Anthropogenic PMx air pollution susceptibility using AHP method in Java Island, Indonesia

Hasan Adi Nugraha[1], *Putri* Ragita[1], *Bayu* Kurniawan[1], *Hana Syafi* Raihan[1], *Yumna Rohadatul* Aisy[1], *Indah* Sawitri[1], *Clara* Alverina[1], *Bagus Dwi* Prasetya[1], *Nirmala Hasna* Styawan[1], *Ananda Shabrina Putri* Gunawan[1], *Emanuel Tatag* Krisanto[1], *Ratih Fitria* Putri[1*], *Anugrah Aditya* Insani[2], and *Ikhwan* Amri[2,3]

[1]Faculty of Geography, Universitas Gadjah Mada, Yogyakarta, 55281, Indonesia
[2]Center for Disaster Studies, Universitas Gadjah Mada, Yogyakarta, 55281, Indonesia
[3]The Graduate School of Universitas Gadjah Mada, Yogyakarta, 55281, Indonesia

Abstract. Various health and welfare problems in human society originate from air pollution. PMx as one of the hydrometeorological hazards caused by humans is sustainable, ironically having an impact on the lives of human society, especially in areas that are densely populated. This research aims to estimate the susceptibility of PMx air pollution in Java Island, Indonesia. This island was chosen because it has a large population (151.59 million people in 2020) and is growing into a regional economic and industrial center. Java Island also has various cases of extreme air pollution. In this study, the Analytical Hierarchy Process (AHP) method is utilized to assess the susceptibility of anthropogenic PMx air pollution, taking into account factors like morphology, rainfall, mining area buffers, industrial area buffers, and traffic buffers. The results showed that anthropogenic PMx susceptibility was related to active and passive factors. The active factor is anthropogenic activity, while the passive factor is natural inhibition. Anthropogenic activities that have a big influence are industrial activities, followed by mining activities, and transportation. Meanwhile natural inhibitors such as rainfall and morphology, have a relatively smaller influence. Analysis of susceptibility distribution is very important for mitigating air pollution hazards, especially in Java Island.

1 Introduction

Various problems in human society originate from air pollution. Several respiratory and cardiovascular diseases are correlated with air pollution, especially particulate matter, namely solid particles and liquid droplets (PM_X: PM_{10} and $PM_{2.5}$) [1]. In addition, exposure to PM_X is related to the mortality and morbidity of the population, especially in vulnerable groups. Individuals at greater risk of respiratory effects from air pollution include those with pre-existing respiratory conditions, children, and the elderly [2]. Naturally, air contains aerosols of various sizes of particulate matter, >10 μm or PM_{10} and >2.5 μm or $PM_{2.5}$. However, through its various activities, such as mining, industry, and transportation, human society emits PM_X [3]. Because human activities are located in a geographical space, air pollution can be categorized as a spatial entity with characteristics of the activities of human society.

Determining between PM_X resulting from human processes and nature is relatively tricky, especially in areas with landscapes that actively emit PM_X, such as active volcanoes and deserts [3]. This study offers a semi-quantitative alternative to measure the susceptibility of PM_X air pollution using the Analytical Hierarchy Process (AHP) method. AHP is commonly used to assess natural hazard, such as floods, landslides, earthquakes, and tsunamis. AHP can be used to determine the spatial distribution of disaster susceptibility. This study aims to estimate the susceptibility of PM_X air pollution using the AHP method to the study area of Java Island, Indonesia. Java Island was chosen because it has a large population (151.59 million people by 2020) while growing into a global economic and industrial center. Java Island also has various cases of extreme air pollution. This study can explain the susceptibility of PM_X air pollution and determine PM_X air pollution from several anthropogenic activities (human society) on Java Island. The PMx pollution in Java Island has significant implications for the public health and the economy of Indonesia, as it can increase the morbidity and mortality rates, reduce the productivity and quality of life, and damage the natural resources and cultural heritage [4].

