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THE CRITICAL LEVEL OF WATER INFILTRATION MAPPING IN GUNUNGPATI SUB-DISTRICTS, SEMARANG CITY

Ghenady Septio[1], Wawan Budianta[1] and Lucas Donny Setijadji[1]
[1]Geological Engineering Department, Gadjah Mada University, Indonesia
**Email corresponding: wbudianta@ugm.ac.id*

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Abstract *— One of the reasons for the rapid population growth in the 21st century is urbanization. This leads to land degradation, which can result in a lack of water seeping into the ground when it rains in densely developed areas. Most of the water becomes surface runoff that cannot be absorbed by the soil because the runoff exceeds the soil's capacity to absorb water. In response to this situation, research was conducted on the criticality level of water catchment areas in Gunungpati District, Semarang City. The research involved collecting primary data through infiltration rates and lithology taken in the field, as well as secondary data, including information on land use and slope. This data was later verified in the area. The collected data were then analyzed using the Analytical Hierarchy Process (AHP) method by assigning weights to each parameter and sub-parameter. The parameters considered were land use, infiltration rate, slope, and lithology. The weighted values were overlaid to generate a critical level zoning map of water catchment areas in Gunungpati District, Semarang City. The critical level of water catchment areas in the research area can be categorized into "good" with an area of 1307.2 Ha, "normal natural" with an area of 1013.12 Ha, "starting to be critical" with an area of 436.26 Ha, "Slightly critical" with an area of 91.87 Ha, and "critical" with an area of 7.89 Ha, out of a total research area of 2856.34 Ha..*

Keywords*: Water infiltration, Mapping, infiltration rate, Gunungpati, Semarang*

I. INTRODUCTION

Urbanization leads to rapid population growth in the 21st century. Urbanization could be defined as society and zone changing process in non-urban area became urbanized. Urbanization can lead to rapid development and land conversion in urban areas [1]. This caused land degradation which decreased infiltration rate in rainy season specifically in densely developed area. Most of the water will become surface runoff which can't be infiltrated by soil because surface runoff exceeds soil capabilities to infiltrate water [2].

Semarang had a change in land use during 2008-2018 which was 12,556 ha and land development in this area massively increased in this period around 4909 ha [3]. In 2021, Gunungpati District had rapid increases in population density, recorded 97,691 people, increased 1,676 people per hectare [4].

Changes in land use can lead to a decrease in the ability to infiltrate water into the soil. Therefore, this research is necessary to evaluate the level of criticality in the research area by examining several factors such as land use, infiltration rate, slope steepness, and lithology. This evaluation aims to determine and categorize the conditions of water infiltration criticality as good, naturally normal, starting critical, somewhat critical, critical, and highly critical. Thus, it can serve as a reference for the development of a region.

Essentially, rainwater that falls onto the ground surface will infiltrate into the soil. The amount of water that enters the soil is also known as the infiltration rate. The infiltration rate itself is greatly influenced by the saturation condition of the soil and the permeability of the soil profile above the groundwater level. When the soil is saturated with water, the infiltration rate becomes very slow and approaches zero, causing some of the rainwater to become surface runoff.

Based on condition, research was carried out about criticality level of water catchment area in Gunungpati District (Fig. 1), to know about rainwater catchment condition in Gunungpati District and to find out the distribution of these areas that have condition regarding to rainwater catchment area. The rainwater catchment criticality level can be known by using Analytical Hierarchy Process (AHP). The advantage of utilizing a combination of Multi-Criteria Decision Analysis (MCDA) with Geographic Information Systems (GIS) as a method for processing this data is its ability to generate and rank all alternatives with good accuracy within GIS-based decision-making procedures [5].

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A. Regional Geology of Research Area

Based on Magelang-Semarang Geological Map [6], the research area consists of 5 formations namely Kerek Formation which the oldest one, Kalibeng Formation, Damar Formation, Kaligetas Formation, and Alluvium as the top of this sequence. Volcanic breccia, sandstone, lava flow, and alluvial can be found dominantly in research area (Fig. 2).

