IPTEK The Journal of Technology and Science, 32(2), 2021 (e/pISSN:2088-2033, 0853-4098)

DOI: 10.12962/j20882033.v32i2.7735 | Received 10 Sept, 2020; Accepted 28 Aug, 2021

ORIGINAL RESEARCH

THE EFFECT OF PRECIPITATION ON SCAVENGING OF $PM_{2.5}$ IN JAKARTA BASED ON DISTRIBUTED LAG NON-LINEAR MODELS

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Abstract

Fine particles, including $PM_{2.5}$, impact human health, especially in a megacity such as Jakarta. Meanwhile, precipitation is one of the most efficient mechanisms to reduce atmospheric particulate matter, including $PM_{2.5}$. This study investigated the changes in $PM_{2.5}$ concentrations before and after rain events along with the threshold of precipitation and a certain time lag that affects the reduction of $PM_{2.5}$ concentrations in Jakarta from 2017 to 2019. $PM_{2.5}$ concentration datasets from two observation sites at Central and South Jakarta were used in this study. The relative effect and scavenging probability of $PM_{2.5}$ concentrations were calculated to seek further understanding of the effect of rain events on the decrease of $PM_{2.5}$ concentrations using hourly data. A Non-Linear Distributed Pause Model was used in this study with hourly rainfall data and hourly air temperature that controlled the reduction in $PM_{2.5}$ concentrations. This study indicates that higher precipitation provides greater influence to the decrease of $PM_{2.5}$ concentration in both Central Jakarta and South Jakarta. The precipitation threshold for reducing $PM_{2.5}$ concentrations in Central Jakarta is 5 mm of rainfall with no time lag and a maximum delay of up to 12 hours. The South Jakarta area is 5 mm of rainfall with a time lag of up to 10 hours. In addition, the results suggest an increase in the probability of the concentration of $PM_{2.5}$ below the standard (SP) with rainfall and a certain time lag that was greater in South Jakarta, which was up to 19% compared to 11% in Central Jakarta.

KEYWORDS:

Distributed Non-Linear Lag Model, Particulate Matter, Precipitation, Relative Effect, Wet Deposition

1 | INTRODUCTION

Air pollution is a serious problem in a Megacity. It is a consequence of industrial development and increasing urbanization, which negatively impacts the environment and human health[1]. Particulate Matter (PM) is a part of air pollutants that consists of very small particles that contain organic chemicals, metals, soil particles, or dust. PM is categorized based on its aerodynamic diameter[2], one of them is $PM_{2.5}$ with an aerodynamic particle diameter of fewer than 2.5 µm. Emissions from $PM_{2.5}$ are closely associated with increased cardiovascular and respiratory morbidity and premature death due to long-term exposure[3]. In addition to having an impact on health, $PM_{2.5}$ also impacts the environment, such as reducing visibility[4–6].

Jakarta is the capital city of Indonesia, one of the most polluted cities globally, with a high and increasing level of air pollution that threatens public health[7]. The large population with increasing purchasing power causes private vehicles to grow rapidly[8]. Emissions from petroleum-powered vehicles greatly contribute to pollution in fine particles ($PM_{2.5}$) in urban areas[9]. According to the national press release by Badan Meteorologi Klimatologi dan Geofisika[10], there was an increase in pollutant particles throughout June to early July 2019 in Jakarta, with the highest $PM_{2.5}$ concentration reaching 73 µg m^{-3}. This national issue indicates that the $PM_{2.5}$ concentration in Jakarta has exceeded the national ambient air quality standards (BMUA).

Previous studies have shown that meteorological variables can affect PM concentrations such as rainfall, humidity, wind speed, and air temperature[11–13]. Precipitation can be considered the most efficient mechanism in reducing atmospheric particulate pollution[14–16]. The purpose of this study was to obtain a quantitative effect of precipitation on the $PM_{2.5}$ concentrations in Jakarta to help the local government assess the change of air quality in Jakarta after the rain occurred.

2 | PREVIOUS RESEARCHES

Previous research regarding monitoring of ambient air quality in traffic-heavy areas in Jakarta stated that the presence of $PM_{2.5}$ in ambient air is related to vehicles passing at the monitoring location as the source of emissions, in addition to the condition of meteorology plays an important role in the distribution of pollutants[17]. One $PM_{2.5}$ deposition mechanism is scavenging by precipitation or wet deposition of $PM_{2.5}$ by precipitation[18]. The negative correlation between $PM_{2.5}$ and precipitation indicates that $PM_{2.5}$ concentration decreases with increasing precipitation. $PM_{2.5}$ inversely correlates with the amount of accumulated precipitation, which identifies the function of the deposition process in $PM_{2.5}$ pollution[19]. Another study in an urban area in South Korea[13] found that the strongest correlation coefficient is -0.783 to -0.905 during heavy rainfall conditions with more than 30 mm precipitation.

