THE INFLUENCE OF URBANIZATION TO THE WATER INFILTRATION ZONE ON BANYUMANIK SUB-DISTRICT, SEMARANG CITY, CENTRAL JAVA, INDONESIA

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Abstract — The high growth of developed land in the Banyumanik Sub-District, especially in residential and commercial areas, occurred due to the high demand for housing, lifestyle fulfillment, and speculation and investment by the upper-middle-class society. The reduction or loss of land with vegetation cover in the Banyumanik Sub-District increases the potential for flooding due to more significant surface runoff than water absorption during heavy rainfall. This research used integrated spatial analysis to generate information on the critical level of water infiltration in the research area using the Analytical Hierarchy Process (AHP) method. Both primary and secondary data collected will be compiled and subjected to spatial analysis to address the issues at hand. The weight of each parameter class produced by the AHP method is used for modeling and includes infiltration rate, land use, slope, and lithology parameters. The criticality level of the water infiltration zone in the southern part of Banyumanik Sub-District indicates that the water infiltration condition in the research area consists of good class at 13.589%, naturally normal at 18.405%, started to be critical at 16.114%, slightly critical at 20.764%, critical at 18.286%, and very critical at 12.841%. Changes in land use in the research area have become the primary factors causing alterations in the water infiltration conditions. Infiltration wells are one of the solutions to mitigate runoff as part of sustainable rainwater management. The government plays a crucial role as a policymaker in making decisions to address issues related to urban area development towards sustainable development.

Keywords: Water infiltration, GIS, Banyumanik, Semarang

I. INTRODUCTION

Urbanization causes changes in land use that affect the amount of water infiltration during the rainy season. Land use in urban areas is typically dominated by built-up areas and impervious surfaces such as asphalt, concrete, and paving blocks, leading to more significant surface runoff compared to water infiltration during rainfall [1]. These changes inevitably result in alterations to the hydrological cycle patterns in urban areas. The criticality of water infiltration areas is a measure of the land's or soil surface's ability to absorb a certain amount of rainfall [2]. Reducing green spaces that serve as water infiltration areas poses impacts such as puddles, a significant issue in urban areas that must be appropriately addressed [3].

The rapid development and expansion of built-up areas have both positive and negative potential impacts on Semarang City and the Banyumanik Sub-District itself. The reduction or loss of land with vegetation cover in the Banyumanik Sub-District increases the potential for puddles due to more significant surface runoff than water infiltration during heavy rainfall. Furthermore, the negative impact includes the potential loss of this area's primary function as a buffer zone for Semarang City [4]. Additionally, based on flood incident data, an evaluation must be considered in planning Semarang City's future development towards a sustainable city [5].

This study used integrated spatial analysis to generate critical information regarding the level of water infiltration in the study area, employing the Analytical Hierarchy Process (AHP) method. Both primary and secondary data collected will be compiled and subjected to spatial analysis to address the issues at hand. 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 reasonable accuracy within GIS-based decision-making procedures [6]. It is expected that the results of this study will elucidate the water infiltration conditions in the southern part of Banyumanik Sub-District, serving as information and considerations for regional development plans and appropriate mitigation strategies to address potential puddling issues.

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A. Study Area

The study area is located in Banyumanik Sub-District, Semarang City, Central Java Province (Fig.1). Banyumanik Sub-District is one of the sixteen subdistricts within Semarang City, covering an area of 29,74 km^2 with a population of 141.319 inhabitants [7].

Figure 1. Overview of the study area [8]

B. Geological Setting of The Study Area

Based on the Geological Map of Magelang Semarang [9], the stratigraphic sequence from oldest to youngest consists of the Kerek Formation, Kalibeng Formation, Kaligetas Formation, Damar Formation, Jongkong Formation, Kaligesik Volcanic Rocks, Gajahmungkur Volcanic Rocks, and Alluvium. The study area is predominantly characterized by the Kaligetas Formation, which comprises brownish-blackish-coloured volcanic breccia with fragments of andesite and basalt. There are also white to yellowish tuff and brownish-blackish colored mudstone (Fig.2). The Semarang City area has experienced regional geological structural development involving faults and folds, with the latest tectonic activities occurring during the Plio-Pleistocene period [10].

