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Spatial Study of Groundwater Availability Zoning in Bandung City Using Analytical Hierarchy Process Method

Ghina Yusriyyah Salma[1*], *Dede Rohmat*[2], *Haikal Muhammad Ihsan*[3]

[1,2,3]Geographic Information Science Study Program, Universitas Pendidikan Indonesia, Indonesia

*Correspondence: E-mail: ghinays27@gmail.com

ABSTRACT

The demand for clean water continues to increase in line with the growing population. Meanwhile, the availability of clean water in terms of quantity has not increased, and there has even been a significant reduction due to pollution caused by human activities. Bandung City, as the Bandung Basin Urban Strategic National Area, will naturally increase the interest of residents in settling there. This study aims to analyze the dominant factors determining groundwater availability, analyze the zoning conditions of groundwater availability, and analyze the validity of the groundwater availability zoning map in Bandung City. The method used in determining the weight value is using the Analytical Hierarchy Process (AHP). The determining parameters of groundwater availability in this study are land use, slope, soil type, rainfall, geology, water table depth, and aquifer thickness. The results showed 1) the dominant factor determining the availability of groundwater in Bandung City is the water table depth; 2) the zoning of groundwater availability in Bandung City is predominantly classified as medium, covering an area of 48.9% with three sub districts failing into the low groundwater availability category; 3) The groundwater availability map validation is considered to meet the standards, with an overall accuracy of 83.3%. Based on the spatial study results, efforts are recommended to prevent groundwater scarcity in terms of both demand and supply, particularly in areas categorized as having low availability.

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1. INTRODUCTION

Water is the most essential resource for human life and all living beings on Earth. As a primary environmental control factor, water resources play an irreplaceable role in promoting sustainable socio-economic development (Yang et al., 2021). The demand for clean water continues to rise along with population growth (Marbun et al., 2018). However, the quantity of clean water availability has not increased, and there has been a significant reduction due to pollution caused by human activities.

Among the various sources of clean water, groundwater is a crucial resource for humans. Groundwater is of high quality and has low production costs because it is stored deep below the surface, making it less prone to contamination (Krisnawati, 2023). Excessive exploitation of groundwater through various means such as dug wells, pump wells, and boreholes has led to limited groundwater quantity. According to Putranto & Kusuma (2009, cited in Komalawati et al., 2024), several areas have experienced negative impacts, including the reduction in both the quantity and quality of groundwater resources due to over-extraction. If groundwater availability is not properly managed, it may become depleted. Thus, it is essential to maintain groundwater availability to ensure it continues to provide benefits, balance, and sustainability to meet water needs.

Bandung City, as the Bandung Basin Urban Strategic National Area and a National Activity Center (PKN), is the second-largest metropolitan area in Indonesia after Jabodetabekpunjur (Andiana & Hendrakusumah, 2015). This increases the interest of people in settling in Bandung City. The population growth over the past five years can be seen from data provided by the Central Bureau of Statistics. In 2018, Bandung City had a population of 2,452,179, which grew to 2,530,448 by 2022, indicating an increase of 78,269 people, or about 31% over five years (BPS Kota Bandung, 2023).

The increase in population growth will inevitably be accompanied by a rising demand for land. Land use has continuously shifted from open areas and water recharge zones to non-absorbent areas such as buildings. This change impacts groundwater in the area, leading to surface runoff. Surface runoff is rainwater that cannot be absorbed by the soil, vegetation, or depressions and eventually flows into rivers or causes flooding (Rohyanti et al., 2015). According to Dr. Heri Andreas, a Geodesy expert from ITB, Bandung City is expected to face a clean water crisis. He explained that the city is experiencing land subsidence, typically caused by excessive groundwater extraction (Herdiana, 2021). His research recorded land subsidence rates ranging from one to twenty centimeters per year.

Given these issues, spatial studies of groundwater availability are essential to identify and assess groundwater resources. According to research by (Yunandar et al., 2021), one of the techniques used in conducting spatial studies of groundwater availability involves Remote Sensing and Geographic Information System (GIS) technology. This study also utilized the analytical hierarchy process (AHP) method for weighting various factors that affect groundwater availability, such as land use, slope gradient, geological conditions, soil type, rainfall, water table depth, and aquifer thickness in Bandung City. The weights for each parameter were calculated using the AHP.

