

THE CHARACTERISTICS OF INFILTRATION ON THE SOUTHERN FLANK OF MERAPI VOLCANIC PLAIN, YOGYAKARTA, INDONESIA

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ABSTRACT: The broad development of built areas has decreased infiltration areas, which in turn gives impacts on water table subsidence. The infiltration capacity and distribution are factors that need to consider in preserving the groundwater. This research aims to examine the infiltration rate, infiltration capacity, and distribution of potential infiltration on the southern flank of the volcanic foot plain and the fluvial-volcanic plain of Merapi Volcano. The method employed in this research is a direct measurement using a double-ring infiltro-meter. The constant infiltration rate was analyzed using the Horton Method. The results show that the high infiltration rate spreads over an area with an altitude of less than 200 Meter Above Mean Sea Level (MAMSL) which has very deep groundwater. Meanwhile, the infiltration rates above 200 MAMSL tend to be smaller in shallower groundwater depths. The infiltration capacity in the research area tends to be high. The highest infiltration rate is 1.2 cm/minute with the infiltration equation of $ft = 1.20 + (1.967-1.20)e^{-0.0492t}$, while the lowest infiltration rate is 0.1 cm/minute with the infiltration equation of $ft = 0.10 + (0.149-0.10)e^{-0.0396t}$. Most of the research areas have moderate or fairly rapid infiltration capacity that spreads from areas below 200 MAMSL to the top altitude at 400 MAMSL. The potential for water infiltration in the research area mostly belongs to the medium category. Overall, this paper presents new insights to understand the characteristics of infiltration in volcanic plain related to the development of land use.

Keywords: Infiltration capacity, Infiltration rate, Volcanic plain, Merapi Volcano

1. INTRODUCTION

The amount of groundwater reserves becomes an important factor that needs to be taken into account in utilizing and preserving groundwater. The groundwater reserves in a particular place heavily rely on the amount of rainwater that enters the groundwater basin and the amount of groundwater usage. Several factors influence the amount of rainwater infiltration into groundwater basins which include: soil texture, soil structure, soil moisture, depth of litter, the presence of vegetation which covers the ground, waterlogging, the thickness of saturated layers, thickening by rain, and folding by living things especially humans [1-3]. The natural infiltration that is not disturbed by man-made in various places on the earth's surface is varied. The land which has a high infiltration capacity will accelerate the infiltration rate so that the volume of water that enters the aquifer becomes greater. Meanwhile, the slow infiltration capacity will hamper the infiltration process so that a little rainwater will seep into groundwater. If the rainwater seeping into the aquifer is low while the groundwater usage is high, it will accelerate the decline of the water table.

Water subsidence remains a problem that occurs almost all over the world. Lee's research [4] in

Korea shows that groundwater has been exploited recklessly. Annual groundwater usage continues to increase. In 1994, the volume of groundwater usage reached 2.57 billion m³ and it increased to 3.72 billion m³ in 2007. 48.1% of water was consumed for domestic use. Poor groundwater development and management had caused critical groundwater problems in Korea, including a decrease in the volume of water and its quality due to petroleum hydrocarbon pollution. The problems of groundwater usage also occurred in India. Naik et al. [5] show the impact of urbanization on groundwater conditions in the city of Solapur, in Central India, which is experiencing rapid development. Solapur, a city with an area of 178 km², gets a groundwater recharge of around 24 million m³ per year. The reduction of catchment areas continues to occur, usually due to urbanization. On the other hand, an increase in water needs due to the fluctuation of the population also continues to occur.

The Yogyakarta region, Indonesia, is one of the regions which experience an increasingly greater water table subsidence. A research conducted by Wilopo [6] in 1999 in the Yogyakarta Province showed that groundwater degradation had occurred annually with an average of 0.324 - 0.514 m/year from 1983 to 1998. This occurred in the city of

Yogyakarta and several areas in Sleman and Bantul Regency. In the last few years, news on the scarcity of groundwater in urban areas was reported in several daily newspapers in Indonesia. Many areas that should function as infiltration areas have been converted into housing, hotels, paved roads, or concrete in some areas. For example, in the Sleman Regency area, the expansion of yard per year has increased by 0.16%, while paddy fields have decreased by 0.19%. The data from the Sleman Regency Government indicates that a great land change occurred on non-settlement, non-paddy land which changed into settlement land. In the Mlati sub-district, for example, the settlement land was 1,165.3 ha in 1980; it increased up to 1,540.2 ha in 2000. Moreover, in the Ngaglik sub-district, the settlement land was 935 ha in 2001; it grew up to 1,395 ha in 2011. This was due to relatively high population growth.