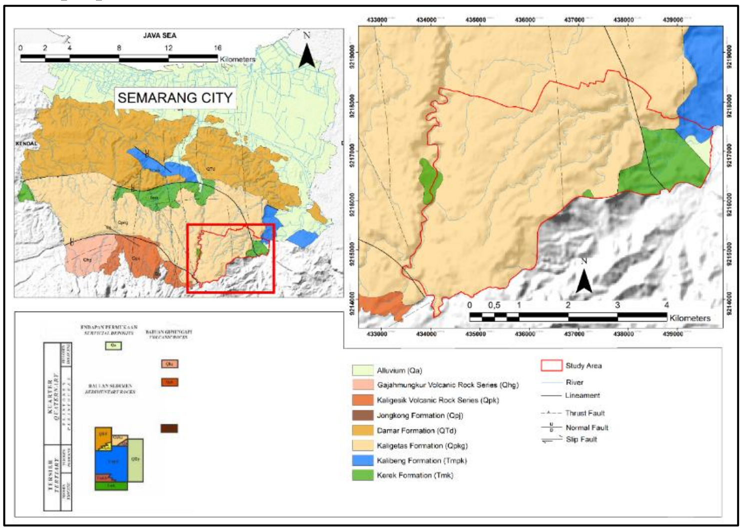

Figure 2. Overview of the geological setting of the study area [9]

II. MATERIALS AND METHODS

The method employed to complete the case in this study consists of several stages, namely the preliminary stage, data collection, data processing, and data analysis, as illustrated in Figure 3.

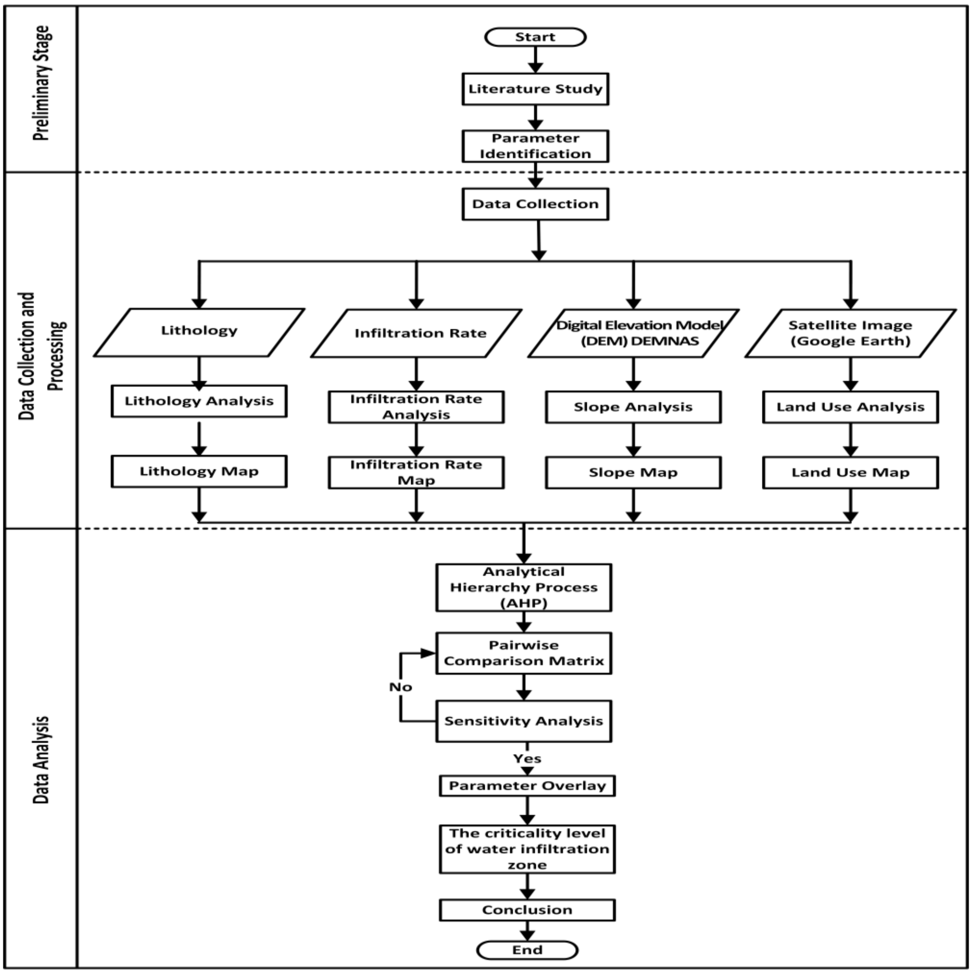

Figure 3. Flowchart of the study [11]