Literature reviews reveal that numerous previous studies have used the AHP method to analyze groundwater availability in various regions. Examples include groundwater potential mapping in North Central Nigeria (Adeyeye et al., 2019), groundwater potential mapping in Kupang City (Sulaiman et al., 2017), groundwater conservation zone management in Kulon Progo Regency (Ramadhika & Hendrayana, 2016), groundwater distribution in Prambanan Subdistrict (Kristanto et al., 2020), and groundwater assessment in the Gobele Basin, Ethiopia

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(Guduru & Jilo, 2022), among others. These studies demonstrate that the weights derived using the AHP method are more accurate.

While the use of AHP for groundwater availability mapping is widespread, its application within the administrative boundaries of Bandung City remains relatively rare. Thus, this study focuses on analyzing groundwater availability in Bandung City using the AHP method. Additionally, this research incorporates several parameters distinct from those used in previous studies on groundwater potential in Kupang City (Sulaiman et al., 2017), offering a novel approach. Consequently, this study aims to identify dominant factors determining groundwater availability, analyze groundwater availability zoning, and evaluate the validity of the groundwater availability zoning map in Bandung City. The findings are expected to contribute to groundwater management efforts in terms of both demand and supply, particularly in areas categorized as having low groundwater availability.

2. METHODS

This study employs a spatial approach to groundwater availability. The method used to calculate the weight of each parameter is the analytical hierarchy process (AHP). The research was conducted in Bandung City from mid to late 2023. Data processing was carried out using Microsoft Excel, map creation was done with ArcGIS, and interviews were conducted using research instruments. The materials used in this study include secondary data from government agencies, such as:

1. SPOT 7 imagery from 2022 provided by BRIN
2. Administrative boundaries and DEMNAS from BIG
3. Soil type data from BBSDLP and Bappeda
4. Rainfall data from the Water Resources Agency (Dinas SDA)
5. Groundwater table depth and aquifer thickness data from the Energy and Mineral Resources Agency (Dinas ESDM)
6. Geological Map, Hydrogeological Map, and Groundwater Resources Map from the Geological Agency's PATGTL.

All stages of the research are summarized in the research flow diagram in **Figure 1**.

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Figure 1. Research Flow Diagram

The implementation of this research begins with data collection and the preliminary processing of each parameter. The next step involves distributing the AHP instrument to academicians and experts in the field of groundwater. The third step is to calculate the scores provided by the academicians and experts using the Analytical Hierarchy Process (AHP) method.

2.1. The Dominant Factors of Groundwater Availability

The factors influencing the level of groundwater availability in a region can be observed based on the results of the Analytical Hierarchy Process (AHP) calculations. The AHP method allows for the occurrence of inconsistency in the evaluation of criteria. However, it is important to note that the level of inconsistency should not exceed a consistency ratio of 10%. The consistency ratio can be obtained through the following steps (Malik & Haryanti, 2018).

- Calculate the maximum lambda (λ max) of each matrix

$$\lambda \max = \frac{\sum a}{n}$$

  Where:
  $\sum a$ = sum of the values in each column of the matrix
  n = number of columns

- Calculate the consistency index

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

  Where:
  CI = Consistency Index
  n = order of the matrix
  λ max = largest eigen value of the matrix of order n

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- Calculate the consistency ratio

$$CR = \frac{CI}{RI}$$

Where:
CR = Consistency Ratio
RI = random index

Table 1 Consistency Ratio Value

	Matrix							Priority	Para-meter	Value	Result
	LU	**Slope**	**Soil**	**Rain**	**Geo**	**WTD**	**Aquifer**				
LU	0.06	0.11	0.07	0.04	0.03	0.08	0.09	0.07	Max Eigen Value	7.369	**Inconsistency is acceptable because consistency Ratio is 4,66%**
Slope	0.02	0.04	0.02	0.03	0.03	0.07	0.05	0.04			
Soil	0.05	0.11	0.06	0.04	0.07	0.07	0.05	0.06			
Rain	0.23	0.22	0.23	0.16	0.26	0.13	0.12	0.19	CI	0.062	
Geo	0.25	0.16	0.12	0.08	0.13	0.14	0.15	0.15	RI	1.320	
WTD	0.22	0.17	0.24	0.36	0.27	0.29	0.30	0.27	CR = CI/RI	4.66%	
Aquifer	0.16	0.20	0.26	0.30	0.20	0.22	0.23	0.23			
S.O.R	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**			

