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Criticality Analysis of Water Catchment Areas in Depok City, West Java

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Abstract: The rapid development of Depok City has led to a high demand for the construction of facilities for housing and commercial areas. This can result in a decrease in water catchment areas, which can cause water shortages and flooding. The purpose of this study was to identify and create a map of water catchment areas using a geographic information system (GIS) and analyze the infiltration rate and cumulative infiltration in Depok City. The method used was spatial data extraction and spatial analysis of the condition of the water catchment area by scoring potential infiltration and actual infiltration. Spatial analysis was also performed by overlapping spatial data for water catchment area zoning. Infiltration measurement using a double-ring infiltrometer based on SNI 7752:2012. Infiltration rate analysis using the Horton model. The mapping results show that Depok City is dominated by slightly critical criteria, covering an area of 15,589.327 ha (77.98%), followed by conditions that are starting to be critical, covering an area of 4,146.347 ha (20.75%), and natural normal conditions, covering an area of 168,515 ha (0.84%). The highest infiltration rate was measured in Cipayung at 0.330 cm/minute, and the lowest was recorded in Cilodong at a rate of only 0.110 cm/minute. The smallest cumulative infiltration value was 15.744 cm/h, and the largest was 51.886 cm/h.

Keywords: double ring infiltrometer; infiltration; Horton Model; GIS

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1. Introduction

Depok City has experienced very rapid growth, and this has caused a high need for the construction of facilities for housing and commercial areas. This development resulted in an impact on changes in land use, which can cause a reduction in infiltration areas, promoting an increase in surface runoff. Furthermore, an increase in peak runoff discharge can cause potential flooding in the area and the potential for lowering the groundwater level due to the increase in built-up area, so that the ability to absorb water decreases.

Infiltration is the process of water entering from the surface of the ground into the soil, which generally comes from rainfall. The movement of water in soil through its pores is influenced by gravity and capillary forces [1]. The inflow of water passes through the ground surface, so it is significantly influenced by the condition of the ground surface. The ground, as a flow median, has several characteristics, such as soil permeability, soil moisture, soil porosity, and soil type. The infiltration rate test is intended to determine the water that enters the soil [2].

The infiltration rate varies across land uses depending on the type of land use and the physical properties of the soil that influence it, including soil texture, organic matter, mass density, porosity, aggregate stability, and water content.

However, further research is needed to determine the infiltration rate for various land uses [3]. Previous research in Depok City reported an infiltration rate in the medium-to-medium fast category [4], and other research found that water absorption in Depok City is divided into six classes ranging from good absorption conditions to very critical conditions [5]. Most of the land in Depok City has been used as residential housing, resulting in the reduction of empty land as a water catchment area. This makes the area prone to flooding [6]. This study aimed to identify and create a map of water catchment areas in Depok City using a geographic information system, analyzing infiltration rates, and cumulative infiltration in Depok City.

2. Method

This study was conducted in several stages. The first stage was to conduct a literature review and determine the parameters related to the water catchment area. The second stage was to analyze the relationship between land use, slope, rainfall, and soil type. Rainfall calculations are required for rainfall data. From the results of the analysis of the data above, it can be determined that the areas that have the potential to be water catchment areas can then be used as a guideline for zoning for the Depok City Area, referring to the Regulation of the Minister of Forestry (No.P.32/MENHUT-II/2009). The next stage was to measure infiltration at 11 points in each sub-district using a double-ring infiltrometer, and then to conduct an infiltration analysis to determine the infiltration rate and cumulative infiltration in Depok City.

2.1. Time and Place

Map data collection and processing were carried out in April 2023, and infiltration rate data collection was carried out in 11 sub-districts of Depok City in October 2024. The research location is shown in **Figure 1**.