A. Preliminary Stages

The primary goal of this stage is to investigate previous research conducted at the research site, which will serve as a guide in designing the research methodology and analyzing the study results. The preliminary stage involves exploring literature reviews and other relevant factors related to the study to determine the parameters used to study the water infiltration zone's criticality level.

B. Data Collection and Processing

The data collection stage in this study comprises field data collection, including infiltration rate data and lithology data (Fig.4). secondary data such as Digital Elevation Model (DEM) data and Google Earth satellite images were collected for this study.

1. Infiltration rate data

The infiltration rate measurements were conducted using the Turf-tec infiltrometer, which had been previously prepared according to procedures. Measurements were performed on Horizon A soil, which results from weathering with criteria of flat and non-rocky land conditions [12]. Each value generated by the infiltrometer device was recorded at every measurement point.

2. Lithology data

Observations were conducted by mapping lithology to acquire information regarding the lateral lithology distribution in the study area, referring to the regional geological map. Field observations involved describing outcrop points in detail, lithological descriptions, and documentation within the research area. Naming of lithological units was performed based on macroscopic analysis.

3. Secondary data collection

The secondary data collection involved the utilization of a Digital Elevation Model (DEM) obtained from DEMNAS, which was utilized as the analytical data to generate slope inclination maps. Additionally, satellite image data from Google Earth was employed in the analysis to create land use maps, which were subsequently verified through fieldwork.

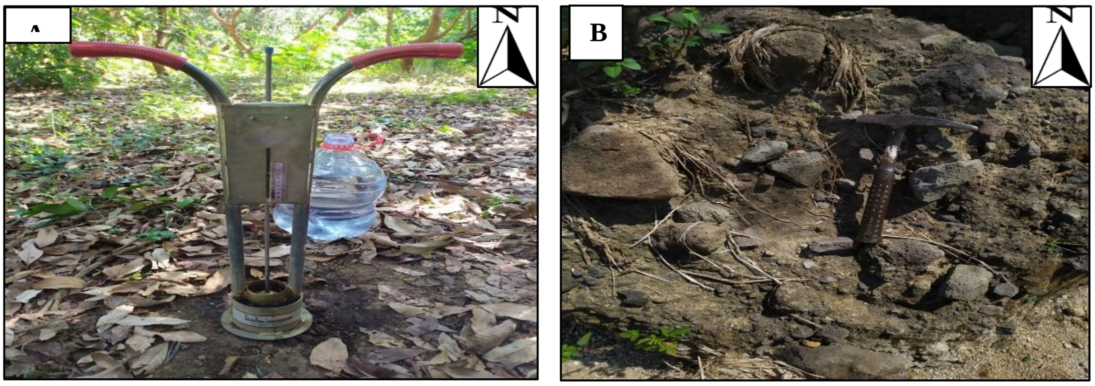

Figure 4. The measurement of infiltration rate (A) and observation of lithology (B) [11]

The data processing stages involved compiling all the data, including infiltration rate, land use, slope inclination, and lithology data, using ArcGIS 10.8 software. This was conducted to generate spatial information utilized as parameters for modeling analysis.

C. Data Analysis

The spatial analysis was conducted using the Analytical Hierarchy Process (AHP) method, which is knowledge-driven, to generate a zonation of the critical level of water infiltration in the study area. The AHP method operates through pairwise comparisons, where each criterion is compared to every other criterion, providing priority values or weights reflecting the relative importance of one criterion over another (Table 1). The comparison matrix generated is then normalized by dividing each element within the matrix by the total value of each column. The model produced by the Analytical Hierarchy Process (AHP) method undergoes Sensitivity Analysis (SA) to assess the stability of the model before becoming a spatial model. After normalization, eigenvalues are calculated for each paired comparison matrix. These eigenvalues become weights for each element. Subsequently, a consistency test is performed on the obtained eigenvalues based on Equations 1 and 2. If the consistency ratio of the obtained pairwise comparison matrix is < 0.1, it can be considered consistent [13].

