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# Groundwater recharge estimation using chloride mass balance method on the southern slope of Merapi Volcano, Indonesia

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**ABSTRACT**

Groundwater is a main resource for the majority of Indonesian people as a source of clean water to meet their daily needs. The increase in groundwater use is unavoidable due to increasing development in Indonesia, especially in Yogyakarta. Groundwater recharge is important in the hydrological cycle to meet groundwater needs. Therefore, this study aims to estimate groundwater recharge by the chloride mass balance (CMB) method on the southern slope of Merapi Volcano in Yogyakarta, Indonesia. This research was conducted in the rainy and dry seasons from August 2022 until January 2023. This research collects annual rainfall near the study area from the Meteorology, Climatology, and Geophysics Agency (BMKG) Yogyakarta station, monthly data collected from eighteen samples of groundwater station, and monthly data collected from fifteen samples of rainwater in the study area. The chemical content of groundwater and rainwater samples is analyzed using argentometry to obtain chloride concentration. The result of annual rainfall in the study area is 3,603.878 mm/year. The average chloride concentration in rainwater is 1.1 mg/L, while the average chloride concentration in groundwater is 8.015 mg/L. The CMB method calculation showed that the recharge in the study area ranges from 171.65 to 1,711.29 mm/year. The groundwater recharge has a positive correlation with elevation and rainfall. High groundwater recharge is also found in the northern area due to fractured lava aquifer.



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## 1. INTRODUCTION

According to sustainable development goals (SDGs) number 6, the quality and availability of water are important in human life and environmental sustainability [1]. In recent decades, population growth and economic development have increased groundwater demand and are projected to increase by around 1% in the next 30 years [2]. The rapid urbanization in Yogyakarta began in the early 1970s with a high rate of development building infrastructure in urban areas [3]–[5]. The result of rapid development in Yogyakarta is massive increases in groundwater use have occurred in the Yogyakarta-Sleman groundwater basin [3], [6], [7]. The southern slope of Merapi Volcano plays an essential role in the Yogyakarta-Sleman groundwater basin as a main recharge zone [8]. Estimating the groundwater recharge rate is the key to achieving sustainable groundwater resource management [9]. However, the recharge estimation in the southern slope of Merapi Volcano, especially in parts with high elevations around the slopes, has not been comprehensively investigated due to the topographic condition and the limitations of the method used to calculate groundwater recharge. Estimating natural groundwater recharge is very challenging because the process is influenced by many factors, such as spatial and temporal variability, climate, geology, hydrology, vegetation, and changes in land use [10]. Several groundwater recharge estimation methods can be applied depending on the field situation and data availability [11]. Scanlon *et al.* [12] have been classified as groundwater recharge estimation methods based on surface water, unsaturated zone, and saturated zone, and also can be categorized into physical, tracer, and numerical-modeling approaches. Chloride mass balance (CMB) is a tracer method in the unsaturated zone [12]. The CMB method for groundwater recharge estimation has been used by several researchers around the world, such as in Nevada [13], [14], Africa [15], and Asia [16]. Different techniques can estimate different rates of groundwater recharge, so it is crucial to choose the method according to the characteristics of the study area [17]. The previous research about groundwater recharge on the southern slopes of Merapi Volcano has been conducted using several methods, such as simple water balance [18] and water table fluctuation [3]. Until now, there is no detailed information related to groundwater recharge distribution on the southern slopes of Merapi Volcano. Previous studies have only focused on the assumption that an area has the same groundwater recharge. Therefore, this study would like to answer whether elevation, rainfall, and geological materials influence groundwater recharge on the southern slopes of Merapi Volcano using the CMB method, which has not been applied in the previous study.

## 2. RESEARCH METHOD

The research was conducted on the southern slopes of Merapi Volcano and circumscribed by the Boyong River on the west and Kuning River on the eastern side. The research location is highly topographic and can be divided into three volcanic landform units: volcanic slope, volcanic foot slope, and fluvio volcanic foot plain [19]. The total area of the research location is 77.6 km2 (Figure 1). The population growth is in line with infrastructure growth in North Sleman, especially in the tourism and hotel sectors. Therefore, groundwater management, especially in estimating groundwater recharge, is vital to ensure the availability of basic needs for the people.

