective and organized strategies for managing, extracting, and conserving groundwater resources, ensuring the long-term sustainability of the water supply in Bengkulu City.

2. Methods and data

2.1. Data

Parameters such as precipitation, land cover, geology, geomorphology, drainage density, elevation, lineament density, and slope gradient were selected to analyze their impact on groundwater potential based on literature reviews and field observations (**Agarwal et al., 2013; Arulbalaji et al., 2019; Nigam & Tripathi, 2020; Saranya & Saravanan, 2020; Maizi et al., 2023; Diriba et al., 2024; Kom et al., 2024; Sikakwe et al., 2024; Saha et al., 2024; Zewdie et al., 2024**). DEMNAS data, with a 0.27-arcsecond spatial resolution, were used to create maps for elevation, slope, lineament density, and drainage density. Geological and geomorphological maps were developed using data from the Geological Survey Center, Geological Agency of Indonesia. Precipitation data were sourced from BMKG Bengkulu Climatology Station and BWS VII Bengkulu. Land cover data were obtained from the Directorate of Forest Resources Inventory and Monitoring, Directorate General of Forestry Planning and Environmental Management – KLHK Indonesia (see **Table 1**). These parameters were integrated to generate a GWPM. The details of the methodological framework followed in this study are presented in **Figure 2**.

2.2. Analytical Hierarchy Process (AHP)

AHP is a decision-making method proposed by **Saaty (1977; 1980)** to quantify qualitative problems. The AHP method calculates the weight of indicators based on expert assessments of the study area and a comprehensive consideration of the differences between indicators, making it highly suitable for solving multi-criteria decision-making problems (**Hasanuzzaman et al., 2022;**

Table 1. Summary of the parameters used in the study area

Parameters	Resolution/Scale	Source
Elevation	0.27-arcsecond	Indonesia Geospatial Information Agency
Slope	0.27-arcsecond	Indonesia Geospatial Information Agency
Lineament Density	0.27-arcsecond	Indonesia Geospatial Information Agency
Drainage Density	0.27-arcsecond	Indonesia Geospatial Information Agency
Geomorphology	1 : 100,000	Geological Survey Center, Indonesian Geological Agency (**Santoso et al., 2007**)
Geology	1 : 250,000	Geological Survey Center, Indonesian Geological Agency (**Gafoer et al., 1992**)
Precipitation	-	BWS Sumatera VII
Land Cover	-	Ministry of Environment and Forestry Indonesia

Table 2. Fundamental scales of AHP (**Saaty, 1980**)

Intensity of Importance	Definition
1	Equally important
3	Moderate importance of one over another
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values between the two adjacent judgments

Wang et al., 2024). It is widely used by researchers globally. Several researchers, including **Chavda et al. (2024), Sikakwe et al. (2024), Wang et al. (2024),** and **Zewdie et al. (2024)**, have applied this method to reduce the challenges and costs associated with conventional groundwater exploration techniques (such as geological, hydrogeological, and geophysical investigations) to map groundwater potential in major cities worldwide. Currently, the AHP method is a cutting-edge technology used to describe GWPM globally. It is a highly effective and cost-efficient technique for providing critical information on groundwater existence and distribution. The overall framework of the study used to accomplish the outlined objectives is depicted in **Figure 2**.

Eight parameters were analyzed to determine their priority using the *Saaty scale* (see **Table 2**). The AHP method's results were validated by the consistency ratio (CR), which is determined by dividing the consistency index (CI) by the random consistency index (RI). The CI is calculated using the formula below:

$$CI = \frac{\lambda max - n}{n-1} \quad (1)$$

where λ_{max} is the largest eigenvalue, calculated from the matrix, and n is the total number of thematic layers (**Zewdie et al., 2024**).

Next, the CR value is calculated for each parameter to assess the level of consistency, with the acceptable threshold being CR = 10% (0.1) (**Saaty, 1980**). If the CR value exceeds 10% (0.1), it is considered inconsistent and requires re-evaluation of the subjective assessments to achieve an acceptable consistency level. The CR value is obtained using the following equation:

$$CR = \frac{CI}{RI} \quad (2)$$

where CI and RI are the consistency and random consistency indices, respectively, which depend on the size of the pairwise comparison matrix and are determined based on Saaty's standard (**Saaty, 1977**), as shown in

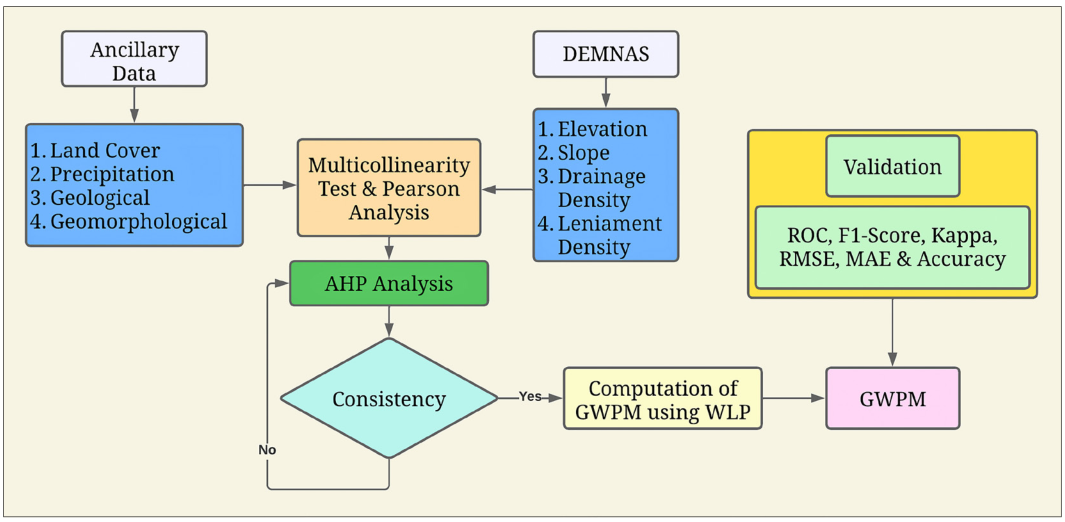

Figure 2. Flow Chart

Table 2. All parameters influencing the occurrence and distribution of groundwater are compared in terms of their relative importance to select the best model, using Saaty's standard scale (**Saaty, 1980**), which includes 9 intensity levels (see **Table 3**).

Table 3. Random Consistency Index Values (**Saaty, 1977**)

N	3	4	6	7	8	9	10
RI	0.58	0.9	1.24	1.32	1.41	1.45	1.51

The influencing parameters/thematic layers are combined and overlaid using the weighted linear combination (WLC) technique (**Malczewski, 1999; Sikakwe et al., 2024; Zewdie et al., 2024**). The following mathematical equation is used to obtain GWPM:

$$GWPM = \sum_{i=1}^{n} W_i R_i \quad (3)$$

where GWPM represents the groundwater potential, W_i is the weight assigned to each thematic layer, and R_i is the value for the classes within the thematic layer derived from the AHP.