$PM_{2.5}$ scavenging by precipitation is classified into in-cloud (ICS) and below-cloud scavenging (BCS)[20]. BCS occurs when $PM_{2.5}$ is captured by raindrops resulting from collisions between aerosol particles and raindrops. The process of BCS is determined by the scavenging coefficient, which is described as the fraction of the aerosol particles captured by the raindrop in units of time[21]. The scavenging coefficient below the cloud depends on the characteristics of the rain, including the size distribution of the raindrops, the chemical properties of the particles, and their concentration in the atmosphere.

However, it is difficult to obtain particle size distribution and chemical composition before and after rain events[22]. This requires an approach that connects observed meteorological parameters such as precipitation amounts[23]. Focusing on precipitation allows direct assessment of changes in air quality after rain events and identifying thresholds that correspond to the amount of precipitation that can identify changes in air quality during rain events[24].

Ikeuchi et al.[14] studied the effect of precipitation on $PM_{2.5}$ scavenging and found that precipitation duration contributed more than its intensity in Tokyo with an average annual reduction of 0.39 µg m^{-3}. In another research on identifying a function of the reduction in $PM_{2.5}$ during summer in Beijing, $PM_{2.5}$ was negatively correlated with the amount of cumulative precipitation with the correlation coefficient ranging from 0.668 to 0.974[15]. Research by Sun et al.[25] regarding the impact of various categories of rainfall on $PM_{2.5}$ concentrations in Beijing by calculating the difference in $PM_{2.5}$ concentrations one hour before and after a rain event suggest that the mechanism that can increase the amount of aerosol dominates during light rain and vice versa with a threshold of 0.5 mm and 10 mm.

A previous study reported that precipitation has a non-linear relationship with aerosol particle concentration[26]. Although many studies quantifying the effect of precipitation on the $PM_{2.5}$ concentration have been conducted, a similar study has never been

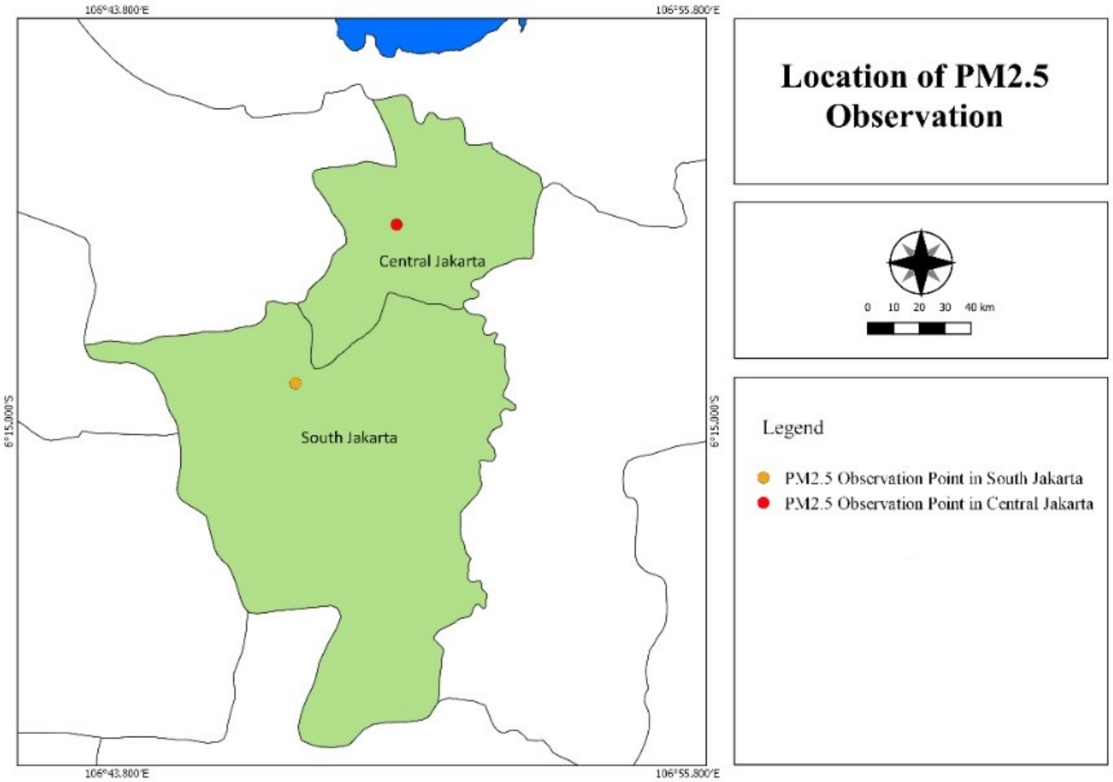

FIGURE 1 Two $PM_{2.5}$ monitoring sites located in Jakarta operated by AirNow Project.

done in Jakarta or other cities with a similar climate to Jakarta. Therefore, this study aims to analyze the non-linear effect of precipitation and the time lag of rain events on the scavenging of $PM_{2.5}$ concentrations using the Distributed Lag Non-Linear Model (DLNM)

3 | MATERIAL AND METHOD

Several points will be explained in this section, i.e., research location, types and sources of datasets used, and a detailed distributed lag-nonlinear model.

