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Groundwater Recharge Assessment in the Gunungsewu Karst Area Using the APLIS Method and a Modified Soil Physics Approach

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Abstract. *Karst areas experience annual drought, making it essential to preserve potential groundwater recharge areas. This study aims to assess the level of groundwater recharge and its spatial distribution in karst regions, with a case study in the Gunungsewu karst area, Paranggupito sub-district, Wonogiri Regency. This research employed the APLIS method (Altitude, Slope, Lithology, Infiltration and Soil) and collected data by creating a Land Mapping Unit (LMU) map. The LMU was generated through an overlay of land use, soil type, slope, rock type, and rainfall, resulting in 20 LMUs. The observed parameters included elevation, slope, soil type, lithology, soil infiltration, and texture, with modification incorporating porosity as an actual soil parameter. Observations and sampling were conducted, and data analysis involved ANOVA and correlation tests to assess the influence of topography on groundwater recharge distribution and its correlation with soil characteristics. The research results indicate that groundwater recharge is classified into medium and high categories. The distribution of groundwater recharge is influenced by topography and soil infiltration, with the highest recharge occurring on slopes of 0-3% and high infiltration values.*
Keywords: *groundwater potential; karst; limestone; texture.*

Type of the Paper: Regular Article.

1. Introduction

Paranggupito sub-district is part of the Gunungsewu Karst Mountains, covering an area of 6,475 hectares, of which 5,845 hectares consist of karst terrain. It features a solutional landform with limestone rocks that form part of the Gunungsewu karst region [1]. Karst landscapes face significant drought issues during the dry season. While surface conditions are typically dry and critical, but below the surface, substantial water resources exist beneath the surface [2]. Water scarcity remains a major challenge in dryland areas [3]. During the dry season, local communities struggle to obtain water sources for their water needs, relying on rainwater before the dry season and acquiring clean water during droughts. Drought, as a form of land degradation, signifies a decline in natural resource quality [4], adversely affecting farmers' livelihoods and local communities [5]. Therefore, increasing groundwater reserves in this karst region is essential to support community needs.

Groundwater recharge is the process by which water moves from the unsaturated zone to the saturated zone below the water table [6]. Groundwater serves as a reservoir, distributed through

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subsurface flow and gradually replenished over extensive spatial scales and long timeframes within the hydrological cycle [7]. Groundwater storage plays a crucial role in ensuring food security and serves as a strategy for climate change mitigation [8]. Approximately one-third of the public drinking water supply comes from groundwater [9]. Karst groundwater ecosystems comprise fractured carbonate rocks, often overlaid by collapsed caves. Due to the open nature of the aquifer, these systems are highly vulnerable to the rapid transport of dissolved surface contaminants [10]. Karst aquifers are highly porous and capable of storing large volumes of water, making karst areas significant sources of water. Communities rely on karst aquifers for 20-25% of their water supply, either directly or indirectly. However, increasing water demand also heightens the vulnerable to water shortages [11]. Karst aquifers cover approximately 10% of the world's land surface [12].

Karst areas exhibit distinct geographical features compared to other natural landscapes, including a subsurface landscape within caves [13]. The hydrological conditions of karst regions are unique, characterized by rapid rock dissolution and well-developed secondary porosity [14]. Although the surface of karst land is dry, significant groundwater resources are stored beneath it [15]. Espinoza et al. [16] conducted research using the APLIS method to compare groundwater recharge classes in aquifer and non-aquifer lands (modified APLIS) in the Peru region. This study modified several land characteristics as non-specific to the karst land under investigation, such as the quality of karst rocks and the depth of karst cavities. Meanwhile, Syafarini et al. [17] conducted research on groundwater recharge classes in karst lands on Rote Island, identifying four classes ranging from very low to high. One of the most accurate methods for determining effective groundwater recharge zones in karst areas is the APLIS (Altitude, Slope/Pendiente, Lithology, Infiltration, and Soils) method, as proposed by Andreo et al. and Nanou et al. [18,19]. This method, which is closely linked to groundwater zones, represents a sound ecological strategy for maintaining environmental quality [20]. The APLIS method is an estimation technique that offers efficient analysis and data utilization, as it relies on spatial data and requires minimal laboratory analysis of actual soil conditions. Furthermore, the APLIS method is highly adaptable to local conditions, with its five main parameters focusing on specific regional characteristics. This approach yields accurate and relevant data and information over the long term within the research area.

The benefits of this research will be realized in the future through the maximization of groundwater potential in karst areas. The aim of this study is to determine groundwater recharge levels and their spatial distribution in karst areas, with a case study in the Gunungsewu karst area, Paranggupito subdistrict, Wonogiri Regency. In this study, the method was modified to identify the impact of environmental factors on groundwater recharge classes and to observe soil characteristics, such as infiltration and soil porosity, in order to determine their relationship with groundwater recharge. The benefits of this research include enabling local communities and stakeholders to maximize the potential of groundwater in karst areas, allowing communities to utilize subsurface water sources during the dry season.