2.3. Multicollinearity and Pearson's Correlation Coefficient (PCC)

In this study, multicollinearity analysis and Pearson Correlation Coefficient (PCC) were applied to select the best parameters for improving the quality of the GWPM. Multicollinearity analysis is essential to eliminate parameters that could negatively affect the accuracy of the resulting model (**Putriani et al., 2023; Bhuyan et al., 2024**). Variance Inflation Factor (VIF) and Tolerance are the most commonly used indicators to assess multicollinearity in earth sciences (**Ozegin et al., 2024; Singha et al., 2024**). Tolerance and VIF are calculated to analyze multicollinearity between the selected parameters, as shown in the following formulas (**Ragragui et al., 2024**):

$$T = 1 - r^2 \quad (4)$$

$$VIF = 1/T \quad (5)$$

where T is Tolerance, r^2 is the coefficient of determination, and VIF is the Variance Inflation Factor.

Additionally, the reciprocal correlation between parameters is assessed using the Pearson Correlation Coefficient (PCC) (see **Figure 7b**). PCC is used to measure the degree to which the relationship between parameters can influence each other. In the PCC graph, coefficients will accurately reflect the similarity between complex parameters (**Han et al., 2020**). The PCC coefficient is calculated using the following formula:

$$PCC = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}} \quad (6)$$

where x_i is the value of variable x in the sample, $\bar{x}$ is the mean of the values of variable x, y_i is the value of variable y in the sample, and $\bar{y}$ is the mean of the values of variable y.

2.4. Validation of the GWPM

Validating a model is a crucial step in scientific research. In this study, the model's performance was evaluated using the receiver operating characteristic (ROC) curve, along with several other metrics, including Accuracy, Precision, Kappa, Recall, F1-score, Mean Absolute Error (MAE), and Root Mean Squared Error (RMSE). These metrics are crucial for assessing model accuracy and ensuring a comprehensive analysis of model performance (**Khosravi et al., 2019; Chahal et al., 2022; Chavda et al., 2024; Wang et al., 2024**). The formulas used are as follows (**Khosravi et al., 2019; Chahal et al., 2022; Hasanuzzaman et al., 2022; Ragragui et al., 2024**):

$$AUC = (\sum TP + \sum TN)/(P+N) \quad (7)$$

$$Accuracy = (TP+TN)/(TP+TN+FP+FN) \quad (8)$$

$$Precision = TP/(TP+FP) \quad (9)$$

$$Recall = TP/(TP/FN) \quad (10)$$

$$F1\text{-}Score = 2/((1/Precision) + (1/Recall)) \quad (11)$$

$$Kappa = (Pc - Pexp)/(1 - Pexp) \quad (12)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(Vi_{Predicted} - Vi_{real}\right)^2} \quad (13)$$

$$MAE = \frac{1}{n} \sum_{1=1}^{n} \left(Vi_{predicted} - Vi_{real}\right)^2 \quad (14)$$

Where: TP refers to True Positive, TN to True Negative, FP to False Positive, and FN to False Negative. P_c represents the number of pixels accurately matched or unmatched, and P_{exp} represents the estimated result. Additionally, $Vi_{predicted}$ is the predicted value of GWPM, while Vi_{real} s the actual value of GWPM, and n refers to the total number of predicted and actual values.

3. Results and discussion

3.1. Geology and geomorphology of the Bengkulu City

Figure 4a illustrates the geological formations of Bengkulu City, obtained from the Indonesian Geological Agency (**Gafoer et al., 1992**). The study area comprises six distinct geological formations: alluvium, andesite, reef limestone, swamp deposits, alluvial terraces, and the Bintunan formation (**Gafoer et al., 1992**). Geological formations are crucial parameters that influence hy-

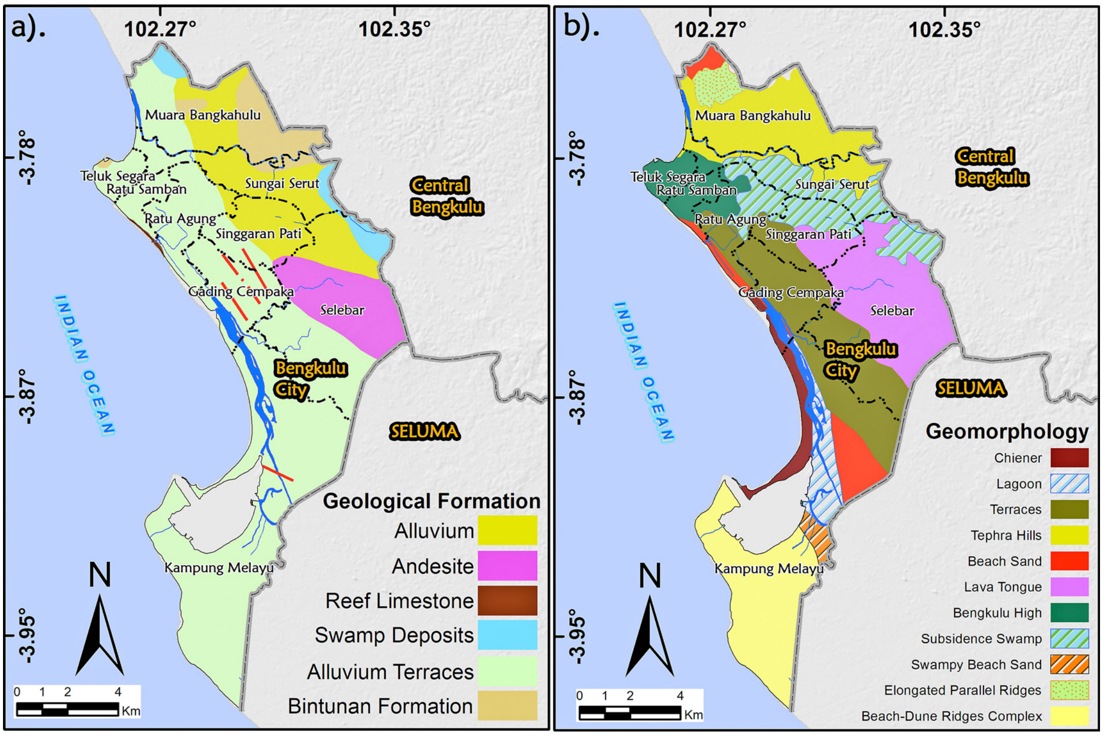

Figure 3. (a) Geological map showing faults (red lines) (modified from Gafoer et al., 1992) and (b) Geomorphological map (modified from **Santoso et al., 2007**) of Bengkulu City, presented in the World Geodetic System 1984 (WGS-84) reference system.

