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Simulation of Rainwater Harvesting Potential to Satisfy Domestic Water Demand Based on Observed Precipitation Data in Jakarta

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Highlights:

- Rooftop rainwater harvesting can cover up to 28% on average of domestic water demand in Jakarta if 30% of its area has an RRWH system installed.
- South Jakarta would have the highest fulfillment of water needs with an average of 28% based on three simulations.
- Central Jakarta would have the lowest fulfillment of water needs with an average of 16.4% based on three simulations.

Abstract. Jakarta as the most populous urban center of Indonesia has a major problem related to clean water availability for the domestic needs of its residents, who mostly depend on the extraction of groundwater. The rooftop rainwater harvesting (RRWH) system is a solution to reduce the use of groundwater to satisfy domestic water needs. This study used demographic data and precipitation observation data from the rain gauge network in Jakarta to simulate the water supply from rainwater harvesting from 2010 to 2019 in each municipality. Three simulations were carried out to calculate the percentage of domestic water demand (DS) satisfied by RRWH based on the proportion of residential areas installed with RRWH (R_A). The results showed that an R_A value of 0.2 produced the lowest DS (approximately 11% to 18.7%), while an R_A value of 0.3 produced a higher DS (approximately 16.3% to 28%). An R_A value of 0.4 resulted in a DS of around 21.8% to 37.4%. Overall, the RRWH system could provide up to 30% of domestic water demand on average, with South Jakarta having the highest fulfillment of water needs with an average of 28% based on the three simulations, while Central Jakarta had the lowest with 16.4%.

Keywords: *domestic water demand; population density; precipitation; rainwater harvesting; Jakarta.*

1 Introduction

Water supply deficiency is a serious threat for residents in Jakarta, the most populous city in Indonesia, with an annual water demand of more than 1 billion

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m^3 [1]. More than 70% of mid to low income inhabitants in Jakarta rely on groundwater as their primary or secondary clean water source for domestic needs, even though saline groundwater sources dominate the northern parts of the city [2]. Past studies have shown that excessive groundwater extraction has caused significant land subsidence [3-6] and broad seawater intrusion in Jakarta [7].

Jakarta has a monsoonal type of rainfall pattern [8] with the rainy season lasting from late November to the middle of March [9]. The Ciliwung River Basin is one of the most important basins in Jakarta. It has high average annual precipitation of around 3,125 mm[10]. The excess rainwater would be highly useful if it could be used to fulfill daily water needs. Rainwater harvesting systems in residential areas have been proposed as an alternative way to maintain the availability of clean water for domestic needs [11,12] and to reduce the dependency on groundwater [13].

The effectiveness of rainwater harvesting systems depends robustly on the collection area, storage and the amount of precipitation in the area where the system is installed [14-16]. One of the most frequently used rainwater harvesting systems is rooftop rainwater harvesting (RRWH), which utilizes the rooftop of a building as rainwater collector [16-19]. Previous studies have assessed the potential of RRWH in Jakarta. Harsoyo [20] estimated that the rooftop rainwater harvesting technique could potentially cover up to 28% of the daily water needs of residents in Jakarta, specifically near the Ciliwung downstream watershed. Sari [21] assessed the application of rainwater harvesting in residential areas in North Jakarta and found that it can cover the annual water needs per household up to 392 m^3. The case study by Kartolo and Kusumawati [22] in West Jakarta found that a roofing coefficient of 90% in collecting rainwater can be used to fulfill more than 75% of domestic water needs for toilet purposes only. Although the aforementioned studies comprehensively evaluated the potential of RRWH in Jakarta, these studies were limited to specific locations and used precipitation data collected from a small number of rain gauges. Therefore, the present study aimed to elucidate the potential of RRWH based on domestic water usage and precipitation datasets collected from a high-density network of rain gauges in Jakarta.