2. Materials and Methods

2.1. Study area

Paranggupito Sub-district is located in Wonogiri Regency, Central Java Province, approximately 68 kilometers south of the regency center. The area of Paranggupito sub-district covers 6,475.42 ha [21]. Paranggupito sub-district has an altitude of 310 meters above sea level (m asl) and is the only sub-district bordering the Indian ocean, with a coastline length of 15 km. The climate in Paranggupito is characterized by an annual rainfall of 2,250 mm, classified as low, and an average temperature ranging from 26ºC to 30ºC throughout the year. Paranggupito sub-district features solutional landform with limestone rocks, part of the Gunungsewu karst area [1]. The Karst landscape is characterized by typical hilly topography, including caves and underground rivers. Karst land has the potential to serve as a natural reservoir if managed properly. As a food production area, Paranggupito must adapt and implement strategies to mitigate disasters [22], such as drought [23], as well as address soil fertility challenges. Karst land faces the primary challenge of drought during the dry season. The surface conditions of karst land are typically dry and critical, but significant water resources exist beneath the surface [2]. During the dry season, the Paranggupito community meets its clean water needs by purchasing water, while in the rainy season, they rely on rain water.

2.2. Research design and data collection

This research employs an exploratory, descriptive method with a parameter-based approach, utilizing field observations and soil analysis results from the laboratory. The survey was conducted through direct inspection of the research site based on the Land Map Unit (LMU) sample points. The point sampling map uses a scale of 1:12,500 (semi-detailed). The sampling stage employed a purposive method based on the coordinates of the LMU, with 20 locations and 3 repetitions, resulting in a total of 60 sampling points based on karst criteria (Fig. 1). The research also incorporates an approach focused on the physical condition of soil porosity.

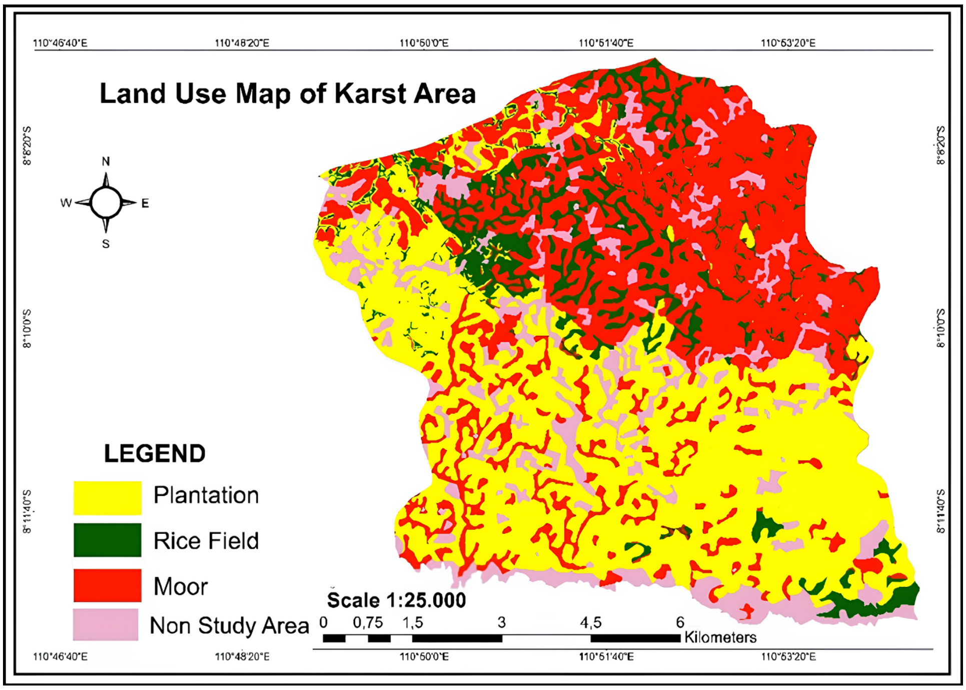
Soil samples were collected using a soil drill at a depth of 0–30 cm for laboratory analysis of soil porosity and infiltration parameters. Porosity measurements were conducted in the laboratory using dried soil samples with a particle size of 0.5 mm, applying the immersion method with a measuring flask [24]. The porosity was calculated by comparing the total bulk density of soil pores with the specific gravity of the soil. Infiltration measurements were conducted using undisturbed soil samples, specifically intact aggregate soil samples. Sampling was performed at a depth of 5–10 cm using a cylindrical sample ring with a diameter of 7.93 cm, a height of 10–20 cm, and a thickness of 1–5 mm, made of metal or copper. In the laboratory, infiltration was measured using an infiltrometer, and calculations were performed using the Horton method as cited in Arsyad [25].