3.1 | Site Locations and Data

The research locations used in this study are the region of Jakarta that are represented by the $PM_{2.5}$ monitoring sites of AirNow networks, as shown in Figure 1 . We used the hourly $PM_{2.5}$ dataset from those two observation sites because they are open-access and located in the traffic-heavy areas of Jakarta. The $PM_{2.5}$ dataset has also undergone quality control from the AirNow project. The data used include observed hourly precipitation data in Central and South Jakarta from the Kemayoran Meteorological Station and South Tangerang Climatology Station, hourly air temperature data from ECMWF ERA5 reanalysis data and Hourly $PM_{2.5}$ concentrations, which data span from January 2017 to December 2019.

3.2 | Distributed Lag Non-Linear Model (DLNM)

According to Gasparrini[27], DLNM is a complex model that can explain the possibility of some variables to show a delayed effect that affects another variable within a certain time lag. DLNM was utilized to determine the threshold and pause of precipitation to reduce $PM_{2.5}$ as formulated in Equation 1. Polynomial and natural cubic spline functions were used to represent changes in precipitation and lag structure in cross-basis functions. Up to 12 hours of lag was used on this model. Hourly air temperature and hourly trend were controlled in this model.

$$log[E(Y_t)] = \alpha + \beta\, RA_{(t,l)} + T_t + NS(Hour, 2) \quad (1)$$

$E(Y_t)$ shows the expected daily particle concentration at t hour, $\alpha$is the intercept, $RA_{(t,l)}$ is a cross-basis function, l is the lag in hours, T_t is the air temperature shown at the t hour, NS represents natural cubic spline function with the degree of freedom of 2. A confidence interval (CI) of 95% was used to calculate the reduction of particles by precipitation.

The scavenging of $PM_{2.5}$ concentration by precipitation was represented using the relative effect (RE). RE was obtained from the calculation results in the Non-Linear Distributed Lag model using the hourly precipitation parameter to determine the reduction in $PM_{2.5}$ concentration. The hourly air temperature parameter was used as control data. RE represents a non-linear relationship between precipitation and the lag effect from 0 to 12 hours of rain events on the $PM_{2.5}$ concentration in Central and South Jakarta. RE provided the threshold value for precipitation in reducing $PM_{2.5}$ and the relationship between precipitation and the lag effect of a rain event. If RE is equal to one (=1.0), it indicates the threshold value of $PM_{2.5}$ is sensitive to the model, while RE value of more than one (>1.0) implies an increase in $PM_{2.5}$ concentration from the threshold value and vice versa. DLNM explains the effect of precipitation on particle concentrations in different time lags. All calculations in this study were processed with the "DLNM" package in R [27].

3.3 | $PM_{2.5}$ Scavenging Probability

The ratio of the number of samples with a $PM_{2.5}$ concentration lower than the threshold of the total number of samples (P_0) was calculated using Equation 2 based on BMUA of 65 µg m^{-3} for 24 hours [28].

$$P_O = \frac{N_{lower\ than\ standard}}{N_{total}} \quad (2)$$

$N_{lower\ than\ standard}$ is defined as the number of samples with a $PM_{2.5}$ concentration lower than the air quality standard during a certain period, N is shown in the total number of samples during a certain period from January 2017 to December 2019. $PM_{2.5}$ Scavenging Probability (SP) for a certain hourly precipitation intensity and a certain time lag was calculated based on Equation 3.

$$SP = (P_{precipitation,lag} - P_O) \times 100\% \quad (3)$$

$P_{precipitation,\ lag}$ is the lag time expressed in the probability of a certain break of hours after precipitation (P_0), refers to the probability for the entire study period from January 2017 to December 2019. The SP calculation is based on different hourly precipitation intensities and time lag values that can reduce $PM_{2.5}$ concentrations.

4 | RESULTS AND DISCUSSION

4.1 | Relative Effect of Rain Events

Figure 2 illustrates a three-dimensional image of RE of precipitation and the time lag in Central Jakarta. In Figure 2 , 0 lag time and precipitation 0 to 4 mm, RE value was shown to be slightly above 1, which indicates a little increase in $PM_{2.5}$ concentration that happens simultaneously with rain events. Meanwhile, the precipitation of 5 mm to 20 mm show RE values below one and continues to decline, which indicates that the $PM_{2.5}$ concentration continues to decrease at this precipitation intensity simultaneously with rain events. This indicates that the higher the precipitation, the bigger influence it will be to decrease the $PM_{2.5}$ concentration in Central Jakarta at the rain events. In addition, longer lag times on precipitation above 4 mm will increase the RE values, which further implies the scavenging $PM_{2.5}$ will be lower as lag time from rain events increases.