Meanwhile, the higher river discharge rate in Yogyakarta and surrounding areas occurred. This is possibly due to the lack of rainwater seeping into the catchment area. The rainwater absorption has a function to enter rainwater into the groundwater bodies directly. Thus, it keeps the function and sustainability of groundwater. On the other hand, the rainwater does not turn into the run-off so that rainwater will not cause flash floods if it seeps into the ground and reaches groundwater bodies. The greater decrease in groundwater level, which is marked by the deepening of wells and the more frequent floods that occur in urban areas, is the impact of development that ignores the environment's perseverance.

The southern flank of the Merapi volcanic plain is an area that offers good potential as a groundwater catchment. This is due to a lot of deposition of pyroclastic and lava material resulted from the eruption of Merapi Volcano which keeps having an impact in the region for thousands of years [7-9]. Lahar deposition mostly occurs in the southern volcanic footplate, it is especially linked with large rivers that tipped in the volcanic cone. The process of lahar deposition not only occurs during the eruption period but also during the rainy season where eruption does not happen [10,11]. This repositioning pyroclastic and lava material form land with high infiltration potential. Santosa and Adji [12] explain that the southern part of the Merapi volcanic foot plain is part of the recharge area of the Merapi aquifer system whose coverage covers Sleman Regency, Yogyakarta City, and Bantul Regency. Based on data from the Central Statistics Agency, the population in these three administrative regions reach 2,629,476 in 2019. This fact indicates that the groundwater catchment area in the Merapi Volcano area supports water resources for many residents, including the urban and sub-urban areas of Yogyakarta whose

population has reached 924,594. However, the potential for absorption is currently hampered by the development of aquaculture buildings. For this reason, it is necessary to preserve catchment areas that are supported by various relevant information including the characteristics of infiltration in this region.

Next, the rest of this paper is organized as follows. Section 2 describes the materials and methods, section 3 explains the results and discussions, and section 4 elaborates the conclusion of this research.

2. MATERIAL AND METHODS

In this section, the method employed in this research is elaborated. This research was carried out in the southern flank of Merapi volcanic foot plain and fluvial-volcanic plain. The research area is limited from the area at an altitude of 400 MAMSL at the top to the transition of the volcanic foot plain with the fluvial-volcanic plain. The eastern part of the research area is bordered with the Kuning River valley while the western part is bordered with the Bedog River valley (Fig.1).

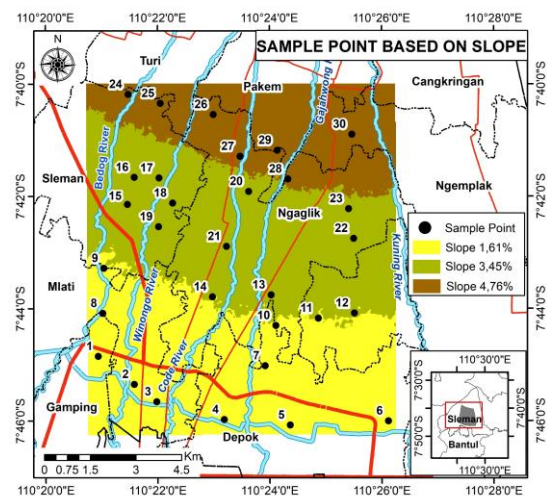


Fig.1 The map of the research area and the distribution of infiltration measurement samples

The research was proceeded by collecting data on infiltration rates, depth of water table, and identification of land use to determine the built and non-built areas. To obtain data on infiltration and water table level, measurements were carried out at 30 sample locations (Fig.1). The sampling was performed by employing a systematic sampling using a grid system. The infiltration measurements were conducted using the Horton Method utilizing the double-ring infiltro-meter Turf Tec (Fig.2). The measurements were carried out in an open yard which is free of trees, gardens, or grass. The groundwater level measurement was performed by

measuring the depth of the surface water in a dug well by using a rolling meter. The locations were measured using GPS.