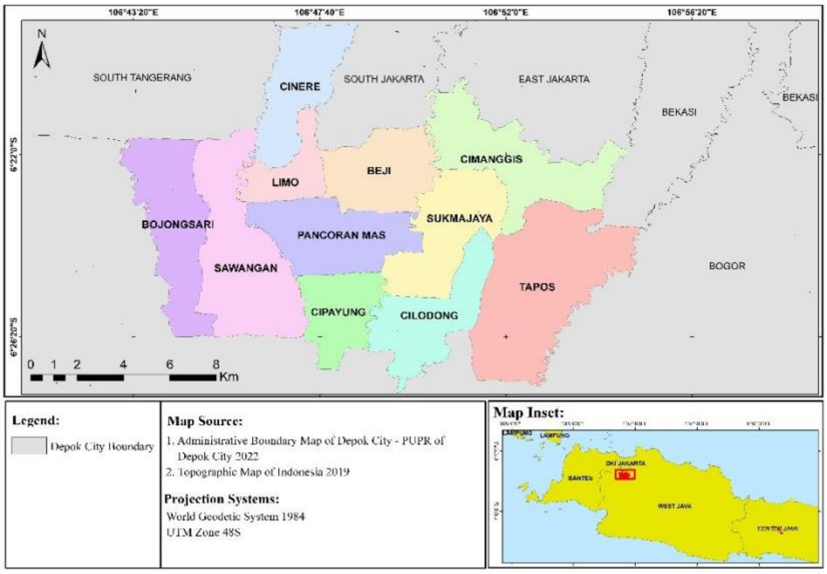

Figure 1. Research location: Depok City, West Java

2.2. Tools and Materials

The equipment used in this study was a double-ring infiltrometer, pliers, ruler, bucket, hammer, stopwatch, Global Positioning System (GPS), and a laptop equipped with Microsoft Office 2013 and GIS program ArcGIS 10.8. The materials used included water, an administrative boundary map of Depok City, a land use map from the Public Works and Spatial Planning Department of Depok City, and a soil type map or soil hydrology group map from the Center for Agricultural Land Resources Research and

Development. In addition, there is also daily rainfall data from the BMKG and digital elevation model (DEM) data.

2.3. Identification of Conditions of Infiltration Areas

A slope gradient map, soil type map, and rainfall distribution map were overlaid onto an infiltration potential map using a geographic information system application, where this technique allows for more accurate hydrological modeling, namely by its ability to accommodate various hydrological parameters [7]. Then, it was scored according to the level of infiltration and its infiltration potential. These three aspects provided an index of the potential natural infiltration level. Land use is influenced by human activities and has different implications for infiltration. The natural aspect reflects potential conditions, and the land use aspect reflects actual conditions [8].

The Thiessen polygon method was used to calculate average rainfall. Thiessen polygon is a method for calculating regional rainfall based on interpolation of rainfall values between one station and another [9]. Spatial interpolation assumes that data attributes are continuous in space, and these attributes are spatially interconnected. The slope map was obtained from the results of processing the National DEM data using ArcGIS software. DEMNAS data were input into ArcGIS software and processed using the "slope" tool [10].

After the slope value was obtained, the slope class classification process was carried out according to the class interval. The soil type map was obtained from Excel data and shapefile data from the Center for Agricultural Land Resources Research and Development, and the land use data were obtained from the Department of Public Works and Spatial Planning of Depok City.

Rainfall, slope, soil type (potential infiltration), and land use (actual infiltration) maps were overlaid and scored based on the regulation of the Minister of Forestry Regulation (No.P.32/MENHUT-II/2009). The overlay stage is a feature used for merging several different layers [11]. Merge all map layers using spatial intersection analysis. Intersect analysis is a combination of intersecting features or layers (points, lines, or polygons) and overlapping features that are combined and recorded in the output. After overlay and scoring, the condition of the infiltration area can be classified by comparing the potential infiltration value with the actual infiltration value using the following determination criteria:

I. Good Condition, namely if the actual infiltration value is greater than the potential infiltration value, for example, from e becomes A, from d becomes B, and so on.
II. Natural Normal Conditions, namely if the actual infiltration value is the same or remains the same as the potential infiltration value, for example from b to B, or from c to C, and so on.
III. Critical Conditions, namely if the actual infiltration value has dropped one level from the potential infiltration value, for example from a to B, or from c to D, and so on.
IV. Slightly Critical Condition, that is, if the actual infiltration value has dropped two levels from its potential infiltration value, for example from a to C, or from b to D, and so on.
V. Critical Condition, namely if the actual infiltration value has dropped three levels from the potential infiltration value, for example from a to D, or from b to E.
VI. Very Critical Condition, namely if the actual infiltration value changes from very large to very small, for example from a to E.

2.3. Infiltration Measurement

Infiltration measurements were performed using a double-ring infiltrometer based on SNI 7752:2012. Double-ring infiltrometer components have different functions: the outer ring reduces the possibility of water not moving horizontally, and the inner ring measures the decrease of water into the soil [12]. Infiltration rate analysis generally uses the Horton Model. The Horton Model is a well-known infiltration model in hydrology compared to other models [13]. The Horton method is formulated in **Equation (1)**.