The Land mapping unit (LMU) (Fig. 6) consists of several thematic maps, including land use (Fig. 1), soil type (Fig. 2), slope (Fig. 3), rainfall (Fig. 4), and lithology (Fig. 5). LMUs are generated using the overlay method of thematic maps. Each LMU is selected through an elimination process based on similarities in land characteristics and a minimum total area of more than 1 hectare within the research area. GIS processing, based on the APLIS equation, combines five environmental parameters—altitude, slope, lithology, infiltration, and soil—to determine the percentage of aquifer presence in the limestone formations of the Gunungsewu area in Paranggupito. The groundwater recharge classification in the study area is determined based on field observation scoring, secondary map data, and laboratory analysis results. The collected data are then compared with the groundwater recharge classification table (Table 1), adapted from Andreo et al. [18].

The non-study area refers to regions within Paranggupito Sub-district that do not exhibit karst formations and are therefore excluded from sampling. Land use in Paranggupito Sub-district includes rice fields, plantations, and moorlands. The soil types in the study area consist of Alfisols and Inceptisols. Sandy-textured soils exhibit a high infiltration capacity, significantly influencing groundwater recharge. Recent soils, such as Alfisols, have the highest infiltration values due to their ability to absorb large quantities of water [26]. The slope ranges in the study area ranges from 0% to 76%. Most karst areas are characterized by steep slopes due to the predominantly vertical development of karst formations [27]. Land with significant slopes is more susceptible to disturbances. In highland areas, soil particle transport frequently occurs through wind dispersion [28]. Additionally, the combination of steep slopes and rainfall increases surface runoff, heightening the risk of landslides [29].

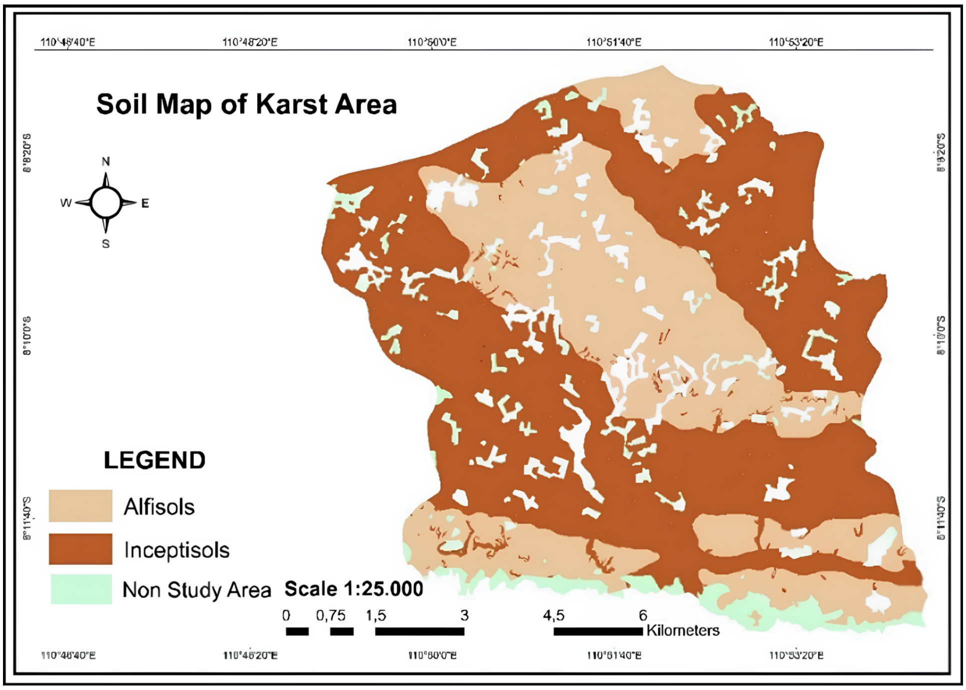
Rainfall in the study area remained consistent at 2250 mm per year. Rainwater that infiltrates the ground contributes to groundwater recharge, either percolating slowly toward the sea or flowing directly through subsurface and surface channels, eventually joining underground river systems [30]. Rainfall influences the volume of water entering the soil, with higher rainfall increasing infiltration through surface flow, particularly in areas with complex land cover [31]. Prolonged and intense rainfall enhances groundwater recharge by supplying more water that permeates the soil or rock, replenishing the aquifer within a groundwater basin system [32].

Limestone is a sedimentary rock formed over millions of years from the accumulation of marine animal shells at the ocean floor [33]. Karstification, the process of karst landform development, is primarily driven by the dissolution of limestone. The delimitation of areas undergoing karstification and those that have not experienced symptoms of karstification and those unaffected is determined based on emerging landform characteristics, such as the sudden disappearance of surface river flows.