PMx pollution is a serious environmental problem in Java Island, especially in urban areas. The high population density and traffic congestion in Java Island exacerbate the exposure of the residents to PMx pollutants, which can cause various adverse health effects, such as respiratory infections, asthma, chronic obstructive pulmonary disease, cardiovascular diseases, and premature mortality [5]. The utilization of AHP as an analytical tool in this research contributes to the measurement of relative impacts of various factors on air pollution. This research provides a better

* Corresponding author: ratihfitria.putri@ugm.ac.id

understanding of air pollution levels on Java Island, which serves as a global economic and industrial center. This understanding can serve as a basis for policy making and actions aimed at reducing air pollution.

2 Methodology

This research was conducted in the Java region, which has a geographical position located at 113°48′10″ - 113°48′26″ East Longitude and 7°50′10″ - 7°56′41″ South Latitude (Figure 1). Java's absolute geographical position plays an important role in determining the climatic and geographical characteristics of the region. In addition, Java's relative position in the context of regional geography also has a significant impact on the air environment in the region. The climatic and topographical conditions in Java play a role in influencing the composition and levels of Particulate Matter (PMx) in the atmosphere [6].

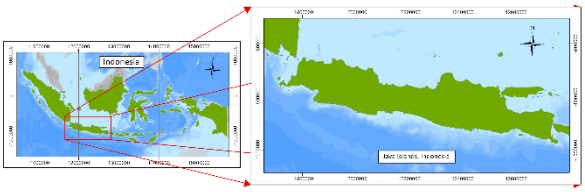

Fig. 1. Research location.

PMx is a form of aerosol that is a light, black-colored solid resulting from the combustion of CO2. PMx is concentrated in areas that have high levels of combustion activity such as transportation and industry. It is also influenced by land system morphology and rainfall. Data from each factor can be searched and used to conduct PMx pollutant estimation studies. Rainfall data is interpolated, industrial and mining location data is analyzed with multiple ring buffers, and road network data uses a similar approach.

The contribution of each factor was ranked using the Analytical Hierarchy Process (AHP) method. Analytical Hierarchy Process is a reliable, rigorous, and robust method for eliciting and quantifying subjective judgments in multi-criteria decision-making [7]. Despite the many benefits, the complications of the pairwise comparison process and the limitations of consistency in AHP are challenges that have been the subject of extensive research [8]. The variables used are rainfall, industrial and mining locations, road network, and morphology. Preprocessing was carried out by processing for each data variable with interpolated rainfall data, industrial and mining location data processed through multiple ring buffers, and road network data also using a similar approach. The results of this data processing are used to provide an initial score which is then overlaid using the AHP method as processing method (Figure 2). The total result will determine the estimated measured PMx pollutants on an arbitrary basis.

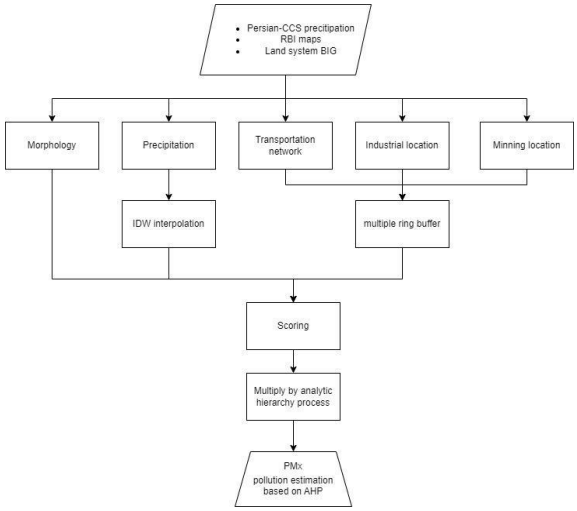

Fig. 2. Research flowchart.

3 Result and discussion

3.1 AHP assessment

The results of this research are quantitative and qualitative. Quantitative results are obtained from AHP calculations based on the parameters used such as Morphology, Rainfall, Buffer Mining Area, Buffer Industrial Area, and Buffer of Traffic which are presented in the form of diagrams and tables (Table 1, Figure 3). Meanwhile, the qualitative results are a description of several factors that influence susceptibility to anthropogenic PMx air pollution.

Table 1. Decision matrix resulting from AHP.