Cumulative infiltration is the amount of water that seeps into the soil during the infiltration period. The cumulative infiltration is formulated in **Equation (2)**.

$$f_t = f_c + (f_0 - f_c)e^{-kt} \quad (1)$$

$$F =_0 \int \quad t\, f = f_0 t + \frac{f_0 + f_c}{k}\left(1 - e^{-kt}\right) \quad (2)$$

with,
f_t: Infiltration rate (cm/min)
F: Cumulative infiltration (cm/hour)
f_c: Constant Infiltration Rate (cm/min)
f_0: Initial infiltration rate (cm/min)
e: exponential
t: time (minutes)

3. Results and Discussion

3.1. Rainfall Classification

Mapping of rainfall in Depok City utilizes rainfall stations that affect areas in Depok City, namely the Banten Climatology Station located in Serang City, Banten, and the West Java Climatology Station located in Bogor City. Based on rainfall data from to 2012-2022, it is known that rainfall in Depok City is in the moderate category based on the South Tangerang Climatology Station, which is 2,271.12 mm/year and the large category based on the Bogor Climatology Station, which is 3,613.85 mm/year. The results of the calculation of the average rainfall for the area showed a value of 3,179.823 mm/year.

3.2. Slope Gradient Classification

The slope gradient map is shown in **Figure 2**. From the classification results, four land slope classes were obtained for Depok City. Areas with flat slopes (<8%) dominate the Depok City area with an area of 16,502.405 ha (82.6%) falling within a fast infiltration rate, areas with gentle slope classes (8-15%) covering an area of 2,998.542 ha (15.0%) with a fairly fast infiltration rate, areas with steep slopes (25-40%) covering an area of 468.303 ha (2.3%) with a fairly slow infiltration rate, and areas with very steep slope classes (>40%) covering an area of 21.372 ha (0.1%) with a slow infiltration value.

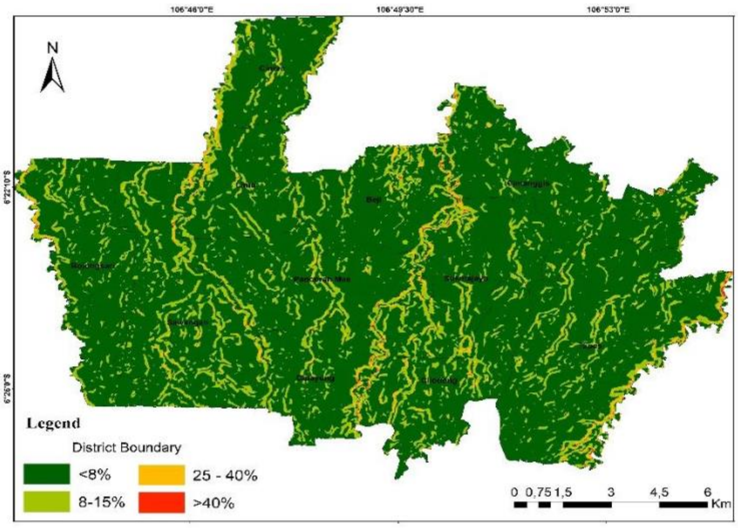

Figure 2. Map of slope gradient of Depok City

The slope condition significantly affects the amount of surface flow and infiltration opportunities [14]. The slope is a factor that determines the speed and amount of water that can seep into the soil. Areas with flat slopes tend to be more efficient in absorbing water because there is less surface flow, providing more opportunities for water to seep into the soil. This condition allows water to remain longer on the soil surface, extending its contact time with the soil and increasing infiltration. As a result, areas with flat slopes generally have better hydrological stability, with higher infiltration rates when compared to areas with steep slopes, where water flows faster and reduces the opportunity to seep [15].

3.3. Classification of Soil Types

Based on the classification results, the types of soil in Depok City are divided into three classes of soil types according to their infiltration levels. The largest type is Latosol and Eutric Oxisol (undulating relief> 3-8%) with an area of 16,949.391 ha (84.79%), and both have relatively small infiltration levels. The next type of soil is District Alluvial and Humic Cambisol (flat relief 0-1%), with an area of 2,645.644 ha (13.23%) and a small infiltration level. The third type of soil is Gleik Alluvial (flat relief 0-1%) with an area of 386.584 ha (1.93%) and a small infiltration level. Alluvial soil types have an infiltration permeability of <0.5 cm/hour and are relatively small in their ability to absorb water [16]. A map of the soil types is shown in **Figure 3**.