Based on obtained RE, it can be used to determine the threshold to show the reduction effect. The defined threshold expresses the limit of the scavenging effect that only the precipitation greater than the threshold value can reduce the $PM_{2.5}$ concentration [24]. Furthermore, this finding also indicates the precipitation intensity is important to analyze the possible change in air quality after rain events. Hence, it can be concluded that there is a threshold in precipitation that can reduce the concentration of $PM_{2.5}$ in Central Jakarta that is 5 with a time lag from 0 to 12 hours.

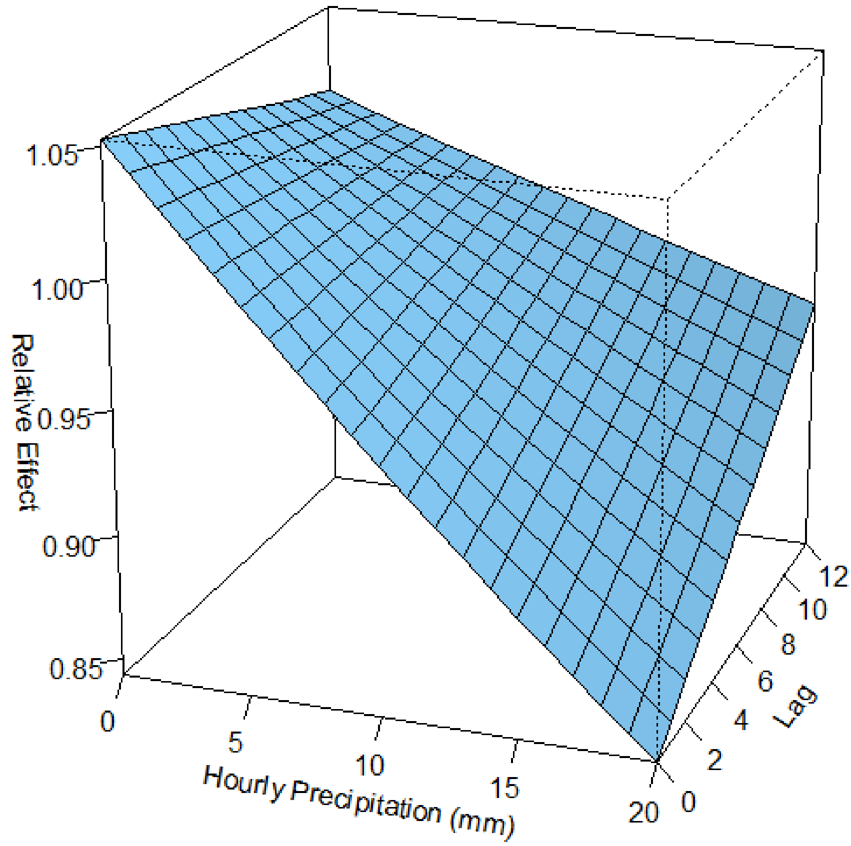

FIGURE 2 Relative Effect of precipitation with lags to the scavenging of $PM_{2.5}$ in Central Jakarta.

Figure 3 demonstrates a three-dimensional image of RE of precipitation and the time lag in South Jakarta. Figure 3 shows that precipitation 0 mm to 4 mm resulted in an RE value of approximately 1.091 to 1.01, which indicates that a slight increase in $PM_{2.5}$ concentration occurs simultaneously with rain events. Meanwhile, the 5 mm to 20 mm precipitation reported RE values below one, which continued to decrease from 0.991 to 0.742. This indicated a continued decline of the $PM_{2.5}$ concentration with rain intensity of more than or equal to 5 mm at 0 lag time. Concurrently with Central Jakarta, at lag 0, greater precipitation resulted in a bigger influence to decrease $PM_{2.5}$ concentration in South Jakarta. It was found that precipitation intensities from 5 mm to 20 mm with a time lag of more than 10 hours resulted in RE values of more than 1. This indicates that 10 hours lag time reduces the scavenging effect of precipitations above the threshold to reduce the $PM_{2.5}$ concentration in South Jakarta.

Precipitation above a certain threshold can improve air quality[24], followed by fresh air and clear skies after the rain[29]. When raindrops fall, they collide with air particles, which will be removed from the air by the droplets[30]. The number of raindrops will increase with the increasing intensity of precipitation[31, 32]. The higher the intensity of the precipitation, the greater the concentration of the raindrops (below-cloud). As such, the collision can occur between the raindrops and the $PM_{2.5}$[9]. The amount of particle exposure by precipitation depends on the precipitation intensity, rain duration, raindrop size distribution, and precipitation intensity[29]. The results suggest that the difference in precipitation intensity and total precipitation between Central Jakarta and South Jakarta is the cause of the difference in the strength of the relative effects in these two locations. Therefore, the effectiveness of reducing $PM_{2.5}$ concentrations by precipitation is strongly influenced by precipitation intensity[25, 33]. These findings are supported by the previous studies, which states that the intensity of rain and the amount of precipitation are some of the major causes of the difference in the strength of the relative effect[24].