Source: analysis results, 2023

The CR (Consistency Ratio) value of 4.66% from the AHP calculation indicates that the AHP results are acceptable (**Table 1**). This is because the CR value is still below 10%, allowing the process to proceed to the next stage for spatial analysis using Geographic Information System (GIS) technology.

Table 2 The Comparison Matrix Square

	LU	**Slope**	**Soil**	**Rain**	**Geo**	**WTD**	**Aquifer**	**S.O.C**	**2nd Eigen Vector**
LU	414.24	755.17	413.13	143.73	186.60	100.77	115.55	2129.18	0.0668133
Slope	226.06	413.42	225.53	78.40	101.79	55.18	63.22	1163.59	0.0365133
Soil	390.54	712.68	390.23	135.97	176.23	95.22	109.16	2010.04	0.0630745
Rain	1188.18	2169.42	1189.51	415.88	537.50	290.89	333.25	6124.63	0.1921897
Geo	896.37	1634.18	895.63	312.54	405.01	218.68	250.56	4612.97	0.1447541
WTD	1659.75	3038.01	1659.13	578.91	748.97	407.16	466.21	8558.15	0.2685529
Aquifer	1410.24	2579.60	1409.63	491.84	636.24	345.63	395.90	7269.08	0.2281023
Total								**31867.6**	**1.00**

Source: analysis results, 2023

The weight values for each parameter can be seen in the eigenvector values multiplied by 100 (**Table 2**).

2.2 Spatial Analysis

Spatial analysis is conducted by inputting the weight values obtained from the AHP calculation into each parameter using ArcGIS software. Once each parameter has a weight value, the next step is to perform overlay and weight summation. The overlay results are then classified into five groundwater availability zoning classes: very high, high, medium, low, and very low. Based on the groundwater availability map, the zoning conditions for groundwater availability in the city of Bandung can be determined.

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The groundwater availability zoning map is then validated against existing conditions in the community by distributing questionnaires. To determine the accuracy level of the research results, an accuracy testing phase is required. The accuracy test is conducted by comparing the number of data points that align with the total amount of data. Based on the spatial study data, recommendations can be made to prevent groundwater depletion, particularly in areas classified as low availability.

3. RESULTS AND DISCUSSION

3.1. Dominant Factors Determining Groundwater Availability

1. Land Use

Land use changes are driven by the rapid development of a region. Changes in land use can lead to various impacts, one of which is the conversion of land previously designated for water infiltration into recreational areas or residential settlements. Based on the processing and analysis of land use maps, it is found that the city of Bandung is dominated by residential land use, covering 5,738.87 ha or approximately 34% of the city's total area.

2. Slope

Slope is one of the factors influencing groundwater availability. Bandung, located within the Bandung Basin, is dominated by flat slopes, covering 9,227.06 ha. Meanwhile, the area with the smallest slope, categorized as very steep, covers only 109.89 ha.

3. Soil Type

Soil type is a significant factor affecting groundwater availability in a region. This is because some soil types allow water to pass through easily, while others do not. Based on soil type maps, Bandung has four types of soil: alluvial, andosol, latosol, and kambisol. The dominant soil type in Bandung is alluvial, covering 11,999.52 hectares, or about 71% of the city's area.

4. Rainfall

Rainfall is a crucial factor in groundwater availability in a region. The higher the rainfall, the greater the groundwater availability, and vice versa. Bandung is a highland city, and thus experiences high rainfall levels. According to data from rainfall stations, Bandung has an average rainfall ranging from 1,741 mm/year to 2,395 mm/year.