3.4. Land Use Classification

Depok City is an urban area, and its land use consists of five types: dry land agriculture, mixed dry land agriculture, rice fields, settlements, and water bodies. The settlement is the largest area in Depok City, 15,440.818 ha (77.2%), with a small infiltration value. The area of dry land agriculture was 3,730.482 ha (18.7%), with a relatively small infiltration rate, while mixed dry land agriculture was 213.345 ha (1.1%), with a relatively small infiltration rate. Paddy fields had an area of 519.544 ha (2.6%) with a low infiltration rate, and water bodies had an area of 86,433 ha (0.4%). The land use map of Depok City is shown in **Figure 4**.

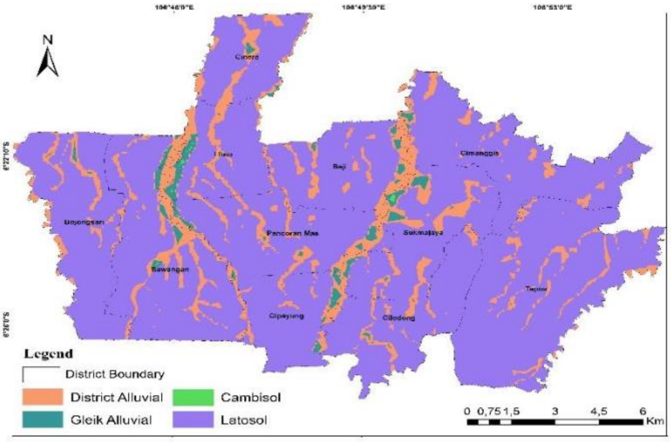

Figure 3. Map of soil types in Depok City

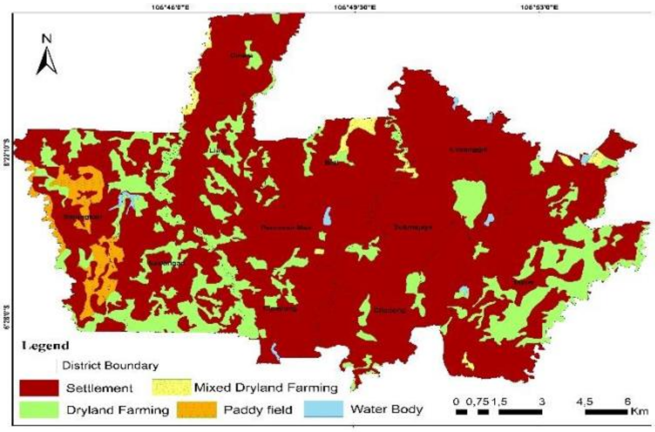

Figure 4. Land use map of Depok City

3.5. Classification of Critical Conditions of Infiltration Areas

In this case, Depok City is assumed to be a rainwater catchment area in the approach model used to determine catchment areas. The areas of Depok City have different abilities in absorbing (infiltrating) water due to factors such as rainfall, slope, soil type, and land use. Catchment areas can be classified based on differences in these factors, which can cause different levels of infiltration. Based on the scoring and overlay carried out in accordance with the Regulation of the Minister of Forestry (No.P.32/MENHUT-

II/2009), the classification of critical catchment areas in Depok City is divided into three classes: natural normal conditions, starting to be critical, and somewhat critical. The spatial distribution of the critical conditions of the catchment areas of Depok City is shown in **Figure 5**.