Topography at the research location consists of the volcanic slope, volcanic foot slope, and fluvio volcanic foot plain, which are included as volcanic landform units [20]. The base map used in this research is the Indonesia Topographic Map (RBI) obtained from the Geospatial Information Agency (BIG) [20], while the digital elevation model (DEM) data is obtained from USGS Satelite with a resolution of 90 m [21]. Based on DEM data (Figure 2), the topographical elevation at the research location is 135-1,085 meters above sea level. The highest elevation is in the northern part of the study area, categorized as volcanic slope, and the lowest elevation is in the southern part, classified as fluvio volcanic foot plain. At the research location, two main rivers make up the research location: Boyong River and Kuning River.

The underlying rocks of the study area included young Merapi deposits, according to [22]. The research location consists of mostly gravelly sandstone and sandstone, with a little claystone and siltstone layering [6]. The rock is formed from the sedimentation process and is composed of volcanic products called fluvial-volcaniclastic at the research location [8]. There is also influence from a volcanic product such as tuff. From the northern to the southern area, fine-grained rock is increasing due to the decreasing energy of the sediment moving from the source of the Merapi Volcano.

Groundwater recharge estimation of the study area uses the CMB method. This method is one of the tracer methods in the unsaturated zone [12]. The method is based on the mass conservation between the atmospheric chloride input and the chloride output in groundwater [23]. The groundwater recharge by the CMB method is estimated using equation (1) [24].

$$\mathrm{R_T} = \frac{P_a * \mathrm{Cl_p}}{\mathrm{Cl}_{gw}} \tag{1}$$

Where $R_T$ is total recharge (mm/y), $P_a$ is annual precipitation (mm/y), $Cl_p$ is the harmonic mean of chloride concentration in rainfall water (mg/l), and $Cl_{gw}$ is the harmonic mean of chloride concentration in groundwater (mg/l). The harmonic mean of chloride concentration of groundwater and rainfall samples is calculated using (2) [25].

$$\overline{Cl} = \frac{\sum Cl}{\mathrm{n}} \tag{2}$$

Where $\overline{Cl}$ is the harmonic mean of chloride concentration, $\sum Cl$ is the sum of all samples' chloride concentration, and n is the number of samples.

The monthly rainfall data were collected from the Meteorology, Climatology, and Geophysics Agency (BMKG) on nine rainfall stations from February 2022 to January 2023 (Figure 2). The rainfall water was collected from 15 locations near the groundwater samples, as shown in Figure 3. In addition, the groundwater samples were collected from 18 sites of dug wells and springs (Figure 4). The water samples were collected using a liter high-density polyethylene (HDPE) bottle, washed with the sampled water three times, and filled until full and tightly sealed. The water samples were transferred to the Center for Environmental Health Engineering and Disease Control (BBTLKPP) Yogyakarta for chloride analysis accredited by the National Standard Committee (KAN). The chloride analysis using the argentometry method. The result of annual rainfall ($P_a$), chloride concentrations in groundwater ($Cl_{gw}$), and chloride concentration in rainfall water ($Cl_p$) have been known, and then the estimation of groundwater recharge can be calculated. The interpolation of chloride and recharge data using the inverse distance weighting (IDW) method using GIS software.