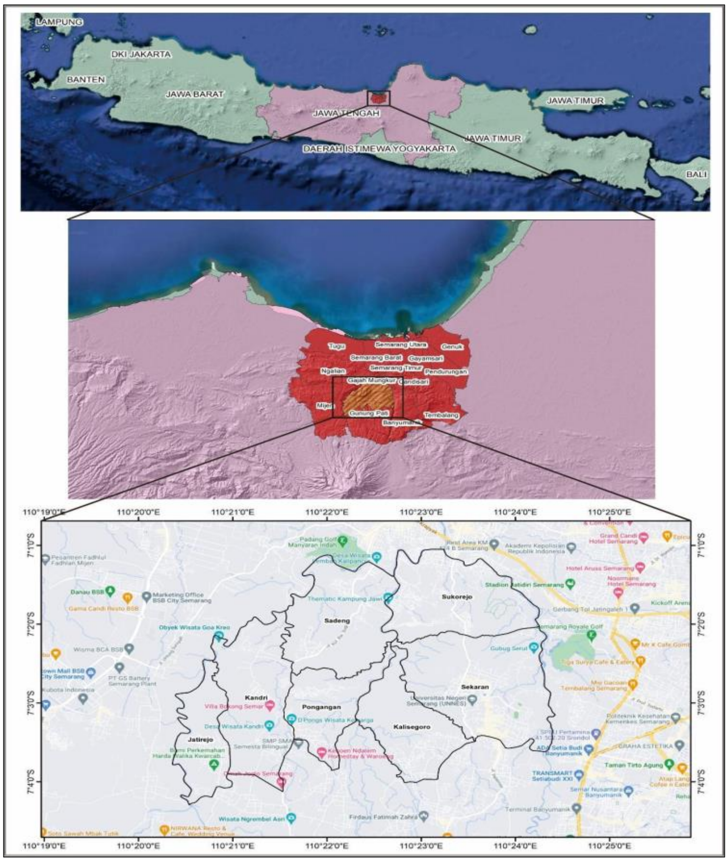

Figure 1. Research Area [7]

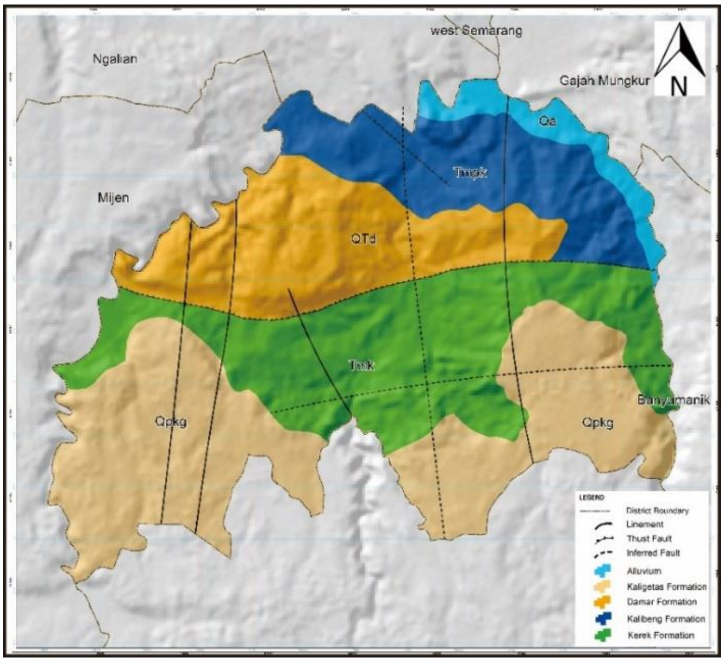

Figure 2. Regional Geological Map [6]

II. RESEARCH METHODS

Research method was carried out in this research which consist of preparation, data collection, data processing, and data analysis (Fig. 3).

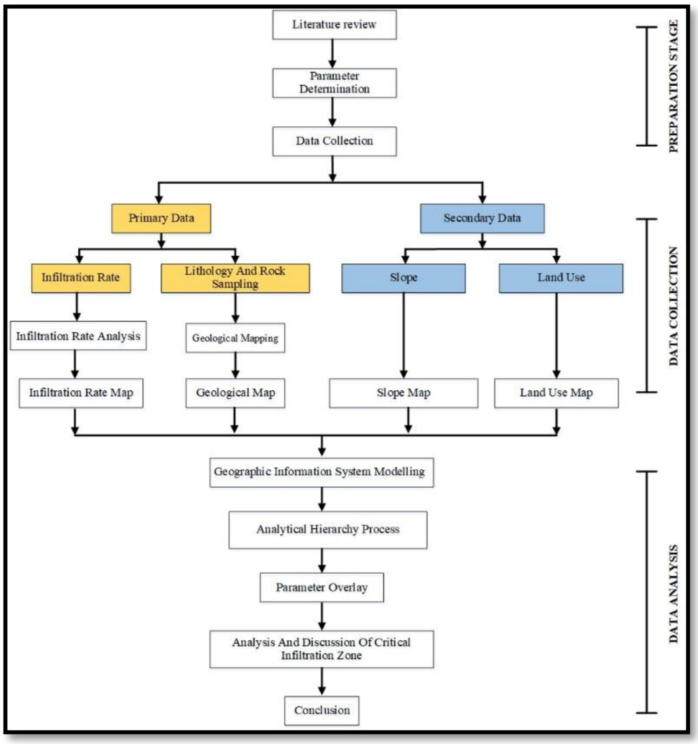

Figure 3. Research Flow Chart [9]

A. Preparation Stage

The preparation stage starts with conducted literature study by collecting reference from various sources that relate to the research, and continued by identifying each parameter that will be used to determine criticality of water catchment in research area.