	Rain fall rate	Morpho logy	Buffer of Industri al Area	Buffer of Mining Area	Buffer of Traffic
Rainfall rate	1	3	0.11	0.14	0.33
Morpho logy	0.33	1	0.14	0.2	0.25
Buffer of Industrial Area	9	7	1	2	7
Buffer of Mining Area	7	5	0.5	1	3
Buffer of Traffic	3	4	0.14	0.33	1

The PMx Exposure Probability Map in Java Island shows the distribution of PMx gas variability based on data processing using the AHP method. Figure 4 represents the distribution of the highest PMx levels in urban areas which are dominated by metropolitan and industrial areas. Some of the areas included in the highest PMx are Jakarta, Bogor, Depok, Tangerang, Bekasi, Tasikmalaya, Brebes, Semarang, Surabaya, and Sidoarjo. The areas with low PMx distribution are

mostly in the northern part of Java Island, while the moderate PMx areas are in the south of Java Island.

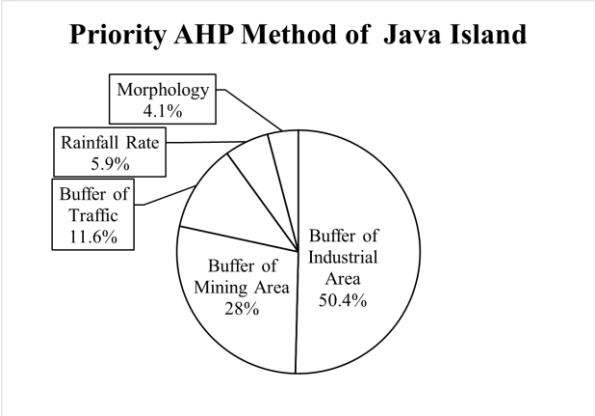

Fig. 3. AHP priority.

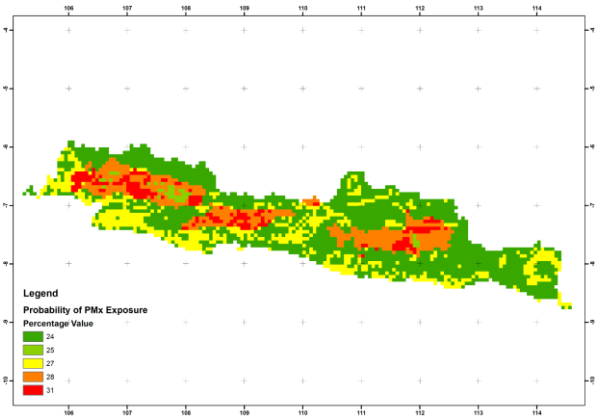

Fig. 4. Maps of PMx exposure probability on Java Island.

3.2 Morphological influence to air pollution

The relationship between morphological conditions and anthropogenic PMx is complex and multifaceted. Anthropogenic PMx pollution, primarily composed of tiny solid particles or liquid droplets suspended in the air, can have significant effects on the surrounding environment and human health. The morphological conditions of an area, such as its topography, urban layout, and land use, can influence the dispersion and accumulation of PMx pollutants [9]. For example, urban areas with tall buildings and narrow streets may experience more significant pollution "canyon" effects, where pollution is trapped and concentrated due to limited airflow.

Spatial distribution of PMx is influenced by various factors such as meteorology, topography, land use, and emission sources. The urban form and structure can also affect the PMx levels by altering the wind field and turbulence intensity in the urban canopy layer [8]. The urban morphology, which is defined by the shape and arrangement of buildings, streets, and open spaces, affects the local climate and air quality by modifying the urban boundary layer, surface energy balance, and pollutant dispersion [10].

This study indicate that morphology does not have a substantial effect on AHP values (4.1%). The variations in topography, urban layout, and land use across the island are relatively consistent or do not significantly impact the criteria evaluated through AHP in Java. This research outcome can be valuable in understanding the specific case of Java and may inform urban planning and policy decisions for the island, where other factors might play a more dominant role in influencing the AHP values. It's essential to note that this conclusion may not be generalizable to regions with highly heterogeneous morphological conditions, where the effects of morphology on AHP values might be more pronounced.

