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RESEARCH ARTICLE

Groundwater Potency Analysis Using Remote Sensing and Analytical Hierarchy Process To Overcome Drought In Rembang Regency, Indonesia

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Abstract Water is an indispensable need for all living beings, including humans, who require this vital resource for consumption, bathing, and agricultural irrigation. One of the sources of clean water is groundwater, which meets 80% of the drinking needs. However, only 82.1% of the population in Central Java has access to clean water, while the remaining 17.9% have limited accessibility. This condition was caused by the prevalence of droughts, particularly in Rembang Regency, indicating that several efforts are needed to overcome this problem. Therefore, this study aims to analyze the groundwater potential in Rembang Regency using remote sensing and Analytical Hierarchy Process (AHP) methods. The remote sensing technique was used to determine the lithology, hydrogeology, lineament density, slope, rainfall, vegetation cover, and land use of the area, while the AHP method was utilized to assess groundwater potential. The results showed that the hydrogeology parameter had the greatest influence with a weight of 21.8%, followed by lithology (15.8%), rainfall (15.1%), vegetation cover (13.5%), land use (10.9%), lineament density (14%), and slope (9.4%). These findings were then validated with existing points of interest, including dug wells, deep wells, and reservoirs. The analysis results showed that the study area can be divided into 4 zones based on the groundwater potential, namely very low (1.2 – 2.24), low (2.24 – 3.48), moderate (3.48 – 4.72), and high (4.72 – 5.96) with areas of 0.19 km^2, 234.8 km^2, 173.4 km^2, and 51.9 km^2, respectively. Furthermore, based on the validation, 90 out of 108 (83%) interest points were in line with the groundwater potential map zones.

1. Introduction

Water is a fundamental necessity for all living beings, including animals, plants, and humans (Saravanan, 2012). For humans, it is required for various purposes, such as consumption, bathing, and agricultural irrigation. Furthermore, groundwater is formed by rainwater that seeps below the ground surface due to geological layering structure, differences in soil moisture potential, and the earth's gravity (Asdak, 2010). It is also one source of clean water (Suganthi, et al, 2013), which meets approximately 80% of drinking needs (Nandhiskumar et al, 2014). Several studies have shown that the availability of clean water remains a challenge in Central Java. Based on data from the Socio-Economic Survey (Central Bureau of Statistic Central Java, 2019), only 82.1% of the population has access to this resource(Central Bureau of Statistics of the Republic of Indonesia, 2014-1019), while the remaining 17.9% lacked access. These conditions are been exacerbated by the prevalence of drought in several areas in Central Java, particularly in Rembang Regency. In 2020, a total of 29 villages spread across 11 sub-districts were affected by drought (Okta, 2020), which limited the accessibility of clean water for residents. Previous studies showed that rainfall in Rembang decreased between 2016 and 2019 from 1,954 mm/year to 1,189 mm/year, but slightly increased by 1,670 mm/year in 2020 (Central Bureau of Statistic Rembang 2017-2021). The population growth in several areas of the regency continues to increase annually, further exacerbating the demand for clean water. To overcome this problem, efficient and economic exploration, assessment, and groundwater development methods are needed (Saadi et al., 2021). According to Central Bureau of Statistic Rembang 2021 data, a total of 61 drought events occurred in Rembang, especially in the western and southern parts. Therefore, several efforts must be made to address this issue, such as the use of remote sensing to determine the groundwater potential of various regions. Several studies (Khumar and Khrisna, 2018; Malik et al, 2016; Rahmati et al, 2015) have also utilized geospatial techniques for detection purposes. Although satellite imagery cannot directly detect groundwater due to the complex subsurface environment, the curated features of these datasets (landscape and fracture geological structures) can provide predictive analysis (Mir et al, 2021).

Remote sensing techniques offer several benefits for understanding the parameters affecting the availability and movement of groundwater, including geology, geomorphology, flow patterns, land use, and lineament patterns (Aggarwal et al., 2018). These methods have been widely used in several studies, and have been proven effective (Mir et al., 2021; Khan et al., 2020; Ferozur et al., 2019; Magesh et al., 2012) for potential water analysis. One of the most significant advantages of remote sensing for hydrogeological studies and monitoring is the ability to provide high-quality spatial and temporal information for analysis, prediction, and validation of water potential (Sarma and Saraf, 2002).

Based on literature reviews, satellite imagery and GIS are commonly used for hydro-geomorphological investigations (Mir et al, 2021). For example, Mir et al. (2021) utilized remote sensing and Analytical Hierarchy Process (AHP) to analyze potential groundwater in North Kashmir, Western Himalayas, India. Several influential factors were also considered in this study, including lithology, slope, rainfall, lineament density, and land use. Arunbose et al (2021) explored the potential zoning of groundwater using remote sensing and AHP by considering the lithology, geomorphology, slope, rainfall, lineament density, drainage density, wettability index, surface temperature, soil type, roughness, and land use. In this current study, the parameters used include lithology, slope, rainfall, alignment density, land use, and vegetation cover. They were selected from two previous studies, with the addition of regional hydrogeological conditions as an additional parameter. These parameters were then used to create thematic maps and weights were assigned to each of them. The maps were overlaid to obtain groundwater potential zoning of the study area (Saravanan et al, 2021: Thapa et al, 2017: Dar et al, 2011) and validated with points of interest, such as dug wells, deep wells, and reservoirs. Therefore, this study aims to create a geospatial integration and decision-making approach for the Rembang Regency area by mapping groundwater potential zoning.

2. Methods

Site Description

This study was carried out in 6 (six) sub-districts in Rembang Regency, namely Rembang, Kaliori, Sulang, Sumber, Bulu, and Gunem. Furthermore, the geographical coordinates were 525876-559624 mE and 9237932-9261491 mS, ranging from 6°53'20"-6°42'40"S to 111°12'0"-111°33'20"E, as shown in Figure 1.

Based on the regional geological maps (Kadar and Sudijono, 1993), the study area was characterized by several rock formations. These formations were ordered chronologically from oldest to youngest and included Tawun (Tmt), Ngrayong (Tmtn), Bulu (Tmb), Wonocolo (Tmw), Ledok (Tml), Mundu (Tmpm), Paciran (Tpp), Selorejo (QTps), Lidah (QTI), Lasem Volcano (Qla), and Alluvium (Qa).

The Tawun Formation was the earliest Miocene (oldest) and was composed of claystone and limestone with sandstone, siltstone, and calcarenite. Meanwhile, Ngarayong was made up of sandstone, shale, claystone, and siltstone with limestone. The Bulu Formation, which dates back to the middle of the Miocene was composed of white-grey limestone lithology with sand-sized grains and thin layers. It was characterized by several fossil fragments at the bottom and marl inserts in the middle. Wonocolo, a middle Miocene formation, had an unconformity position with Ledok. It was composed of claystone and thin limestone inserts, with glauconite sandstone at the bottom. Ledok was formed in the late Miocene and underlay the Mundu Formation. It consisted of grey claystone, marl, thin-layered calcarenite limestone, and glauconite sandstone. Furthermore, Mundu, which ranged from late Miocene to Pliocene, was composed of massive whitish-grey marl rich in planktonic foraminiferal fragments. Paciran was formed between Pliocene and Pleistocene and consisted of massive limestone with a wavy surface caused by weathering. It usually had a dolomite nature and contained coral algae and foraminifera. The Selorejo Formation was composed of alternating limestones and sandstones rich in planktonic foraminiferal fragments of fossils. Lidah Formation was Pleistocene in age and aligned above Mundu. It was composed of blackish-grey claystone and mollusc fragments of sandstone inserts with mollusc-rich horizons (Ostreae). This formation also had an unconformity with Selorejo, as shown in Figure 2.