Fig.2 The double ring infiltro-meter Turf Tec

The data collected on the coverage and distribution of settlements and the built areas such as paved roads, cemented yards, was carried out through the interpretation of remote sensing images using Quickbird Imagery. The interpretation of remote sensing imagery was also supported by direct observation in the field to obtain more accurate data. The identification of the built areas will then be used to make a map of residential areas. The mapping process was performed by employing the GIS method using ArcGIS.

After collecting the data, the data were analyzed. There are three stages of data analysis in this research, namely: (1) infiltration rate analysis, (2) infiltration capacity class analysis, (3) infiltration potential areas analysis. The infiltration rate analysis was performed using the Horton Model [13], with the following Eq. (1).

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

Where f_t is infiltration rate at a certain time t , f_0 is initial infiltration rate, f_c is constant infiltration rate, t is time, and K is constant.

Based on the first stage of analysis, the infiltration rate varies between sample locations. The infiltration rate variations are then used in the second stage of analysis to determine the infiltration capacity class. The analysis was performed by the scoring method and the results were divided into several categories. The second stage of analysis finds five classes of infiltration capacity. Each infiltration capacity class is then mapped by employing the IDW interpolation using ArcGIS to determine the distribution of its territory.

The next stage of analysis was carried out to determine the potential of the recharge area. The

analysis was performed by employing the overlay technique in GIS. The results of the mapping on the built areas which had been carried out as a follow up from the interpretation of the Quickbird image were then overlaid with a map of infiltration capacity. This analysis produced a map showing the built areas which disturb the catchment areas. Furthermore, the potential for catchment areas was determined by an overlap between the distribution of groundwater depth and the built area and the combination of groundwater depth and capacity and the built areas.

The input of this analysis is a map of the built areas resulted from quick bird image interpretation with a map of potential recharge areas that produce a map of catchment areas whose function has changed. Then, the recharge areas which have changed its function are measured. The areas whose function has changed is categorized as the function-disturbed area and the function-normal area. This categorization becomes the basis for consideration and calculation in optimizing the design of artificial infiltration models. Fig.3 shows the procedure of this research.

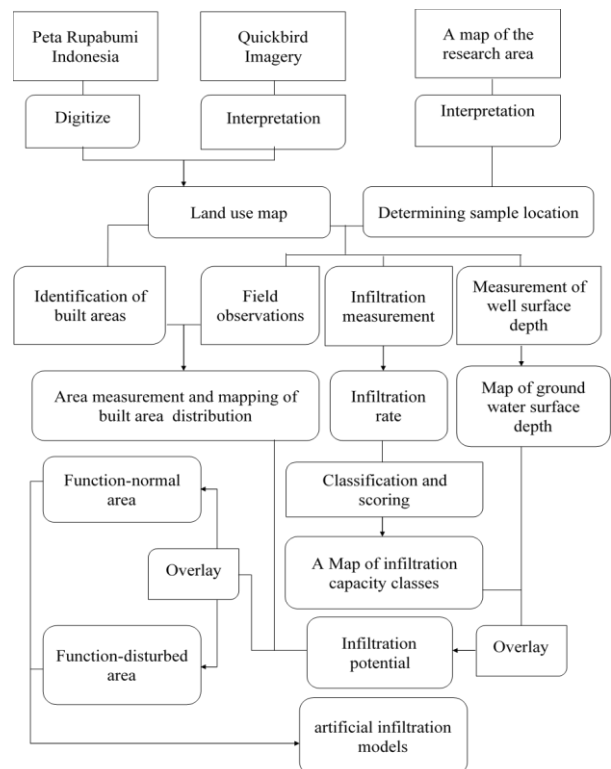


Fig.3 Research Procedures

3. RESULT AND DISCUSSION

3.1 The Characteristics of the Physical Environment of the Research Area

The research area is astronomically located between 110013 '00" to 110033 '00" East longitude

and 7034 '51 "to 7047 '03" South latitude. Administratively, the research area covers 9 sub-districts in Sleman Regency, Yogyakarta Special Province. Geomorphologically, the research area is located in the southern part of the Merapi volcanic plain. The height varies from 150 to 400 MAMSL, while the slope is relatively similar, which ranges from 1.61 to 4.76%. The research area is composed of materials produced by young Merapi activities in the form of sand and volcanic ash deposits. This type of material spreads evenly in all parts of the region. Volcanic rock outcrops can be identified in cliffs and river valleys in the research area.