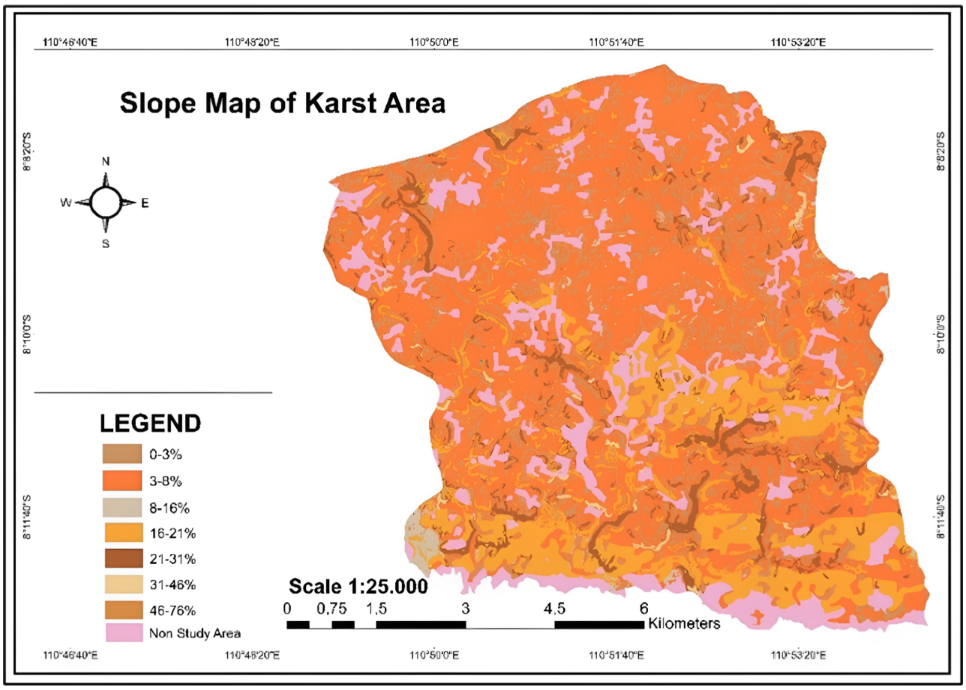
Source: Ina Geospasia (https://tanahair.indonesia.go.id/portal-web/)

Fig. 1. Land use map of karst area



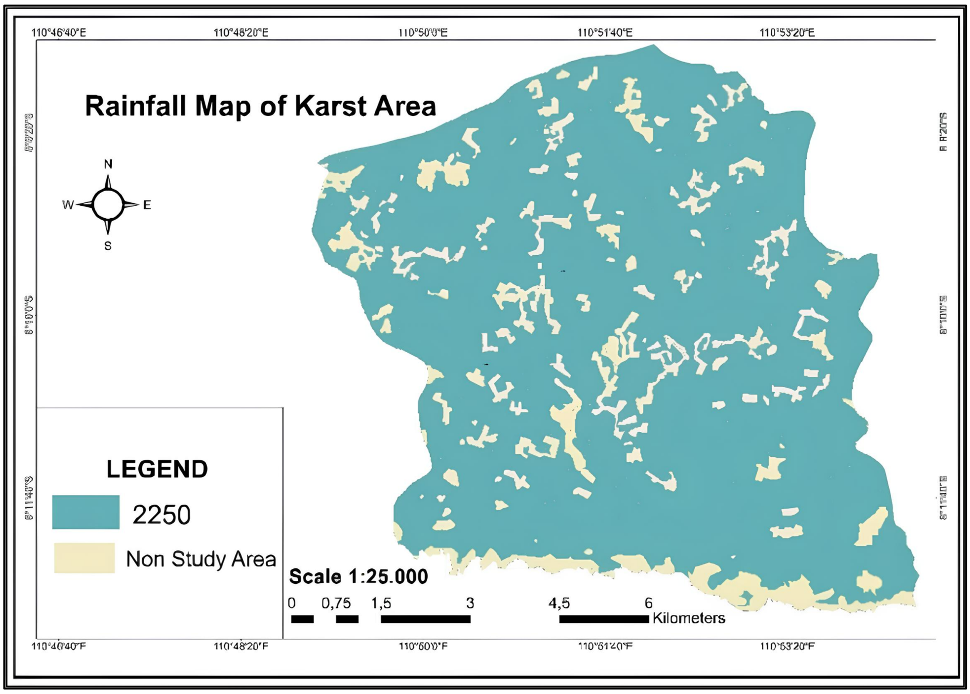
Source: Balai Besar Pengujian Standar Instrumen Sumberdaya Lahan Pertanian (BSIPSDLP) [34] (https://sdlp.bsip.pertanian.go.id/)