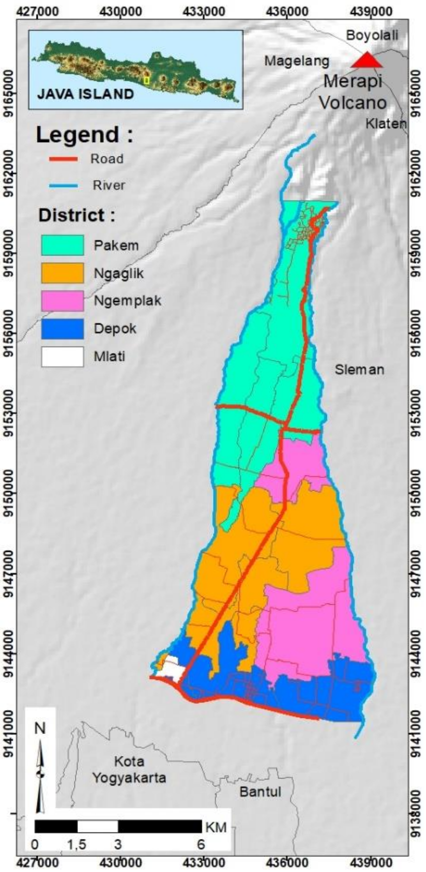



Figure 1. Location map of the study area

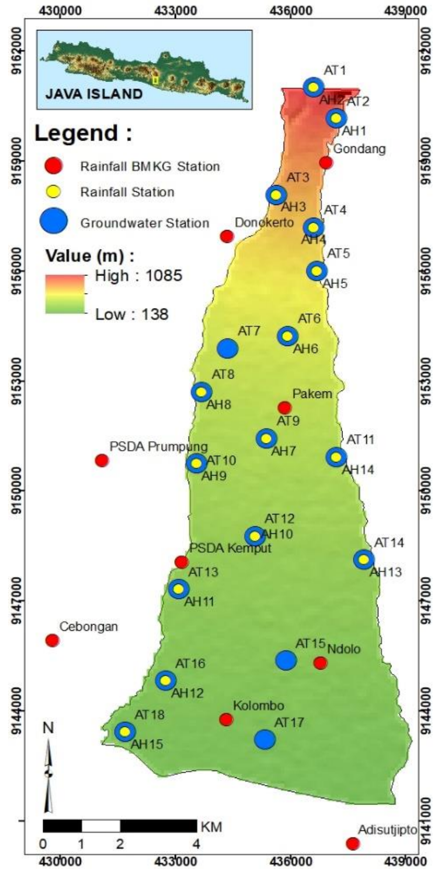



Figure 2. Topographic map of the study area

## 3. RESULTS AND DISCUSSION

### 3.1. Chloride concentration in rainfall water

Chloride concentrations in rainfall water are not significantly different within the study area. The spatial distribution of chloride concentration in rainfall can be seen in Figure 3. The average chloride concentration ranges between 0.5 and 1.42 mg/L from fifteen rainwater stations collected monthly. The highest average chloride concentration was found at AH10, with 1.42 mg/L as the average chloride concentration. The lowest average chloride value in rainfall was found at AH6, with 0.50 mg/L as the average chloride concentration. The highest average chloride concentration in rainfall water was found in the rainy season of January 2023, with 1.79 mg/L. The lowest average chloride concentration in rainwater was found in the dry season in August 2022, with 0.62 mg/L. It can be concluded that chloride concentration in rainfall water tends to be a random distribution with no significant difference in chloride concentration results.

### 3.2. Chloride concentration in groundwater

The chloride concentrations in groundwater samples significantly differ from rainfall due to a water-rock interaction. The spatial distribution of chloride concentration in the groundwater can be seen in Figure 4. The average chloride concentration ranges between 2.60 and 14.46 mg/L from eighteen groundwater stations collected monthly from August 2022 until January 2023 in the study area. The lowest average chloride concentrations in groundwater were found at AT1 with 2.60 mg/L in the northern part of the study area. In comparison, the highest average of chloride concentrations in groundwater was found at AT13 and AT17, with more than 14 mg/L in the southern part of the study area. However, the significantly different chloride concentrations in groundwater are affected by other sources of chloride rainfall, such as chloride from anthropogenic activities. High chloride concentration was found in the southern part than in the northern part of the study area due to the land use dominated by settlements, as shown in Figure 5. The land use type needs special attention in estimating groundwater recharge by the CMB method since this method assumes that the source of chloride is only from precipitation.