2 Methodology

2.1 Study Area

Five municipalities of Jakarta Province (DKI Jakarta) were chosen as study areas: East, West, Central, South and North Jakarta. Kepulauan Seribu District was excluded from North Jakarta Municipality considering that it is an islands-district separated by the Java Sea from mainland Jakarta. All of these municipalities have the same monsoonal type of rainfall, although they differ in the length of the rainy and dry seasons. The southern parts of Jakarta have a longer rainy season, from the end of October to the end of May, while in the northern parts it lasts from early December to mid-March [23].

Precipitation data were collected from 24 rain gauges in Jakarta for the 2010-2019 period. The rain-gauge datasets used in this study underwent quality control carried out in accordance with the hydrometeorological data management standards issued by the Agency for Meteorology, Climatology and Geophysics of the Republic of Indonesia (BMKG). The location details of the rain gauge network in Jakarta are shown in Figure 1.

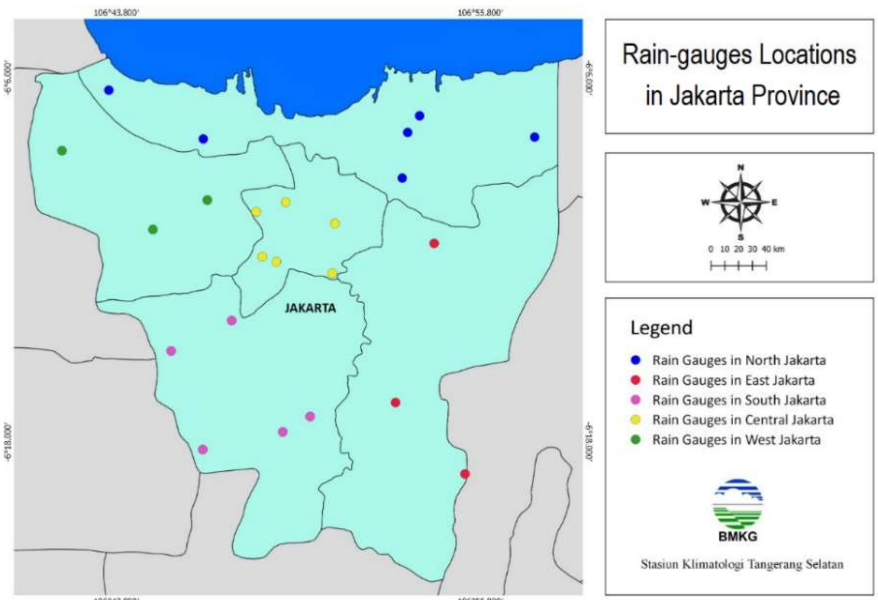

Figure 1 Rain-gauge locations in Jakarta Province.

2.2 Domestic Water Demand

Demographic data obtained from the Department of Population and Civil Registration of DKI Jakarta Province and BPS-Statistics Indonesia [24] were utilized to calculate the population density (people/m^2) in five Jakarta municipalities: Central Jakarta, West Jakarta, East Jakarta, South Jakarta and North Jakarta (excluding Kepulauan Seribu) for each year from 2010 to 2019. The daily average domestic water demand per household, WD_h (liter household^{-1} day^{-1}), in Jakarta was assumed based on Kooy, *et al.*[2] without taking into account the consumption of refill water and bottled mineral water as it may be used for drinking purposes.

Water demand was assumed to vary annually based on changes in population density only. The domestic water demand per area, WD (liter/m^2), in each municipality was calculated for a 10-day period using Eq. (1).

$$WD = \frac{WD_h}{average\ nr.\ of\ members\ per\ household} \times population\ density \times 10\ day \qquad (1)$$

where the average number of members per household in Jakarta is around 4 people based on the demographic data. A 10-day time scale was utilized to follow the definition of the onset of the dry season and the rainy season issued by the BMKG, which is determined based on 10-day accumulated precipitation.