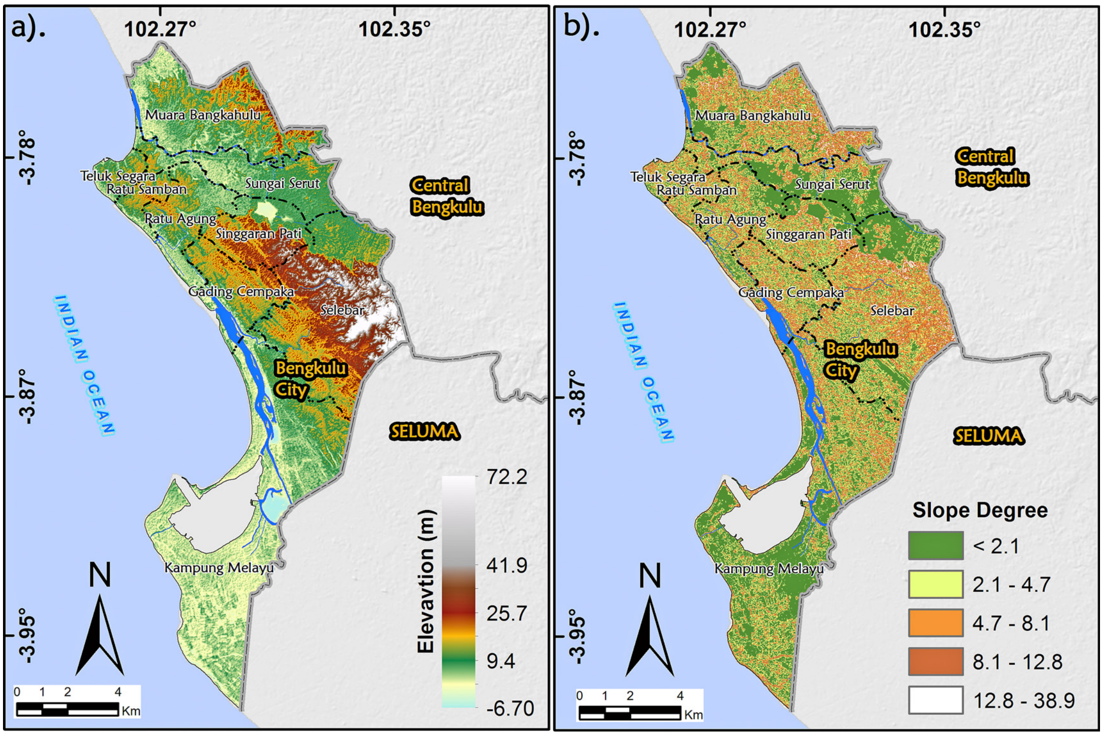

Figure 4. (a) Elevation map and (b) Slope map of Bengkulu City in the World Geodetic System 1984 (WGS-84) reference system.

drogeological properties such as porosity and hydraulic conductivity in aquifer materials (**Ragragui et al., 2024**). These formations determine soil characteristics and quality, as soil forms the uppermost layer of the unsaturated zone, with its texture influencing water infiltration and retention (**Chowdhury et al., 2010; Ragragui et al., 2024**). Coarser soil particles allow for greater infiltration, while smaller particles reduce permeability.

Clay soils tend to cause waterlogging, whereas sandy soils enhance infiltration.

One of the key parameters often used in GWPM is geomorphology, which describes the landscape of an area (**Ozegin et al., 2024**). The geomorphological units in the study area (see **Figure 3b**) are categorized into several types: chenier, lagoon, terraces, tephra hills, beach sand, lava tongue, Bengkulu highlands, subsidence swamp, swampy beach sand, elongated parallel ridges, and beach-dune ridge complexes (**Santoso et al., 2007**). Geomorphology, which refers to the landform of an area, is a crucial factor influencing groundwater movement (**Saravanan et al., 2020**) and is considered highly important in determining GWPM (**Kom et al., 2024**).

3.2. Elevation and slope of the Bengkulu City

DEMNAS data (0.27-arcsecond) from the Indonesian Geospatial Information Agency was used to create elevation maps (see **Figure 4a**) and slope gradient maps (see **Figure 4b**) for the study area. Bengkulu City has an elevation range of -6.7 to 72.2 meters (see **Figure 4a**), with most of the area consisting of low to moderate elevations. Elevation influences water movement and surface flow, with lower elevation areas (plains) storing water for longer periods, allowing greater infiltration. In contrast, areas with steep elevations experience significant water runoff and lower infiltration rates (**Saha et al., 2024**). Elevation plays a crucial role in GWPM, recharge capacity, and water transport (**Ozegin et al., 2024**). The slope gradient in Bengkulu City is shown in **Figure 4b** and classified into five classes: class 1 (>2.1°), class 2 (2.1° - 4.7°), class 3 (4.7° - 8.1°), class 4 (8.1° - 12.8°), and class 5 (12.8° - 38.9°). The majority of the study area features gentle to moderate slopes. Areas with high groundwater potential are more likely to be found in regions with low slopes compared to high-slope areas (**Shao et al., 2020; Kom et al., 2024**). This is due to elevation changes that trigger gravity, affecting water movement. Water infiltration is closely related to slope, with steeper slopes causing surface pooling and reducing groundwater recharge, as water has less time to seep below the surface (**Murmu et al., 2019**).