The precipitation threshold sets the limit of the effect of reducing $PM_{2.5}$ concentration by precipitation, meaning that only precipitation that exceeds the threshold can potentially reduce the concentration of $PM_{2.5}$[24]. The same threshold for precipitation

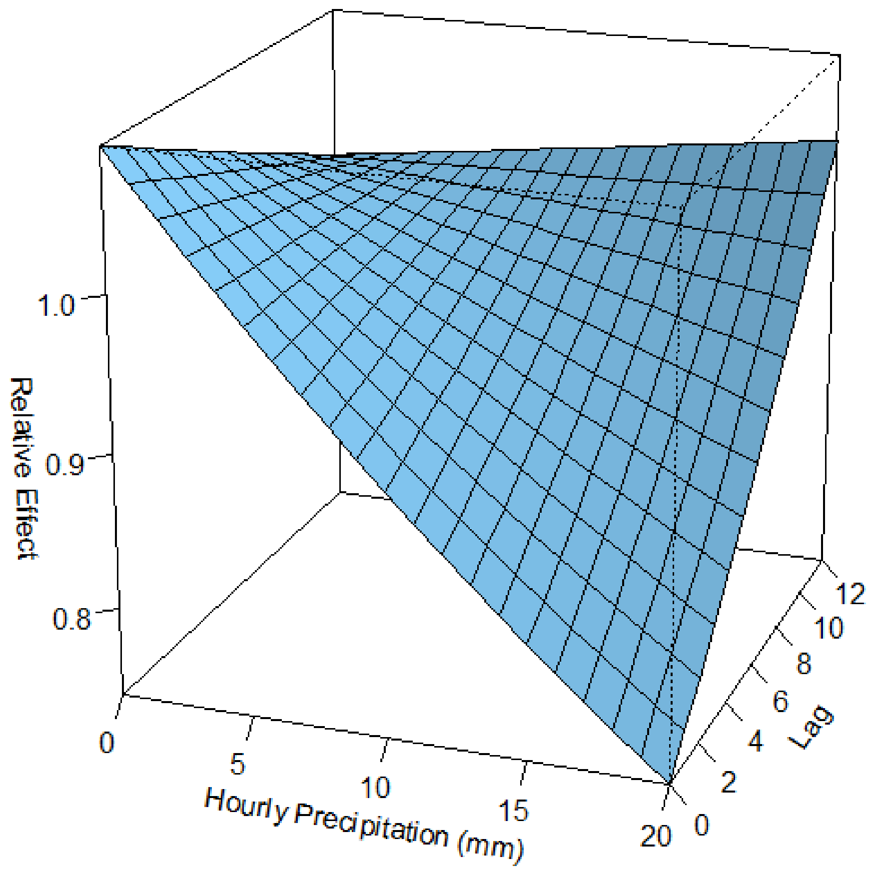

FIGURE 3 Relative Effect of precipitation with lags to the scavenging of $PM_{2.5}$ in South Jakarta.

in Central and South Jakarta is 5 mm, meaning that 5 mm of precipitation is the initial value that can start to reduce $PM_{2.5}$ concentrations directly. The reduction in $PM_{2.5}$ in Central Jakarta with a time lag of up to 12 hours and up to 10 hours in South Jakarta indicates that there is a difference in lag time which Central Jakarta has a longer time lag of rain events that can potentially reduce the $PM_{2.5}$ concentration compared to South Jakarta.

4.2 | $PM_{2.5}$ Scavenging Probability

The number of samples with a $PM_{2.5}$ concentration of less than 65 µg m^{-3} in Central Jakarta was 22,622 from 25,380 total samples with an hourly $PM_{2.5}$ total probability (P_0) of 0.89. Meanwhile, in South Jakarta, the number of samples with a $PM_{2.5}$ concentration of less than 65 µg m^{-3} was 19,943 from 24,591 total $PM_{2.5}$ samples during the study period with a P_0 of 0.81. The probability of reducing the concentration of $PM_{2.5}$ at certain precipitation and interval is called $PM_{2.5}$. Scavenging Probability (SP) during the 2017 - 2019 period in Central Jakarta was calculated by reducing the probability of precipitation and a certain interval ($P_{(rainfall,lag)}$) from the total probability (P_0). The results of the probability value are shown in Tables 1 and 2 .

Table 1 shows the value of the increase in the probability of $PM_{2.5}$ concentration below the BMUA for each rain event and the time lag in Central Jakarta. Based on Table 1, smaller SP obtained from precipitation with a lag larger than 0 hours tends to decrease compared to 0 hours lag. Negative SP showed in larger time lag depict that the concentration of $PM_{2.5}$ might not be affected by the rain events. The highest SP is mostly found at lag 0, with a maximum SP of 11%. Meanwhile, for precipitation above 18 mm, the SP value does not decrease with the increase in lag or only experiences a slight decrease in longer lag.