Table 1. The scale of priority by Saaty [14]

Scale of Priority	Description
1	Equally important compared to the others
3	A little more important compared to the others
5	Quite important compared to the others
7	Very important compared to the others
9	Extremely important compared to the others
2,4,6,8	The value lies between two close assessments

Table 2. Random index consistency [13]

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

$$CI = (\lambda max - n)/(n - 1) \quad (1)$$

$$CR = CI/RI \quad (2)$$

The weights of each parameter class generated by the AHP method are utilized in modeling, incorporating parameters such as infiltration rate, land use, slope, and lithology using the raster calculator tool in ArcGIS 10.8. The classes for the water infiltration criticality levels consist of categories such as good, naturally normal, started to be critical, slightly critical, critical, and very critical [2].

III. Results and Discussion

The combination of Multi-Criteria Decision Analysis (MCDA) with Geographic Information Systems (GIS) as a method for processing the data generated a model assessing the criticality levels of the water infiltration zone in the study area.

A. Analytical Hierarchy Process (AHP) Development

The prioritization assessment of parameters towards the model evaluating the criticality level of the water infiltration zone in the study area, which was knowledge-driven, was conducted to observe the interrelation of each parameter (Table 3) with the constructed model. An ideal condition for a well-functioning water infiltration zone should feature natural open spaces, a fast infiltration rate, flat topography, and rocks capable of optimally absorbing rainwater.

Table 3. Pairwise comparison matrix [11]

Parameter	P1	P2	P3	P4
Land use (P1)	1.000	3.000	5.000	7.000
Infiltration rate (P2)	0.333	1.000	3.000	5.000
Slope (P3)	0.200	0.333	1.000	3.000
Lithology (P4)	0.143	0.200	0.333	1.000
Total	**1.676**	**4.533**	**9.333**	**16.000**

Table 4. Normalized [11]

Parameter	P1	P2	P3	P4	Vector Priority	Weight	Eigenvalue
P1	0.597	0.662	0.536	0.438	2.232	0.558	0.935
P2	0.199	0.221	0.321	0.313	1.053	0.263	1.194
P3	0.119	0.074	0.107	0.188	0.487	0.122	1.137
P4	0.085	0.044	0.036	0.063	0.228	0.057	0.910
Total	**1.000**	**1.000**	**1.000**	**1.000**	**4.000**	**1.000**	**4.177**
Consistency Index (CI) 0.059							
Ratio Index (RI) 0.900							
Consistency Ratio (CR) 0.065							

The model generated by the Analytical Hierarchy Process (AHP) underwent Sensitivity Analysis (SA) to determine its stability before becoming a spatial model. The consistency ratio value obtained from the pairwise comparison matrix was 0.065, indicating consistency [13]. Based on the weights obtained in Table 4, the respective values for each sub-parameter can be determined (Table 5).

Table 5. The weighting of the criticality level of the water infiltration zone [11]

Parameter	Sub-Parameter	Local weight	Global weight	Rate
Land use	Settlement, Paddy field	0.500	0.279	1
	Farmland	1.000	0.558	2
Infiltration rate	Slow (1-5 mm/hr)	0.250	0.066	1
	Slightly slow (5-20 mm/hr)	0.500	0.132	2
	Moderate (20-65 mm/hr)	0.750	0.198	3
	Slightly fast (65-125 mm/hr)	1.000	0.263	4
Slope	> 40 % (Very Step)	0.200	0.024	1
	26 – 40 % (Step)	0.400	0.049	2
	16 – 25 % (Wavy)	0.600	0.073	3
	8 – 15 % (Sloping)	0.800	0.097	4
	< 8 % (Flat)	1.000	0.122	5
Lithology	Volcanic-breccia	0.333	0.019	1
	Sandstone	0.667	0.038	2
	Alluvial	1.000	0.057	3

B. GIS Based AHP

The data utilized encompassed infiltration rates, land use, slope, and lithology, which were analyzed using ArcGIS 10.8 software to generate spatial data (Fig. 7). The spatial data produced were in raster form to conduct an analysis combined with the previously executed weighting using the AHP method, resulting in a model assessing the criticality level of water infiltration zone in the study area.