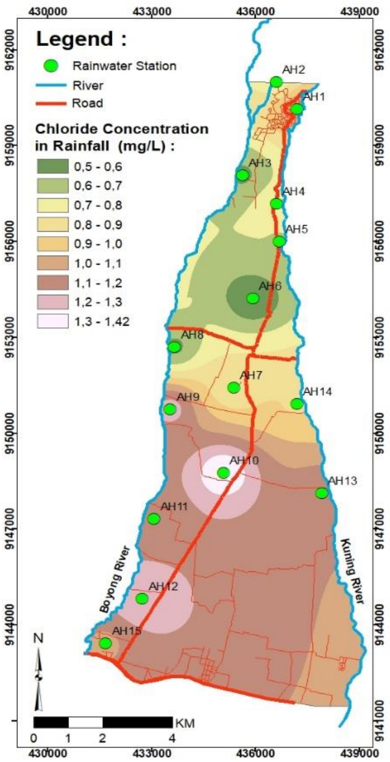



Figure 3. Spatial distributions of chloride in rainwater

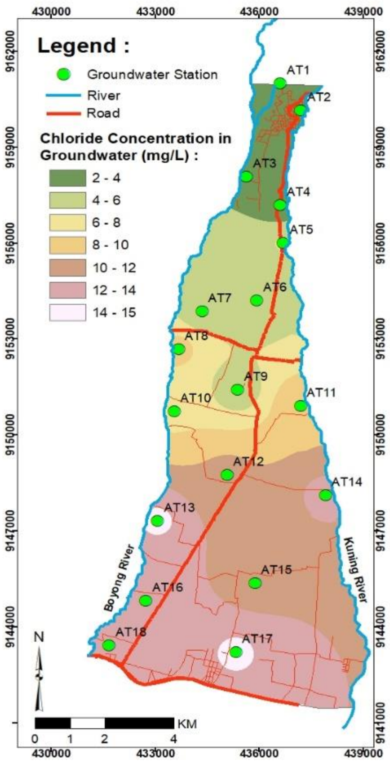



Figure 4. Spatial distributions of chloride in groundwater

### 3.3. Estimated groundwater recharge

The groundwater recharge estimation spatial distribution using chloride mass balance can be seen in Figure 6. The CMB method shows that the annual recharge rate in the study area is between 171.65 mm/year and 1,711.29 mm/year, with the percentage of recharge between 8.1% and 35.5% of the effective annual rainfall in the research area, as shown in Table 1. The highest recharge estimation was found at AT1 or in the northern area of the study area, with 1,711.29 mm/year. In contrast, the lowest recharge estimation was found at AT17 or in the southern area of the study area with 171.65 mm/year. However, one of the main factors that affect the value of estimation groundwater recharge using chloride mass balance is the rainfall data in the northern part of the study area has a higher rainfall value, such as in Gondang station, with an annual rainfall of more than 5,000 mm/year than in the southern area such as in Kolombo station with annual rainfall less than 3,000 mm/year. The difference in rainfall data makes a difference in the value of the recharge estimation. The other important parameter in recharge estimation using the CMB method is chloride concentrations in groundwater since the chloride concentration in rainfall water is not significantly different throughout the research area. The southern part of the study area with higher chloride concentrations in groundwater is possible from another source than precipitation based on the land use map. The rapid settlement in the study area's southern part certainly affects the CMB method's recharge estimation result. The result of groundwater recharge estimation by the CMB method is similar to previous researchers. The previous research that used water table fluctuation (WTF) shows that on the southern slope of Merapi Volcano of Yogyakarta City, the groundwater recharge ranges from 158 to 538 mm/year [3]. In comparison, using the simple water balance method shows that on the southern slope of Merapi Volcano (Indonesian Islamic University and surrounding areas), the groundwater recharge is 598 mm/year [18]. In addition, the latest research on groundwater recharge in a similar area using the simple water balance method is 689.48 mm/year [26].

