Groundwater Recharge Estimation Using Chloride Mass Balance (CMB)

Case Study: an Old Residential Area and a New Residential Area of Yogyakarta, Indonesia

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ABSTRACT

Water is an essential natural resource for improving economic activities, especially in urban areas which have domestic and industrial activities. The massive freshwater resource on earth is groundwater. In contrast, the volume of groundwater resources is minimal compared to the whole water volume in the world. Information on groundwater recharge is essential for optimum utilization. Therefore, this study aimed to estimate groundwater recharge using the Chloride Mass Balance (CMB) method in old and new residential areas in Yogyakarta City, Indonesia. This study was carried out during a period of the dry season and the wet season starting from September 2021 to February 2022. Collected data in this research were daily rainfall of 6 months of observation, nine groundwater samples, and three rainwater samples of each study area. The chemical content of groundwater and rainwater samples was analyzed using ion chromatography to obtain each sample's Cl- concentration. The analysis showed that the average yearly rainfall in both study areas is 2972.39 mm/year. The average Cl^- concentration of groundwater in old and new residential areas was 21.06 mg/L and 22.65 mg/L. The average Cl^- concentration of rainwater in old and new residential areas was 0.90 mg/L and 0.83 mg/L. Using the CMB method equation, the average groundwater recharge in old and new residential areas was 126 mm/year and 109 mm/year. These values were far below the result of groundwater recharge estimation reported by previous studies.

Keywords: *Groundwater resource, Groundwater recharge, Chloride mass balance method.*

1. INTRODUCTION

Yogyakarta City is the capital city of the Special Region of Yogyakarta Province which is known as a centre of Indonesian education and classical Javanese culture. According to BPS-statistics of Yogyakarta, the population density of Yogyakarta City has increased in the last 20 years from 10.489 to 11.495 per square km [1]. Yogyakarta City has been experiencing urban expansion due to rapid urbanization since 1970 [2]. It may influence not only Yogyakarta City itself but also the peri-urban area around Yogyakarta City namely Sleman and Bantul Agglomeration Area [3][4]. Land use transformation from open and agricultural land towards settlement areas is massive, especially in Sleman and Bantul Agglomeration Areas. Land-use change induced by urbanization causes significant changes in the frequency and volume of groundwater recharge, although these changes cannot be measured directly [5]. Therefore, urban groundwater recharge study must become a priority issue since it will give a significant impact on the total groundwater resources both quantity and quality aspect. Estimation of groundwater recharge rate is a prerequisite for sustainable groundwater resource management [6].

Since groundwater recharge is difficult to be measured, previous researchers use multiple approaches to estimate groundwater recharge. Various groundwater recharge estimation techniques can be used depending on data availability and the field situation [7]. [8] classified groundwater recharge estimation method based on the three hydrologic zones, namely surface water, unsaturated zone, and saturated zone. Moreover, those can be categorized into physical, tracer, and numerical-modelling approaches. Techniques based on surface water and unsaturated zone estimate potential recharge

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while saturated zone techniques generally estimate actual recharge [8], [9]. [9] have reviewed various commonly used recharge estimation methods in Southern Africa according to limitations, applicability (range of fluxes, spatial, and temporal scales) and ratings (accuracy, ease of application, cost). Based on those parameters, the following methods are categorized as promising methods: Chloride Mass Balance (CMB), Cumulative Rainfall Departure (CRD), Water Table Fluctuation (WTF), Groundwater Modelling (GM), and Saturated Volume Fluctuation (SVF).

Groundwater recharge studies in Yogyakarta City have been conducted by previous researchers such as [10] and [11] using several techniques namely the Simple Water Balance (SWB) method and Water Table Fluctuation (WTF) method. These provide a range of groundwater recharge rates in Yogyakarta City. In comparison, this study aimed to estimate groundwater recharge in Yogyakarta City using Chloride Mass Balance (CMB) which has not been applied in a study area. From the result, this study will interpret how significant the difference in estimation is from the previous studies.

2. METHOD

The study areas consist of two distinct ages of residences, namely old and new residential areas of Yogyakarta City. The old and new residential areas are located in Kraton Subdistrict, Yogyakarta City and Ngestiharjo Village, Bantul Regency. Those were selected based on the similarity in geogenic factors and the difference in anthropogenic factors. Geogenic factors consist of the characteristic of the unsaturated zone, slope, elevation, and average annual precipitation, whereas anthropogenic factors consist of the age of settlement, type of sanitation system, and source of water. Values of those parameters are summarized in **Table 1**. The location of the study areas is shown in **Figure 1**.

Table 1 Criteria selection of study areas.