Table 2 shows the value of the increase in the probability of $PM_{2.5}$ concentration below the BMUA for each rain event and the time lag in South Jakarta. Based on Table 2, the most appeared value and highest SP in lag 0 was 19%, while some SP values of 31% were found at lag 8 to lag 10 with precipitation of 16 mm. Concurrently with Central Jakarta, smaller SP is obtained from

TABLE 1 The $PM_{2.5}$ scavenging probability value for each precipitation and certain time lag in Central Jakarta.

Hourly Precipitation	SP at Lag n hour (%) Lag0	Lag1	Lag2	Lag3	Lag4	Lag5	Lag6	Lag7	Lag8	Lag9	Lag10	Lag11	Lag12
1 mm	8%	4%	4%	5%	3%	0%	0%	-1%	-1%	-3%	-1%	-2%	0%
2 mm	11%	5%	2%	5%	3%	4%	3%	2%	2%	1%	1%	0%	3%
3 mm	11%	5%	5%	2%	5%	3%	5%	8%	0%	0%	-3%	1%	0%
4 mm	11%	4%	5%	7%	7%	5%	7%	5%	3%	5%	3%	5%	5%
5 mm	8%	1%	0%	3%	11%	6%	8%	8%	6%	3%	3%	0%	0%
6 mm	11%	4%	4%	4%	1%	1%	1%	-2%	1%	1%	4%	1%	4%
7 mm	11%	11%	11%	0%	0%	5%	0%	5%	5%	0%	0%	-6%	-6%
8 mm	7%	7%	7%	7%	7%	3%	-2%	3%	-2%	7%	-2%	2%	2%
9 mm	6%	0%	0%	0%	0%	6%	6%	6%	11%	11%	6%	0%	0%
10 mm	11%	1%	6%	-9%	6%	6%	1%	1%	6%	1%	6%	6%	1%
11 mm	4%	4%	-2%	11%	11%	11%	11%	4%	4%	4%	4%	4%	4%
12 mm	11%	11%	11%	11%	-3%	-32%	-32%	-18%	-18%	-3%	-18%	-18%	11%
13 mm	11%	11%	11%	11%	11%	1%	1%	11%	11%	11%	11%	11%	11%
14 mm	11%	11%	1%	11%	11%	-9%	-9%	-9%	-19%	-19%	-19%	1%	1%
15 mm	11%	11%	11%	11%	11%	11%	-18%	-3%	-3%	11%	11%	-3%	11%
16 mm	11%	11%	11%	11%	11%	11%	11%	-9%	-9%	-9%	11%	11%	11%
17 mm	11%	11%	11%	11%	11%	11%	0%	11%	11%	0%	0%	11%	11%
18 mm	11%	11%	11%	11%	11%	11%	11%	11%	11%	-9%	11%	-9%	11%
19 mm	11%	11%	11%	11%	11%	11%	11%	11%	11%	11%	11%	11%	11%
20 mm	11%	11%	11%	11%	11%	11%	11%	11%	11%	11%	11%	11%	11%

TABLE 2 The $PM_{2.5}$ scavenging probability value for each precipitation and certain time lag in South Jakarta.

Hourly Precipitation	SP at Lag n hour (%) Lag0	Lag1	Lag2	Lag3	Lag4	Lag5	Lag6	Lag7	Lag8	Lag9	Lag10	Lag11	Lag12
1 mm	15%	9%	5%	1%	1%	-1%	-1%	-4%	-5%	-3%	-3%	-5%	-5%
2 mm	15%	-1%	-1%	-2%	-7%	-2%	-2%	2%	-2%	-5%	-1%	-3%	-6%
3 mm	13%	1%	3%	0%	-3%	-3%	-3%	-5%	-2%	-3%	-8%	-6%	0%
4 mm	19%	5%	0%	0%	-3%	-3%	-9%	-6%	-4%	-6%	-9%	-1%	4%
5 mm	16%	2%	4%	-1%	-1%	-1%	-1%	-1%	-8%	-8%	-8%	-5%	-8%
6 mm	11%	5%	5%	5%	-10%	-3%	-10%	-6%	-6%	-10%	-20%	-13%	-3%
7 mm	19%	11%	10%	10%	5%	5%	5%	-4%	-8%	-17%	-13%	-17%	-22%
8 mm	19%	5%	12%	12%	5%	5%	-3%	5%	5%	-10%	-10%	-3%	-3%
9 mm	13%	-3%	8%	7%	7%	7%	1%	7%	-5%	-11%	-11%	-11%	-5%
10 mm	19%	14%	14%	12%	10%	5%	0%	-7%	-4%	-7%	-2%	-5%	-5%
11 mm	19%	8%	8%	8%	8%	8%	-3%	-3%	-3%	-14%	-14%	-3%	-3%
12 mm	5%	5%	5%	5%	-3%	5%	12%	12%	5%	5%	5%	5%	12%
13 mm	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%
14 mm	19%	19%	19%	-31%	19%	19%	19%	19%	19%	19%	19%	19%	-31%
15 mm	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%
16 mm	19%	19%	31%	19%	31%	19%	19%	6%	31%	31%	31%	-6%	19%
17 mm	19%	19%	19%	19%	19%	-14%	-14%	-14%	-14%	-14%	-14%	19%	19%
18 mm	19%	19%	19%	5%	5%	19%	19%	19%	19%	19%	5%	5%	-10%
19 mm	19%	5%	19%	19%	19%	5%	-10%	5%	5%	5%	5%	19%	19%
20 mm	19%	19%	19%	19%	19%	19%	-6%	-6%	-6%	-6%	6%	6%	-6%