Table 1. Estimated groundwater recharge

| Research station | Annual rainfall (mm/year) | Average $CL_p$ (mg/l) | Average $CL_{gw}$ (mg/l) | Recharge (mm/year) | % recharge (mm/year) |
|---|---|---|---|---|---|
| AT1 | 4,826.94 | 0.92 | 2.60 | 1,711.29 | 35.5 |
| AT2 | 4,905.26 | 1.10 | 3.78 | 1,425.95 | 29.1 |
| AT3 | 4,577.00 | 0.69 | 3.20 | 986.92 | 21.6 |
| AT4 | 4,588.56 | 0.75 | 3.59 | 958.08 | 20.9 |
| AT5 | 4,315.21 | 0.80 | 4.17 | 828.65 | 19.2 |
| AT6 | 4,055.49 | 0.75 | 4.10 | 741.86 | 18.3 |
| AT7 | 4,041.00 | 0.75 | 4.50 | 673.50 | 16.7 |
| AT8 | 4,005.34 | 0.75 | 4.71 | 638.34 | 15.9 |
| AT9 | 3,950.35 | 0.67 | 4.57 | 579.28 | 14.7 |
| AT10 | 3,911.39 | 1.00 | 7.55 | 518.00 | 13.2 |
| AT11 | 3,872.77 | 1.10 | 9.79 | 435.19 | 11.2 |
| AT12 | 3,591.36 | 1.25 | 10.55 | 425.56 | 11.8 |
| AT13 | 3,606.60 | 1.17 | 14.46 | 291.74 | 8.1 |
| AT14 | 3,425.51 | 1.17 | 12.63 | 317.30 | 9.3 |
| AT15 | 3,159.78 | 1.00 | 11.05 | 285.95 | 9.0 |
| AT16 | 2,679.28 | 1.32 | 12.96 | 272.81 | 10.2 |
| AT17 | 2,124.79 | 1.16 | 14.36 | 171.65 | 8.1 |
| AT18 | 2,804.06 | 1.10 | 13.06 | 236.19 | 8.4 |

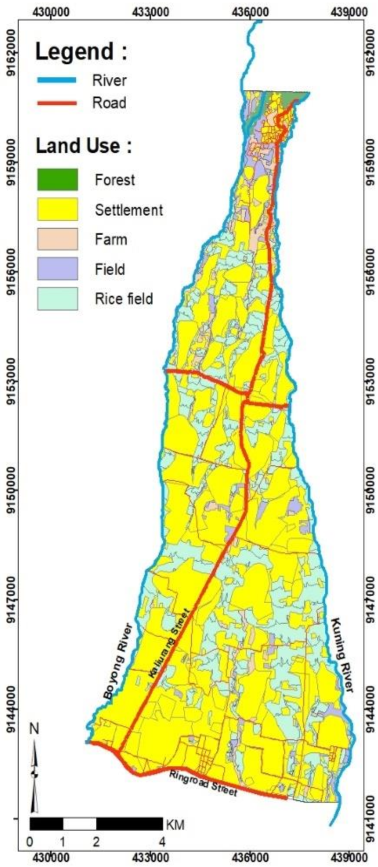



Figure 5. Land use map of the study area

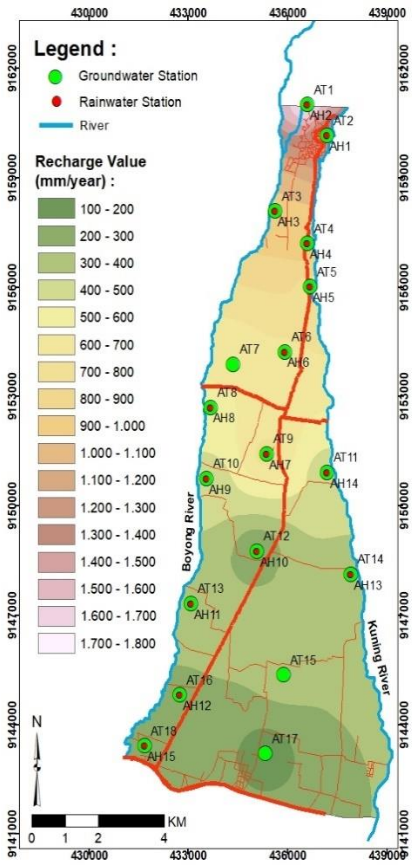



Figure 6. Map of groundwater recharge in the study area

### 3.4. Relations between groundwater recharge and elevation

The study results show that the groundwater recharge values were higher at locations with higher elevations. Hence, the northern part of the study location has a higher recharge value compared to locations with lower elevations in the southern, as shown in Figure 7. The linear equation for the relationship between the elevation value of the research location and groundwater recharge using the CMB method is y = 0.63x + 26.96, while the coefficient of determination is $R^2$ = 0.99. The coefficient of determination close to 1 indicates that groundwater recharge and elevation in the study area have a strong linear relation. The groundwater recharge estimation method using CMB is often used because of its time-integrated recharge estimate and low cost [27].