Parameters	Old Residence	New Residence
[a]Unsaturated zone	Soil, Finer sandy, Coarser sandy	Soil, Finer sandy, Coarser sandy
[b]Slope & elevation	0-8%; 99.83 masl	0-8%; 96.77 masl
[c]Annual precipitation (mm/y)	2207.29 mm/y	2227.25 mm/y
[d]Age of settlement (y.o.)	>20 y.o.	<20 y.o.
[e]Type of sanitation system	Sewered	Unsewered (Septic tank)
[f]Water supply	Water pipeline system & wells	Wells

Description:
[a]log bordata from [10] — [c]Precipitation data from [12] — [e]data from [13]
[b]Digital Elevation Model (DEM) from [14] — [d]Data from [15] — [f]data from [16]

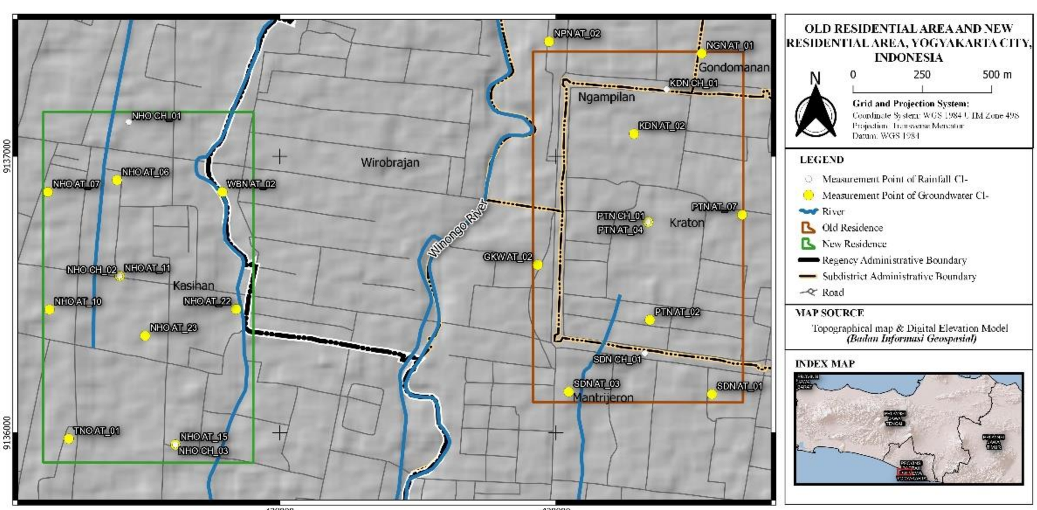

Figure 1 Location of study areas.

The analysis of groundwater recharge rate in research areas was estimated using Chloride Mass Balance (CMB) method. The idea of this method was the mass conservation between the input of atmospheric chloride and the output of chloride in groundwater [9]. The groundwater recharge rate estimation using the CMB method was calculated using the following $\mathrm{R_T} = \frac{P_a * \mathrm{Cl_p}}{\mathrm{Cl_{gw}}}$ (1) [17]:

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

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 (mg/l), and Cl_{gw} is the harmonic mean of chloride concentration in groundwater (mg/l).

Annual precipitation (P_a) data was obtained from the calculation of the daily precipitation data for six months of observation (September 2021 to February 2022) using $P_a = \frac{\sum P_d}{0.5}$ (2):

$$P_a = \frac{\sum P_d}{0.5} \quad (2)$$

Where P_a represents annual precipitation, P_d is daily precipitation (mm), and 0.5 represents half of the year (y).

The daily precipitation was collected from the Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS raster dataset), provided by Climate Hazards Center UC Santa Barbara. Both rainfall and groundwater samples were taken every two months in six rainfall stations and eighteen dug wells spread evenly in study areas (**Figure 1**). The chloride concentration of samples was analyzed using the ion chromatography (IC) method. The harmonic mean of both chloride concentration of groundwater and rainfall samples was calculated using $\overline{Cl} = \frac{\sum Cl}{n}$ (3):

$$\overline{Cl} = \frac{\sum Cl}{n} \quad (3)$$

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

3. RESULTS AND DISCUSSION

3.1. Estimation Result of Groundwater Recharge

The time-series graph of daily precipitation data for six months of observation is shown in **Figure 2**. **Figure 2** showed a positive linear trend, indicating the increase in daily precipitation from the end of the dry season to the early wet season. Using $P_a = \frac{\sum P_d}{0.5}$ (2), the annual precipitation of the study areas was 2972.39 mm/year.

The graph of chloride concentration in groundwater for six months of observation is shown in **Figure 2**. **Figure 2** revealed a positive linear trend representing the increase of chloride concentration in groundwater from the end of the dry season to the early wet season. Increasing chloride during the wet season was caused by the increase of soil leaching during the wet season, causing the number of ions to be brought by the water and entered the saturated zone. Using $\overline{Cl} = \frac{\sum Cl}{n}$ (3), the harmonic mean of groundwater's chloride concentration in old and new residences was 21.06 mg/L and 22.65 mg/L. The harmonic mean of rainwater's chloride concentration in old and new residences was 0.90 mg/L and 0.83 mg/L.