Fig. 2. Soil map of karst area



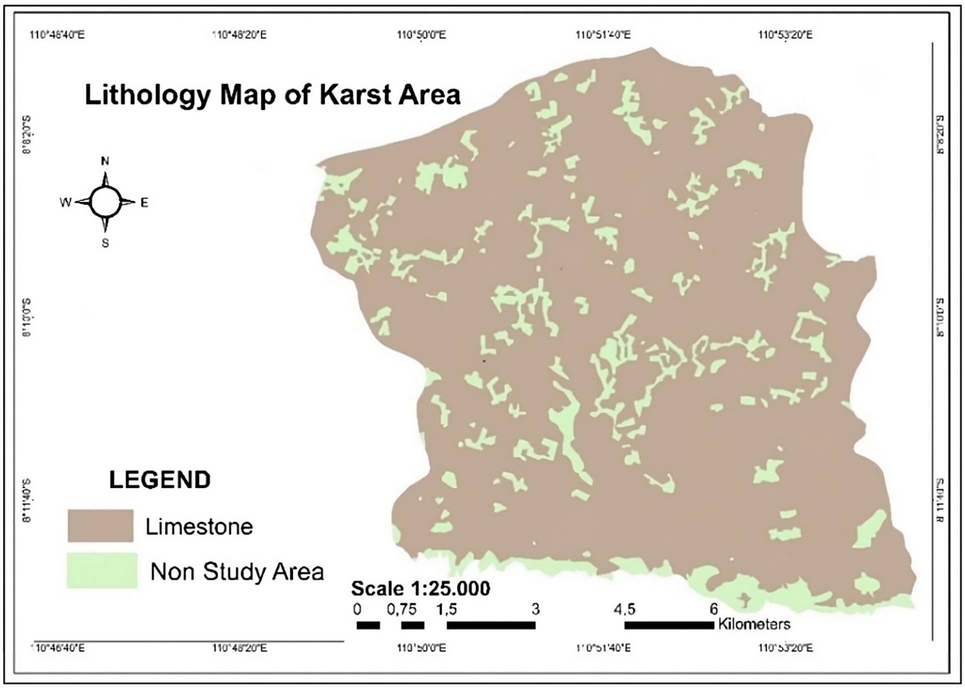
Source: Digital Elevation Model Nasional (DEMNAS)

Fig. 3. Slope map of karst area



Source: Indonesian Agency for Meteorological, Climatological, and Geophysics (https://dataonline.bmkg.go.id/home)

Fig. 4. Rainfall map of karst area



Source: Kebijakan Satu Peta (https://onemap.big.go.id/home/login)

Fig. 5. Lithology map of karst area

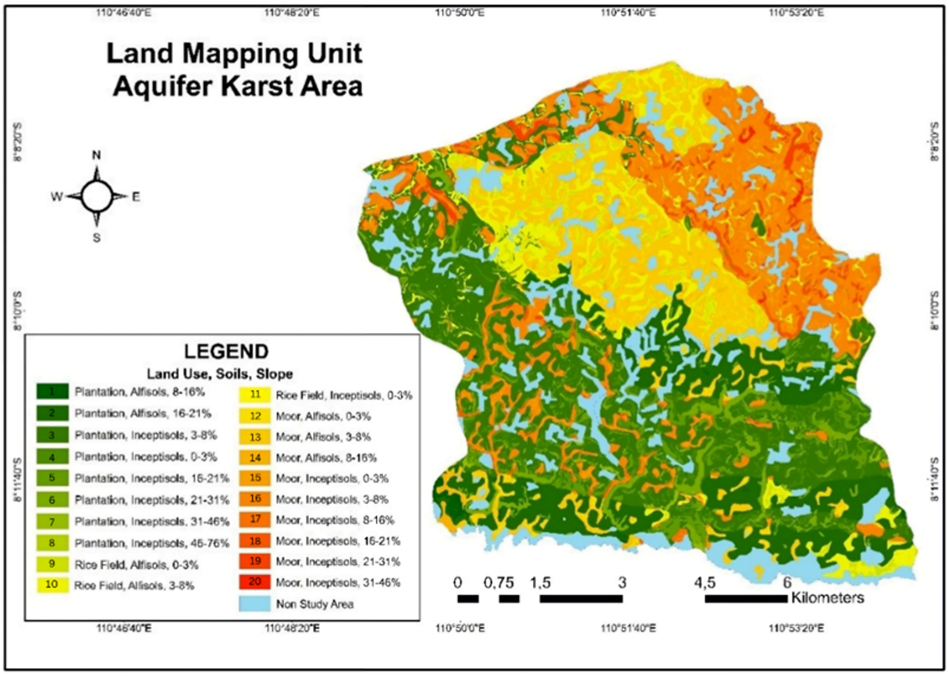


Fig. 6. Observation and sampling point land use

2.3. Data analysis

2.3.1. Groundwater recharge class

Data analysis employs the APLIS method by Andreo et al. [18]. The APLIS is a spatial-based method that overlays several parameters with Geographic Information System tools. The APLIS method has five parameters: altitude, slope, lithology, soil type, and infiltration zone. Each parameter is scored based on the classification of the groundwater recharge value. The five APLIS parameters, which already have their respective scores, are overlaid using the equation formula number (1) [18].

$$R = \frac{A + P + 3L + 2I + 2S}{0.9} \times 100\% \quad (1)$$

R = Groundwater Recharge (%)
A = Altitude
P = Slope
L = Lithology
I = Infiltration Zone
S = Soil

The score for each parameter ranges from 1 to 10 (Table 1), with 1 indicating a minor influence on infiltration and 10 representing a significant effect [18]. The affixation values derived from this method are classified into five categories: very low, low, medium, high, and very high (Table 2), and subsequently presented in map form (Table 1).