3.3. Lineament density and drainage density of the Bengkulu City

Drainage density (see **Figure 5b**) and lineament (see **Figure 5a**) maps were created using only DEMNAS data. Both drainage density and lineament are important parameters related to subsurface groundwater. Drainage density represents the ratio of the total length of the river network in a given area to the size of that area (**Abdelouhed et al., 2021; Ragragui et al., 2024**). Similarly, lineament density quantifies the concentration of linear features, such as faults and fractures, per unit area. These lineaments significantly influence groundwater recharge and storage by acting as conduits for water flow and enhancing aquifer interconnectivity (**Upwanshi et al., 2023; Danso and Ma 2023; Embaby et al., 2024**). Recent studies confirm that areas with high lineament density correlate with increased groundwater potential due to the improved infiltration and water retention in fractured zones (**Upwanshi et al., 2023; Danso and Ma 2023; Meng et al., 2024**). Consequently, drainage and lineament densities are essential for assessing subsurface hydrology and groundwater resources. Areas with high drainage density and lineament values are more likely to have significant groundwater storage, while areas with low values tend to have limited groundwater prospects (**Barua et al., 2021; Ragragui et al., 2024; Sikakwe et al., 2024**). The lineament density map (see **Figure 5a**) is classified into five categories: class 1 (0 - 0.76 km/km²), class 2 (0.76 - 1.52 km/km²), class 3 (1.52 - 2.28 km/km²), class 4 (2.28 - 3.04 km/km²), and class 5 (3.04 - 3.80 km/km²). Similarly, the drainage density map (see **Figure 5b**) is organized into five classes: class 1 (0 - 0.9 km/km²), class 2 (0.9 - 1.7 km/km²), class 3 (1.7 - 2.5 km/km²), class 4 (2.5 - 4.2 km/km²), and class 5 (3.4 - 4.2 km/km²). Joints, lineaments, fractures, and faults in impermeable rock formations generally control the primary pathways for groundwater movement and storage (**Saha et al., 2024**), as they provide high porosity and permeability (**Yeh et al., 2016**). In this study, we specifically analyzed structural lineaments, including faults and fractures, which significantly enhance secondary porosity and create conduits for water flow and storage. Such lineaments, commonly mapped using satellite imagery and field surveys, are vital for identifying groundwater potential zones. Drainage density is a critical factor influencing runoff and infiltration in a watershed. It is often observed that higher drainage density leads to increased surface runoff due to the rapid conveyance of water through the network of streams and rivers. Conversely, this can limit water infiltration into the soil. While soil permeability is an important determinant of infiltration, it is not directly proportional to drainage density, as different factors such as soil texture, structure, and compaction play significant roles. As noted by **Kundu and Nag (2018)**, a higher drainage density typically indicates lower soil permeability. This inverse relationship arises because the presence of numerous drainage channels in an area suggests that the soil may be more compact or have a lower capacity to absorb water, promoting faster runoff instead of infiltration. On the other hand, **Singha et al. (2019)** emphasized that soil permeability is a complex, multi-variable characteristic, and its relationship with drainage density is not necessarily straightforward. In regions with lower drainage density, the soil might exhibit higher permeability, allowing contaminants to infiltrate more readily. Therefore, while drainage density and soil permeability are related, they often function in opposition: high drainage density typically corresponds with lower permeability, which results in reduced infiltration and higher runoff,

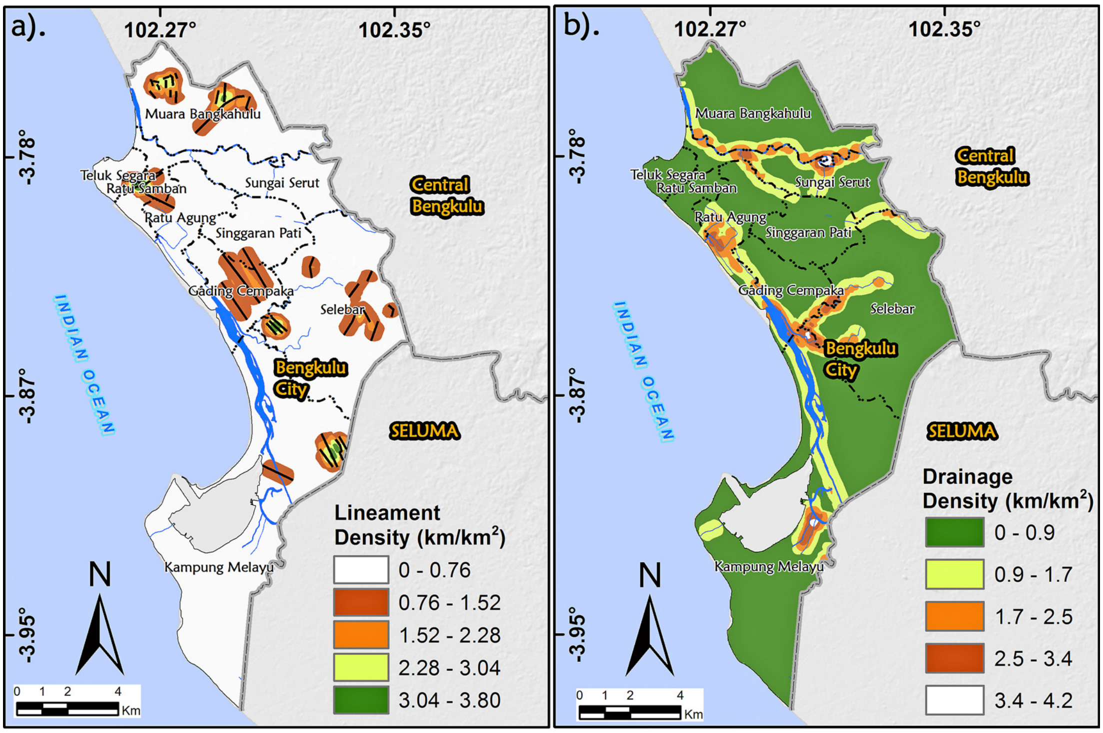

Figure 5. a) Lineament density map (black lines represent lineaments) and b) Drainage density map of Bengkulu City in the World Geodetic System 1984 (WGS-84) reference system.

whereas areas with lower drainage density may have higher permeability, fostering greater infiltration and contaminant movement into the soil.

3.4. Precipitation and land use/land cover of the Bengkulu City

Precipitation serves as the primary recharge mechanism for groundwater (**Ozegin et al., 2024**). It is a crucial hydrological parameter in this study, as it directly influences and controls the amount of water that infiltrates into subsurface groundwater sources (**Ahmed et al., 2021; Ragragui et al., 2024**). Average annual precipitation data for the past several years (2013-2022) were obtained from three precipitation stations of the River Basin Office VII in Bengkulu Province. The resulting map (see **Figure 6a**) is classified into five classes: class 1 with precipitation ranging from 2946 to 3058 mm/year, class 2 from 3058 to 3150 mm/year, class 3 from 3150 to 3223 mm/year, class 4 from 3223 to 3306 mm/year, and class 5 from 3306 to 3448 mm/year. **Figure 6a** shows that precipitation in Bengkulu City varies between 2946 and 3448 mm/year, with precipitation increasing progressively from west to east.

Regional land cover provides essential environmental information and highlights a region's dependence on freshwater through water infiltration (**Abdelouhed et al., 2021; Ozegin et al., 2024**). Based on land use/land cover data from the Indonesian Ministry of Environment and Forestry (see **Figure 6b**), Bengkulu City has nine types of land cover: scrub, pond, agriculture, residential, rice paddy, airport/port, open ground, swampy scrub, and mixed dryland agriculture. Areas with dense vegetation, such as forests and agricultural land, offer greater potential for water infiltration compared to barren land or residential areas (**Kom et al., 2024**). Additionally, scrubland vegetation, which includes species like chaparral and sagebrush, is also highly conducive to groundwater recharge. Scrublands, characterized by shallow-rooted plants, help enhance infiltration by reducing surface runoff and promoting water retention in the soil. Recent studies indicate that areas dominated by scrub vegetation often exhibit significant groundwater potential due to their ecological characteristics and ability to maintain soil moisture balance (**Souei et al., 2023; Kazakis et al., 2024; Haidery et al., 2024; Embaby et al. 2024**).