1. Land use

Reducing green spaces that function as water infiltration zones leads to consequences such as stagnant water, which becomes a significant issue in urban areas. Land use in the study area predominantly comprises settlements and paddy fields (Fig. 5), reaching 59.121% (Table 6). Settlements and paddy fields have a suboptimal capacity for absorbing rainfall.

Table 6. The percentage of land use in the study area [11]

Sub-Parameter	Pixel count	Percentage (%)
Settlement, Paddy field	372720	59.121
Farmland	257721	40.879

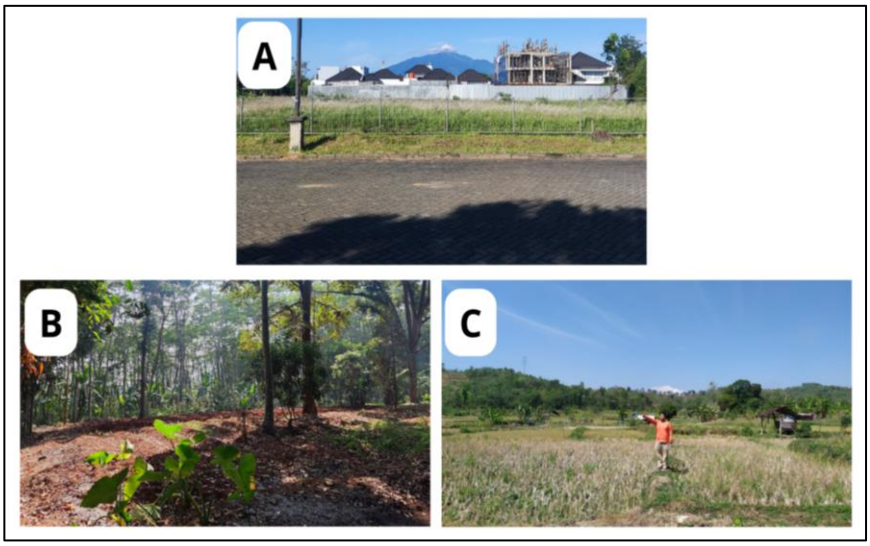

Figure 5. Settlement area (A), farmland (B), and paddy field (C) in the study area [11]

2. Infiltration rate

Infiltration is a crucial process in the hydrological cycle as it determines how much rainfall penetrates the soil. In soil conservation, infiltration holds significance as it regulates the relationship between rainfall and controls surface runoff by enhancing the soil's ability to absorb water. The infiltration rate obtained from direct field measurements consists of 4 classes [15], with the slightly slow infiltration rate (5-20 mm/hr) dominating, reaching a percentage of 74.866% (Table 7).

Table 7. The percentage of infiltration rate in the study area [11]

Sub-Parameter	Pixel count	Percentage (%)
Slow (1-5 mm/hr)	819	2.095
Slightly slow (5-20 mm/hr)	29265	74.866
Moderate (20-65 mm/hr)	7399	18.928
Slightly fast (65-125 mm/hr)	1607	4.111

3. Slope

Slope steepness influences optimal water catchment zones, and the water infiltration decreases as the slope becomes steeper [16]. In the study area, the slope is predominantly within the range of 8 – 15% (Sloping), accounting for 32.564% (Table 8).

Table 8. The percentage of slope in the study area [11]

Sub-Parameter	Pixel count	Percentage (%)
> 40 % (Very Step)	11125	4.915
26 – 40 % (Step)	25059	11.071
16 – 25 % (Wavy)	54357	24.014
8 – 15 % (Sloping)	73711	32.564
< 8 % (Flat)	62105	27.437

4. Lithology

Lithology significantly influences the evaluation of water infiltration areas, depending on the rock's structure and texture. More excellent permeability leads to more optimal water infiltration [17]. In the study area (Fig. 6), the lithology is dominated by a volcanic-breccia unit with a grey color (weathered), having a matrix composed of medium-coarse-grained sand, poorly sorted, and matrix-supported texture, accounting for 92.517%. Additionally, sandstone units with medium to coarse grain sizes in grey color (weathered) comprised 6.8315%, and alluvial units consisting of sand pebbles represented 0.652% (Table 9).