2.3 RRWH Parameters

10-day accumulated precipitation for each municipality, P_{10} (mm), defined as the accumulation of average daily precipitation from all rain gauges located in the same municipality for 10 days. The unit of P_{10} was not converted, as 1 mm of precipitation falling in an area of 1 m^2 is equal to 1 liter of water per m^2.

The percentage area of buildings installed with RRWH, R_A, was assumed to be equal for all Jakarta municipalities with building coverage lower than 0.55%, as discussed by Ardiansyah, *et al.* [25]. Three different simulations were undertaken, based on R_A values of 0.2, 0.3, and 0.4 respectively. The collection efficiency of the RRWH system used in this study, C_E, was 0.9, as used in Mun & Han [16]. The rainwater collected in the water storage was assumed to be used directly for daily domestic purposes. As such the storage capacity was not included in the water supply calculation. The water supply for a 10-day period, WS (liter/m^2), was calculated using Eq. (2).

$$WS = R_A \times C_E \times P_{10} \qquad (2)$$

The percentages of domestic water demand satisfied by RRWH, DS (%), from the three simulations and the five municipalities were compared to analyze the RRWH potential in Jakarta using Eq. (3).

$$DS = \frac{\sum WS}{\sum WD} \times 100\% \qquad (3)$$

3 Results and Discussions

3.1 Precipitation Climatology in all Jakarta Municipalities

The P_{10} climatology was calculated for all Jakarta municipalities from 2010 to 2019 to understand the variability of precipitation and its seasonal characteristics in each area, as presented in Figure 2. All municipalities had the highest precipitation in the middle of January (from 134.3 mm to 156 mm) and the lowest precipitation at the end of August (from 16.4 mm to 27.3 mm). In general, South Jakarta had the highest precipitation among the Jakarta municipalities, while North Jakarta had the lowest precipitation. The graph indicates that the precipitation in all municipalities was of the monsoonal type, as confirmed by Tjasyono, *et al.* [8].

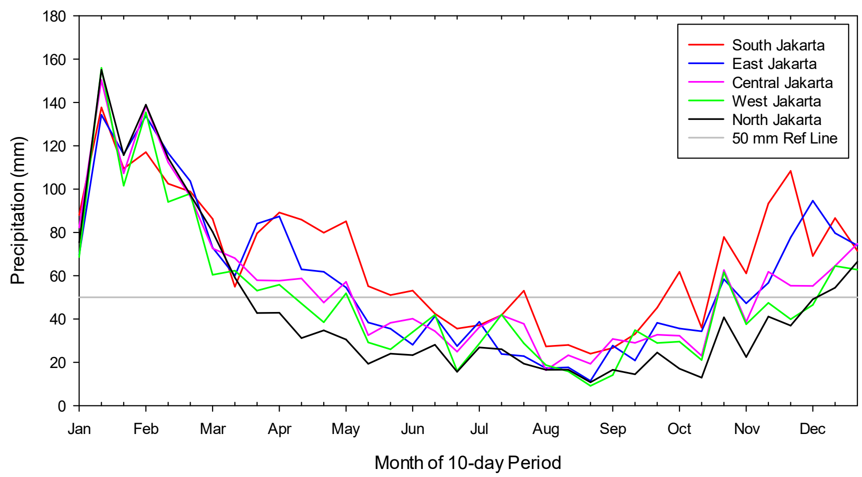

Figure 2 The 10-day precipitation (P10) climatology in all Jakarta municipalities from 2010 to 2019.

A threshold of 50 mm for ten days of accumulated precipitation was utilized to determine the rainy or the dry season in all municipalities. The result shows that South Jakarta had the longest rainy season (the shortest dry season), from the end of October to early July. In contrast, North Jakarta had the shortest rainy season (the longest dry season) from December to the middle of March. These findings corroborate the precipitation climatology calculated from longer data periods by the Agency for Meteorology, Climatology and Geophysics [23].