3.5. Multicollinearity and Pearson's Correlation Coefficient (PCC)

In this study, multicollinearity analysis and Pearson correlation were used to assess the linear relationships between parameters to improve the quality of the Groundwater Potential Zone Map (**Sharma et al., 2024; Ragragui et al., 2024**). The results of the Pearson correlation, shown in **Figure 7a**, indicate for example that elevation (Elev) has a correlation coefficient of 0.62 with geology (Geo1), while geomorphology (Geo2) shows a coefficient of 0.48. To evaluate multicollinearity, two criteria were applied: tolerance (TOL) should exceed 0.1, and the Variance Inflation Factor (VIF)

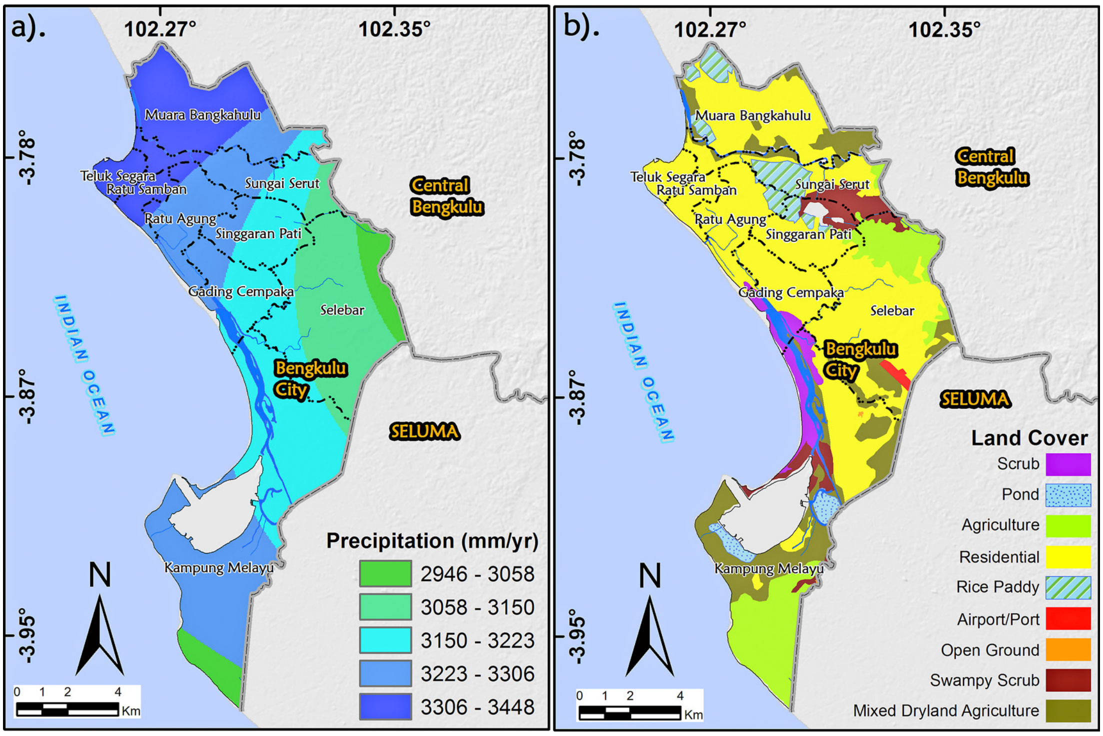

Figure 6. a) Precipitation map and (b) Land use/land cover map of Bengkulu City in the World Geodetic System 1984 (WGS-84) reference system.

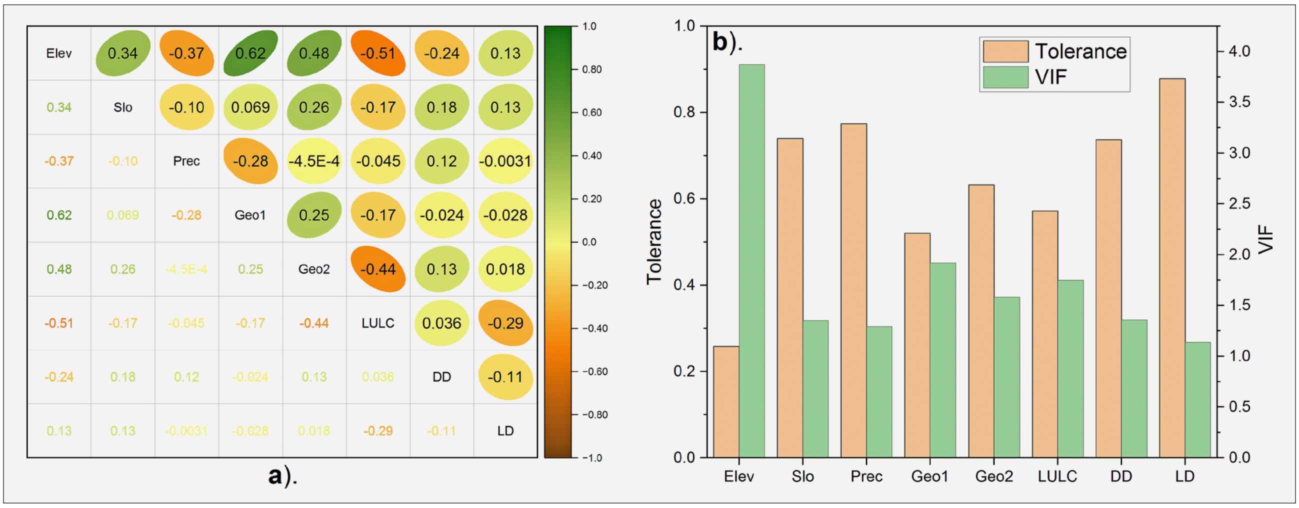

Figure 7. a) Multicollinearity test and b) Pearson Correlation Coefficient (PCC) between the groundwater causative factors. Elev: Elevation, Slo: Slope, Prec: Precipitation, Geo1: Geology, Geo2: Geomorphology, LULC: Land use/land cover, DD: Drainage Density, LD: Lineament Density.

should be 10 or lower. These criteria ensure that the parameters are suitable and that there is no uncertainty caused by multicollinearity issues (**Oyamenda & Olubusola, 2024; Sharma et al., 2024**). As shown in **Figure 7b**, no multicollinearity problems were found among the parameters used.