Table 9. The percentage of lithology in the study area [11]

Sub-Parameter	Pixel count	Percentage (%)
Volcanic-breccia unit	36461	92.517
Sandstone unit	2692	6.831
Alluvial unit	257	0.652

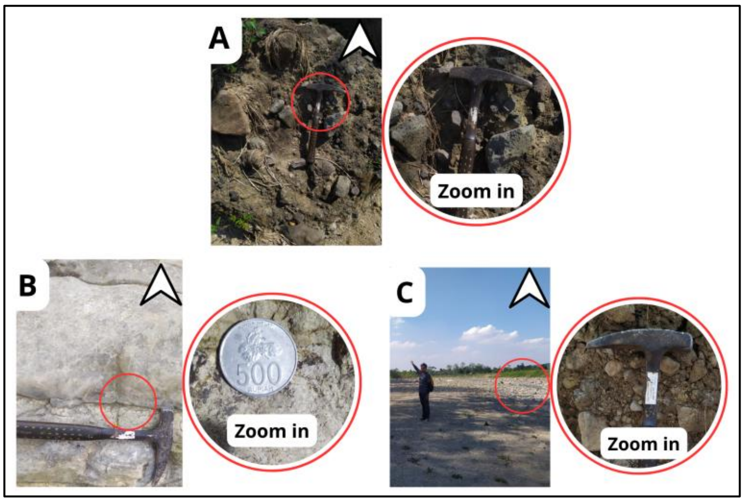

Figure 6. Volcanic-breccia unit (A), sandstone unit (B), and alluvial unit (C) [11]

Table 10. Classification of each parameter [11]

Parameter	Sub-Parameter	Type	Description
Land use	Settlement, Paddy field	Factors	The more natural the land use, the better the water infiltration
	Farmland	Factors	
Infiltration rate	Slow (1-5 mm/hr)	Factors	The faster the infiltration rate, the better the water infiltration
	Slightly slow (5-20 mm/hr)	Factors	
	Moderate (20-65 mm/hr)	Factors	
	Slightly fast (65-125 mm/hr)	Factors	
Slope	> 40 % (Very Step)	Factors	Slope inclination affects the optimal water catchment area; the steeper the slope, the lower the water infiltration.
	26 – 40 % (Step)	Factors	
	16 – 25 % (Wavy)	Factors	
	8 – 15 % (Sloping)	Factors	
	< 8 % (Flat)	Factors	
Lithology	Volcanic-breccia	Factors	The higher the permeability, the more optimal the water infiltration
	Sandstone	Factors	
	Alluvial	Factors	

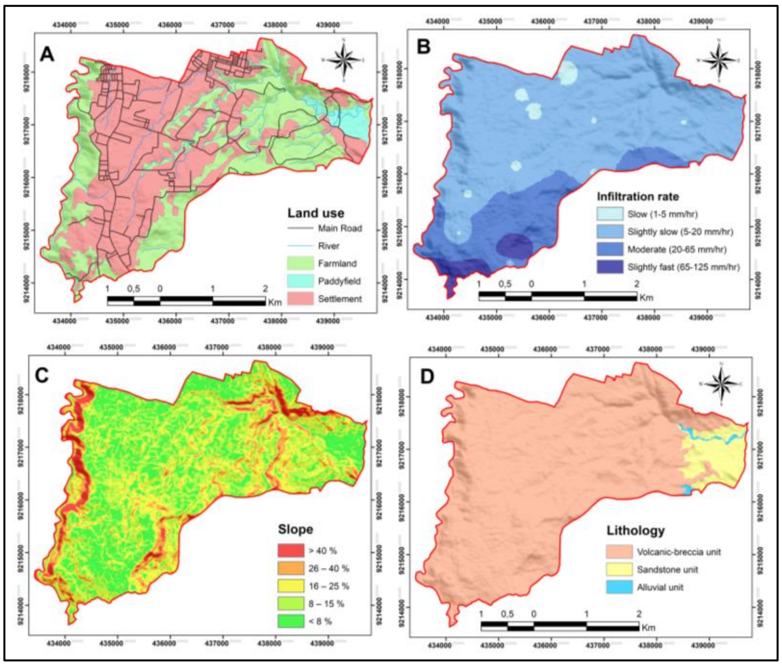

Figure 7.Land use (A), infiltration rate (B), Slope (C), and lithology (D) in the study area [11]