Said and Sukrisno (1988) reported that the regional hydrogeological map of the study area was divided into 3 (three) categories based on their productivity as well as

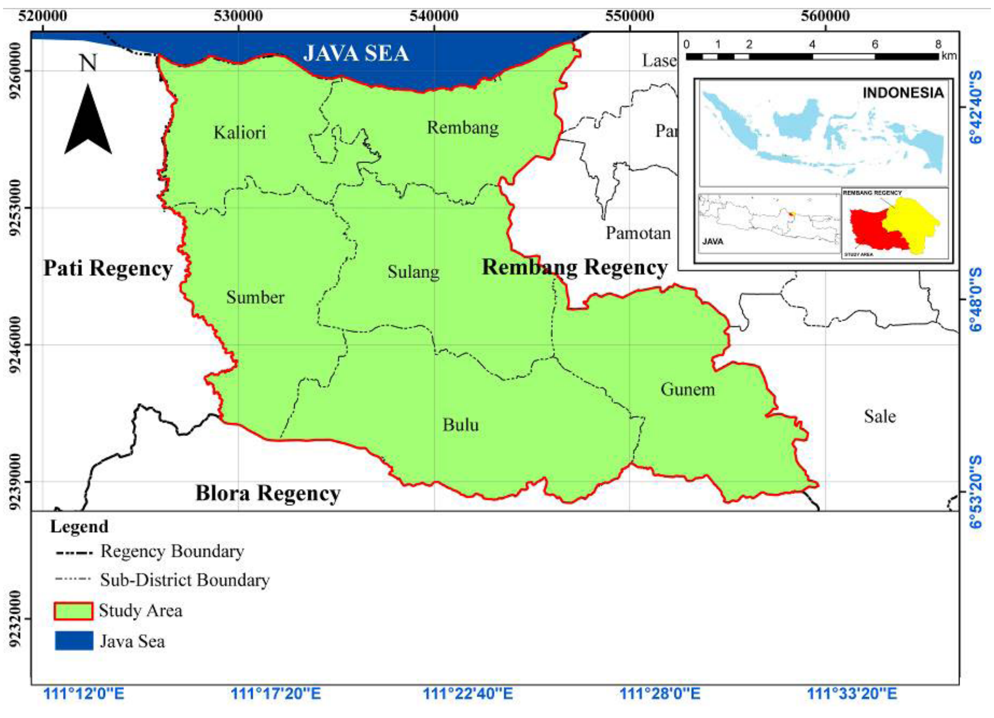

Figure 1. Study area

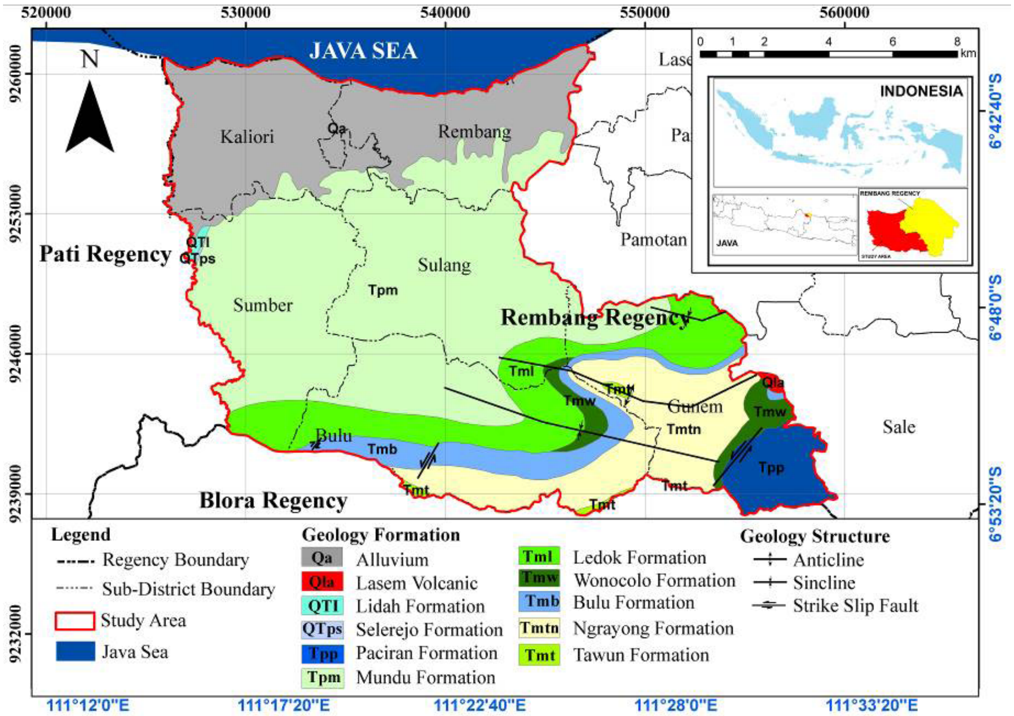

Figure 2. Regional geological map.

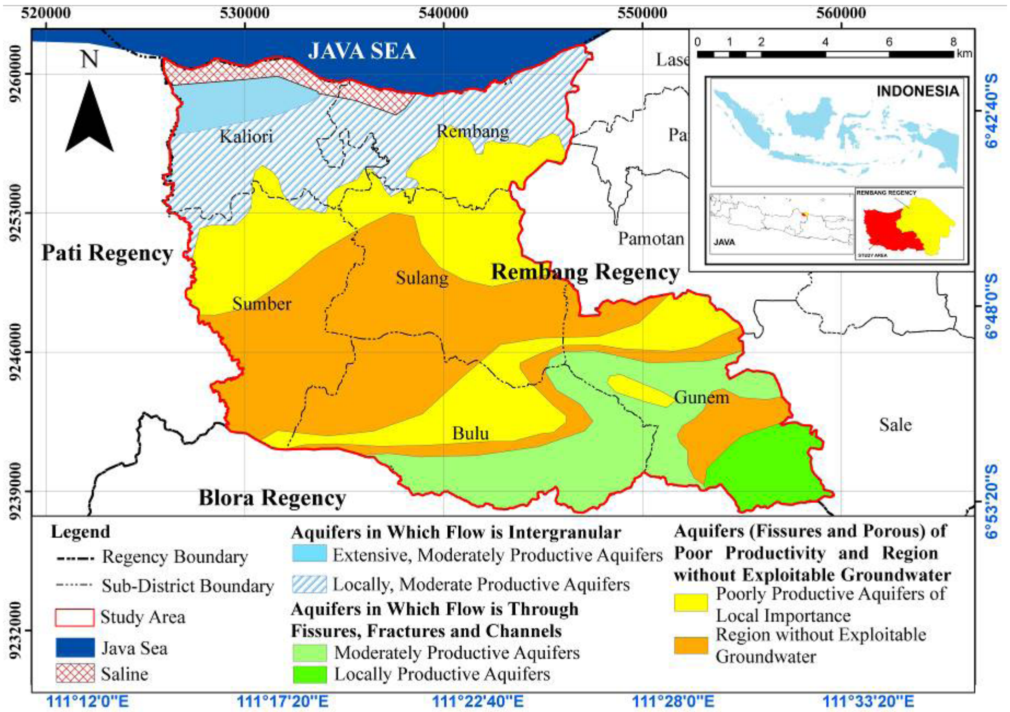

Figure 3. Regional hydrogeological map.

the presence of groundwater, as shown in Figure 3. These categories included 1) aquifers with an intergranular flow, 2) aquifers with flow through fissures, fractures, and channels, and 3) aquifers with poor productivity and region without exploitable groundwater.