The hydrological condition of the research area is marked by various large rivers, including Boyong, Kuning, Winongo, Gajahwong, and Code River. These rivers support the development of irrigated rice fields which are developing in the upper part of the region (see Fig.1). Meanwhile, viewed from the geohydrological side, the Merapi volcanic plain has relatively abundant water resources. The identification of groundwater potential in this area has been carried out by Mc Donald and Partner (1985) who introduced the term Merapi aquifer system. The direction of groundwater regionally flows from north to south. The recharge area is on the slope of Merapi Volcano in the north, while the discharge area is on the south marked by leakage in the form of springs. The results of observation indicate that springs that spread from a height of 148 MAMSL to 421 MAMSL are found in the research area.

In general, the research areas have similarities in terms of land and rock forms, but they have different groundwater-surface characteristics. Some areas have very shallow groundwater depths, some are shallow, and others are very deep (Fig.4). The very shallow region is usually located next to a spring. The very deep groundwater region is found in the southern part of the study area. The productive aquifers with wide expansion, moderate to high permeability, and shallow groundwater levels are found in the volcanic foot plain [14]. This aquifer is composed of young Merapi volcanic deposits in which the flow goes through gaps between particles and space between particles.

The research area is also occupied by many residents. The research area covers nine of the 17 sub-districts in Sleman Regency, namely Gamping, Mlati, Depok, Kalasan, Ngemplak, Ngaglik, Sleman, Turi, and Pakem. Based on the data from the Central Statistics Agency of Sleman Regency, the population in the nine districts in 2018 reached 835,955 people.

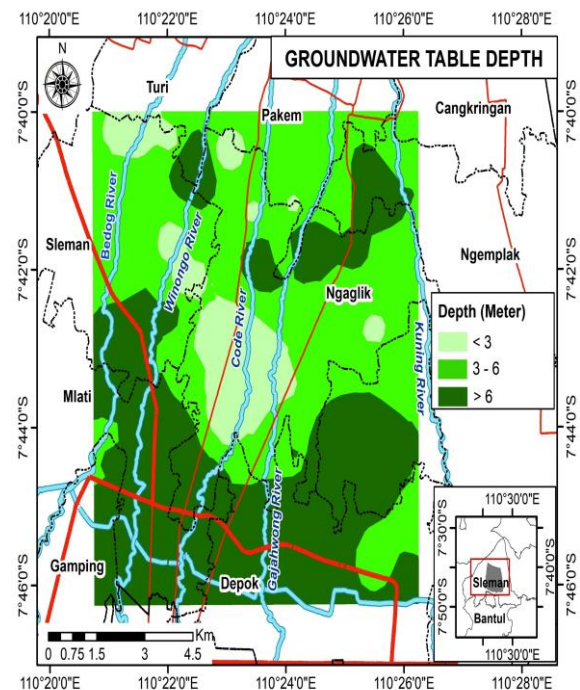


Fig.4 The map of water table depth in the study area

This great number of population has implications for land use. Irrigation settlements and rice fields are the forms of land use that dominates in the research area. The land use in the form of gardens and dry fields in the area is very small.

3.2 The Infiltration Capacity on the Southern Flank of the Merapi Volcanic Plain

The results of measurements carried out on 30 sample locations indicate that the infiltration capacity varies greatly. However, the infiltration rate in the research area generally tends to be high. Referring to the classification of infiltration rates as proposed by Rickard and Cossens [15], the entire infiltration rate in the research area is included in the very high category. When referring to the USCS classification [16], the infiltration rate varies between rather quickly to very quickly. Meanwhile, referring to the classification of Kohnke [17], the infiltration rate is included in the moderate to the very fast category. The results of measuring the infiltration rate conducted at 30 sample locations are presented in Fig.5 and Table 1 below.