3.6. Analytical Hierarchy Process (AHP) for GWPM of The Bengkulu City

All parameters utilized in the study were assigned weights to assess their relative importance, as indicated in **Table 2**, using an 8 X 8 pairwise comparison matrix outlined in **Table 4**. The pairwise comparison results indicate that geomorphology, lineament density, geology, and slope have higher weights. The eigenvector calculated from the pairwise comparison matrix shows that the most influential parameter in this study is geomorphology, contributing approximately 30%, while drainage density has the smallest contribution at 4%, consistent with the findings of **Sikakwe et al.** (**2024**). The λmax and CI values in this study were 8.96 and 0.14, respectively, and the CR value was 0.098 or 9.8%, which falls

Table 4. Pairwise comparison matrix of eight parameters GWPM of Bengkulu City

Parameter	Geo1	DD	LD	Slope	Geo2	LC	Precipitation	Elevation
Geo1	1	3	3	4	3	6	5	2
DD	0.33	1	0.25	0.33	0.33	0.33	0.33	0.50
LD	0.33	4	1	2	3	2	3	2
Slope	0.25	3	0.5	1	0.33	3	2	1
Geo2	0.33	3	0.33	3	1	3	2	3
LULC	0.17	3	0.50	0.33	0.33	1	0.33	0.50
Precipitation	0.20	3	0.33	0.50	0.50	3	1	2
Elevation	0.50	2	0.50	1	0.33	2	0.5	1
SUM	3.12	22	6.42	12.17	8.83	20.33	14.17	12.00

Note: Geo1: Geomorphology; DD: Drainage Dennsity; LD: Lineament Density; LULC: Land Use/Land Cover; and Geo2: Geology.

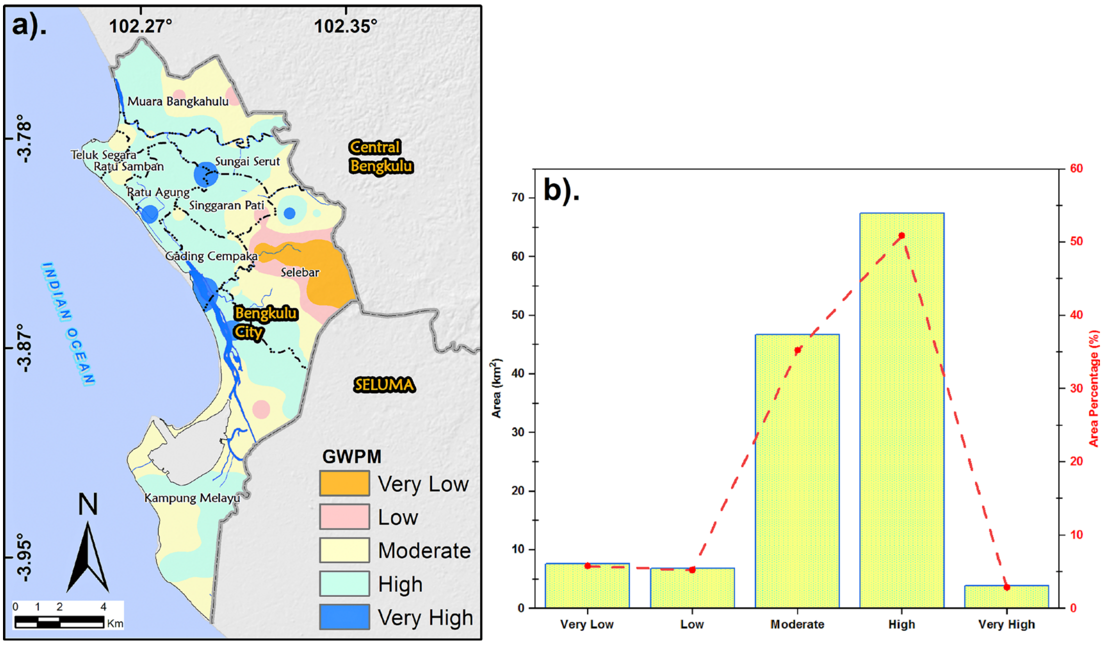

Figure 8. a) GWPM of Bengkulu City and b) Graph of the Area Distribution and Percentage of GWPM Grouping in Bengkulu City.

within the acceptable limit according to **Saaty (1980)**, allowing the analysis to proceed. In the next stage, these values were integrated to produce a spatial distribution map of GWPM in Bengkulu City using **Equation 3**. The results of the pairwise comparison matrix indicate that land cover, drainage density, lineament density, elevation, and slope are the most significant parameters contributing to the GWPM model. Land cover, particularly in areas dominated by forests, agricultural fields, and scrubland, enhances groundwater infiltration and recharge due to higher porosity and permeability compared to urban or barren areas. Drainage density, which measures the length of the river network relative to the area, influences surface runoff and infiltration; regions with moderate drainage density are often optimal for recharge as they strike a balance between water flow and retention. Lineament density, representing the concentration of fractures and faults, significantly impacts groundwater flow by serving as pathways for subsurface water movement (**Saha et al., 2024**). Elevation and slope also play crucial roles in groundwater recharge by controlling water flow direction and speed. Gentle slopes and moderate elevation zones are more conducive to infiltration, whereas steep terrains are dominated by rapid runoff. In the very high GWPM areas of Gading Cempaka, Ratu Agung, Sungai Serut, Singgaran Pati, Selebar, and Kampung Melayu, these parameters align synergistically. These areas exhibit favorable land cover (e.g. agricultural or vegetated land), moderate drainage and lineament densities, gentle slopes, and suitable elevations that collectively enhance groundwater potential.

Figure 8a illustrates the spatial distribution of the GWPM map, while **Figure 8b** classifies the GWPM areas into five categories: very high (3.83 km²), high

(67.47 km²), moderate (46.71 km²), low (6.88 km²), and very low (7.64 km²). The very high GWPM areas, covering approximately 2.9% of the study area, are concentrated in Gading Cempaka, Ratu Agung, Sungai Serut, Singgaran Pati, Selebar, and Kampung Melayu. The high GWPM category, covering more than half of the study area (50.9%), is widely distributed across almost all parts of Bengkulu City, except for the Selebar area. These findings confirm that the spatial alignment of favorable parameters strongly supports groundwater potential in the study area. The moderate category is found in Muara Bangkahulu, Singgaran Pati, Selebar, and Kampung Melayu, covering 35.2% of the study area. Whereas, the low category accounts for 5.2% of the study area and is spread across Muara Bangkahulu, Kampung Melayu, and mostly Selebar area. The very low category covers approximately 5.8% of the study area, found only in the Selebar area of Bengkulu City. This region is characterized by andesite geological formations, consisting of hard soil and coarser, gravelly clay, supported by geomorphological features such as lava tongues, which exhibit very low levels of porosity and permeability. However, the northern part of the lava tongue shows very high groundwater potential, as highlighted in the GWPM map (see **Figure 8a**). This anomaly can be attributed to the presence of secondary porosity created by fractures and lineaments in the andesite rock. Fractures and faults often act as conduits for water flow, significantly enhancing groundwater recharge in otherwise impermeable formations. Additionally, localized geomorphological features, such as weathering or jointing in volcanic rocks, can further increase infiltration capacity and water retention in specific zones (**Saha et al., 2024**). These findings suggest that while lava tongues generally hinder groundwater movement due to low primary porosity, their hydrological potential can vary significantly depending on structural and geological modifications. This highlights the importance of integrating lineament density and geomorphological analysis into GWP assessments to accurately delineate high-potential areas