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C. The criticality level of the water infiltration zone

The results obtained from the combination of AHP-based GIS methods are displayed in the zoning of the criticality level of water infiltration in the southern part of Banyumanik Subdistrict, Semarang City, Central Java (Fig. 8). The results were obtained by conducting overlay analysis for each predetermined parameter, with their respective weights assigned, using ArcGIS 10.8 software. Based on the modeling, it was determined that the conditions of the water infiltration zone in the study area consist of classes ranging from good, naturally normal, started to be critical, slightly critical, critical, and very critical [2].

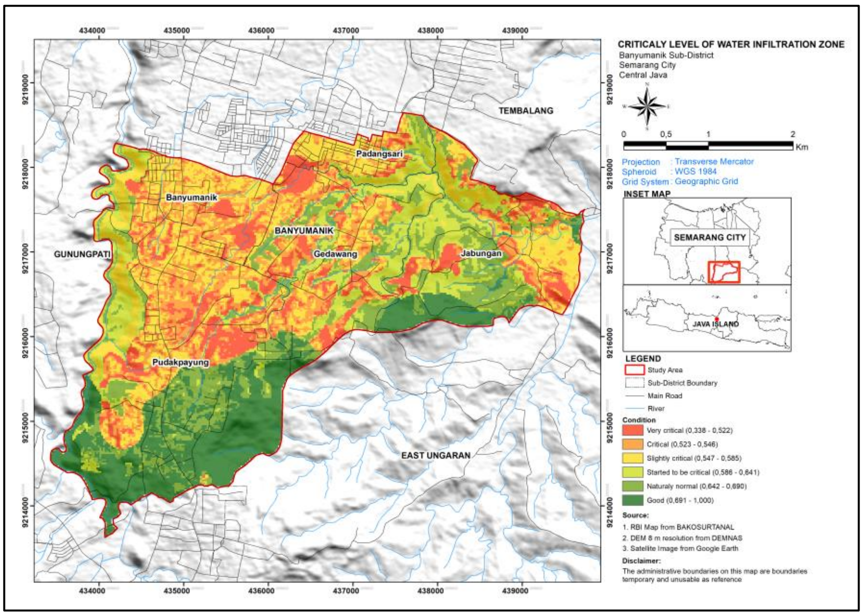

Figure 8. The criticality level of the water infiltration zone in the study area [11]

The criticality level of water infiltration, ranging from good to naturally normal, is distributed in the southern regions of Pudakpayung and Jabungan, constituting 31.994%. This is influenced by the land use in the southern parts of Pudakpayung and Jabungan, characterized by farmland (Fig. 7), which exhibits more significant water infiltration than built-up areas in the study area (Table 11).

Table 11. The percentage of the criticality level of the water infiltration zone in the study area [11]

Condition	Pixel count	Percentage (%)
Good	5248	13.589
Naturally normal	7108	18.405
Started to be critical	6223	16.114
Slightly critical	8019	20.764
Critical	7062	18.286
Very critical	4959	12.841

On the other hand, areas categorized as critical to very critical are predominantly located in Banyumanik and Padangsari. Both regions are densely populated, characterized by settlements (Fig. 7), and have smaller water infiltration capacities than farmland. Additionally, rice fields (Fig. 7) exhibit similar water infiltration categories as settlements, such as in Jabungan, resulting in a critical to very critical condition in the study area of 31.217%. The criticality level of water infiltration, categorized as starting to be slightly critical, is distributed, representing 36.878%. Steep slopes and lithology significantly influence the water infiltration levels, as depicted in the zoning distribution pattern in Figure 8. Based on the analysis, the criticality level of water infiltration, ranging from critical to highly critical, reached 68.005%. Thus, treatment was needed to address the potential flooding during high-intensity rainfall, which disrupted community activities