The infiltration rate in the research area is varied ranging from 0.10 cm/minute to 1.2 cm/minute. The variety of infiltration rates is caused by different factors although it is on the same type of soil. These factors include soil congestion, soil moisture, depth of groundwater, and the presence of plants.

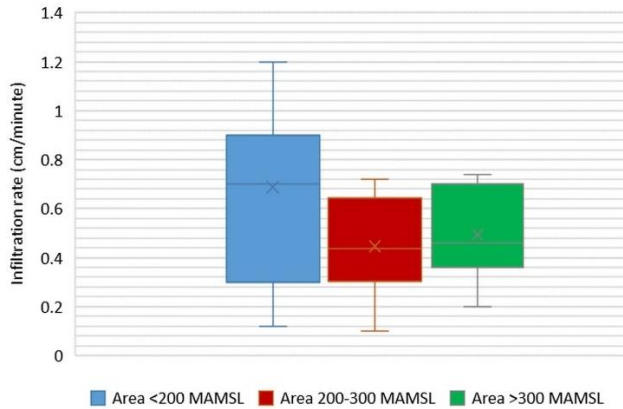


Fig.5 The boxplot for the infiltration rate in the study area

Table 1 The infiltration rate and water table in the study area

| <200 MAMSL | | | 200-300 MAMSL | | | >300 MAMSL | | |
|------------|------|------|---------------|------|------|------------|------|-----|
| SN | IR | WT | SN | IR | WT | SN | IR | WT |
| 1 | 1,20 | 7,7 | 12 | 0,67 | 4,8 | 24 | 0,20 | 1,2 |
| 2 | 0,90 | 10,5 | 13 | 0,31 | 5,2 | 25 | 0,36 | 2,2 |
| 3 | 1,20 | 10,4 | 14 | 0,52 | 12,2 | 26 | 0,70 | 1,1 |
| 4 | 0,85 | 8,8 | 15 | 0,30 | 0,9 | 27 | 0,74 | 2,4 |
| 5 | 0,70 | 11,2 | 16 | 0,38 | 2,5 | 28 | 0,40 | 9,6 |
| 6 | 0,80 | 6,8 | 17 | 0,41 | 3,0 | 29 | 0,60 | 2,5 |
| 7 | 0,62 | 8,2 | 18 | 0,10 | 0,5 | 30 | 0,46 | 12 |
| 8 | 0,12 | 2,0 | 19 | 0,25 | 9,0 | | | |
| 9 | 0,30 | 5,2 | 20 | 0,68 | 3,6 | | | |
| 10 | 0,18 | 1,3 | 21 | 0,72 | 4,3 | | | |
| 11 | 0,69 | 6,9 | 22 | 0,56 | 2,4 | | | |
| | | | 23 | 0,46 | 8,3 | | | |
| Av | 0,69 | 7,2 | | 0,46 | 4,7 | | 0,49 | 4,4 |

Source: Field measurement (2019)

MAMSL = meter above sea level (elevation), SN = sample number, IR = infiltration rate (cm/minute). WT = water table (meters), Av = average

The depth of the groundwater level affects the slower infiltration. This condition is shown by the results of measurements at sample locations of 15, 16, 17, 18, and 19. The measurements on these locations are carried out at relatively close locations and at residential land use which is not too dense. The depth of the groundwater level in sample 18 is shallower than the other four sample locations. A similar physical environmental condition but the depth of the groundwater level is different, the infiltration rate in sample 18 is only 0.11 cm/minute. Meanwhile, samples 17 and 19 have greater infiltration rates (see Table 1). The shallower of the groundwater is, the faster the soil saturation will be. Therefore, it causes a slower infiltration rate. This is relevant with [18] and [19] that the infiltration rate is influenced by soil saturation, which can occur due to the changes in groundwater levels which is getting shallower. Abdullahi and Garba [20] explain that the maximum infiltration

estimated during October-December correlates with a decrease in groundwater levels from June-August.