Table 1. Scoring of groundwater recharge parameters

Score	APLIS Parameters				
	Altitude (m)	Slope (%)	Lithology	Infiltration zone	Soil
1	≤300	>100	Skis, slate, and plates	Clays	Vertisols
2	300-600	76 - 100	Plutonic and metamorphic rocks	Silty clay	Planosols
3	600-900	46 - 76	Conglomerate	Sandy clay	Chromic luvisols
4	900-1200	31 - 46	Colluvial sand and gravel	Silt	Histosols, luvisols and Alfisols
5	1200-1500	21 - 31	Cleaved limestone and dolomite	Clay loam, Silty clay loam	Eutric cambisols
6	1500-1800	-	Cleaved limestone and dolomite	Silty loam	Cambisols and Inceptisols
7	1800-2100	16 - 21	Moderately calcified limestone and dolomite	Sandy loam, loams	Eutric regosols and solonchak
8	2100-2400	8 - 16	Moderately calcified limestone and dolomite	Silty sands, loamy sands	Calcareous regosols and fluvisols
9	2400-2700	3 - 8	Limestone and dolomite	Sands	Arenosols and xerosols
10	>2700	<3	Limestone and dolomite	Many Infiltration Landforms	Leptosols and Lithosols

Source: [18]

Table 2. Groundwater recharge class

R-Value (%)	Class
≤20	Very Low
20-40	Low
40-60	Medium
60-80	High
80-100	Very high

Source: [18]

2.3.2. Determinant factor

In this study, data analysis was conducted using one way ANOVA and Pearson’s correlation test. A normality test was conducted beforehand to assess whether the data from 60 sample points followed a normal distribution. One way ANOVA was used to determine the effect of slopes (as environmental factors) on groundwater recharge. If ANOVA results are significant, further analysis was conducted using the Duncan Multiple Range Test (DMRT). The correlation test identified the groundwater recharge parameters most strongly associated with groundwater recharge and served as a key determinant in illustrating relationships between land characteristics, soil condition, and groundwater recharge. The study design is shown in Fig. 7.

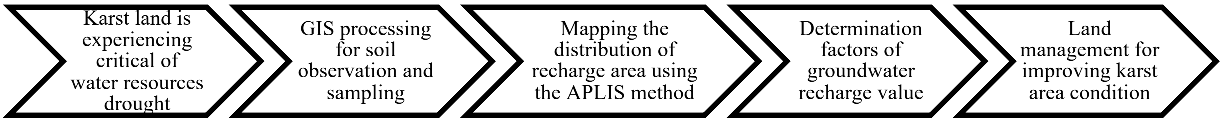


Fig. 7. Research Design

3. Results and Discussion

3.1. Groundwater recharge potential

The water recharge class represents the percentage of rainwater that infiltrates the aquifer. In Paranggupito Subdistrict, groundwater recharge is distributed across eight villages: Songbledek, Ketos, Paranggupito, Gudangharjo, Gunturharjo, Sambiharjo, Johunut, and Gendayakan. As shown in Fig. 8, groundwater recharge class is divided into two groups: medium (40-60%) and high class (60-80%). The medium class covers 3,330.12 ha, while the high class spans 1,190.78 ha.

Medium-class groundwater is found in LMU 1, 2, 5, 6, 7, 8, 10, 13, 14, 15, 18, 19, and 20. Alfisols dominate this groundwater recharge class compared to Inceptisols, which have a higher soil recharge score. However, soil type does not significantly affect the groundwater recharge class (p-value = 0.847, F-count = 0.038, N = 60). The slope in the study area ranges from 0 - 76%. In LMU 6, 7, 8, 19, and 20, with slopes of 21% - 76%, have low soil recharge scores. In contrast, LMU 1, 2, 5, 10, 13, 14, 15, and 18 show no significant relationship between slope and groundwater recharge class (p-value = 0.000, F-count = 9.885, N = 60). Medium-class groundwater is associated with plantation and rice field land in Alfisols (1, 2, 5, 6, 7, 8, 10, 13, and 14) and dry fields in Inceptisols, (15, 18, 19, and 20). However, land use does not significantly affect the groundwater recharge class (p-value = 0.078, F-count = 2.676, N = 60).

High-class groundwater recharge occurs in LMU 3, 4, 9, 11, 12, 16, and 17. LMU 3 and 4, classified as Inceptisols, consists of plantations with slopes of 0-3% and 3-8%, respectively. LMU 9 and 11 are rice fields with 0-3% slope, containing both Alfisols and Inceptisols. LMU 12 and 16 are moorland with Alfisol and Inceptisol soil types, with slopes of 0-3% and 3-8%, respectively. Among the evaluated parameters, lithology has the highest weight, followed by infiltration, elevation, slope, and soil type. The hydrological properties of rock influence groundwater storage by determining water retention in intergranular voids or fractures [35]. The study area is characterized by limestone and dolomite, with a lithology score of 9.5. The karst morphology of dolomite and limestone differs significantly, affecting soil depth, the development of rock fractures, and water retention capacity, which in turn influence vegetation growth [36]. Infiltration in the study area was measured based on soil texture, which significantly influences the rate of water infiltration. Infiltration is classified into four classes: clay (score = 1), silty clay (score = 2), silty clay loam (score = 5), and silty loam (score = 6). Clay-textured soil retains water more effectively than sand-textured soil due to its larger adsorptive surface area. Fine- textured soil with high clay content exhibits superior water-holding capacity [37]. The study area contains two soil types, Alfisols and Inceptisols, with respective scores of 4 and 6.