III. RESULTS AND DISCUSSION

The change in land use in the study area has become a primary factor causing alterations in the condition of water infiltration in that region (Fig. 8). The rapid expansion of built-up areas replacing previously open spaces, which used to serve as rainwater infiltration zones have led to an increased potential for runoff as the impact of urbanization. In urban areas, infiltration wells (Fig. 9) are one of the solutions to mitigate runoff as part of sustainable rainwater management [18]. The selection of locations should consider geological conditions and distance from pollution sources; choosing the right location ensures efficiency in absorbing rainwater. Additionally, the design of infiltration wells should consider their size, depth, and the type of materials used. Ideally, infiltration wells should be part of an integrated rainwater management system.

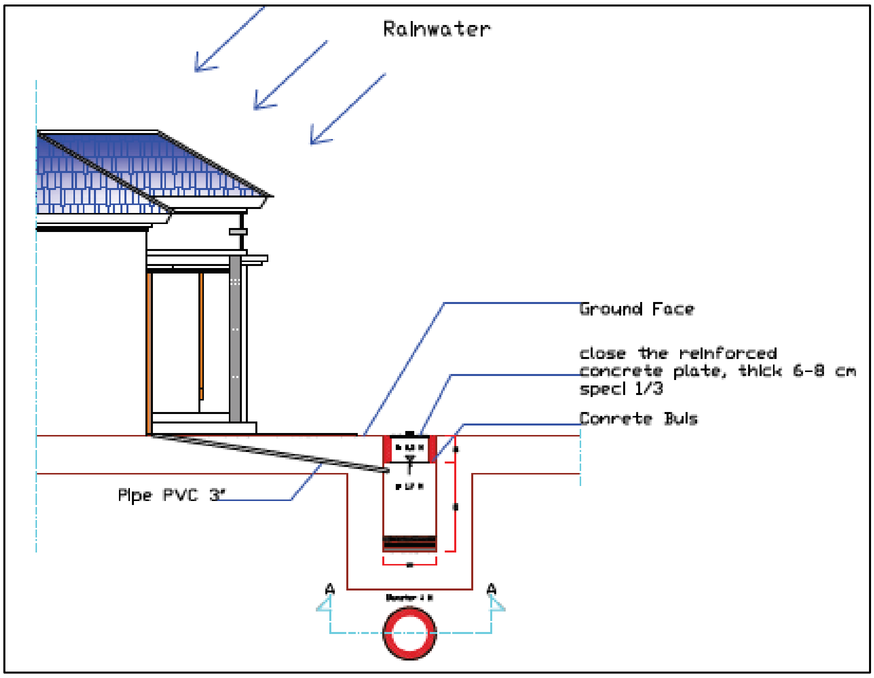

Figure 9. Design of infiltration well [19]

Educating the community about the significance of infiltration wells and how to maintain and use them correctly cannot be overstated. Involving the community in the planning and upkeep of infiltration wells is also crucial for long-term success. Therefore, there is a need for regulations or policies that support the use of infiltration wells in urban planning. This can help promote a broader and more effective use of infiltration wells. Regular monitoring of the performance of infiltration wells is also necessary to evaluate their effectiveness. This practice aids in adjusting designs or conducting essential maintenance to ensure the optimal functioning of the wells. Implementing infiltration wells requires thorough planning and seamless integration with existing infrastructure, expecting these wells to address waterlogging issues in urban areas effectively.

IV. CONCLUSION

The criticality level of water infiltration in the southern part of Banyumanik Sub-District, Semarang City, Central Java, indicated that the water infiltration conditions in the research area comprised the following categories: good class at 13.589%, naturally normal at 18.405%, starting to be critical at 16.114%, somewhat critical at 20.764%, critical at 18.286%, and highly critical at 12.841%. Changes in land use in the research area have been identified as the primary factor causing alterations in the water infiltration conditions in that region. Infiltration wells are one of the solutions to mitigate runoff as part of sustainable rainwater management. The government plays a crucial role as a policymaker in making decisions to address the issues concerning urban area development towards sustainable growth.

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