Soil moisture is a factor that determines the rate of infiltration in the research area. The results indicate that areas with high soil moisture have slower infiltration rates. The measurements conducted in sample 10, for example, show an infiltration rate of 0.18 cm/minute, while sample 13 which are relatively close to each other show a greater infiltration rate (Table 1). The land use in those two sample locations is settlements, however, settlements in sample 10 are denser than that of sample 13. The slope of the sample 13 is also greater. These factors influence the surface runoff which flows faster at sample 13. The greater soil saturation may occur in the land where the surface runoff is hampered. Ren et al. [21] show that the initial soil moisture is an important factor that influences the rate of infiltration in urban areas. However, they further explain that this factor offers a small effect on regions with narrow coverage. Meanwhile, in our research, a wide range of research areas allows for variations in infiltration rates between locations.

Soil congestion becomes a very influential factor affecting the infiltration rate in the research areas. The results indicate that the degree of congestion is positively correlated with the infiltration rate. This is relevant with [22] that vegetation type and soil density have a significant effect on the initial infiltration rate. Our research finds that soil congestion occurs due to the development of built areas. Also, land use for paddy farming may affect soil congestion, but it is not the focus of this research. Congestion in paddy fields occurs due to the formation of dense materials as a result of long-term rice planting patterns. This is relevant with [23] in which bulk density inhibits the infiltration rate. While in residential areas, which become the focus of this research, variations in population activity affect the soil density.

Meanwhile, Yimer et al. [24] say that land management for agriculture is a factor that causes congestion. The changes in land use from agriculture to non-agriculture are also likely to be factors that increase soil density [25]. However, the results of measurements carried out in urban settlements that have widely developed are not much different from the new settlements which are still surrounded by agricultural, and from rural areas. The samples number 2, 3, 4, 5 measured in densely populated urban areas are not much different from the samples number 12, 20, 22, 30 measured in rural areas, with groundwater levels above 6 meters. This is slightly different from the findings of Wang et al. [26] that the rate of soil infiltration decreases along with the increasing density in urban areas.

The difference vegetation is a factor that influences the infiltration rate. Field data

measurements in this research were carried out in the yard. Therefore, the variation of vegetation is relatively small so that the impact on the infiltration rate is possibly small. The findings of this research indicate that the infiltration rate in the yard that lacks a large amount of vegetation as in samples 3, 4, 5 have a greater infiltration rate than in the yard which has larger vegetation as in sample 20, 24, 26. This finding is different from the results of the previous studies which showed that differences in vegetation affect the infiltration rate and the changes in vegetation types affect the infiltration rate [22,25-29]. The location of measurement on a relatively narrow yard with a small variation of vegetation is thought to be a factor that causes the smaller influence of vegetation on the infiltration rate. Meanwhile, the soil saturation and the depth of the groundwater level play a role in determining the infiltration rate.

Some infiltration rate samples which include very fast, fast, and quite fast were analyzed by calculating the Horton model and producing different equations and graph models. The constant infiltration rates of 1.1 cm/minute, based on the data processed, are presented in Table 2. The infiltration equation is: $f_t = 1,10 + (2,222-1,10)e^{-0,044t}$, which is illustrated in Fig 6.

Table 2 Determining the smallest $[f_{\text{measured}} - f_{\text{predicted}}]^2$ for $f_c=1,1$

| t (min) | K | f_0 | f_{measured} (cm/min) | $f_{\text{predicted}}$ (cm/min) |
|------------|--------|-------|-----------------------------------|------------------------------------|
| 5 | 0,1832 | 3,350 | 2,000 | 2,000 |
| 10 | 0,1098 | 2,659 | 1,460 | 1,340 |
| 35 | 0,0627 | 2,332 | 1,200 | 1,340 |
| 55 | 0,0440 | 2,222 | 1,200 | 1,164 |
| 65 | 0,0372 | 2,184 | 1,180 | 1,164 |
| 105 | - | - | 1,100 | 1,111 |