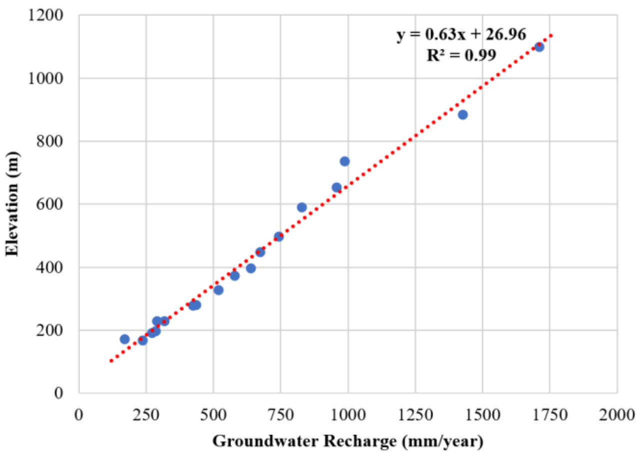



Figure 7. Relations between groundwater recharge and elevation

### 3.5. Relations between groundwater recharge and rainfall intensity

The study results show that the groundwater recharge is affected by the rainfall intensity in the study area. In the northern part of the study area, which generally has a high rainfall value, groundwater recharge is also high, while in the southern part of the study area, which has lower rainfall, groundwater recharge is also lower than in the northern part. After calculating the relationship between the rainfall intensity and the value of groundwater recharge in the study area, it was found that the rainfall intensity and groundwater recharge had a logarithmic relationship with y = 1,127.50 ln(x) – 3,264.40, while the coefficient of determination is $R^2$ = 0.92 (Figure 8). Similar to the relations between groundwater recharge and elevation, The coefficient of determination close to 1 indicates that groundwater recharge and rainfall intensity in the study area have a strong logarithmic connection.