3.3 Mining area's contribution to air pollution

Mining is one of the main economic sectors in Indonesia, especially in Java Island. However, mining also poses significant social and environmental challenges, such as land conflicts, displacement of communities, air pollution from particulate matter and greenhouse gases, and contamination of soil and water by toxic substances [10]. Mining processes can generate dust and fine particles that are carried by the wind, causing air pollution [11]. In addition, activities such as rock blasting and the use of heavy machinery can also produce harmful gases and chemicals that can pollute the air. Coal mining, for example, often contributes to greenhouse gas emissions and other air pollutants. The use of chemicals in the mining process can also increase the risk of air pollution. This air pollution not only impacts the environment but can also endanger the health of people living around the mining area. The mining process unfolds through five fundamental stages: prospecting, exploration, development, production, and rehabilitation [12]. Mining activities broadly categorized as either underground or above-ground, give rise to significant air pollution in mining areas, primarily from Particulate Matters (PMs) and Methane (CH4) gas emissions. Open and underground mining operations contribute to this pollution. Surface mining, involving blasting activities, releases dust into the air, while the use of explosives triggers chemical reactions, emitting gases such as CO2, H2O, N2, CO, NOx, and SO2 [13].

The gases emitted during mining activities pose considerable health risks to workers at the mining site [14]. Exposure to respiratory pollutants is the most common thing, especially among those who work in the mining industry. The likelihood of acquiring occupational diseases is higher for individuals exposed to mining-related pollutants. Striving for zero harm to occupational health, it becomes crucial to identify elements contributing to air pollution in production [15]. Comprehensive measurements are necessary to analyze and mitigate risks associated with dust exposure, ensuring the well-being of workers. Advances in sensor technology enable real-time monitoring of air quality throughout the production stages. Cloud-backed continuous measurement systems facilitate the examination of environmental impacts from mining activities, contributing to the creation of healthy and secure working conditions in enterprises.

Mining operations in Java Island, Indonesia can cause serious environmental problems, including air pollution [16]. Generation of particulate matter (PM) during activities such as blasting and material

transportation, methane (CH4) emissions from ventilation and fuel combustion, and release of toxic gases such as sulfur dioxide, nitrogen oxides, carbon monoxide and heavy metals such as lead and mercury. Are significant contributors to mining-related air pollution. These pollutants have the potential to damage ecosystems, harm populations, and cause climate change. However, mining companies can take steps to mitigate these problems, thereby reducing their environmental impact and protecting public health. Some of these steps include dust management, methane capture, cleaner fuel use, and soil reclamation. Mining activities, including exploration, construction, operation, maintenance, expansion, abandonment, decommissioning and mine reuse, can impact social and environmental impacts according to many positive and negative ways, directly and indirectly [17]. Mining can bring many benefits to society but can also cause conflict, especially over land use above and underground. Mine abandonment, decommissioning and reuse can also lead to significant environmental impacts, such as soil and water pollution. In addition to mines, infrastructure built to support mining activities, such as roads, ports, railways and power lines, can affect animal migration routes and increase habitat fragmentation.

The mining industry on the island of Java contributes 28% of air pollution due to factors such as less regulated small-scale mining operations, extraction of minerals such as coal and limestone, and dust levels. high and near densely populated areas. In addition, the use of explosives and heavy machinery, material transportation and storage also contribute to harmful air pollution. To address these challenges while recognizing the economic importance of the industry, potential solutions include stricter environmental regulations, support for pollution control in small-scale mines, adoption of cleaner technology, reduced land prices, strategic planting of vegetation to minimize dust, and the possibility of relocating mining operations originating from densely populated areas. These measures, if implemented, could help minimize the impact on the environment and ensure the well-being of people on the island of Java.

3.4 Industrial area's impact on pollution

Air pollution in Indonesia, especially the island of Java, is the worst area in the national environmental quality category [18]. This is because as technology develops and the industrial revolution increases, there are many industrial factories on the island of Java. The industrial areas of Java span a wide range of economic sectors, including manufacturing activities, energy use, production volumes, air emissions, chemical use, inappropriate environmental regulations, increased mobility and logistics, some pollutant-generating industrial activities, and services. It is also an important location for many national and international companies that play a major role in Indonesia's economic growth. Industry is always associated with sources of pollution because industry is an activity that is very visible with the release of various chemical compounds into the environment. Industrial activities cause air pollution because they produce smoke as a point source with quite high concentrations. Apart from that, there are gases resulting from industrial waste disposal which have an impact on air quality, such as the smoke content of industrial factories, such as carbon dioxide (CO2), carbon monoxide (CO), sulfur oxide (SO) and other particulate pollutants [19].