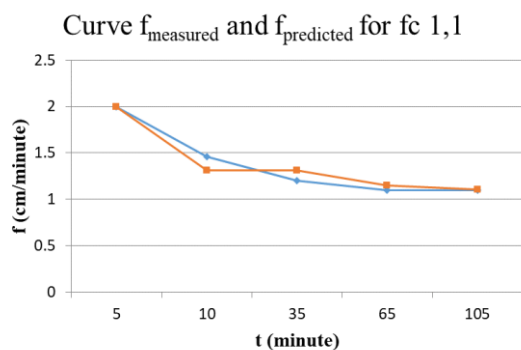


Fig.6 The curves of the f_{measured} (blue line) and $f_{\text{predicted}}$ (orange line) calculated from the infiltration measurement

The f_{measured} and $f_{\text{predicted}}$ curves in the research area are varied therefore they could illustrate the absorption characteristics in the research area. The f_{measured} curve and other results of the infiltration

calculation using the Horton model are presented in Fig.7.

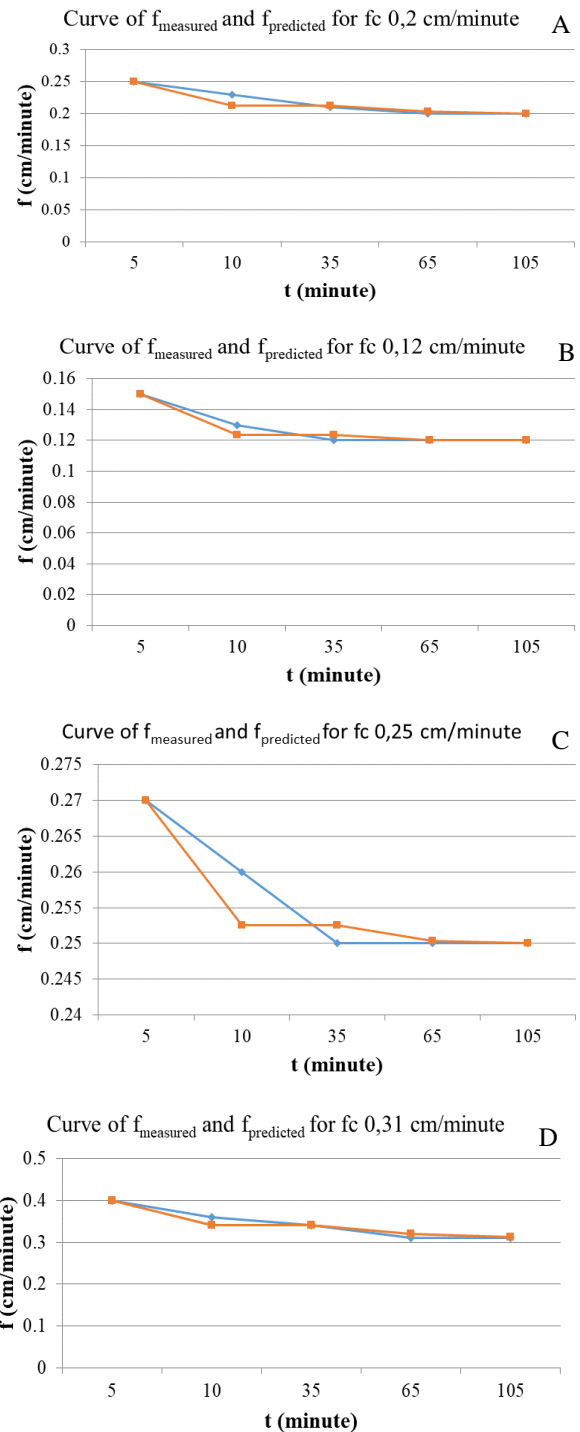


Fig.7 The curves of f_{measured} and $f_{\text{predicted}}$ show the low f_c infiltration results. Each curve has a different characteristic of the infiltration rate. Figure B shows stability from the beginning, for example at the 35th minute. Figures A, C, and D, indicate an infiltration that takes more than 60 minutes to achieve stability.

Groundwater and soil density are thought to have a major effect on the stability of the infiltration

rate which varies in various research samples. Under these conditions, to determine the Horton equations, the difference in the f_{measure} and f_{predict} squares is calculated. In that position, the two curves have joined. Thus, each of them represent an infiltration capacity of 0.1 cm/minute, 0.25 cm/minute, 0.5 cm/minute, 0.75 cm/minute, and 1.0 cm/minute.