5. Geology

The geological conditions of a region are an important factor in determining groundwater availability. This is because the condition and distribution of aquifers are controlled by the physical structure and geological deposits, known as lithology (Prastistho et al., 2018). Each type of rock has different capabilities for storing and transmitting water. There are six geological formations in Bandung: lake deposits, young undifferentiated volcanic materials, old undifferentiated volcanic materials, lava, pumice tuff, and sand tuff.

The dominant geological formation in Bandung is pumice tuff, covering 7,486.51 hectares, located in the central part of the city. The smallest formation is lava, covering just 1.21 hectares in the northern part of the city.

6. Water Table Depth

The depth of the groundwater table provides an indication of the groundwater quantity in a given area. In this study, groundwater table depth data were obtained from secondary sources, specifically the relevant government agency, the Ministry of Energy and Mineral Resources (ESDM). The dominant groundwater table depth in Bandung is between 17 and 24 meters below the surface, covering 7,334.48 hectares, or about 44% of the city’s area. The groundwater table depth score is based on how shallow or deep the groundwater is in a

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region. The shallower the groundwater table, the easier it is to access water in the area; conversely, the deeper the groundwater table, the more difficult it is to obtain water.

7. Aquifer Thickness

Aquifer thickness is another factor influencing groundwater availability in a region. Aquifer thickness indicates the maximum capacity of groundwater that the aquifer can store (Dharmawan & Purnama, 2018). In Bandung, the most widespread shallow aquifer thickness is between 23 and 31 meters, covering 9,665.9 hectares. The thickest aquifers, between 39 and 47 meters, have the highest scores, while the thinnest, between 7 and 15 meters, have the lowest scores. This is because the thicker the aquifer, the greater its capacity to store groundwater.