Industry on the island of Java continues to increase in line with the level of community needs. In Indonesia, especially on the island of Java, which is an industrial center where most of the large cities are located on the island of Java, such as metropolitan cities, which causes many manufacturing factories to operate based on energy. Energy needs on the island of Java are related to the increasing energy needs of society. The fairly high growth of economic activity and urbanization in both urban and sub-urban areas has great potential to increase energy consumption [20]. Industrial factories on the island of Java still use fossil fuels and produce a lot of exhaust gas which is released into the air, as well as residues which are thrown into the environment. Fossil fuels such as coal, petroleum and natural gas have driven industrial development.

Burning fossil fuels is the main source of pollutants released into the air, such as COx, NOx, SOx, SPM (suspended particulate matter), Ox and various heavy metals. The combustion is released in the form of smoke resulting from processing fossil fuels through a pipe and directly interacts with the surrounding air. The peak of smoke formation is usually in the afternoon when the temperature is highest and there is lots of sunlight. Although lower layers of smoke and ozone form in urban areas with heavy traffic or highly industrialized areas, prevailing winds can carry them several hundred miles to other cities. This will have an impact on air quality in the industrial area and the surrounding area. The findings of this study are consistent/inconsistent with the research conducted by Liu in the year 2020 [21]. This shows that pollution knows no boundaries. That way the industrial area becomes the biggest contributor to pollution compared to other parameters, such as rainfall rate, Morphology, Mining area, and Traffic. Based on the results of research with the AHP method (50.4%) of pollutants are contributed by industrial areas, it can be seen on the priority chart. The decision matrix table (Table 1) shows that the comparison of industrial areas compared to rainfall rate has a value of 0.11, 0.14 compared to Morphology, 0.5 compared to Buffer Mining area, and 0.14 compared to Buffer Traffic.

3.5 Traffic density and air pollution

Java Island, especially Jakarta and its surroundings, is the largest industrial center in Indonesia, including industrial estates in Jakarta, Bogor, Depok, Tangerang, and Bekasi. Various types of industries, including manufacturing, trade, and services, are very strong sectors. In these metropolitan areas, most PM2 particles originate from human or anthropogenic activities including transportation, space heating, biomass burning, industry, and fugitive emissions from traffic

[21]. Java as the largest island in Indonesia has the most industrialized sector with Karawang, which is located in West Java province, is home to a large number of industrial estates, mainly in the manufacturing, automotive, and electronics sectors. Cilegon, located within Banten province, has many factories and heavy industries, including steel manufacturers and chemical industries. Semarang, in Central Java province, has a thriving industrial park with diverse manufacturing sectors. Surabaya is an important port city and has diverse manufacturing, shipping and trading industries.

Based on the results of analysis and data processing on traffic density, it was found that traffic contributed at least 11.6% to the level of air pollution susceptibility on the Java Island, Indonesia. Traffic parameters are among the top three pollutant contributors after industrial areas and mining areas. Based on the priority scale table, traffic has a decision matrix value in the middle range, which means it has an influence on air pollution susceptibility on Java Island. Java Island plays a central role in the country of Indonesia because it is the capital country (Jakarta) and has a large population and is important economic zones [22]. Population density in Java Island can cause various kinds of negative impacts both in the short and long term. One of them can affect the existing air condition. The parameters taken in determined traffic include roads, railways, ports and airports in each province on the Island of Java.

The pollution impact of each traffic source can vary depending on a number of factors, including traffic volume, vehicle type, pollution control technology, and regional travel patterns. However, in general, roads are a significant source of pollution in most urban areas in the world, including Java. This is due to the increase in the number of road users in connection with their activities such as the start of school hours for students and work hours by workers in the morning, the completion of school hours and the existence of work breaks for workers during the day, and the completion of work hours for workers in the afternoon [23]. Many people choose to use private vehicles rather than public transportation, which can reduce air pollution. Motorized vehicles produce CO2 emissions, fine particles (PM2.5), NOx, volatile organic compounds and other air pollutants. These pollutant gases are very dangerous for the environment, for example Carbon Monoxide (CO). Carbon Monoxide gas is one of the air polluting gases that usually only exist in urban areas where air space is limited by streets, buildings, tunnels and underground parking lots such as in many hotels and crowded centers [24]. Therefore, roads, ports, airports, and railways contribute to pollutant emissions, supported by high mobility between Java regions.