B. Data Collection

2 kinds of data will be used in this research, primary and secondary. Primary data is collected in the field which consists of infiltration rate and lithology sample in research area. Secondary data is collected from other parties which consists of land use data from Google Earth [7] and slope data from DEMNAS with 8 meters spatial resolution [8].

C. Data Analysis

Based on literature study and data collection, data analysis was conducted by using infiltration rate data, land use data, slope data, and lithology data by using AHP. This method calculates the comparison scale in each parameter that will be used. First step of this method is decomposition which compare in pairs based on the criteria. After that, conduct Comparative Judgment by filling in the pair comparison matrix using a scale from 1-9 based on the level of importance. Continue by normalizing each parameter weight to get eigenvalue. Last, conduct a consistency test which refers to CR value (Consistency Ratio). CR value obtained from CI (Consistency Index) and RI (Random Indices). Valid CR value if CR < 0.1

$$CI = (\lambda - n)/(n-1) \tag{1}$$

$$CR = CI/RI \tag{2}$$

λmax value is eigenvalue and n are many elements or matrix. RI value can be determined from (Table 1). [10]

Table 1. RI Value [10]

N	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

III. RESULTS AND DISCUSSION

From data analysis by using AHP methods, weighting calculations were carried out for each parameter (Table 2).

Table 2. AHP Calculation on each parameter [9]

	Land Use	**Infiltration Rate**	**Slope**	**Lithology**	***Eigenvalue***
Land Use	1	2	3	5	0.469
Infiltration Rate	1/2	1	3	4	0.316
Slope	1/3	1/3	1	2	0.135
Lithology	1/5	1/4	1/2	1	0.078
λmax					**4.043**
CI *(Consistency Index)*					**0.0146**
RI *(Random Indices)*					**0.9**
CR *(Consistency Ratio)*					**0.016**

A. Land Use

Land use data obtained from Google Earth as secondary data, which is verified by field observation as shown in (Table 3). The classification that used for land use is [11] (Table 3). and land use distribution can be seen in (Fig 4 & Fig. 5).

Table 3. Land Use vs Infiltration Rate Classification [11]

No	**Land Use**	**Infiltration Classification**
1	Dry land forest	Very Fast
2	Plantations	Fast
3	Shrubs and grassland	Moderate
4	Dryland farming	Slow
5	Settlements, paddy field, body of water, Streets	Very Slow

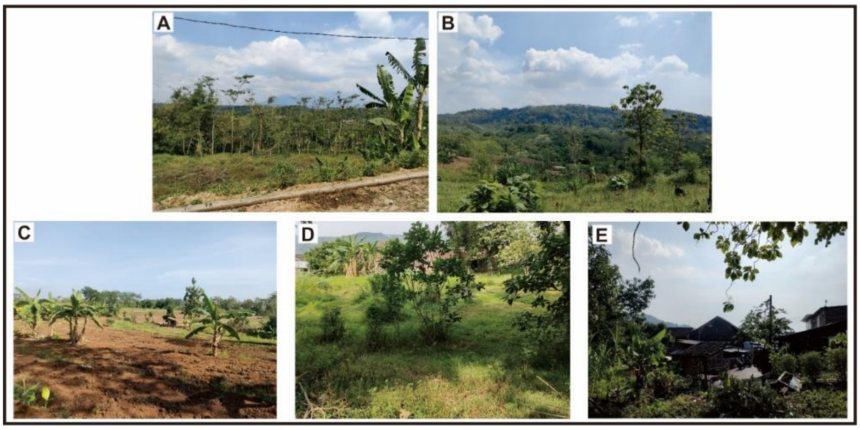

Figure 4. (A) Forest , (B) Plantations, (C) Shrubs, (D) Dryland Farming, (E) Settlement [9]