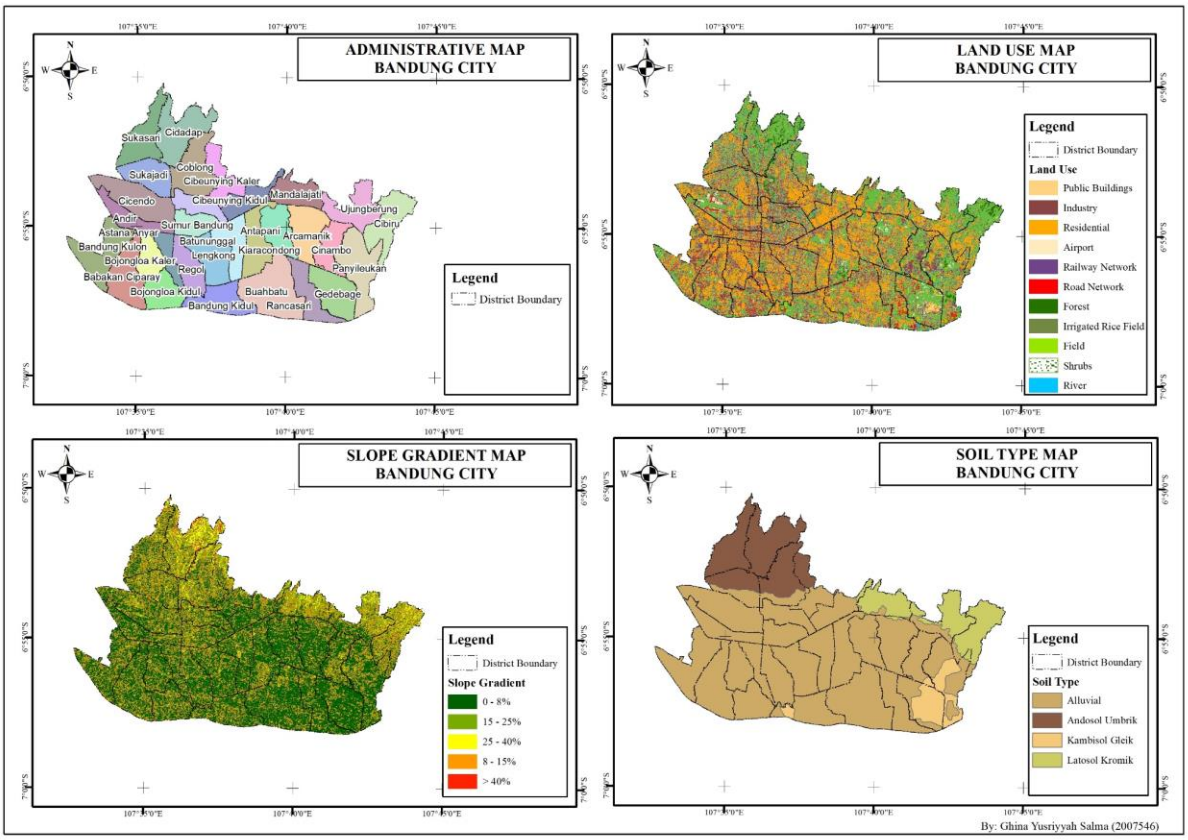

Figure 2 Map of a) Administrative; b) Land use; c) Slope; d) Soil Type

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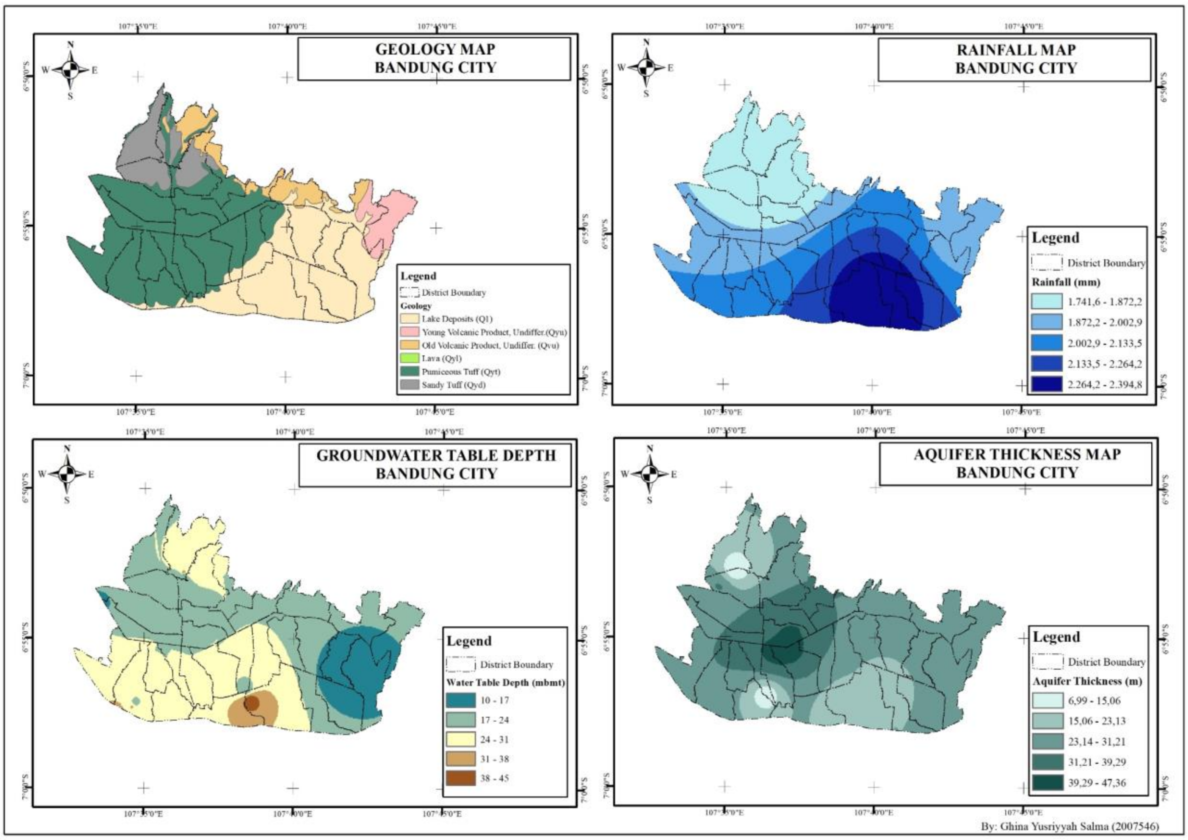

Figure 3 Map of a) Geology; b) Rainfall; c) Water Table Depth; d) Aquifer Thickness

In this study, the method used to determine the weight values of each criterion is the Analytical Hierarchy Process (AHP). Below are the parties involved in filling out the AHP instrument scores (**Tabel 3**).