Table 1 shows that South Jakarta had the highest annual precipitation in almost all years, followed by Central and East Jakarta, while North Jakarta had the lowest, followed by West Jakarta. Most of the annual precipitation in all municipalities was above 1,500 mm in all years, except in 2011 and 2012, when precipitation was 1,000 mm and 1,500 mm.

Table 1 Annual precipitation in all Jakarta municipalities (2010-2019).

Year	South Jakarta	East Jakarta	Central Jakarta	West Jakarta	North Jakarta
2010	3,377	2,521	2,513	2,313	1,902
2011	1,479	1,116	1,287	1,413	1,013
2012	2,469	1,318	1,561	1,228	1,017
2013	3,014	2,661	2,471	2,225	1,896
2014	2,972	2,939	2,708	2,461	2,300
2015	1,540	1,710	1,924	1,549	1,895
2016	2,978	2,844	2,726	2,305	1,910
2017	3,020	2,363	2,019	1,790	1,712
2018	1,865	1,764	1,451	1,279	1,433
2019	1,626	1,815	1,468	1,457	1,338

3.2 Domestic Water Demand in all Jakarta Municipalities

The average domestic water needs per inhabitant in Jakarta, derived from Kooy, *et al.* [2], is approximately 422.7 liter per day. The 10-day accumulated domestic water demand per m^2 (WD) was calculated as shown in Figure 3.

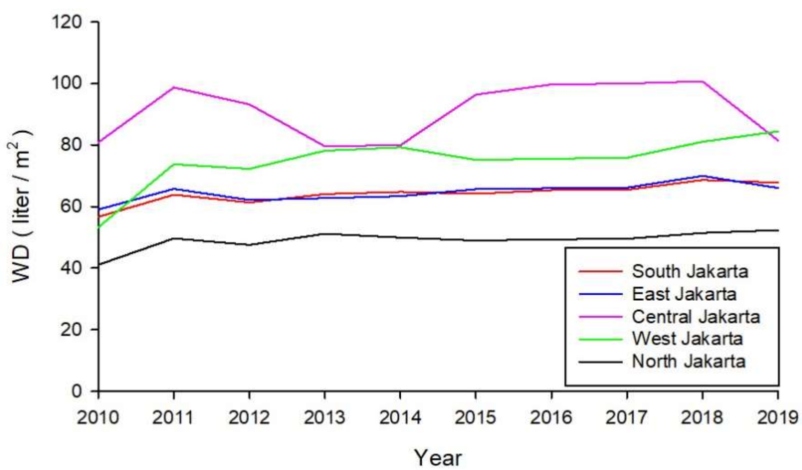

Figure 3 10-day accumulated domestic water demand (WD).

Figure 3 indicates that Central Jakarta has the highest WD, at around 80 to 100 liter per m^2 area, while North Jakarta has the lowest WD, at 41 to 53 liter per m^2

area. This higher WD in Central Jakarta is caused by its higher population density compared to the other municipalities around (21,538 inhabitants/km^2). Therefore, more water supply is required to satisfy the domestic water needs in Central Jakarta as compared to the other municipalities.

Meanwhile, North Jakarta has a lower population density (about 11,626 inhabitants/km^2), which results in the lowest WD among all Jakarta municipalities. Although this area has lower WD compared to the others, satisfying the domestic water demand will be difficult because the precipitation in this area is also lower than in the other municipalities, as shown in Figure 2 and Table 1. Annual variability in WD is mostly related to the migration and changes in population density in Jakarta, considering the city is one of the fastest growing cities in Indonesia [26].

3.3 Water Supply Estimation from RRWH

The average 10-day WS values displayed in Figure 4 are based on the assumption that 20% of the area in each municipality has RRWH systems installed, resulting in much lower WD values. The WS value with RA equal to 0.2 was significantly lower compared to the other simulations, where it ranged between 4.3 to 28 liter per m^2, or about 13% to 25% of the average WD in each municipality. The average WS values have the same seasonal variability as Pr_{10}, because the water supply was calculated based on observed precipitation data. The highest WS occurred in mid-January, while the lowest was at the end of August for almost all municipalities.