The study area has relatively flat or gently sloping topography in its western and southern region, which makes it an ideal location for groundwater recharge. This area also experiences high precipitation intensity (> 3000 mm/year), placing it in the very high to moderate groundwater potential category due to factors such as moderate to high lineament and drainage densities, flat/sloping slopes, and low elevations. Additionally, the geological formations in the western part consist of alluvial terraces made up of silt, clay, sand, and gravel (**Mase et al., 2023**). These formations are supported by geomorphological features such as terraces, lagoons, and subsidence swamps, which exhibit high levels of porosity and permeability, allowing for greater groundwater storage due to large pore spaces. In contrast, areas with low to very low groundwater potential, such as the Selebar area, have limited groundwater recharge capabilities. The eastern part of the study area, which includes most of Selebar, experiences lower precipitation, has steeper slopes, higher elevations, lower lineament and drainage densities, and more extensive residential development.

3.7. Validation of the GWPM

In this study, the performance of the GWPM model was evaluated using the receiver operating characteristic (ROC) curve and various other metrics, including accuracy, precision, kappa, recall, F1-score, Mean Absolute Error (MAE), and Root Mean Squared Error (RMSE). These popular metrics are crucial for assessing the accuracy and effectiveness of the model to ensure an optimal and comprehensive evaluation (**Dahal et al., 2023; Putriani et al., 2023; Ozegin et al., 2024; Ragragui et al., 2024; Sharma et al., 2024**). The ROC curve is used to assess the model's suitability and accuracy (**Putriani et al., 2023**). An Area Under the Curve (AUC) value greater than 0.8 reflects high model sensitivity and very satisfactory performance (**Putriani et al., 2023; Ragragui et al., 2024**). **Figure 9a** shows the ROC curve for the GWPM model in Bengkulu City, with an AUC of 0.89 (89%). Additionally, the GWPM model performed well based on other metrics (see **Figure 9b**), with an accuracy of 0.81, MAE of 0.19, RMSE of 0.43, kappa of 0.62, precision of 0.86, recall of 0.80, and an F1-score of 0.83. These findings indicate that the model is very effective in mapping groundwater potential in Bengkulu City. While these results underscore the utility of the GWPM model, areas identified as having very high groundwater potential. For example, in Bengkulu City, the very high GWP zones (e.g. Gading Cempaka, Ratu Agung, and Sungai Serut) align with favorable geological features such as increased lineament density and gentle slopes. These areas are ideal candidates for additional geophysical surveys to ensure sustainable groundwater extraction. Such assessments can help stakeholders identify priority zones for water resource development, mitigating the risks of over-extraction or poor water quality. In contrast, focusing solely on very low potential areas, such as the lava tongue formations in Selebar, is less beneficial for immediate stakeholder decision-making. Integrating detailed investigations into the very high GWP areas provides a more comprehensive approach for resource management and planning.

The GWPM prediction model provides an effective strategy for guiding proper and optimal management of water resources. Consequently, researchers are developing innovative models and experiments to produce reliable and accurate GWPM. The application of the MCDMA AHP method in this study demonstrates its potential for improving the accuracy and effectiveness of GWPM assessments and broadening its applicability to other regions around the world or within Indonesia. However, applying this method in different areas requires a com-

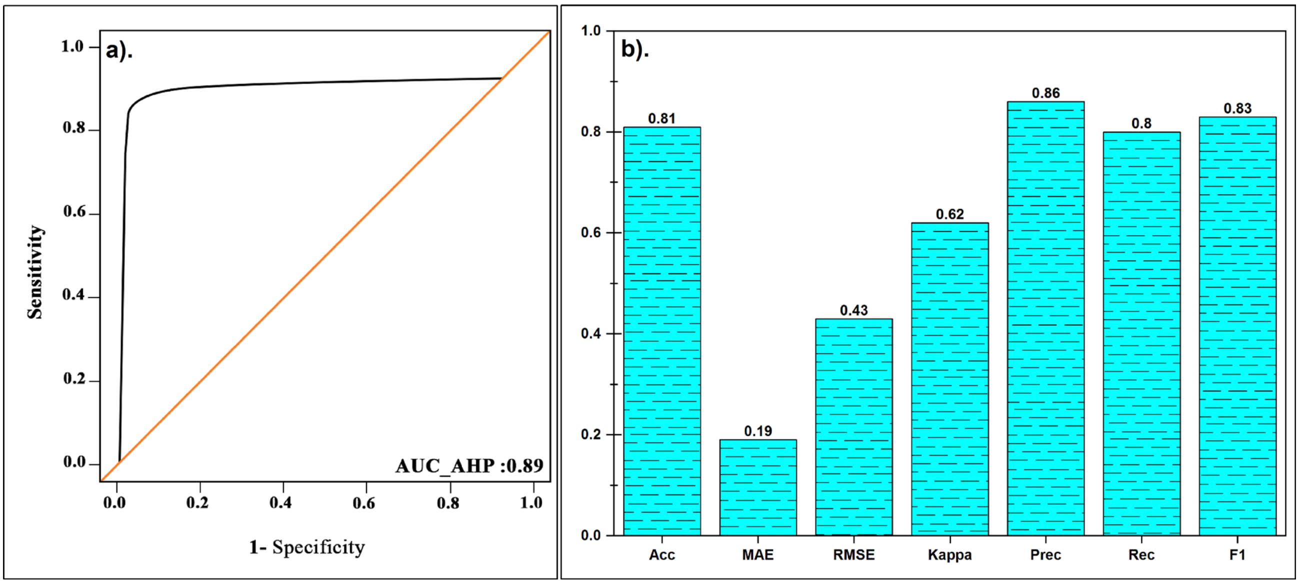

Figure 9. a) ROC curve of GWPM for Bengkulu City and b) Graph of performance parameter values of GWPM for Bengkulu City. Acc: Accuracy; Prec: Precision; Rec: Recall; F1: F1-score.

prehensive review or assessment of the parameters used. This is crucial because climate change can alter precipitation intensity and increase temperatures unexpectedly, affecting evaporation rates and groundwater levels. Moreover, anthropogenic activities such as land use changes, urbanization, and agricultural practices can significantly impact groundwater systems. To ensure an accurate representation of current conditions and to anticipate future changes, it is important to periodically update and adjust the model based on these evolving dynamics.