Aquifers that flowed intergranularly can be divided into 2 types, namely locally moderately productive and extensive moderately productive. They were mainly distributed in the north of the study area and comprised alluvium. Meanwhile, aquifers that flowed through fissures, fractures, and channels were in the southern region with some faults and folds. The lithology in this area consisted of sandstone and limestone belonging to the Ngrayong and Bulu Formations. This type of aquifer system was classified into moderately and locally productive. The well yield varied widely with some favorable sites yielding more than 10 L/s. In some areas, the water table was deep, and the well yield and spring discharge were generally low. Aquifers with poor productivity and region without exploitable groundwater were dominantly located in the center of the study area. The lithology in this region comprised claystone and marl as the impermeable layers. Furthermore, in the salt fields, groundwater tended to have high salinity due to seawater intrusion.

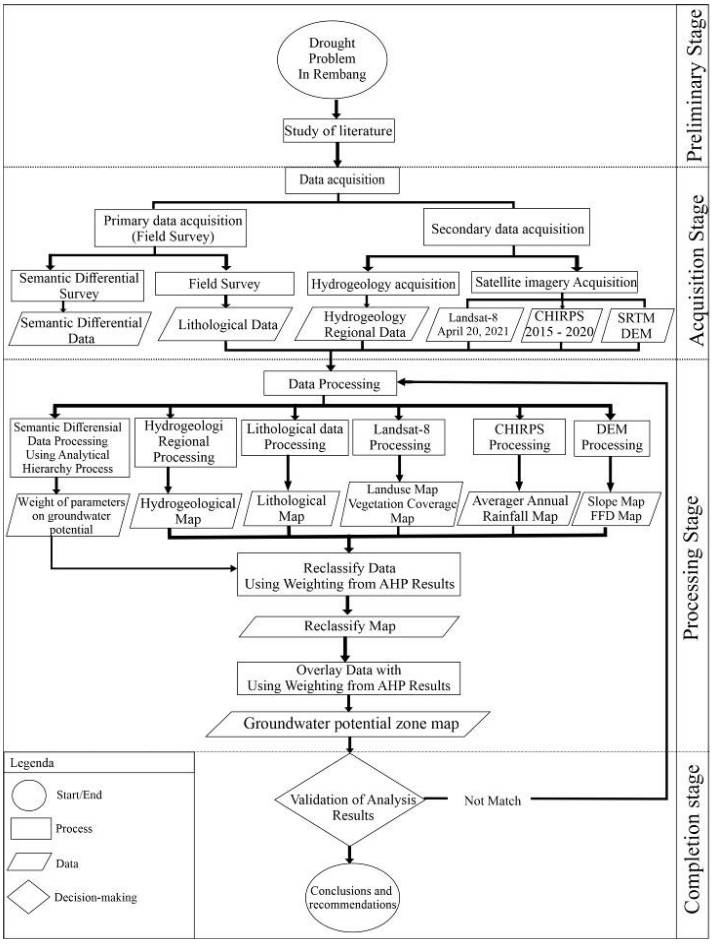

Figure 4. Flow chart of the research

Materials

This study was carried out through several stages, including the preliminary, data acquisition, data processing, and completion stages. The flow chart of the process is presented in Figure 4.

The introduction of this study identified the problem of drought disaster in Rembang Regency and conducted a literature review to explore related studies and reports. The primary data were obtained through a direct geological survey, including the acquisition of geological data by direct mapping and differential semantic data by surveying several respondents. Secondary data were collected indirectly through journals and the internet to obtain Landsat-8 image data, DEM SRTM, CHIRPS, and regional hydrogeological maps.

The data processing stage was carried out by analyzing image, hydrological, and environmental (geology, climate, and others) data. Some of the data used as study material, included lithological data for the study area, Landsat 8 OLI (acquisition April 2021) as well as topographical and regional geological map (Rembang sheet). They also included DEM data derived from USGS SRTM 59 (2014), regional hydrogeological map (Semarang sheet), CHIRPS image data 2015 – 2020, and differential semantic questionnaire data from various respondents.

The process stage was performed with several remote sensing software, including ArcGIS 10.5, Global Mapper, and ENVI 5.1, which produced groundwater potential zones. Subsequently, the completion stage was carried out to validate the results with conditions in the field through hydrogeological mapping.

Methods

This study was carried out using two methods, namely remote sensing and Analytical Hierarchy Process (AHP). The remote sensing method was used to process groundwater potential parameter data, such as rainfall, vegetation cover, and others, and it produced results in the form of maps. Meanwhile, the AHP technique was applied to determine the most influential parameters on groundwater potential in the study area using the Expert Choice 11 application. This technique was one of the decision-making methods developed by Saaty in the 1970s to organize and analyze complex decisions (Nithya et al., 2019) by integrating expert opinion with empirical data (Nithya et al., 2019). In this study, it was used to generate the percentage of the weight of the groundwater potential parameter to the groundwater potential. To achieve this, several parameters were applied, including lithology, regional hydrogeology, slope, lineament density, rainfall, vegetation cover, and land use, as shown in Table 1. The weight of the 7 parameter maps was then integrated using Arc GIS 10.8 software to describe the groundwater potential zone in the area.

Each parameter was divided into different classes with a minimum value of 1 and a maximum of 8 (n). Furthermore, the higher the class, the greater the ease of water storage. The weight value of each parameter (w) was obtained and multiplied by the grade (n) to obtain a score using equation 1:

$$Wt = w \times n \quad (1)$$

Table 1. Research parameter

Parameter	Impact
Lithology	Groundwater infiltration
Slope	Groundwater infiltration
Vegetation cover	Groundwater infiltration
Land use	Groundwater infiltration
Regional hydrogeology	Aquifer property
Lineament Density	Fractures, Infiltration, springs
Precipitation	Groundwater recharge

Source: (Arunbose et al., 2021; Mir et al., 2021; Mitra, 2022).