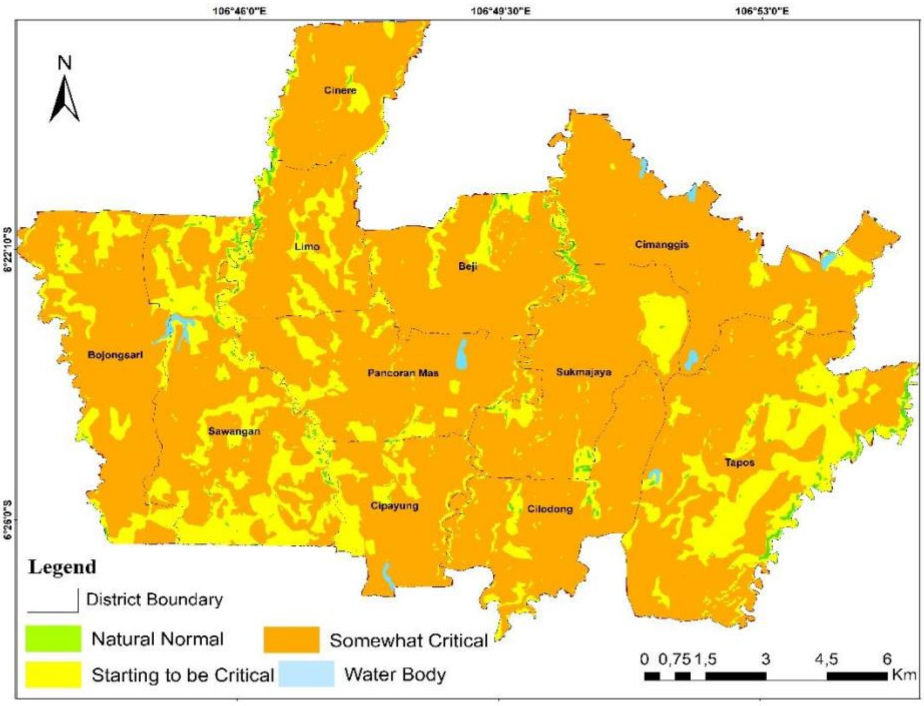

Figure 5. Map of the condition of the Depok City catchment area

Depok City has an area dominated by catchment areas within a critical category. With most of the catchment areas in a rather critical condition, this indicates a decrease in the soil's ability to absorb water optimally, which can worsen various environmental problems. The critical conditions of the catchment areas are listed in **Table 1**.

Table 1. Criticality of the catchment areas of Depok City

No	Category	Area	
		(Ha)	(%)
1	Natural Normal	168.515	0.84
2	Starting to be Critical	4,146.347	20.75
3	Somewhat Critical	15,589.327	77.98
4	Water Body	86.433	0.43
	Total	19,990.622	100.00

3.6. Infiltration Analysis

For infiltration data collection, measurements were taken at 11 locations spread across Depok City and located in different sub-districts (**Figure 6**). In the actual method, data processing is performed by measuring the height of the water drop in the inner and outer rings until a constant infiltration rate is achieved. The infiltration rate can be calculated using the formula set out in SNI 7752:2012. The processed data were obtained directly by observing and measuring the infiltration rate (the actual method). The data observed when measuring the infiltration rate, namely, the time difference and the water level in the outer and inner cylinders. The outer cylinder determines whether there is a leak in the inner cylinder, which functions as a measure of the infiltration rate [4].

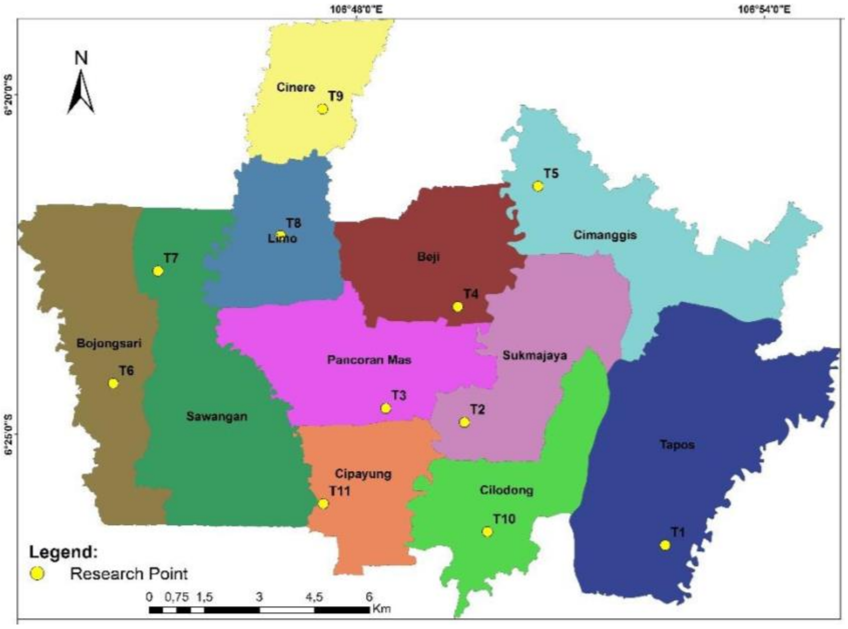

Figure 6. Location of infiltration rate measurement

Primary data obtained in the field were then processed by calculating the infiltration rate value using the Horton method. Calculations were also carried out using Excel to reduce errors. The calculation results were then graphed to determine the differences between the field results and Horton calculations. An example of a graph can be seen in **Figure 7**.