Table 3 Parties Involved in Filling Out the Instrument

ID	Respondent Name	Instituion
1	Hendro Murtianto, S.Pd., M.Sc.	UPI
2	Ir. Yakub Malik, M.Pd.	
3	Ardi Ariandi, S.T.	ESDM
4	Fariz Gania	BP Cekban
5	Handi Sandi Abdullah	
6	Munib Ikhwatun Iman, S.T., M.T.	PATGTL
7	Fajar Dwinanto, S.T., M.T.	

The experts' opinions were then combined using the geometric mean (geomean). The geomean values were then entered into the comparison matrix. Following that, summation and averaging were performed for each criterion. The AHP method still allows for some inconsistency in criterion assessments. However, the inconsistency must have a consistency ratio value of less than 10% or exactly 10%. The consistency ratio value is obtained by dividing the consistency index by the random index. In this study, the consistency ratio (CR) value is 4.66%, meaning the inconsistency is still acceptable as it is less than 10%.

The weight values for each parameter can be seen in the second eigenvector values multiplied by 100. Therefore, based on **Table 4**, it can be concluded that the dominant factor

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affecting groundwater availability is the groundwater table depth, followed by aquifer thickness, and rainfall.

Table 4 Weight Values for Each Parameter

Criteria	Weight	Rank
Landuse	7%	5
Slope	4%	7
Soil Type	6%	6
Rainfall	19%	3
Geology	14%	4
Water Table Depth	27%	1
Aquifer Thickness	23%	2

Source: analysis results, 2023

In the assessment of various criteria, it is common to encounter uncertainty or inconsistency. This inconsistency may arise due to several factors, such as errors in inputting values, low concentration, insufficient information, or an inadequate hierarchical structure model. Through the AHP method, these uncertainty issues are expected to be addressed. The final results of the study are highly influenced by the assessments of the respondents. Therefore, an instrument is needed to standardize the respondents' rating scale, as well as the importance of selecting respondents based on experts and stakeholders in the relevant field. Thus, even if inconsistency occurs, the inconsistency value remains below 10%.

Based on the calculation of scores from experts using the Analytical Hierarchy Process (AHP), the weight values for each factor determining groundwater availability can be determined. The dominant factors influencing groundwater availability in this study are the groundwater table depth, followed by aquifer thickness, and rainfall. The groundwater table depth represents the ease of groundwater extraction. The shallower the groundwater table, the easier it is to find water in that area, while the deeper the groundwater table, the harder it is to obtain water in that area. In this case, the ease of extracting groundwater increases the level of groundwater availability in a region. The second factor significantly influencing groundwater availability is aquifer thickness. This is relevant because, through aquifer thickness, the maximum groundwater capacity that can be stored by the aquifer can be determined; in other words, the thicker the aquifer, the more water it can hold. The third factor that influences groundwater availability is rainfall. This is quite relevant because this study focuses on groundwater availability in unconfined aquifers, where climatic factors significantly affect groundwater availability. These results are consistent with research by (Hendrayana et al., 2021), which examined water-scarce areas in Kulon Progo, Yogyakarta, where areas with dry climatic conditions exhibited water scarcity, indicating that climatic factors significantly influence groundwater availability. Additionally, this is in line with the research by (Hussain et al., 2022), which studied the response of the groundwater table to rainfall, where a good linear correlation was found between groundwater table response and rainfall.

3.2. Groundwater Availability Zoning in Bandung City

Based on the findings of the study, seven main criteria or parameters were identified that support the determination of groundwater availability zoning in Bandung City. These seven parameters were assigned scores and weights. After the scores and weights were input, the next step was the analysis process using the overlay tool in ArcGIS software. Once the final

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scores were obtained, classification was performed. In this study, classification was divided into five groundwater availability zoning classes: very low, low, moderate, high, and very high.