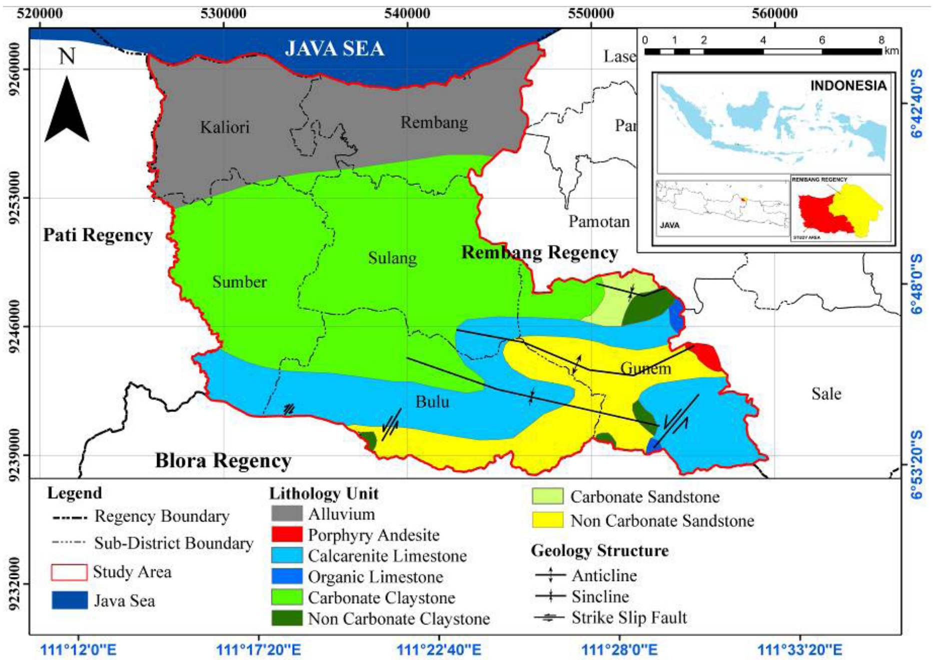

Figure 5. Research lithology map

The parameters were then overlaid to produce a groundwater potential zoning, which was validated with existing points of interest. Furthermore, the point of interest in this study was the absence of air, which enabled the digging of wells, deep wells, springs, and reservoirs.

3. Results and Discussion

Lithology

Based on the geological mapping results, a total of 75 observation points (STA) were obtained. Furthermore, the data processing results showed that the study area, which comprised the Districts of Sulang, Sumber, Rembang, Kaliori, Bulu, and Gunem, had several lithological units, namely alluvium, carbonated and non-carbonated sandstone, calcarenite limestone, organic limestone, carbonated claystone and non-carbonated claystone, as well as porphyry andesite (Figure 5).

The northern part was composed of surface lithology in the form of alluvium, while the region comprised non-carbonate sandstone and calcarenite limestone. This area had good to moderate permeability, which had a positive influence on the groundwater potential.

The middle area consisted of carbonated and non-carbonated claystone, carbonated sandstones, organic limestones, and porphyry andesites. Furthermore, this region had poor to moderate permeability, leading to low groundwater potential.

Based on the lithological condition, the central part had low to moderate potential, while the northern and southern regions had moderate potential.

Regional Hydrogeology

The study area had 7 regional hydrogeology units, including salt fields, groundwater scarce areas, as well as wide-spread productive, locally distributed productive, small productive, medium-productive, and locally productive aquifers.

Mitra et al (2022) revealed that the hydrogeological conditions had a great influence on the groundwater potential. Furthermore, hydrogeology was a determinant of flow rates and aquifer conditions, thereby playing an important role in the formation and distribution of groundwater. Good aquifer conditions are essential for efficient storage and drainage, which increases the potential of the region.

The northern part of the study area has regional hydrogeological conditions composed of aquifers that pass through the space between grains, while those in the southern part passed through fissures and fractures. This difference correlated with the lineament density, where the northern part had low levels, leading to little or no fracture formation for water to flow. Meanwhile, the southern region had a low to very high lineament density value, indicating the presence of several fractures.

The regional hydrogeological conditions correlated with the zoning analysis results of the groundwater potential. The central region had poor conditions, as it was classified as a groundwater-scarce area with small productive aquifers, leading to low potential. However, these findings were inconsistent with the potential analysis results, as the region still had low to very low potential zoning.

The northern and southern areas tended to have good regional hydrogeological conditions with productive aquifer conditions, leading to high groundwater availability These findings correlated with the potential analysis, which showed medium to high potential.

Slope

Based on classification of the Director General of Rehabilitation and Reforestation in 1998, the study area had varied topograghy conditions, as shown in Figure 6. The northern part was characterized by flat (0-8%) to gentle slopes (8-15%). Meanwhile, Bulu and Gunem were dominated by wavy (15 – 25%) to very steep (> 40%) slopes.

Duan et al. (2016) in Putra et al. (2018) stated that the flatter the slope, the greater the groundwater potential. The topography of a region has been reported to be associated with the process of *recharge* and infiltration. Areas with steep slopes were characterized with high water flow rates, increased surface runoff, and low infiltration of water into the ground to *recharge* groundwater. These conditions often caused a decrease in the quantity of groundwater. Meanwhile, areas with flat slopes have higher infiltration, thereby increasing their potential.

Lineament Density

Lineament density conditions can be assessed using alignment density, as shown in Figure 7. The analysis results showed that most of the study area had low alignment density (0 -1.07), indicating the presence of limited structures. Meanwhile, higher values were obtained in the southeastern part (1.07 – 5.35, showing the presence of numerous structures.

Alignment conditions have been reported to have a positive relationship with groundwater potential. Based on the analysis results, the existence of subsurface structures in the form of fractures can become aquifers as well as affect groundwater movement. For example, water can flow through formed fractures until it emerged as a spring on the surface. Alignment also caused an increase in porosity, permeability, and weathering zones. Therefore, areas with high values have greater groundwater potential compared to other regions.

Precipitation

Table 8 shows that the study area tended to have moderate levels of precipitation with a rainfall range of 1,000 to 2,000 mm/yr. These levels of rainfall were considered low based on the classification by the Indonesian Center for Agricultural Land Resources Research and Development (ICALRD) in Azizi et al. (2020). Several studies reported that the precipitation conditions of an area can affect its groundwater potential. Rainwater was one of the main sources of water that played a role in replenishing groundwater. This indicates that high rainfall can increase the supply of water for recharge, thereby increasing the potential of the area.

Land Use

The study area has 5 land use units, namely forests, fields, rice fields, settlements, and vacant land, as shown in Figure 9. The northern part tended to be used as salt ponds, settlements, rice fields, and reservoirs, while the southern region served as rice fields, fields, and forests.

These land use conditions have been reported to influence the groundwater infiltration process. For example, residential areas involving pavements can close the soil pores, leading to reduced infiltration. Furthermore, land use conditions can affect the level of vegetation in a region. Areas with salt ponds, reservoirs, and settlements were characterized by low vegetation levels, leading to a reduction in the amount of water infiltrating the soil. Paddy fields, fields, and forests often have a medium-high level of vegetative cover, thereby increasing the infiltration potential.