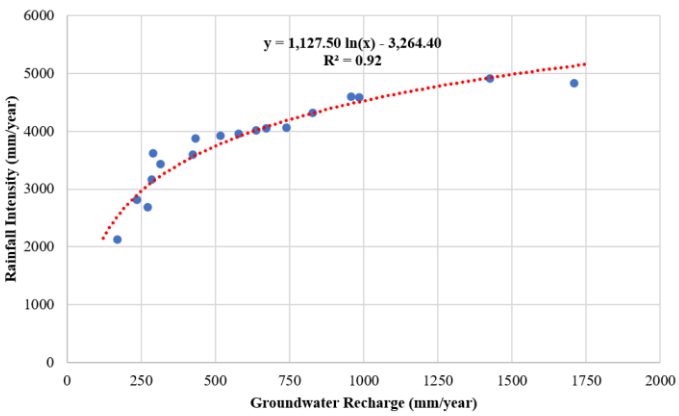
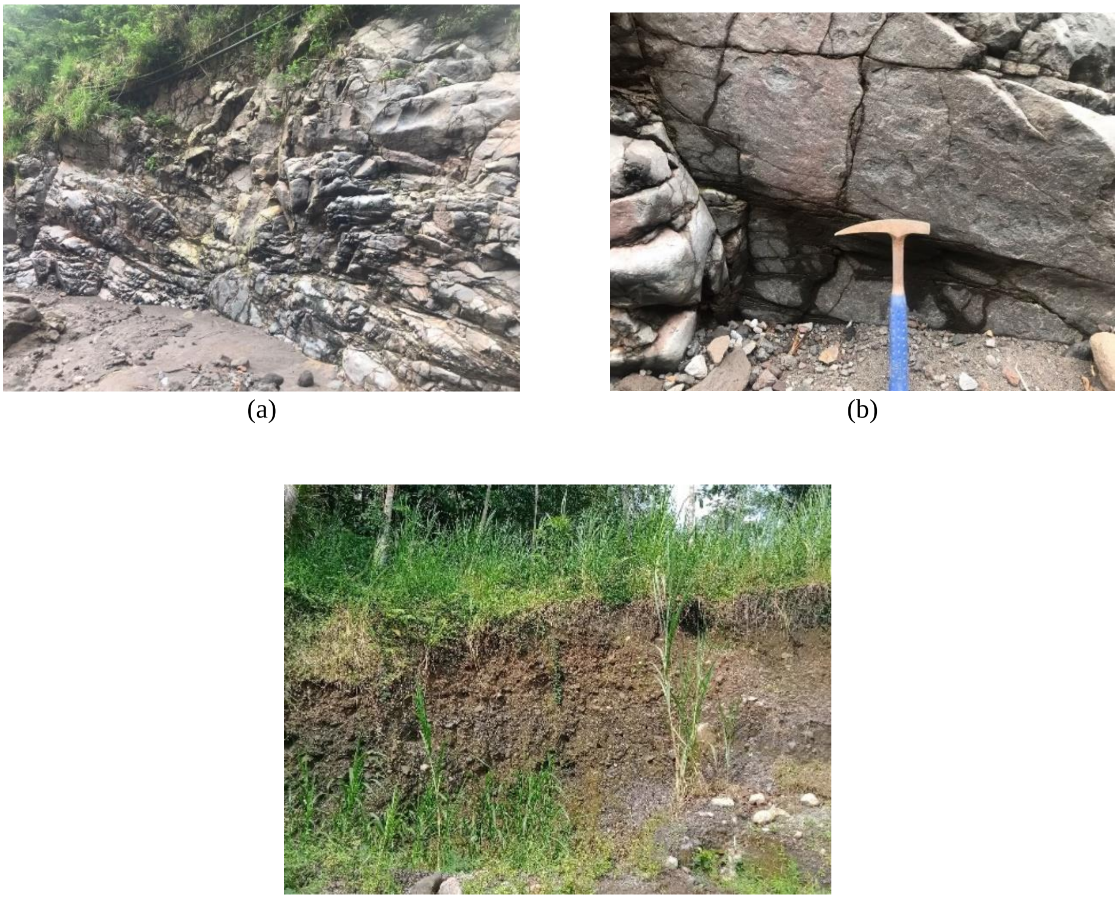



Figure 8. Relations between groundwater recharge and rainfall intensity

### 3.6. Relations between groundwater recharge and lithology

Figure 9 shows fractures in lava. The northern part of the research area is dominated by lava flows that are massively fractured and interconnected, as shown in Figures 9(a) and (b). However, going south, the lithology changed to the Merapi volcanic deposit, as shown in Figure 9(c). Fractures in lava are secondary porosity, which will increase the permeability value of the lava. With these interconnected cracks, the permeability value of lava is greater than that of Merapi volcanic deposits, which only have a porosity between grains; therefore, more rainwater will be infiltrated in the lava.



(a) (b) (c)

Figure 9. Fractures in lava (a) fractured lava outcrop around the upstream Boyong river, (b) close-up picture of fractured lava, and (c) outcrop of Merapi volcanic deposit at Umbulharjo Village

## 4. CONCLUSION

The groundwater recharge estimation at the southern slope of Merapi Volcano using the chloride mass balance method is 171.65-1,711.29 mm/year, with the highest value being in the northern part and the lowest in the southern part of the study area. These values are similar to previous studies for groundwater recharge estimation results. The recharge rate positively correlates with rainfall intensity with logarithmic relation y = 1,127.50 ln(x) - 3,264.40, with $R^2$ = 0.99. The recharge rate also positively correlates with an area's elevation with linear relation y = 0.63x + 26.96 and $R^2$ = 0.92. High recharge value in the northern part was also due to lava fracturing being more porous than the Merapi Volcanic deposit in the southern region. Therefore, this result can be used as basic information for developing groundwater use based on the safety yield on the south slope of Merapi Volcano. The CMB method for estimating groundwater recharge is still suitable, especially in areas that are still natural, with the source of chloride being only from precipitation. This method also has advantages compared to other methods that are cheaper, easier, and faster. However, one should be careful using the chloride mass balance method if the assumption of chloride source not only from precipitation and boundary conditions are not well known.

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