Based on Table 2, an R_A value of 0.2 produced the smallest DS (about 11% to 18.7%), while an R_A value of 0.3 produced a higher DS (around 16.3% to 28%). The highest R_A value in the simulations resulted in a DS of around 21.8% to 37.4%. The higher DS resulted from a higher R_A value because R_A represents the percentage area of buildings with RRWH installed in each area. According to the DS simulation results, the RRWH system could provide up to 30% of domestic water demand on average.

Central Jakarta had the lowest DS with an average of 16.4% due to having the highest population density. Meanwhile, South Jakarta had the highest DS with an average of 28%, which is in accordance with Harsoyo [20], as this municipality is part of the Ciliwung downstream watershed. An interesting finding in this simulation is that although North Jakarta had the lowest P_{10}, the municipality generated the second highest DS, with a small difference compared to South Jakarta.

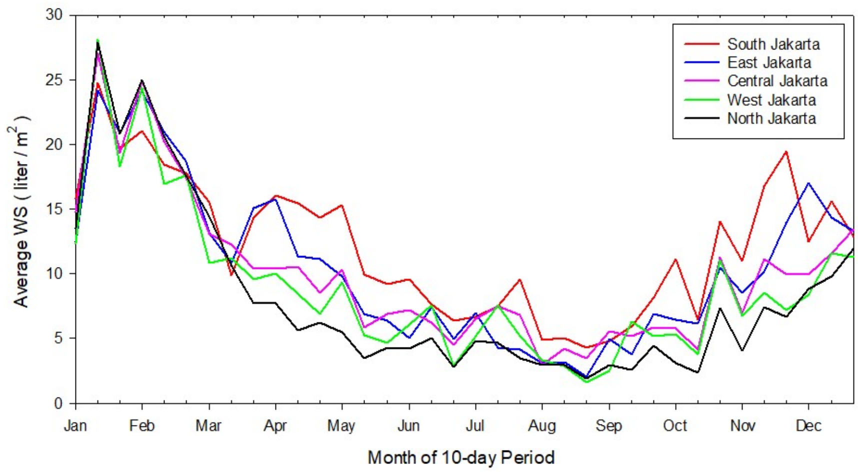

Figure 4 The average WS in all Jakarta municipalities from 2010 to 2019 based on an R_A value of 0.2.

Table 2 The DS from three simulations and average population density in all Jakarta municipalities for 2010-2019.

		DS (%)				
		South Jakarta	**East Jakarta**	**Central Jakarta**	**West Jakarta**	**North Jakarta**
	0.2	18.7	16.0	10.9	11.9	16.5
$\mathbf{R_A}$	0.3	28.0	24.1	16.3	17.8	24.7
	0.4	37.4	32.1	21.8	23.7	32.9
Average Population Density per km²		15,036	15,186	21,332	17,261	11,459

4 Conclusions

This study simulated water supply fulfillment using RRWH to satisfy domestic water demand based on demographic data and observed precipitation data collected from the rain-gauge network in Jakarta. It was found that Central Jakarta has the highest domestic water demand due to having the highest population density among all Jakarta municipalities, while North Jakarta has the lowest demand. The water supply simulation of the RRWH system showed the same variability pattern as precipitation variability but with 20% lower values in each area.

Based on different proportions of areas installed with RRWH system, the simulation results demonstrated that South Jakarta, followed by North Jakarta, has higher domestic water needs fulfillment by RRWH, while Central Jakarta was found to have the lowest value. It can be concluded from the simulation results that the RRWH system can cover approximately 15% of domestic water demand under the lowest area installed with RRWH system and up to 30% under the highest area installed with RRWH system in the simulation.

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