Based on the map (**Figure 4**), the most dominant groundwater availability zoning in Bandung City is in the moderate class, covering 48.9% of the city's area. The lowest zoning class is very low, covering only 0.5% of the city's area.

The groundwater availability zoning in the moderate class is widespread and dominates the city of Bandung. The very low and low classes are located in the northern and southern parts of the city, including the districts of Sukasari, Cidadap, Coblong, Buahbatu, Bojongloa Kidul, and Bandung Kidul. Meanwhile, the very high and high groundwater availability zones are scattered in the central and southeastern parts of Bandung City.

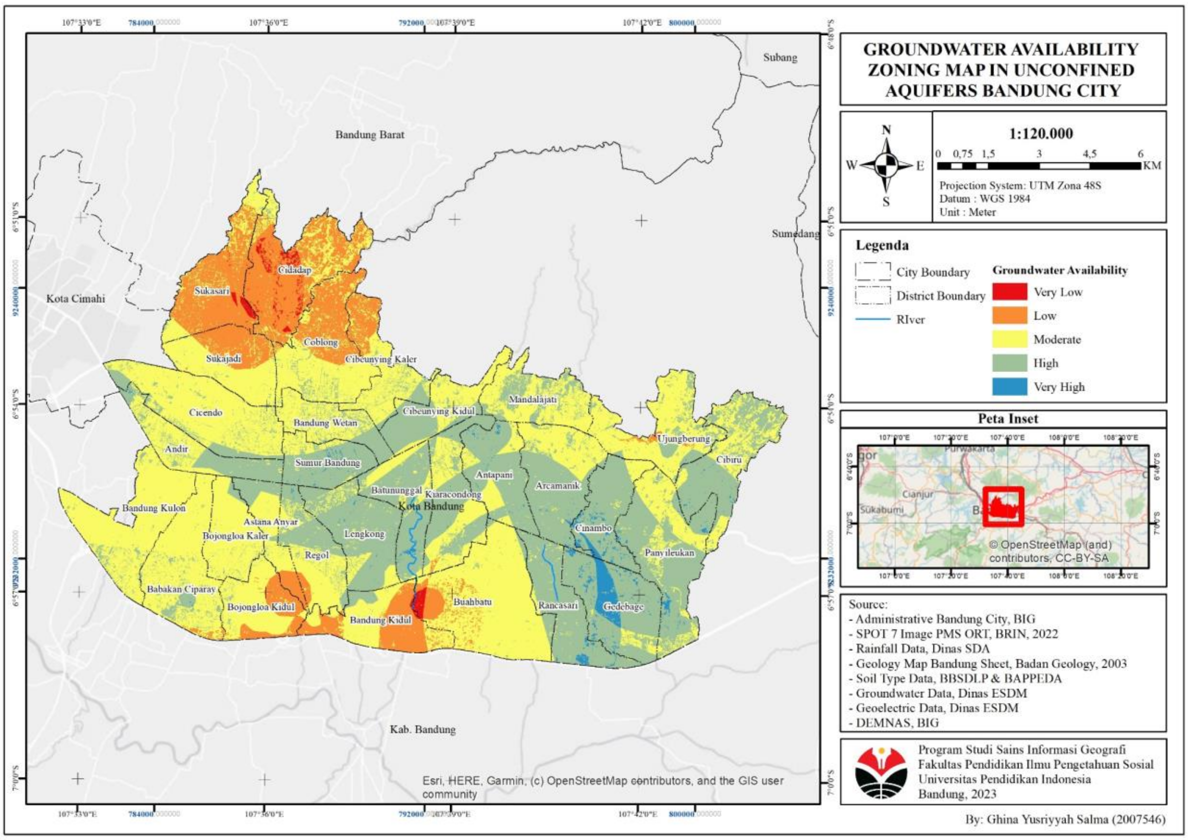

Figure 4 Groundwater Availability Zoning Map of Bandung City

Based on the visualization of the groundwater availability zoning map in Bandung City, the groundwater availability classes can be considered quite relevant and show novelty. One relevant aspect is that in the northern part of the city, groundwater availability is lower compared to the central and southeastern regions. This is due to Bandung City being part of the Bandung Groundwater Basin, and based on the basin's characteristics, the slope in the northern region is steeper than in the central and southern regions, which results in faster runoff in the northern part. Additionally, higher areas typically require a deeper depth to reach groundwater. This finding aligns with research by (Sulaiman et al., 2017), which stated that groundwater conditions are lower in areas with steep to very steep slopes compared to areas with flat slopes.