Each parameter has its score based on its classification, which is then used to determine groundwater recharge values. The category of APLIS parameters in the Paranggupito karst area is presented in Table 3. The research categorizes altitude into two altitudes: < 300 m asl and 300-600 m asl. The elevation in the study area falls within the low class. Climatic and hydrological conditions over the past decade, particularly rainfall, can be assessed through highland observations, where areas with low vegetation cover generally experience excessive rainfall [38]. The study area is classified into seven slope classes: 0-3%, 3-8%, 8-16%, 16-21%, 21-31%, 31-46%, and 46-76%. Steeper slopes receive lower scores, as they facilitate water runoff. Slope dramatically affects the water recharge area, steeper slopes increase surface runoff, limiting water infiltration, whereas flatter slopes enhance water seepage into the soil [39]. Consequently, sloping terrain receives higher scores, with groundwater recharge values decreasing as slope steepness increases [40].

Table 3. APLIS Classification and Parameter Scores on Karst Land in Paranggupito Sub-District

Parameter	Classification	Scores
Altitude	≤300 m dpl	1
	300-600 m dpl	2
Slope	46-76	3
	31-46	4
	21-31%	5
	16-21%	7
	8-16%	8
	3-8%	9
	<3%	10
Lithology	Limestones and dolostones karstified	9.5
Infiltration zone	Clay	1
	Silty clay	2
	Silty clay loam	5
	Silty loam	6
Soil	Alfisols	4
	Inceptisols	6

The lithology of the study area consists of limestone, with a score of 9.5. Limestone with extensive cracks, fractures, or faults can become a groundwater storage aquifer; however, excessive anthropogenic activity in an aquifer causes groundwater depletion [41]. Well-fractured limestone has a high recharge rate [42]. Infiltration refers to the process of water entering the soil or aquifer zone. The study area includes silty clay, silty clay loam, and silty loam, with silty loam having the highest infiltration score (6), followed by silty clay loam (5), and silty clay (2). Soil texture influences infiltration rate due to the density of the constituent materials; sandy soil, for example, exhibits high drainage rate but low water retention ability [43]. The study area includes two soil types: Calcic Luvisols and Calcic Cambisols. Calcic Cambisol is characterized by increasing clay content with depth, which can enhance infiltration [44]. Inceptisols, depending on organic matter content, exhibit variable infiltration rates ranging from slow to fast [45].

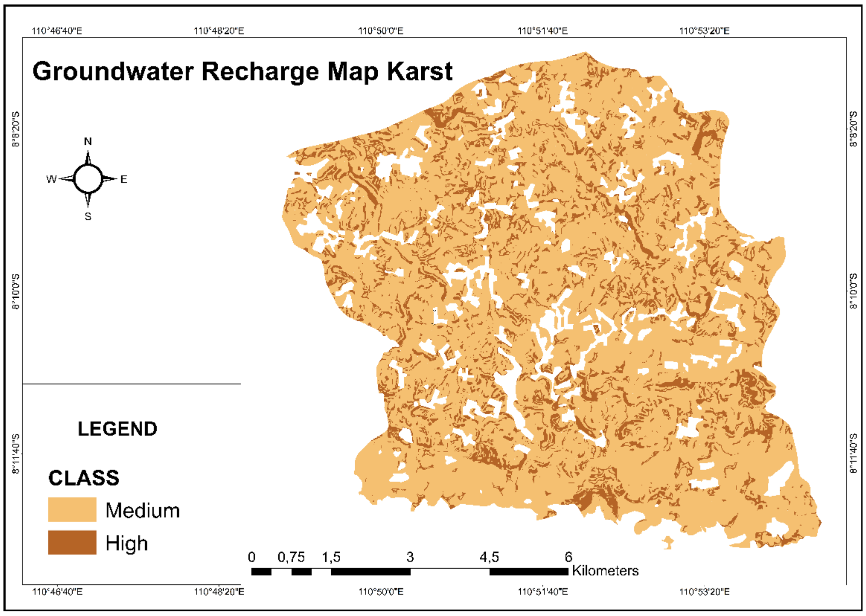


Fig. 8. Spatial distribution of groundwater recharge

3.2. Environmental factors on soil physics characteristics and the relationship to groundwater recharge

Environmental factors in the study area include elevation, slope, rocks, infiltration, and soil type. The findings indicate that slope is a significant factor, as variations in slopes influence the physical properties of the soil. These soil physical properties serve as indicators of soil conditions, which are essential for assessing groundwater recharge potential and how soil conditions can determine the potential for groundwater recharge. The study results are presented in Table 4.