Apart from land transportation by road, air transportation such as airplanes produces quite large pollutant emissions in the air. For example, short-haul domestic or regional flights typically have CO2 emissions per passenger per kilometer of around 0.2 to 0.3 kilograms of CO2. Even though airplanes are now more sophisticated and environmentally friendly and produce lower emissions, it cannot be denied that in reality these activities can contribute to air pollution to a certain extent. Another source comes from sea transportation, namely ships. These ships use fossil fuels, such as marine fuel oil, which produces exhaust emissions in the form of sulfur dioxide (SO2), fine dust particles (PM2.5), carbon dioxide (CO2), and volatile organic compounds. (VOC). Ports on the island of Java are the center of goods shipping and distribution activities. Ships anchored at this port often use internal combustion engines to carry out various operations such as loading and unloading and refueling. This can produce exhaust emissions that pollute the air.

3.6 Rainfall's influence on air quality

Rainfall plays a significant role in influencing air quality, particularly with respect to particulate matter (PMx). It serves as a natural mechanism for cleansing the atmosphere of fine airborne particles that can contribute to air pollution. When rain falls, water droplets assist in the deposition of these particles onto the Earth's surface, effectively reducing the concentration of PMx in the atmosphere. This process not only enhances air quality but also mitigates health risks associated with air pollution. Moreover, rainfall aids in the removal of larger PMx particles that may be associated with various air pollutants, such as vehicular emissions and industrial dust. Inverse Distance Weighting (IDW) can be used to estimate unknown spatial rainfall data from data of known locations and adjacent unknown locations. The utilization of monotemporal rainfall data solely from the year 2021 presents certain limitations due to its relatively short measurement period. Such a narrow temporal scope may not adequately capture the full spectrum of rainfall variability, particularly given the substantial influence of seasonal fluctuations and natural climate phenomena such as El Niño, La Niña, and the Madden-Julian Oscillation (MJO) on rainfall patterns. Rainfall, a known mitigator of PMx concentration, aids in the removal of particulate matter from the atmosphere. However, the effectiveness of this process can exhibit temporal variations contingent on the interplay of climate events and local meteorological conditions.

Furthermore, the AHP analysis, which yielded the 5.9% contribution of rainfall, underscores the existence of other dominant factors in shaping PMx concentrations. Consequently, the broader implications of this study imply the significance of considering not only the temporal but also the multifaceted climatic aspects of rainfall when assessing susceptibility to PMx air pollution. Many studies have approached the problem of precipitation in aerosol removal from the perspective of atmospheric observations. From this perspective, the cleaning effect of precipitation is found to vary according to the aerosol particle size. In particular, rainfall is believed to have a greater precipitation effect on larger and smaller aerosol particles but is less effective in removing medium-sized aerosols [25]. These findings highlight that the processes involved in the influence of rainfall on air pollution are complex and involve multiple interrelated factors and mechanisms. To comprehend this phenomenon comprehensively, it is crucial to adopt a broader perspective, one that encompasses the intricate

and diverse interactions among meteorological and atmospheric variables contributing to the concentration of PMx in the atmosphere.

4 Conclusion

Numerous health issues and the overall welfare of human society stem from PM_X air pollution, particularly in densely populated and active regions. Due to its substantial population and its emergence as a global economic and industrial hub, Java Island experiences various instances of severe air pollution. The findings reveal that anthropogenic PM_X susceptibility is related to human activities as the active factor, while natural inhibitors are passive factors. Based on the results of the AHP, human activities with the most significant influence on anthropogenic PMx are industrial activities (50.4%), followed by mining activities (28%), and transportation (11.6%). Natural inhibitors, such as rainfall and morphology, have a relatively smaller influence, specifically around 5,9% and 4,1%, respectively.

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