precipitation with a lag larger than 0 hours and tends to decrease compared to 0 hours lag. The SP value is greater in the South Jakarta area than Central Jakarta, with the same precipitation and time lag. In South Jakarta, for precipitation above 12 mm to 16 mm, the SP value tends to not decrease along with the increase in lag.

5 | CONCLUSION

Higher precipitation results in a smaller value of RE (RE less than 1), indicating that the greater the precipitation, the more influential it will be to decrease the $PM_{2.5}$ concentration in Central Jakarta and South Jakarta. The probability of having a $PM_{2.5}$ concentration of less than 65 µg m^{-3} is 89% and 81% in Central and South Jakarta, respectively. This result indicates that $PM_{2.5}$ concentration, which is less than 65 µg m^{-3}, occurred more in Central Jakarta than South Jakarta. The findings of this study confirmed that a few hours after rain with a certain amount of precipitation would reduce the concentration of $PM_{2.5}$ in Jakarta.

We suggest that hourly precipitation of 1 to 20 mm and a time interval of up to 10 hours reduce $PM_{2.5}$ concentration in both observation sites in Jakarta.

ACKNOWLEDGMENT

We are thankful to the EPA AirNow program for providing the $PM_{2.5}$ concentration datasets. Further thanks to the Head of Tangerang Selatan Climatological Station for the climatological data at the site locations.

CREDIT

Rista Hernandi Virgianto: Conceptualization, Methodology, Formal analysis and investigation, Writing- original draft preparation; **Nanda Putri Kinanti:** Writing- review and editing; **Ervan Ferdiansyah:** Writing- review and editing; **Qurrata A'yun Kartika:** Writing- review and editing.

References

1. Jephcote C, Chen H. Environmental injustices of children's exposure to air pollution from road-transport within the model British multicultural city of Leicester: 2000–2009. Science of the Total Environment 2012;414:140–151.

2. Anderson JO, Thundiyil JG, Stolbach A. Clearing the air: a review of the effects of particulate matter air pollution on human health. Journal of Medical Toxicology 2012;8(2):166–175.

3. Vodonos A, Awad YA, Schwartz J. The concentration-response between long-term PM2. 5 exposure and mortality; A meta-regression approach. Environmental research 2018;166:677–689.

4. Khanna I, Khare M, Gargava P, Khan AA. Effect of PM2. 5 chemical constituents on atmospheric visibility impairment. Journal of the Air & Waste Management Association 2018;68(5):430–437.

5. Wang X, Zhang R, Yu W. The effects of PM2. 5 concentrations and relative humidity on atmospheric visibility in Beijing. Journal of Geophysical Research: Atmospheres 2019;124(4):2235–2259.

6. Sun X, Zhao T, Liu D, Gong S, Xu J, Ma X. Quantifying the influences of PM2. 5 and relative humidity on change of atmospheric visibility over recent winters in an urban area of East China. Atmosphere 2020;11(5):461.

7. Pun V, Mungkasa O, Lestari P, Kusuma R, Tang L, Mehta S, et al. Approaches on implementing innovations to achieving faster progress on air quality improvement in DKI Jakarta, Indonesia. Environmental Epidemiology 2019;3:318.

8. Kirana DC, Bowo PA. Determinant of Car Demand in Java Island. Economics Development Analysis Journal 2019;8(1):1–8.

9. Tong R, Liu J, Wang W, Fang Y. Health effects of PM2. 5 emissions from on-road vehicles during weekdays and weekends in Beijing, China. Atmospheric Environment 2020;223:117258.

10. Herizal, Badan Meteorologi Klimatologi dan Geofisika, editor, Pemerintah Terus Meningkatkan Pemantauan dan Upaya Perbaikan Kualitas Udara. Badan Meteorologi Klimatologi dan Geofisika; 2019. https://www.bmkg.go.id/press-release/?p=pemerintah-terus-meningkatkan-pemantauan-dan-upaya-perbaikan-kualitas-udara&tag=press-release&lang=ID.

11. Li L, Qian J, Ou CQ, Zhou YX, Guo C, Guo Y. Spatial and temporal analysis of Air Pollution Index and its timescale-dependent relationship with meteorological factors in Guangzhou, China, 2001–2011. Environmental Pollution 2014;190:75–81.