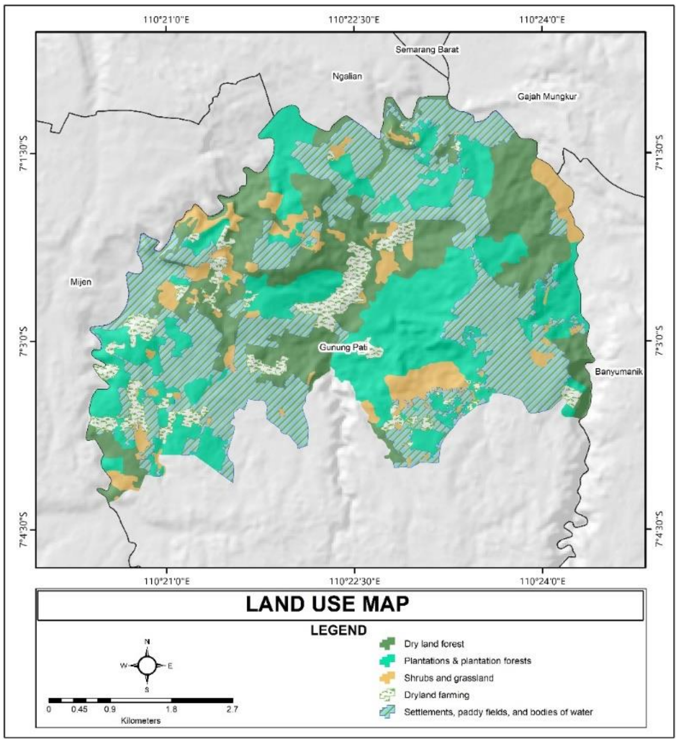

Figure 5. Land Use Distribution Map of Research Area [9]

Table 4. Area of Land Use [9]

Land Use	Area (Km^2)	Area (%)
Dry land forest	6.52	22
Plantations	8.55	29
Shrubs and grassland	2.88	10
Dryland farming	1.95	7
Settlements, paddy field, body of water, Streets	10.03	34

In the land use of the research area, the largest area is occupied by Residential Areas, Rice Fields, Water Bodies, and Asphalt Roads, covering an area of 10.03 km². Residential areas dominate the northern part of the research area in the Sadeng and Sukorejo districts, as well as the southeastern part in the Sekaran district (Table 4). Residential Areas, Rice Fields, Water Bodies, and Asphalt Roads are classified as having the slowest infiltration rates. This can affect water percolation into the soil due to unnatural conditions caused by the transformation of the soil into impermeable layers, leading to waterlogging. The massive urban development in the area can be observed in (Fig. 5), depicting the extensive land changes that have been ongoing in the research area over the past 10 years [17].

B. Infiltration Rate

Infiltration rate data was measured in field by using *Turf-Tec Infiltrometer* (Fig. 6). Classification for infiltration rate was using [13] and measurement of infiltration rate [14] (Table 5). Infiltration rate distribution map as shown in Figure 7.

Table 5. Infiltration Rate Classification [13]

Infiltration Rate (mm/jam)	Infiltration Class
< 1	Very Slow
1 - 5	Slow
5 - 20	Slightly Slow
20 - 65	Moderate
65 - 125	Slightly Fast
125 - 250	Fast
> 250	Very Fast

Figure 6. Infiltration rate data collection in research area [9]

Table 6. Area of Infiltration [9]

Infiltration Rate (mm/jam)	Area (Km^2)	Area (%)
5 – 20 (Slightly Slow)	0.14	0.5
20 – 65 (Moderate)	1.64	5.8
65 – 125 (Slightly Fast)	5.17	18.3
125 – 250 (Fast)	10.06	35.7
> 250 (Very Fast)	11.18	39.7

Infiltration rate measurements were directly conducted in the field, and the infiltration rate was calculated to obtain somewhat fast to very fast rates. Interpolation processes were then performed to generate the Infiltration Rate Distribution Map as shown in Figure 7. This area still maintains relatively good rates between fast and very fast, approximately 11.8 – 10.6 km². This is because some areas still retain natural characteristics, resulting in fast to very fast infiltration rates, while developed residential areas exhibit somewhat slow to somewhat fast rates (Table 6).