As we mentioned in **Figure 9b** that the evaluation of the model's performance in predicting groundwater potential was based on several metrics: Acc (Accuracy): This metric measures the proportion of true results (both true positives and true negatives) among the total number of cases examined. A higher accuracy value indicates that the model correctly predicts groundwater potential in the study area (**Sharma et al., 2024**). Prec (Precision): Precision, also known as positive predictive value, quantifies the number of true positive predictions (correctly predicted high potential areas) out of all positive predictions made by the model. A high precision value suggests that the model has a low rate of false positives, meaning it correctly identifies areas with actual high groundwater potential (**Putriani et al., 2023**). Rec (Recall): Also known as sensitivity or true positive rate, recall measures the proportion of actual positives (true high groundwater potential areas) correctly identified by the model. A higher recall value indicates that the model effectively identifies most of the areas with high groundwater potential (**Dahal et al., 2023**). F1-score: The F1-score is the harmonic mean of precision and recall, providing a single metric that balances both. It is especially useful when the data has imbalanced classes, such as when high potential areas are less frequent than low potential areas. The F1-score gives a comprehensive measure of the model's accuracy in identifying high potential zones (**Ragragui et al., 2024**).

4. Conclusions

This paper presents the results of the first study on GWPM in Bengkulu City, using the AHP method. The model was developed using a spatial database that includes eight parameters controlling subsurface groundwater. This study examines, evaluates, and interprets GWPM using eight parameters: geomorphology, geology, elevation, slope, lineament density, drainage density, land cover, and precipitation. The key conclusions from this study are as follows:

- The parameters used were evaluated using a multicollinearity test, employing the tolerance and Variance Inflation Factor (VIF) methods. The results indicated no multicollinearity problem among the parameters used.
- Furthermore, the model demonstrated a very satisfactory level of accuracy (AUC = 0.89, accuracy = 0.81, RMSE = 0.43, precision = 0.86, MAE = 0.19, recall = 0.80, kappa = 0.62, and F1-score = 0.83). The validation results confirm that the AHP method successfully identified and accurately explored GWPM in Bengkulu City.
- The resulting GWPM is classified into five classes: very high, high, medium, low, and very low, covering areas of 3.83 km^2 (2.9%), 67.47 km^2 (50.9%), 46.71 km^2 (35.2%), 6.88 km^2 (5.2%), and 7.64 km^2 (5.8%), respectively. Areas with high to very high GWPM are predominantly located along the west coast of the study area, especially in the Gading

Cempaka, Ratu Agung, Singgaran Pati, and Kampung Melayu areas. In contrast, the eastern part of Bengkulu City, particularly in the Selebar and Muara Bangkahulu areas, exhibits low to very low GWPM.

- The results of this study can serve as a guide for stakeholders (e.g. government) in planning well drilling and boreholes for community and agricultural water supply, as well as for artificial infiltration projects in Bengkulu City, ensuring sustainable groundwater utilization.
- Additionally, the findings of this study form the basis for further investigations using more detailed geophysical, geological, and hydrogeological methods.

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SAŽETAK

Mapiranje potencijala podzemne vode korištenjem procesa analitičke hijerarhije u gradu Bengkulu, Indonezija

Brza urbanizacija i industrijska ekspanzija doveli su do povećane potražnje za vodom. Podzemne vode igraju ključnu ulogu u urbanim sredinama za sanitarne uvjete, pitku vodu i poljoprivredu. Ovo istraživanje nastoji procijeniti potencijal podzemnih voda u gradu Bengkulu, Indonezija, korištenjem procesa analitičke hijerarhije (AHP). Studija uključuje osam primarnih čimbenika: gustoću lineamenta, gustoću drenske mreže, oborinu, geomorfologiju, geologiju, nagib, pokrov tla i nadmorsku visinu. Test multikolinearnosti potvrdio je nepostojanje multikolinearnosti među ovim parametrima. Matrica usporedbe parova dale je omjer dosljednosti od 0,098 (9,8 %), što upućuje na prihvatljivu dosljednost u usporedbama parametara. Analiza ponderirane linearne kombinacije (WLC) kategorizirala je potencijal podzemne vode u pet razina: vrlo visok (2,9 % ili 3,83 km^2), visok (50,9 % ili 67,47 km^2), umjeren (35,2 % ili 46,71 km^2), nizak (5,2 % ili 6,88 km^2) i vrlo nizak (5,8 % ili 7,64 km^2). AHP model dao je jake metrike performansi, uključujući ROC vrijednost od 0,89, točnost od 0,81, MAE od 0,19, RMSE od 0,43, Kappa od 0,62, preciznost od 0,86, osjetljivost od 0,80 i F1 rezultat od 0,83. Oborina, gustoća lineamenta i gustoća drenaže bili su ključni čimbenici koji utječu na potencijal podzemne vode. Ova studija pokazuje da je AHP metoda vrlo učinkovita za mapiranje potencijala podzemnih voda, posebno u urbanim područjima kao što je Bengkulu. Rezultati mogu pomoći u donošenju utemeljenih odluka u vezi s bušenjem zdenaca za pitku vodu, poljoprivredne svrhe i projektima umjetnoga prihranjivanja, pridonoseći održivom upravljanju podzemnim vodama u regiji.

Ključne riječi:
AHP, Bengkulu, GIS, potencijalna zona podzemnih voda

Author's contribution

Citra Febiola Ariska (Student, Geophysics): Conceptualization, writing the initial draft, methodology, and data analysis. **Darmawan Ikhlas Fadli** (Researcher, Geophysicist): Modelling and assisting with data interpretation and analysis. **Muhammad Afif Nabhan** (Student, Geophysics): Conducted field data acquisition and collection, as well as visualization. **Rahma Alshenta Nugraha** (Student, Geophysics): Conducted field data acquisition and collection, in addition to project administration. **Belliya Hafiza** (Student, Geophysics): Conducted field data acquisition and processing. **Isra Amalia** (Student, Physics): Conducted validation and visualization. **Erlan Sumanjaya** (Researcher, Geodesy & Geomatics): Correction and refinement of the manuscript, as well as analysis and mapping of groundwater potential. **Arif Ismul Hadi** (Dr, Associate Professor, Geophysicist): Research concept and design, correction and refinement of the manuscript. **Refrizon** (Associate Professor, Geologist): Correction and improvement of the manuscript. **Ayu Maulidiyah** (Researcher, Hydrology): Correction and improvement of the manuscript.
All authors have read and agreed to the published version of the manuscript.