3.3 The Distribution of Potential Recharge

The results of the analysis on the distribution of absorption potential show that the recharge potential varies such as slow, slightly slow, medium, fast, and very fast. The slow infiltration rate zone only occupies a very narrow area, which is 143.40 ha or 1.25%. The slightly slow recharge zone occupies a wider area of 2805.90 ha or 24.50%. Meanwhile, the largest zone is the medium recharge zone which reaches 62.00% (Table 3).

Table 3 Infiltration Zone Area

| Infiltration Zone | Infiltration rate(cm/min) | Area (ha) | Percentage (%) |
|-------------------|---------------------------|-----------|----------------|
| Slow | <0,10–0,25 | 143,40 | 1,25 |
| Slightly slow | >0,25–0,50 | 2805,90 | 24,50 |
| Medium | >0,50–0,75 | 7102,88 | 62,00 |
| Fast | >0,75–1,00 | 1007,59 | 8,80 |
| Very fast | >1,00 | 395,76 | 3,45 |
| Total | | 11.455,55 | 100,00 |

The highest absorption potential is mostly found in the southern part of the research area (Fig 8). The built areas in the very potential infiltration zone are found in the regions which have infiltration rates above 0.432 cm/minute. The infiltration areas which belong to quite a potential category spread in the west and slightly in the middle of the research areas indicated with an infiltration rate of 0.212–0.423 cm/minute. Less potential areas are likely to be distributed in a small part of the research areas which are usually located around a reservoir or spring. This is due to the influence of soil moisture which causes a slow infiltration rate as explained by [19,28].

On the other hand, the land which initially functioned as natural infiltration, such as yards and agricultural land, no longer works because it has been covered with buildings such as housing and roads. Most of the settlements are equipped with a rainwater drainage channel that joins with the sewer flowing to the nearest river. As a result, rainwater that falls on the housing roof immediately becomes surface runoff and enters the river flow. This causes non-potential absorption and increases the river flow. Concerning this, Soewarno [20] explains that 10-30% of rainwater in the built areas did not run

off while formerly it could reach 80%.

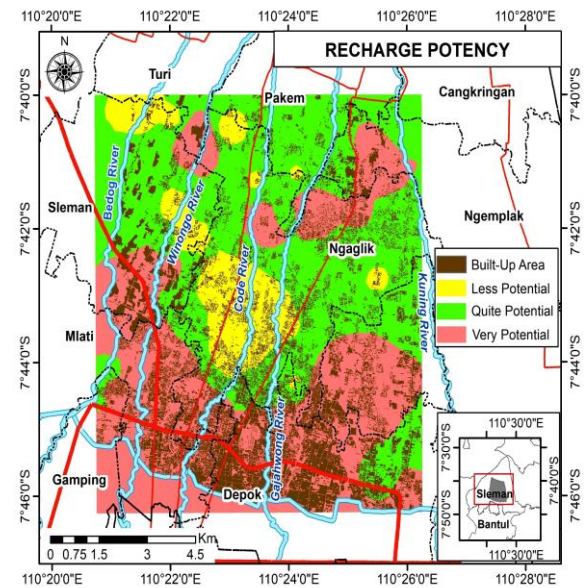


Fig.8 Map of recharge potency in the study area

4. CONCLUSION

The conclusions are as follows. (1) High infiltration rates spread over an area of less than 200 MAMSL, while infiltration rates above 200-300 MAMSL and 300 - 400 MAMSL tend to be smaller. The infiltration capacity tends to be high. The classification using ILRI and USCS for the research area is less appropriate because the soil is too porous. The Kohnke classification is more appropriate to be applied. (2) Based on the land cover, the area which is mostly covered with buildings is close to the urban area of Yogyakarta. The densely built area extends to the south, while the least dense built area stretch in the northern region. In the research area, the farther from the urban area is, the lower the built area will be. Conversely, the closer to the urban area is, the wider the built area will be (3) The built area which is very potential as a catchment area spread below 200 m high to around Mataram Ditch and in the northern regions at an altitude of up to 400 meters.

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