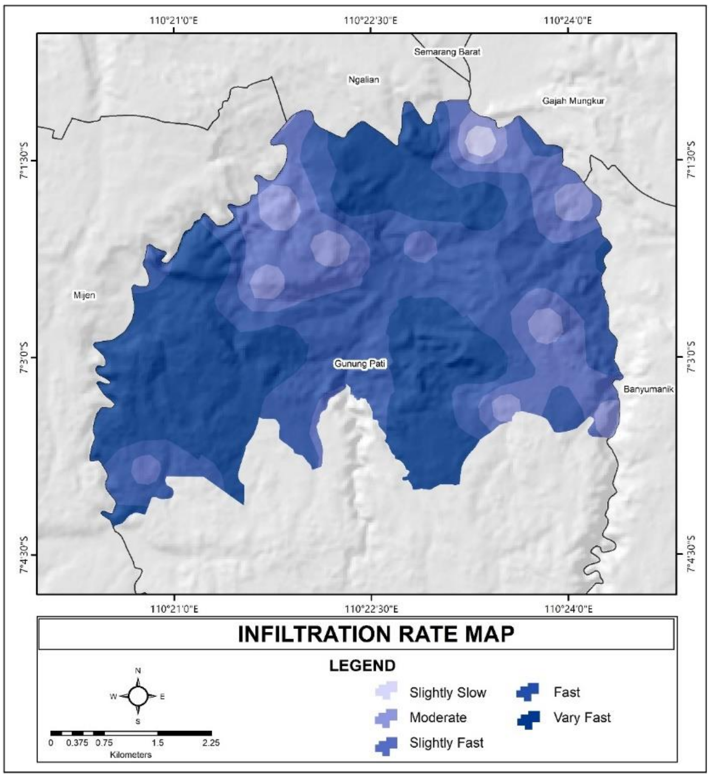

Figure 7. Infiltration rate distribution map in research area [9]

C. Slope

Slope data was obtained as secondary data from DEMNAS with 8m spatial resolution [8]. Classification for slope is [12] and shown in (Table 7). Distribution of slope in research area (Fig. 8).

Table 7. Slope vs Infiltration Rate Classification [12]

Slope (%)	Description	Infiltration Class
< 8	Flat	Very Fast
8 - 15	Gentle	Fast
15 - 25	Wavy	Moderate
25 - 40	Steep	Slow
> 40	Very Steep	Very Slow

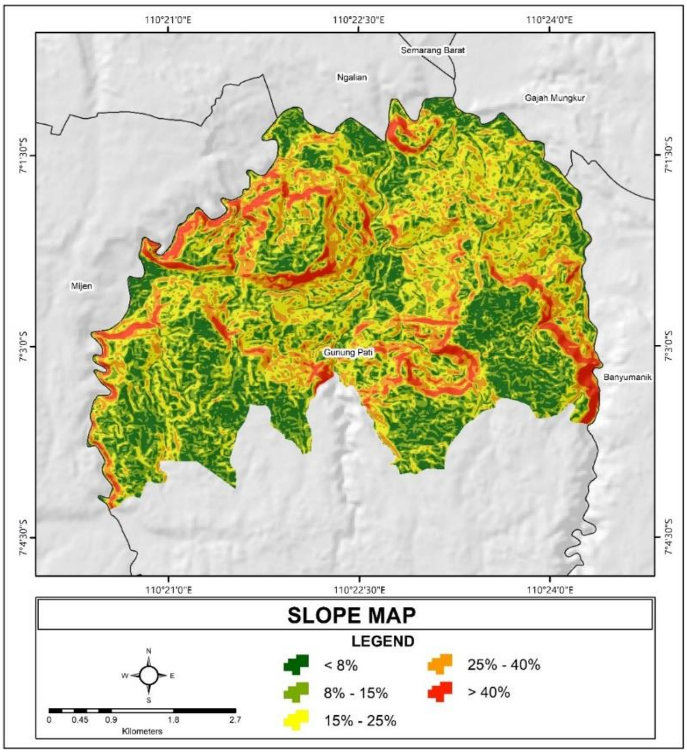

Figure 8. Slope distribution map in research area [9]

Table 8.Area of Slope [9]

Slope (%)	Description	Area (Km^2)	Area (%)
< 8	Flat	5.49	20
8 - 15	Gentle	7.45	27
15 - 25	Wavy	8.23	29
25 - 40	Steep	4.81	17
> 40	Very Steep	1.95	7

In the research area, the slope terrain exhibits relatively tight or steep contours. This is mainly characterized by gentle and undulating slopes, covering areas of 7.45 km² and 8.23 km² respectively. Locations with gentle to steep slopes are predominantly found in the Sadeng district and the northern part of the Kandari district. Meanwhile, flat to gently sloping terrain is prevalent in the Jatirejo and Kalisegoro districts, as well as the southern part of the Kandri district (Table 8).

D. Lithology

Lithology data obtained based on Magelang – Semarang Geological Map [6] which validated by field observation by conducting geological mapping to know distribution of rock unit in research area. Classification for lithology is [15] (Table 9). For the distribution map (Fig. 9 & Fig. 10).

Table 9. Lithology and Permeability Relationship [15]

Lithology Type	Infiltration Rate (m/day)	Classification
Pebble and sand (*Unconsolidated rock*)	9×10^{-7} - 3×10^{-2}	Very Fast
Sandstone	3×10^{-10} - 6×10^{-6}	Moderate
Shale	10^{-11} – 10^{-9}	Slow
Massive igneous rock	3×10^{-14} - 3×10^{-10}	Very Slow