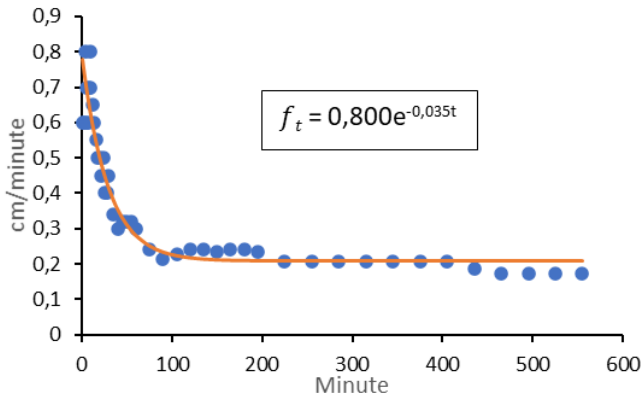

Figure 7. Comparison of actual and Horton infiltration rates

The results of the field measurements show that the infiltration rate decreases over time and eventually becomes constant, in line with the Horton infiltration model theory. In the Horton model, the infiltration rate is usually higher at the beginning of the rain and then decreases over time until it reaches a constant value. This decrease in the infiltration rate occurs because of the soil saturation process and a decrease in the capacity of the soil to absorb water during rain. At some point, the infiltration reaches a constant value known as the infiltration rate constant in the Horton model. The smaller the error value, the closer the actual value is to the Horton method value [17]. Based on the processing results using Excel, the infiltration rate values obtained are listed in **Table 2**.

Table 2. Results of Horton model data processing

Location	Horton				
	f_0 (cm/minute)	f_c (cm/minute)	k	f_t (cm/minute)	*Error*
Tapos	0.800	0.253	0.025	0.250	0.303
Sukmajaya	0.850	0.113	0.014	0.150	0.260
Pancoran Mas	1.050	0.280	0.010	0.300	0.286
Beji	0.350	0.107	0.014	0.120	0.065
Cimanggis	0.800	0.290	0.020	0.290	0.135
Bojongsari	0.800	0.207	0.035	0.210	0.155
Sawangan	0.400	0.140	0.029	0.140	0.147
Limo	0.800	0.283	0.008	0.320	0.793
Cinere	0.400	0.140	0.028	0.140	0.140
Cilodong	0.350	0.107	0.014	0.110	0.073
Cipayung	0.800	0.273	0.005	0.330	0.438

The highest initial infiltration rate was observed in Pancoran Mas, reaching 1.050 cm/minute, whereas the lowest initial infiltration rates were recorded in Beji and Cilodong, both at 0.350 cm/minute. The highest constant infiltration rate was found in Limo at 0.283 cm/minute, and the lowest was in Cilodong at 0.107 cm/minute. Additionally, the highest overall infiltration rate was measured in Cipayung at 0.330 cm/minute, and the lowest was recorded in Cilodong at a rate of only 0.110 cm/minute. The values from the processing using the Horton method are then processed to determine the cumulative infiltration. Cumulative infiltration is the amount of water that seeps into the soil during the infiltration period [18]. Cumulative infiltration is calculated assuming it rains for 1 h and can be seen in **Table 3**.

Table 3. Cumulative Infiltration for 1 hour

Location	Time (minute)	Cumulative Infiltration (cm/hour)
Tapos	60	32.178
Sukmajaya	60	36.857
Pancoran Mas	60	51.886
Beji	60	16.316
Cimanggis	60	35.012
Bojongsari	60	27.282
Sawangan	60	15.744
Limo	60	41.825
Cinere	60	15.886
Cilodong	60	16.226
Cipayung	60	43.479

Based on **Table 3**, the cumulative infiltration at the survey points is known. The total amount of water that can be absorbed by the soil layer from rainfall in a certain time is considered cumulative infiltration [19]. The highest cumulative infiltration was recorded in Pancoran Mas at 51.886 cm/h, and the lowest was observed in Sawangan at 15.744 cm/h. The cumulative infiltration value is processed using inverse distance weighting (IDW) interpolation. The IDW method directly implements the assumption that objects that are close to each other are more similar than those that are far from each other [20]. The results of the IDW interpolation overlaid with the open land area of Depok City are shown in **Figure 8**.