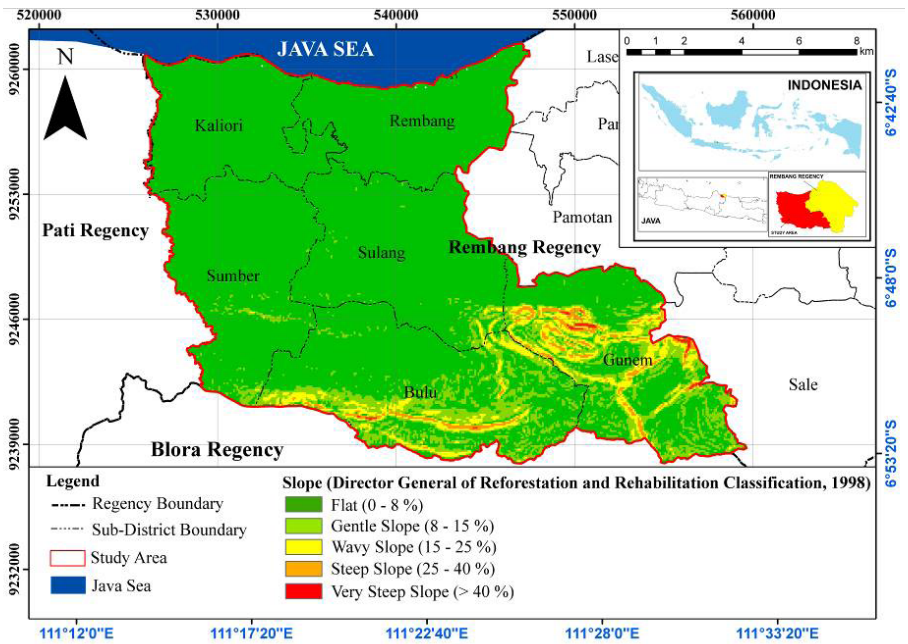

Figure 6. Slope map

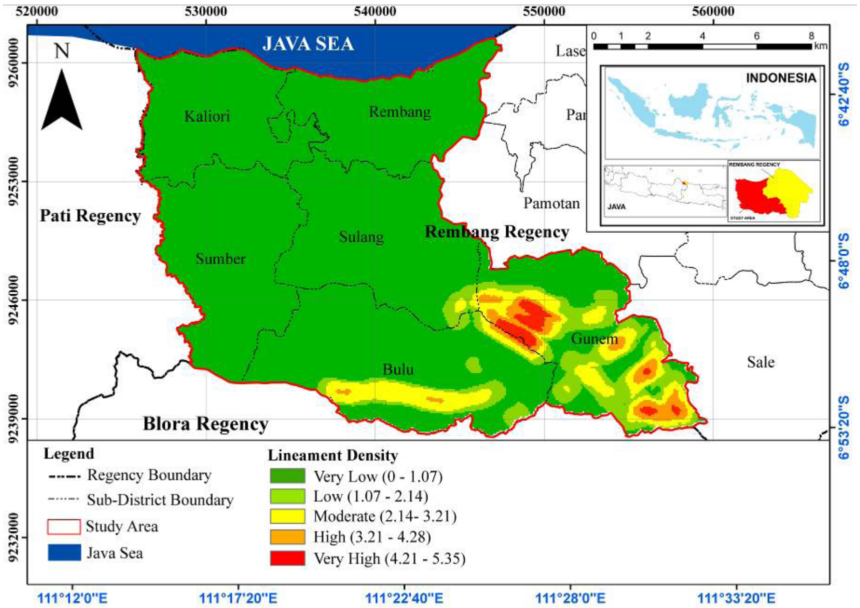

Figure 7. Lineament density map

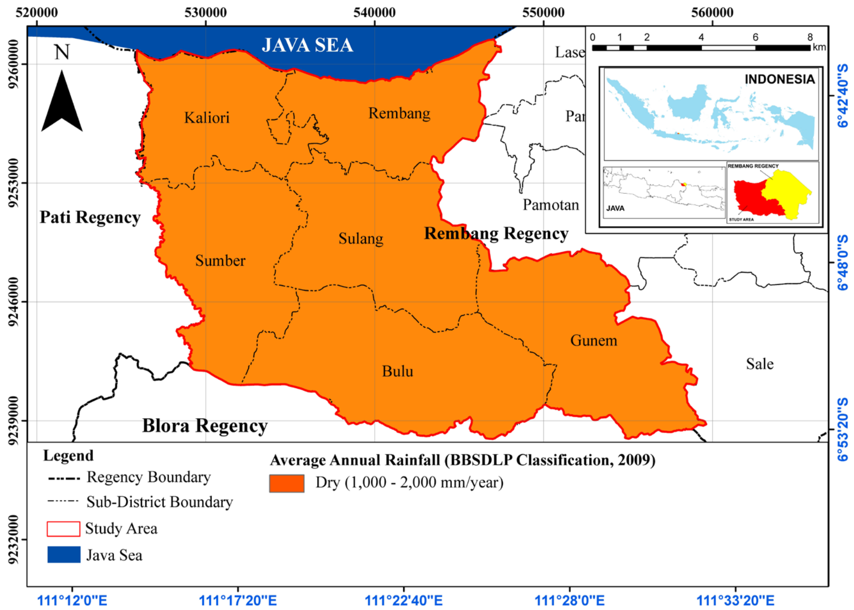

Figure 8. Rainfall map

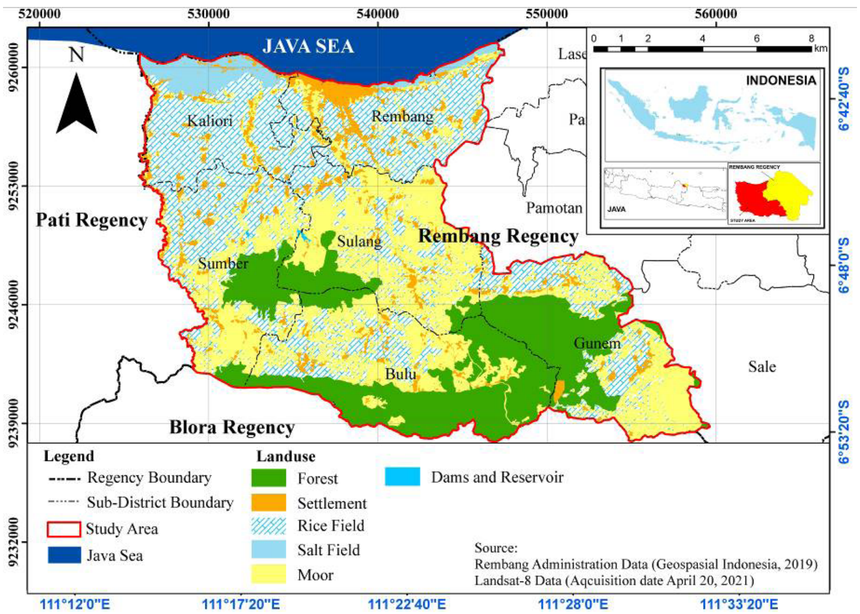

Figure 9. Land use map

Vegetation Cover

The vegetation cover condition of the study area had values between -0.5 to 0.85, and ranged from moderate and high levels, as shown in Figure 10. The northern part was dominated by very low to no vegetation levels due to the land use conditions in Rembang and Kaliori, namely settlements, rice fields, and salt ponds.

In the southern part, the area was dominated by low to high-vegetation units, which were often used as forests, fields, rice fields, and settlements. Forests are known to have high vegetative cover, while cultivated areas have moderate levels. Based on previous studies, salt ponds, reservoirs, and settlements were characterized by low vegetation.