The results indicate a positive relation between soil infiltration and porosity parameters with groundwater recharge ($r = 0.908^{**}$ and $r = 0.471^{ns}$, n= 60). Soil infiltration exhibits a strong positive correlation, as coarse-textured soils facilitate water infiltration, whereas finer-textured soils impede it. Sandy soils provide efficient drainage due to larger pore spaces, while clay soils retain water due to their high water-holding capacity [46]. Soil porosity is also significantly positively correlated, a higher porosity indicates the presence of numerous macro pores. According to

Kodoatie [47], macropores contain gravitational water or air, allowing water to percolate into deeper layers efficiently.

Table 4. Relationship of soil condition to groundwater recharge zone

Soil Physics Characteristics	Correlation value
Infiltration	0.908**
Porosity	0.471ns

Remark: **) significant value of < 0.01; ns) non-significant but still has a correlation

The study area's topography is classified into seven slopes categories: 0-3%, 3-8%, 8-16%, 16-21%, 21-36%, 36-46%, and 46-76%. The results indicate that slope significantly affects groundwater recharge (P-value: 0.000, F-count: 9.885). Based on the difference in mean values, the DMRT test was conducted, as presented in Table 5. The highest groundwater recharge occurs at slope <3%, with an average value of 60,038, followed by slopes of 3-8% (57.502), 8-16% (56.483), 16-21% (52.407), 21-31% (51.292), 36-46% (49.996), and 46-76% (49.443).

Table 5. The distribution of groundwater infiltration under various topography of study area

Slope	Groundwater Recharge Potential
46-76 %	49.4433a
36-46 %	49.9967a
21-31 %	51.2933a
16-21 %	52.4078ab
8-16 %	56.4833bc
3-8 %	57.5025c
0-3 %	60.0380c

Remarks: Numbers followed by the same letter indicate no significant difference in the DMRT test at the 5% confidence level.

Table 5 indicates that groundwater recharge is highest on steep slopes (0-3%), with a value of 60.038. According to Harjanto et al. [32], slope significantly influences the water infiltration process. Steeper slopes facilitate greater water infiltration, while both slope gradient and soil depth affect water percolation [48]. Additionally, infiltration varies across different slope types. To identify key influencing factors, soil conditions were analyzed for correlation. Porosity and infiltration were found to be critical determinants of groundwater recharge.

3.3. Land management efforts to maintain groundwater recharge

Recommendations for maintaining groundwater recharge areas should consider key determinants such as slope, infiltration, and porosity. High-grade areas should be designated as groundwater protection zones. A suitable conservation strategy is mechanical soil conservation, which includes physical treatment and structural interventions like *rorak*. The *rorak* system functions as a sediment trap, increasing soil water retention by increasing infiltration [49]. *Rorak* structures and infiltration channels utilize available space without disturbing land use. *Rorak* is a water reservoir with infiltration made in the cultivation field or channels. On dry land in arid climates, *rorak* serves as a rainwater and surface flow. Additionally, incorporating organic materials is recommended to improve soil water retention.

Organic matter improves soil physical properties, including soil porosity. Its addition increases soil porosity by contributing to smaller pore volume. Organic materials interact with various soil characteristics, improving structure and stabilizing soil aggregates [50]. These aggregates form soil pores, both large pores (macro) and small pores (micro). According to Murphy et al. [51], soils with high organic content exhibit greater aggregate stability and increased porosity, enhancing water absorption and storage capacity.

4. Conclusions

The primary issue in the karst area is drought during the dry season, leading to water scarcity in local communities. Research findings indicate that the groundwater falls within medium (40-60%) to high (60-80%) categories. Soil infiltration and porosity parameters show a significant positive correlation with groundwater recharge. A suitable recommendation for addressing this issue is mechanical soil conservation, such as implementing *rorak,* to reduce water flow. The benefits of this research include optimizing the potential of groundwater in karst areas for use by local communities and stakeholders. It provides valuable information for future water resource planning and management to ensure a sustainable water supply during dry seasons. Furthermore, the APLIS method applied in this study can be utilized in other karst areas to identify effective groundwater recharge zones, contributing to a broader understanding and conservation of karst hydrological systems.

Abbreviations

LMU	Land Map Unit
APLIS	Altitude, Slope, Lithology, Infiltration, and Soil
ANOVA	Analysis of Variance
DMRT	Duncan Multiple Range Test

Data availability statement

The data supporting this study will be shared by corresponding author upon reasonable request by the readers.

CRediT authorship contribution statement

Mujiyo Mujiyo: Conceptualization, Funding acquisition, Supervision, Interpretation of data & Final approval manuscript. **Rinta Faradila Surachman**: Acquisition of data, Analysis data, Visualization, Draft writing & editing. **Sumani**: Draft writing – review & editing. Dwi Priyo Ariyanto: Draft writing – review & editing.

Declaration of Competing Interest

The authors of this manuscript declare that there is no conflict of interest or competing interest.

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