Using $R_T = \frac{P_a * Cl_p}{Cl_{gw}}$ (1), the total groundwater recharge estimation in old and new residences was 126 mm/year and 109 mm/year. Considering the extent of the study area is 0.96 km^2, the groundwater recharge rate in old and new residences was 1.21 x 10^8 l/year and 1.05 x 10^8 l/year.

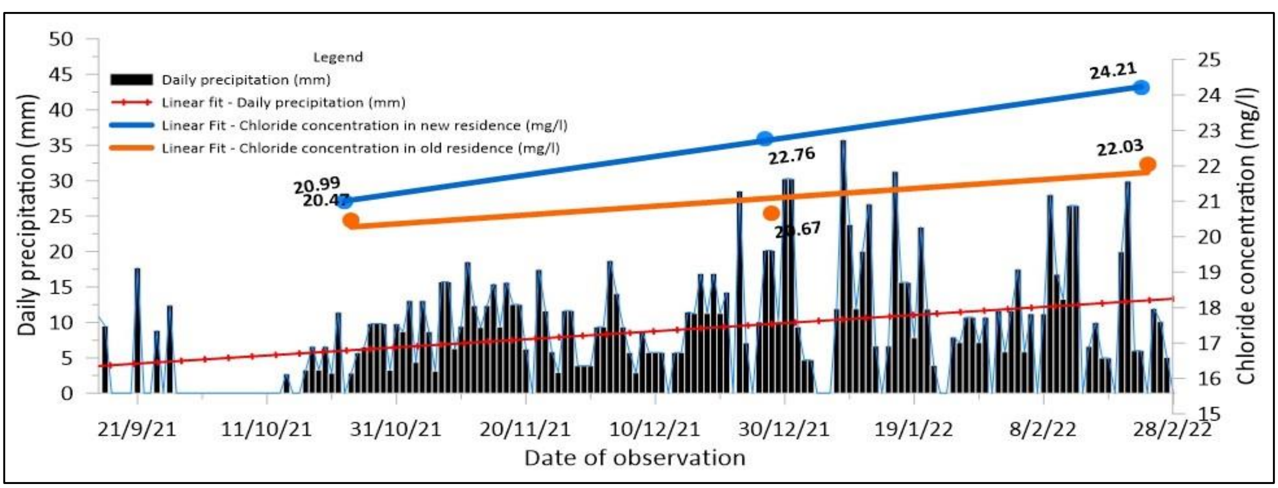

Figure 2 Daily precipitation vs. chloride concentration of groundwater in study areas.

3.2. Comparison Results with Previous Studies

Table 2 shows a compilation of groundwater recharge estimation from previous studies compared to this study in Yogyakarta City. Based on **Table 2**, the estimation of groundwater recharge using the CMB method was far below the result of groundwater recharge estimation reported by previous studies.

The significant difference in results between this study and previous studies is logic scientifically due to the difference in the use of the method. CMB method applies the concept of chloride mass conservation between rainfall as input and groundwater as output. This concept represents how rainfall contributes to the groundwater as groundwater recharge. On the other hand, the WTF method is based on groundwater level fluctuation data representing the change from the dry season to the wet season. This concept represents how groundwater recharge affects the change of groundwater level from the dry to the wet seasons.

Based on the input parameter, the CMB method only considers precipitation recharge as a component of recharge, while the WTF method considers all of the water that can be possible to recharge groundwater. In the case of urban areas, sources of recharge are various due to the effect of urbanization. In general, There are three major sources of groundwater recharge in urban areas, such as precipitation recharge, leakage of wastewater from sanitation systems, and leakage of the pipeline water system. Therefore, the CMB method will give an underestimate result.

Table 2 Comparison of groundwater recharge estimation in Yogyakarta.

Authors	Study area	Time of observation	Method	Groundwater recharge (mm/y)
[10]	Northern of Yogyakarta city	2005	Water Table Fluctuation (WTF)	600
[10]	Yogyakarta city	2007	Simple Water Balance (SWB)	434
[11]	Central of Yogyakarta city	April 2014 – Mei 2015	Water Table Fluctuation (WTF)	539
Present study	Kraton subdistrict, Yogyakarta city	September 2021 – February 2022	*Chloride Mass Balance* (CMB)	126

CONCLUSION

Using the CMB method equation, the average groundwater recharge in an old residential area is 126 mm/year, while the average groundwater recharge in a new residential area is 109 mm/year. These values are far below the result of groundwater recharge estimation reported by previous studies due to the difference in input parameters of the groundwater recharge source.

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