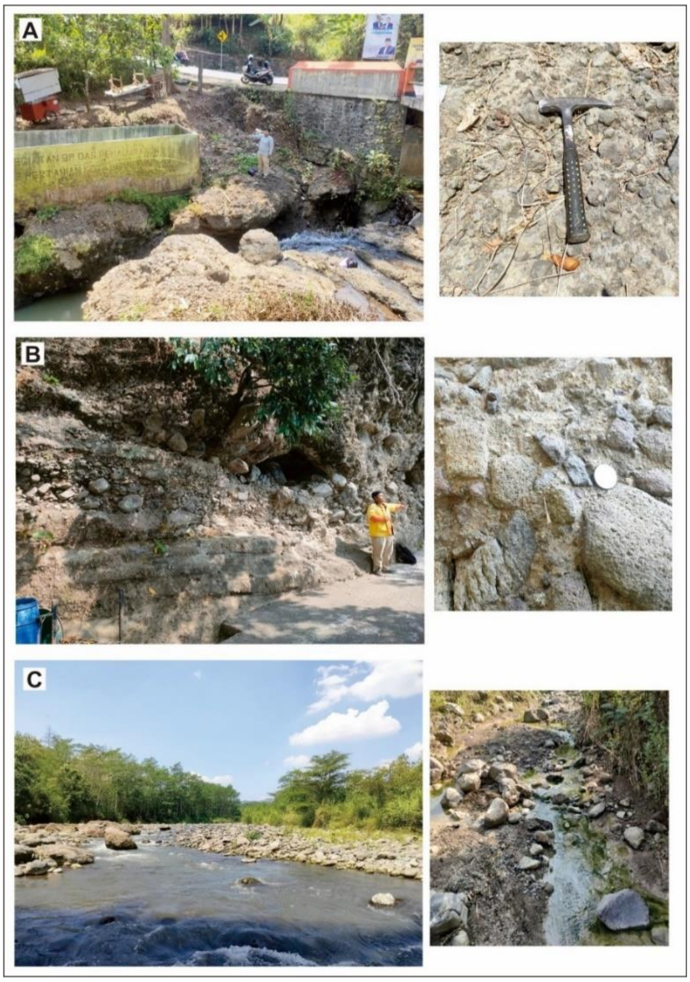

Figure 9. Volcanic Breccia (A), Sandstone with interbedded conglomerate (B), Sand-Pebble (C) [9]

Table 10. Area of Lithology [9]

Lithology Type	Area (Km^2)	Area (%)
Volcanic Breccia	19.85	71
Sandstone with interbedded conglomerate	7.18	26
Sand-Pebble	0.91	3

In this research area, three rock units were identified. These units consist of the carbonate claystone with conglomerate interbeds unit, volcanic breccia unit, and sandstone-conglomerate interbeds unit. The research location is predominantly dominated by the volcanic breccia unit, covering 71% of the area. This unit is estimated to originate from the Damar Formation, formed through sedimentation processes and the deposition of volcanic sedimentary materials from Mount Ungaran in the northern part of the research area, resulting in the formation of volcanic breccia lithology. Sandstone with interbedded conglomerate, part of the Kalibeng Formation, covers 26% of the area. This lithology is formed through sedimentation processes involving the transportation of volcanic materials that are subsequently sedimented and deposited to form sedimentary rocks with sandstone-conglomerate lithology. The sand-Pebble unit is classified as alluvium, covering 3% of the total research area and located in the northeast. This unit is formed through the transportation process of sandstone-Pebble material originating from Mount Ungaran, carried by river streams (Table 10).

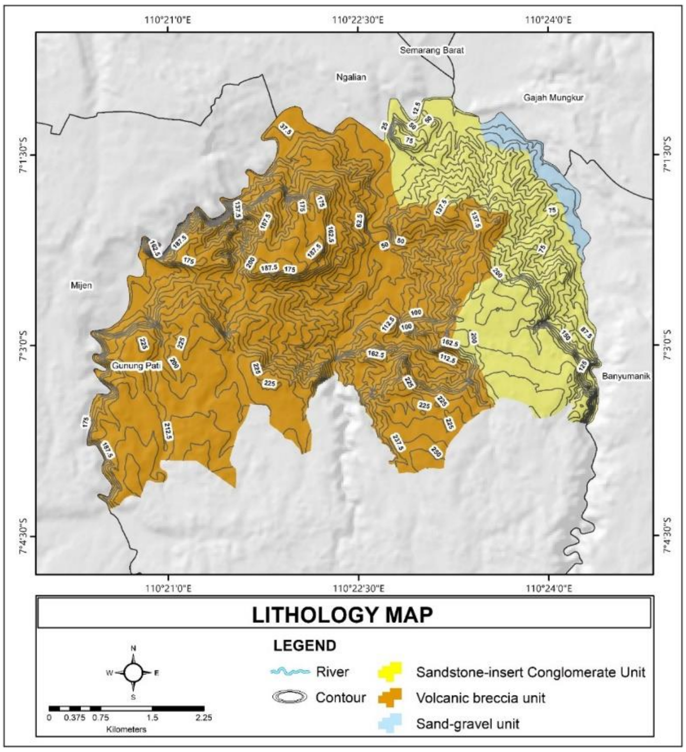

Figure 10. Lithology distribution map in research area [9]

E. Analytical Hierarchy Process Approach

Score determination in AHP approach was conducted by doing weight analysis on each parameter and sub-parameter. After that, calculate the parameter score between sub-parameters. Weighting and score of each sub-parameter (Table 11).