The novelty of the groundwater availability map is seen in the low and very low zones in the southern region, such as in the districts of Bandung Kidul, Bojongloa Kidul, and Buahbatu. This can be rationalized by the accumulation of river sediments in the southern areas over time, causing the groundwater table depth to increase. Additionally, this could be due to

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excessive groundwater extraction in these areas, leading to a continuous decline in the groundwater table. This rationale is in line with research by (Hutabarat, 2017), which studied land subsidence in DKI Jakarta caused by excessive groundwater extraction, leading to a decrease in the groundwater table. The impacts of continued groundwater table decline include potential water crises in the future, land subsidence, and a prolonged recovery period.

3.3. Groundwater Availability Zoning Validity

The distribution of sample points is based on the groundwater availability zoning levels in Bandung City using the Anderson formula. The total number of samples to be used is 36 points, with 18 points for the moderate class, 13 points for the high class, and 5 points for the low class. Based on proportional comparison with the area of each zone, two classes are excluded from validation due to their percentage value being less than 1%. However, the researcher still examines these classes with one sample each, though they are not included in the accuracy test calculation.

The survey data obtained are then calculated using an error matrix or confusion matrix. The overall accuracy of the three classes tested is calculated by dividing the number of correct samples by the total number of samples. **Table 5** shows the overall accuracy of the error matrix as 83.3%.

Table 5 Error Matrix

		Interpretation Results			Total
	Class	**Low**	**Modertae**	**High**	
Field data	**Low**	**2**	1	0	3
	Moderate	0	**16**	1	17
	High	3	1	**12**	16
Total		5	18	13	**36**

Source: analysis results, 2023

Based on the table above, the accuracy of all categories is:

$$\frac{2+16+12}{36} = \frac{30}{36} \text{ x } 100 = 83{,}3\%$$

Based on the comparison of classes between the community survey and the map results, the overall accuracy of the groundwater availability zoning map is 83.3%. McCoy (2005, cited in Rini & Susatya, 2019) states that the results of data processing can be used for analysis if the accuracy level reaches at least 80-85%. Therefore, an accuracy of 83.3% meets the required standard. Additionally, the validation results for the very high and very low samples, which were not included in the accuracy test calculation, showed correct category validation. Including these two samples in the accuracy test calculation would result in an overall accuracy of 84.2%. This is also consistent with the study by (Pratama et al., 2018), which identified groundwater potential with a validation value of 82.93%, indicating that the data is reliable and sufficiently accurate, as the accuracy exceeded 80%.

4. CONCLUSION

Based on the research findings presented, it can be concluded that groundwater availability in Bandung City can be analyzed using the Analytical Hierarchy Process method. According to expert opinions on the seven parameters used in this study, the dominant factor determining groundwater availability is the groundwater table depth. The spatial analysis of groundwater availability zoning in Bandung City is classified into five classes: very high, high,

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moderate, low, and very low. The results show that the moderate class dominates Bandung City, covering an area of 48.9%. Meanwhile, the very low class has the smallest area, occupying only 0.5% of Bandung City.

Based on the validation of existing conditions by distributing questionnaires to the public, the overall accuracy of the groundwater availability zoning map was found to be 83.3%. This is in accordance with the minimum accuracy requirement of 80%. Therefore, the overall accuracy of 83.3% can be considered to meet the standard.

Recommendations for similar studies include ensuring that the data used has a higher map scale or spatial resolution. If possible, direct well surveys should be conducted in the field to obtain better and more accurate results.

5. ACKNOWLEDGMENT

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6. AUTHORS' NOTE

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The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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