The vegetation condition of a region can affect its groundwater potential. The presence of numerous plants often increased the process of water infiltration due to the penetration of roots into the rock layers as well as the formation of fractures for water flow. These findings indicated that areas with high vegetation have better groundwater potential compared to others.

Analytical Hierarchy Process (AHP)

The AHP analysis was carried out to determine the value of each parameter involved in creating a groundwater potential map. This was achieved by decomposing each parameter and assigning weights based on the impact on groundwater potential. Furthermore, during the AHP analysis processing, lithology, regional hydrogeology, slope, lineament density, rainfall, vegetation cover, and land use were assessed. To obtain accurate results, semantic input data were obtained from several participants and then analyzed to account for any inconsistency. The maximum inconsistency limit was set at 0.1 or 10%, and the analysis results were presented in Table 2.

After the input data were collected and processed, the AHP analysis produced a set of weights for each parameter influencing the groundwater potential with an inconsistency value of 0.1. The influence of each parameter is presented in Figure 11. Furthermore, the results showed that regional hydrogeology had the greatest influence with a value of 21.4%, followed by lithology and rainfall with 15.8% and 15.1%, respectively. Vegetation cover, land use, lineament density, and slope had impact values of 13.5%, 10.9%, 14%, and 9.4%, respectively.

Each parameter was divided into several classes based on its effect on the potential value of groundwater. Lithology was classified based on rock characteristics, such as permeability and carbonate properties, while regional hydrogeology was divided using the aquifer condition. Furthermore, the slope was categorized based on its steepness, where steeper areas had smaller classes. The lineament density was classified using the value obtained, where higher density indicated greater class values.

Rainfall was divided based on the amount of rain, while vegetation cover was classified based on its level. Land use was categorized using the level of influence on groundwater potential.

The value assigned to each class was based on its effect on the groundwater potential. Furthermore, the scoring was carried out by multiplying the parameter weight with the class value, and the results are presented in Table 3.

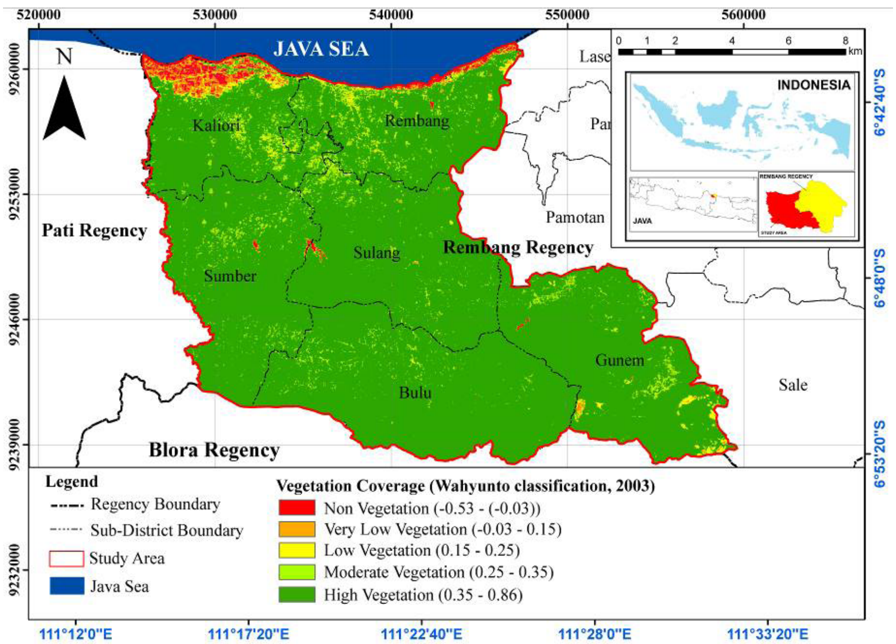

Figure 10. Map of vegetation cover

Table 2. The results of the inconsistency values of the semantic questionnaire data

Name	Work	Inconsistency
Respondent 1	ESDM Department Staff	0.1
Respondent 2	Lecturer	0.08
Respondent 3	Student	0.09
Respondent 4	Public	0.08

Source: own study

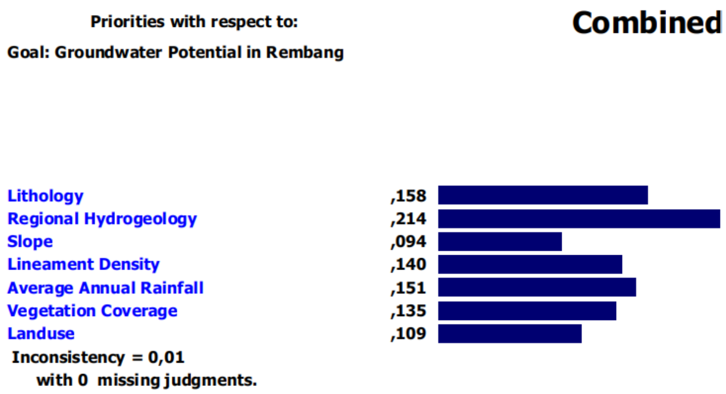

Figure 11. Results of data calculations on AHP

Table 3. Weighting

Parameter	Weight (w)	Parameter class	Grade grade (n)	Score (Wt=wxn)
Lithology	15.8%	Andesite porphyry	1	0.16
		Carbonate Clay	2	0.32
		Non-carbonate claystone	3	0.47
		Organic Limestone	4	0.63
		Calcarenite limestone	5	0.79
		Carbonate Sandstone	6	0.9
		Non-carbonate sandstone	7	1.05
		Alluvium	8	1.2
Regional hydrogeology	21.4%	salt field	1	0.21
		Water scarce area	2	0.43
		Local small productive aquifer	3	0.64
		Local productive aquifer	4	0.86
		Productive aquifers are spreading locally	5	1.07
		Productive aquifers are widely distributed	6	1.2
		Medium productive aquifer	7	1.49
Slope	9%	Very steep (> 40 %)	1	0.09
		Steep (25 – 40 %)	2	0.19
		Wavy (15 – 25 %)	3	0.28
		Ramps (8 – 15 %)	4	0.38
		Flat (0 – 8 %)	5	0.47
Lineament density (km/km^2)	14%	Very low (0 – 1.07)	1	0.14
		Low (1.07 – 2.4)	2	0.28
		Currently (2.4 - 3.21)	3	0.42
		Tall (3.21 – 4.28)	4	0.56
		Very high (4.28 - 5.35)	5	0.70
Rainfall (mm/yr)	15.1%	Very dry (<1,000)	1	0.15
		Dry (1,000 – 2,000)	2	0.30
		Medium (2,000 – 3,000)	3	0.45
		Wet (3,000 – 4,000)	4	0.60
		Very wet (>4,000)	5	0.76
Vegetation cover	13.5%	Non-vegetated land	1	0.14
		Very low vegetation	2	0.27
		Low vegetation	3	0.41
		Enough vegetation	4	0.54
		High vegetation	5	0.68