Table 11. Score value of each parameter and sub-parameter [9]

Parameter	Parameter Weight	Sub-parameter	Sub-parameter weight	Sub-parameter Score
Land Use	0.47	Dryland Forest	1	0.47
		Plantations	0.8	0.38
		Shrubs and grassland	0.6	0.28
		Dryland Farming	0.4	0.19
		Settlement, Paddy Field & Body of Water	0.2	0.09
Infiltration Rate	0.32	> 250 mm/hour	1	0.32
		125 - 250 mm/hour	0.8	0.25
		65 - 125 mm/hour	0.6	0.19
		20 - 65 mm/hour	0.4	0.13
		5 - 20 mm/hour	0.2	0.06
Slope	0.14	< 8 %	1	0.14
		8 - 15 %	0.8	0.11
		15 - 25 %	0.6	0.08
		25 - 40 %	0.4	0.05
		> 40 %	0.2	0.03
Lithology	0.08	Sand – Cobble Unit	1	0.08
		Calcareous Shale with Interbedded Conglomerate Unit	0.667	0.05
		Volcanic Breccia Unit	0.333	0.03

After getting score for each sub-parameters, next overlay of each sub-parameters in ArcMap software. Value from overlay divided into 6 classes as formula (3). “I” variable shown class interval, “c” is highest value, “b” is lowest value and “k” expected number of classes [16].

$$I = \frac{c-b}{k} \tag{3}$$

After dividing into 6 classes, classification can be made as shown in (Table 12). Criticality of water catchment area (Fig. 11).

Table 12. Water Catchment Criticality Classification [9]

Infiltration Rate	Infiltration Criticality Condition
> 0.47	Good
0.47 – 0.397	Natural Normal
0.397 – 0.324	Seems Critical
0.324 – 0.251	Quite Critical
0.251 – 0.178	Critical

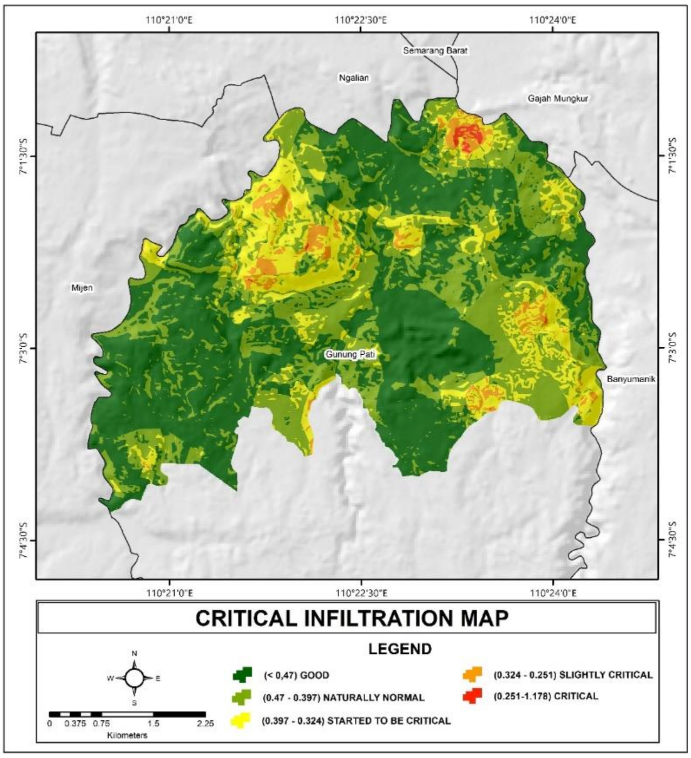

Figure 11. Water Infiltration Criticality distribution map in Gunungpati District, Semarang Regency [9]