12. Westervelt D, Horowitz L, Naik V, Tai A, Fiore A, Mauzerall DL. Quantifying PM2. 5-meteorology sensitivities in a global climate model. Atmospheric Environment 2016;142:43–56.

13. Nguyen MV, Park GH, Lee BK. Correlation analysis of size-resolved airborne particulate matter with classified meteorological conditions. Meteorology and atmospheric physics 2017;129(1):35–46.

14. Ikeuchi H, Murakami M, Watanabe S. Scavenging of PM2. 5 by precipitation and the effects of precipitation pattern changes on health risks related to PM2. 5 in Tokyo, Japan. Water Science and Technology 2015;72(8):1319–1326.

15. Ouyang W, Guo B, Cai G, Li Q, Han S, Liu B, et al. The washing effect of precipitation on particulate matter and the pollution dynamics of rainwater in downtown Beijing. Science of the Total Environment 2015;505:306–314.

16. Cugerone K, De Michele C, Ghezzi A, Gianelle V. Aerosol removal due to precipitation and wind forcings in Milan urban area. Journal of Hydrology 2018;556:1256–1262.

17. Muliane U, Lestari P. Pemantauan kualitas udara ambien daerah padat lalu lintas dan komersial DKI Jakarta: analisis konsentrasi PM2, 5 dan black carbon. Jurnal Teknik Lingkungan 2011;17(2):178–188.

18. Blanco-Becerra LC, Gáfaro-Rojas AI, Rojas-Roa NY. Influence of precipitation scavenging on the PM2. 5/PM10 ratio at the Kennedy locality of Bogotá, Colombia. Revista Facultad de Ingeniería Universidad de Antioquia 2015;76:58–65.

19. Wang J, Ogawa S. Effects of meteorological conditions on PM2. 5 concentrations in Nagasaki, Japan. International journal of environmental research and public health 2015;12(8):9089–9101.

20. Loosmore GA, Cederwall RT. Precipitation scavenging of atmospheric aerosols for emergency response applications: testing an updated model with new real-time data. Atmospheric Environment 2004;38(7):993–1003.

21. Luan T, Guo X, Zhang T, Guo L. Below-cloud aerosol scavenging by different-intensity rains in Beijing city. Journal of Meteorological Research 2019;33(1):126–137.

22. Chate D, Rao P, Naik M, Momin G, Safai P, Ali K. Scavenging of aerosols and their chemical species by rain. Atmospheric Environment 2003;37(18):2477–2484.

23. Quérel A, Monier M, Flossmann AI, Lemaitre P, Porcheron E. The importance of new collection efficiency values including the effect of rear capture for the below-cloud scavenging of aerosol particles. Atmospheric research 2014;142:57–66.

24. Guo LC, Zhang Y, Lin H, Zeng W, Liu T, Xiao J, et al. The washout effects of rainfall on atmospheric particulate pollution in two Chinese cities. Environmental pollution 2016;215:195–202.

25. Sun Y, Zhao C, Su Y, Ma Z, Li J, Letu H, et al. Distinct impacts of light and heavy precipitation on PM2. 5 mass concentration in Beijing. Earth and Space Science 2019;6(10):1915–1925.

26. Barmpadimos I, Hueglin C, Keller J, Henne S, Prévôt A. Influence of meteorology on PM10 trends and variability in Switzerland from 1991 to 2008. Atmospheric Chemistry and Physics 2011;11(4):1813.

27. Gasparrini A. Distributed lag linear and non-linear models in R: the package dlnm. Journal of statistical software 2011;43(8):1.

28. Humairoh GP, Syafei AD, Santoso M. Identification of Pollutant Sources of PM2, 5 and PM10 in Waru, Sidoarjo, East Java. Jurnal Teknik ITS 2019;8(2):D24–D28.

29. Ma CJ, Sera K. The chemical nature of individual size-resolved raindrops and their residual particles collected during high atmospheric loading for PM 2.5. Asian Journal of Atmospheric Environment 2017;11(3):176–183.

30. Seinfeld JH, Pandis SN. Atmospheric chemistry and physics: from air pollution to climate change. John Wiley & Sons; 2016.

31. Laakso L, Grönholm T, Rannik U, Kosmale M, Fiedler V, Vehkamäki H, et al. Ultrafine particle scavenging coefficients calculated from 6 years field measurements. Atmospheric Environment 2003;37(25):3605–3613.

32. Rigby E, Marshall J, Hitschfeld W. The development of the size distribution of raindrops during their fall. Journal of Meteorology 1954;11(5):362–372.

33. González C, Aristizábal B. Acid rain and particulate matter dynamics in a mid-sized Andean city: The effect of rain intensity on ion scavenging. Atmospheric Environment 2012;60:164–171.

How to cite this article: Virgianto R.H., Kinanti N.P., Ferdiansyah E., Kartika Q.A. (2021), The Effect Of Precipitation on Scavenging of $PM_{2.5}$ in Jakarta Based on Distributed Lag Non-Linear Models, *IPTEK The Journal of Technology and Science*, *32(2):115-124*.