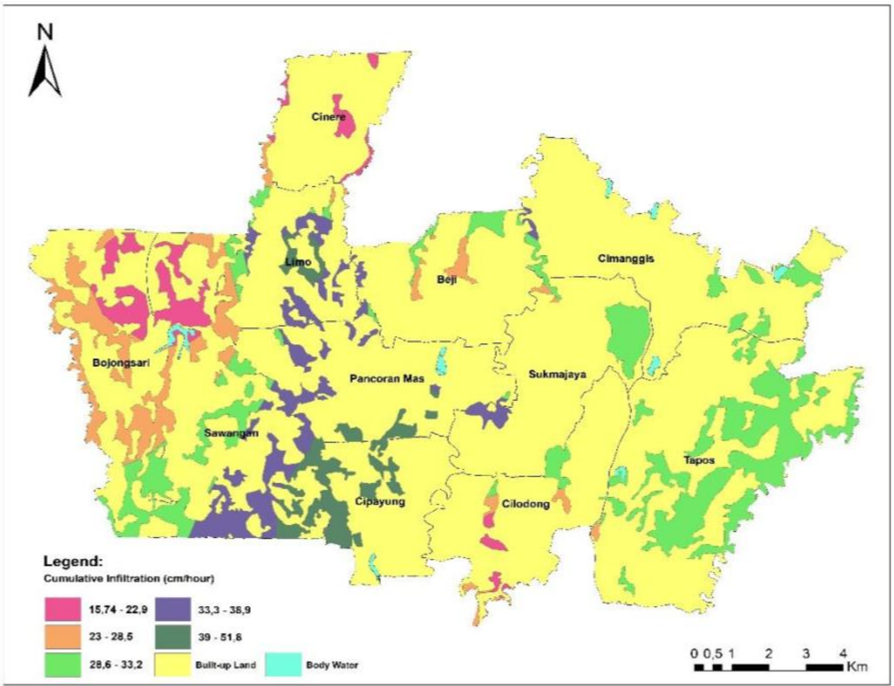

Figure 8. Cumulative infiltration map on open land in Depok City

Depok City had different variations in the cumulative infiltration values. Based on **Figure 8**, areas with cumulative infiltration values between 15.74 cm/hour to 22.9 cm/hour are found in an area of 465,653 ha (10.2%). The next cumulative infiltration value is between 23 cm/hour and 28.5 cm/hour which covers an area of 876,659 ha (19.3%). In addition, areas with cumulative infiltration values between 28.6 and 33.2 cover the largest area, namely 1,979,276 ha (43.5%). This indicates that most areas of Depok have better infiltration capabilities, which can play a role in rainwater management and reduce the risk of flooding. On the other hand, areas with cumulative infiltration values between 33.3 cm/hour to 38.9 cm/hour are located in an area of 797,365 ha (17.5%), and areas with values between 39 cm/hour to 51.8 cm/hour cover 430,851 ha (9.5%).

This data provides a clear picture of the potential for water infiltration in various parts of Depok City, which is very important for planning water resource management and flood disaster mitigation. As a strategic step, the Depok City Government can use the results of this cumulative infiltration calculation as a basis for environmentally friendly development planning. In this case, Depok City Regional Regulation Number 1 of 2015 concerning the spatial planning of Depok City for 2012-2032 provides guidelines for flood control and sustainability of water resources. Several important steps can be taken, including revitalizing and optimizing the function of lakes, normalizing the city's drainage system, and controlling groundwater subsidence through the construction of infiltration wells.

4. Conclusion

The recharge area classification map was generated through the overlay and scoring of rainfall, slope gradient, soil type, and land use maps in accordance with applicable regulations. Depok City is categorized into three classes of recharge area vulnerability: natural normal conditions covering 168.515 ha (0.84%), critical conditions covering 4,146.347 ha (20.75%), and somewhat critical conditions covering 15,589.327 ha (77.98%). The highest infiltration rate was found in Cipayung at 0.33 cm/min, while the lowest was recorded in Cilodong at 0.11 cm/min. This data provides a clear picture of the potential for water infiltration in various parts of Depok City, which is very important for planning water resource management and flood disaster mitigation. As a strategic step, the Depok City Government can use the results of this cumulative infiltration calculation as a basis for environmentally friendly development planning.

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