Parameter	Weight (w)	Parameter class	Grade grade (n)	Score (Wt=wxn)
Land use	10.9%	Salt pond	1	0.11
		Reservoir	2	0.22
		Settlement	3	0.33
		Ricefield	4	0.44
		Field	5	0.55
		Forest	6	0.66

Source: adapting from (Arunbose et al., 2021; Mir et al., 2021)

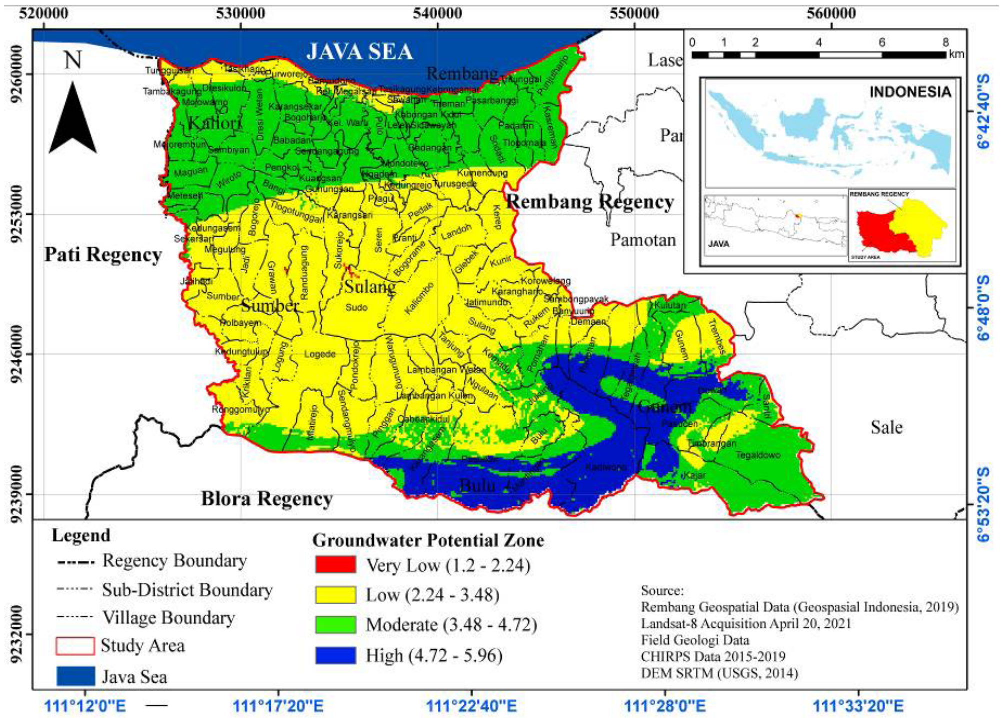

Figure 12. Map of groundwater potential

Groundwater Potential

The results of the groundwater potential analysis showed that the study area consisted of 4 potential zonings, namely very low, low, moderate, and high, as shown in Figure 12.

a Very low potential zone.

The first potential zone was the low zone, which covered an area of approximately 0.19 km^2 (0.04%). Furthermore, this region was located on the border of Sulang and Sumber with a carbonate claystone lithology and a water-scarce area hydrogeology. Claystone has a low permeability value, which lowered the level of water infiltration. The hydrogeological conditions were water scarce, indicating that the aquifers were not productive. This condition was exacerbated by dry rainfall (1,000 – 2,000 mm/yr), which provided a small groundwater recharge supply and low lineament density (0 -3.21 km/ km^2). Based on these findings, the area had minimal structural activity, indicating the presence of few or no fractures, which played a role in water infiltration. The region also had low vegetation conditions and its usage as a reservoir affected the level of infiltration. Although the flat slope (<8%) topography had a positive effect on groundwater, the condition of other parameters was poor, leading to very low potential in the area.

b. Low potential zoning.

The low potential zoning region had an area of approximately 234.8 km ^{2} (51%) and was located in the coastal part of Kaliori and Rembang as well as the central part of the study location. Furthermore, the coastal areas of Rembang and Kaliori were influenced by regional hydrogeological conditions and land use. The regional hydrogeological conditions were in the form of salt fields, indicating that the area had a large volume of groundwater. However, the groundwater tended to be salty due to high salinity, leading to poor water potential. The land use was in the form of salt fields, settlements, and rice fields, thereby causing low vegetation levels and reduced potential. The central area, namely Sulang and Sumber, had a flat slope with a low alignment density and its land use was dominated by settlements, fields, and rice fields. Based on the lithological conditions, alignment density, and land use of the region, it was very difficult for water to infiltrate. This was because the rocks had poor drainage, and there were few or no structures that can facilitate infiltration. Furthermore, the residential land use, which was often characterized by paved roads and concrete, prevented water infiltration. These conditions were then further exacerbated by regional hydrogeological conditions that tended to include rare and small production areas.

c. Moderate groundwater potential zone.

This zone dominated the study area from north to south, covering approximately 173.4 km2 (37.66%). Furthermore, the region was influenced by lithological conditions in the form of alluvium, carbonated sandstone, non-carbonate sandstone, calcarenite, and organic limestones. The regional hydrogeological conditions tended to be small to medium productive areas. It also had flat-wavy slopes with low-medium alignment densities and landscaping. The land use was dominated by fields, rice fields, settlements, and forests. Based on the characteristics of this area, it tended to have moderate groundwater potential.

d. Zone of high groundwater potential.

This zoning was located in a small part of the Bulu and Gunem with an area of approximately 51.9 km^2 (11.3%). Furthermore, the region was triggered by lithological conditions in the form of non-carbonate sandstone and calcarenite limestone, which tended to have good permeability, leading to high infiltration. It also had steep slopes with high alignment density, and the land use was dominated by fields and forests. These conditions were often coupled with regional hydrogeology characterized by moderate to productive aquifers, leading to high groundwater potential.

Result Validation

In this study, result validation was carried out by developing hydrogeological mapping, as shown in Figure 13. Based on the validation results, there were 108 hydrogeological observation points with 60, 46, and 2 in the low, medium, and high potential zones, respectively.

The low potential zone comprised 60 observation points, most of which were located in residential areas and rice fields. The observation points in the middle of the study area tended to have low water and were often dry during the dry season, indicating a low potential. Meanwhile, those in the northern region tended to have relatively large water volumes with high salinity, and this reduced their groundwater potential. Discrepancies were also found in the field conditions, such as several drilled wells and springs (SB-4, SB-76, SB-77, SB-64, SB-110, SB-108, SB-109, SB-94, SB-100, MA-107, MA-101, MA-103, and MA-102) that tended to have sufficient water and were not dry during the dry season.

The medium potential zone had 46 observation points located in areas with moderate to high vegetation. These observation points had high groundwater potential, as the water did not dry during the dry season. However, discrepancies were found in the field, such as in points SG-16, SG-34, SG-42 and SB-93, which had brackish or salty water and were no longer used by residents, indicating a low potential.

In the high-potential zone, there were 2 points on MA-18, and SB-98. These areas were often used as fields and forests with abundant water that does not dry out during the dry season. Furthermore, there were no observation points in central Gunem, which was a forest area with q steep slopes.

The mapping results showed that 91 out of 108 hydrogeological observation points were in line with the analysis results, with an accuracy of approximately 84% accurate. The value obtained exceeded the accuracy limit of 80%, indicating that the findings from the analysis were accurate (Purwandhi, 2006).