F. Discussion

The analysis of the overlay and weighting of all parameters used reveals the distribution of criticality levels in the research area. This analysis employed the Analytical Hierarchy Process (AHP), yielding conditions ranging from good to critical. Such variations stem from the primary factors of land use and infiltration rate. Land use holds the highest weight at 0.47, signifying its significant impact. Areas altered from their natural state experience diminished water infiltration into the soil. The second factor, infiltration rate, carries a weight of 0.32. Infiltration rates span from slightly slow to very fast, indicating varying effectiveness in water infiltration. The third factor, slope steepness, holds a weight of 0.14. Locations with gentle to steep slopes prevail, potentially suboptimal for water infiltration. Flat slopes may retain water longer, whereas steep areas may induce runoff. The fourth factor, lithology, bears the lowest weight at 0.08. Lithologies such as volcanic breccia exhibit poor water infiltration due to their dense nature, while unconsolidated rocks like sand facilitate faster infiltration. The weighted outcomes delineate the distribution of water infiltration criticality conditions in the area (Table 13)

Table 13. Area of Infiltration Criticality Condition [9]

Infiltration Criticality Condition	**Area (Km^2)**	**Area (%)**
Good	13.07	45.76%
Natural Normal	10.13	37.47%
Seems Critical	4.36	15.27%
Quite Critical	0.92	3.22%
Critical	0.08	0.28%

1. Good Condition
   Based on overlay parameter that used in this method, highest score which < 0.47 has good water catchment criticality. This classification has a widespread area in Gunungpati District with approximately 13.07 km^2 (45.76% of total area). In good water catchment critality, dominated by forest land use and high infiltration rate.
2. Natural Normal Condition
   Based on overlay parameter that used in this method, Natural normal condition has score 0.47 – 0.397. Natural normal condition mostly found in forest and plantations land use. This class has a percentage of 37.47% of total area in Gunungpati.
3. Seems Critical Condition
   Based on overlay parameter that used in this method, 0.397 – 0.324 is classified as seems critical water catchment condition. This class is dominated by shrubs and farming, with quite fast infiltration rate and wavy – very steep slope. 15.27% of total area in Gunungpati classified as this class.
4. Quite Critical Condition
   Based on overlay parameter that used in this method, 0.324 – 0.251 classified as quite critical water catchment condition. This class mostly is settlement and farming with quite fast infiltration rate. In quite critical condition has 0.92 km^2 or 3.22% of total area in Gunungpati District.
5. Critical Condition
   Based on overlay parameter that used in this method, 0.324 – 0.178 classified as critical condition for water catchment. In this class consist of shrubs, settlement and fast infiltration rate with very steep slope. Lithology in this area dominated by calcareous shale with interbedded conglomerate and also volcanic breccia. This class only represents 0.28% of total area in Gunungpati District.

The change in soil physical properties and land use in the study area has become a primary factor causing alterations in the condition of water infiltration in that region. The rapid expansion of built-up areas replacing previously open spaces, which used to serve as rainwater infiltration zones, has led to an increased potential for waterlogging and disruption of community activities. This can be observed in areas exhibiting somewhat critical to critical conditions, as shown in the map (Fig. 11), indicated by the red color, resulting from changes in land use to residential areas. This has reduced the soil's ability to absorb water, particularly in the northern, northwest, and southeast regions. These somewhat critical to critical conditions can have adverse effects if left unaddressed, leading to flooding due to the altered water infiltration conditions. These somewhat critical to critical conditions are prevalent in the Sekaran district, which is experiencing massive development due to the presence of Semarang State University in the area [17].

The change in the condition of water infiltration areas from somewhat critical to critical, reaching 18.77%, may not seem significant at first glance. However, due to the extensive conversion of land use to urban areas, it will lead to worsening conditions over time. Therefore, it is necessary to address areas that have entered critical zones by implementing infiltration wells to minimize the occurrence of floods during high-intensity rainfall. Additionally, there is a need for sustainable runoff management and control measures.

For sustainable management in controlling the criticality level of water infiltration, government and community involvement is necessary through regulations requiring the installation of infiltration wells in every household. This measure aims to reduce the occurrence of floods. Additionally, spatial planning in development projects should ensure that land functions in water infiltration are not compromised. This is essential to minimize the impact of changes in land use on water infiltration.

IV. CONCLUSION

The level of water infiltration criticality in the southern part of Gunungpati Subdistrict, Semarang City, Central Java, indicates that the water infiltration conditions in the research area consist of the following categories: good class at 45.76%, naturally normal at 37.47%, starting to be critical at 15.27%, somewhat critical at 3.22%, and critical at 0.28%. One of the research locations that has experienced significant changes in water infiltration level is the Sekaran sub-district, where there has been a considerable conversion of land use, partly due to its proximity to Semarang State University. Changes in land use conditions resulting in the decline of land function quality in water infiltration in the research area have been identified as the primary factors causing changes in water infiltration conditions in that region. The government plays a crucial role as a policymaker in making decisions to address issues related to urban area development towards sustainable growth, and the community also plays a very important role in flood prevention as a result of declining water infiltration quality in the research area by installing infiltration wells in every household to reduce environmental impact.

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