During the validation process, several reservoirs were identified, which served as means to collect water from rivers and rain to create reserves. They were often situated in areas experiencing water drought problems, to overcome these conditions. These findings are in line with groundwater potential analysis results, where more than half of the total amount of silt and reservoirs were located in areas with low potential.

Comparisons were made with previous studies by comparing the methods used as well as the results obtained. This study used previously reported methods, namely the AHP technique and remote sensing. However, the parameters used in the analysis were slightly different, with the addition

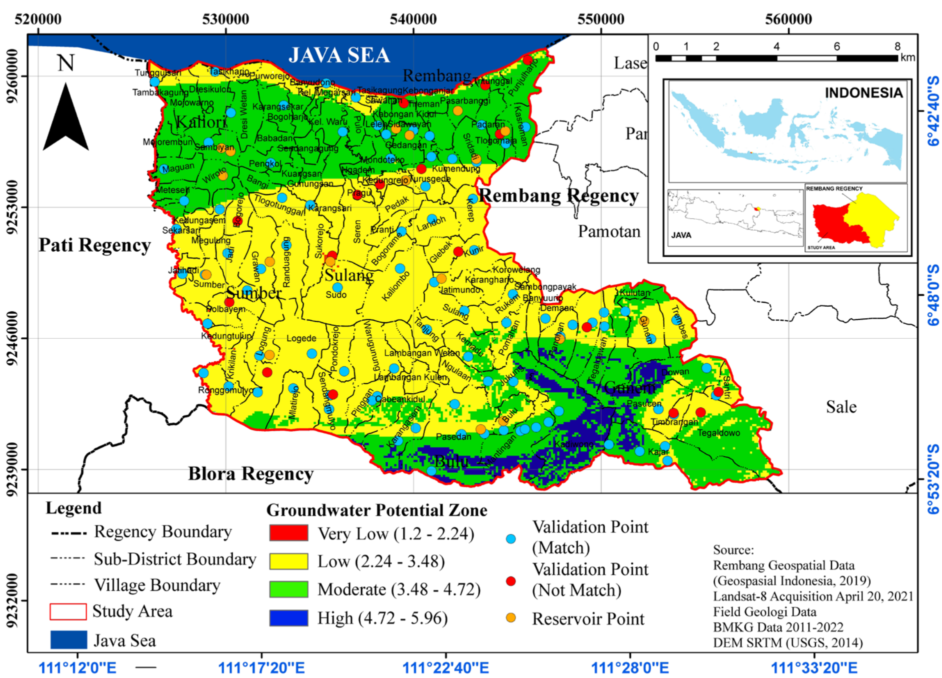

Figure 13. Validation Map

of regional hydrogeological parameters based on the research of Mitra et al. (2022) who identified hydrogeology as one of the factors affecting groundwater potential. In two previous studies, GSI (Geological Survey of India) maps were used for lithological data and rainfall data were obtained from the local meteorological agency with a monthly range of up to 1 year. For this study, lithological conditions were obtained through direct field surveys, leading to more accurate and reliable results. Rainfall data from CHIRPS 2015-2020 was used to determine the average annual rainfall for the last 6 years. The AHP method was utilized in this study to help decision makers in identifying the best alternative among the selected elements. Pair-wise comparisons were used to create a matrix that described the comparison between each element (saaty, 1980). Arunbose et al, (2021) reported that parameters, such as lithology had an effect of 10.6%, while geomorphology, slope, rainfall, lineament density, drainage density, soil type, land use, vegetation cover, surface temperature, wettability index, roughness, elevation, and curvature had 12%, 6%, 9.3%, 8%, 0.66%, 8%, 6.6%, 6.6%, 6.6%, 5.3%, 4%, 5.3%, and 4%, respectively. Furthermore, based on Mir et al, (2021), the influential parameters included drainage density (15%), TPI (10%), TWI (10%), slope (5%), lineament density (25%), lithology (10%), rainfall (15%), and land use (10%). In this study, lithology (15.8%), slope (9.4%), rainfall (15.1%), lineament density (14%), land use (13.5%), vegetation cover (10, 9%), and hydrogeology (21.6%) were reported to be influential. The difference in the level of effect was due to AHP method weaknesses, namely the inability to overcome the uncertainty factor faced by decision makers when they must give a definite value to a concept based on multiple criteria through pairwise comparisons (Permadi, 1992).

A comparison of the results obtained from the potential zoning and validation was also carried out, and some similarities were observed. Areas with very low potential tended to have lithology with poor permeability as well as land use with low vegetation. Meanwhile, areas with high potential had lithology with good permeability and land use with medium to high vegetation. The third validation of the results was carried out with different methods. In Mir et al. (2021), an indirect validation method was applied using the ROC (Receiver Operating Characteristic) technique with a relative accuracy value of 75%. Arunbose et al. (2021) used the VES (Vertical Electric Sounding) method directly in the field with data accuracy ranging from 76.9%. In this study, validation was carried out through hydrogeological mapping with a suitability level of 84 % accuracy. The high level of conformity of the results was considered an advantage.

Comparison to other related studies

Although several remote sensing and analytical methods have been used in previous studies, their combination can be applied to different lithologies, hydrogeologies, and geographical areas. Some of these studies were conducted in tropical (Arunbose et al., 2021; Mir et al., 2021; Mitra and Roy, 2022; Kumar and Khrisna, 2018) and subtropical (Rahmati et al., 2015) regions. However, the addition of a new parameter, namely hydrogeology, increased the safety of the validation results by up to 84%. This was because regional hydrogeology was one of the important parameters in determining the presence of groundwater, and it had the highest contribution of 21.4% compared to others.

4. Conclusions

Based on remote sensing, the potential zoning of groundwater in the study area was influenced by several factors, namely lithology, density, rainfall, vegetation cover, land use, slope, and hydrogeology. Therefore, this assessment was expected to contribute to future groundwater management.

The study area comprised 7 units of surface lithology, including alluvium, organic limestone, calcarenite limestone, carbonate sandstone, non-carbonate sandstone, carbonate claystone, non-carbonate claystone, and porphyry andesite. The southern part of the study area was also characterized by the presence of several structures.

The results of the Analytical Hierarchy Process showed that regional hydrogeological parameters had a greater influence on groundwater potential, with a weight of 21.8%, followed by lithology (15.8%), rainfall (15.1%), vegetation cover (13.5%), land use (10.9%), lineament density (14%), and slope (9.4%). Furthermore, the Rembang area had 4 groundwater potential zones, namely very low, low, medium, and high with areas of 0.19 km ^{2} (0.04%), 234.8 km ^{2} (51%), 173.4 km ^{2} (37.66%), and 51.9 km ^{2} (11.3%), respectively. The validation results showed that 90 of the 108 observation points were in line with the potential zoning, with an accuracy of 84%, which exceeded the requirements, namely > 80%.

Based on the results, the government can exploit the Gunem and Bulu areas to overcome the problem of drought due to their high groundwater potential. There is also a need for effective management of air resources to address this issue. For areas with very low, low, and moderate potential, artificial recharge techniques can be utilized to thicken the groundwater column, thereby preventing over-exploitation.

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