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Dispersion Simulation of Ambient Particulate in Cilegon Industrial Zone Using the Gaussian Plume Models and SCREEN3

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Abstract

Natural events and human activities (anthropogenic) will emit components, whether reactive or not, to the atmosphere. Particulate, as one of the pollutant components, spread hundreds or even thousands of kilo meters from their source. This research aims to predict the particulate concentration and simulate particulate dispersion downwind from the industrial stacks. This study used 18 stacks of data from 5 industries at the Ciwandan District in Cilegon City. The analysis data was taken from January – December 2019. The Gaussian Plume Model and SCREEN3 were used to calculate particulate concentration at downwind distances ranging from 500 – 5000 m. The modelling result compared with measurement data to evaluate the model performance. The model evaluation for particulate modelling showed poor agreements. There were significant differences between the accumulation of particulate concentration by model and observed. This condition means that the study area's particulate is affected by industrial stack emission and other sources.

Keywords: dispersion, emission, Gaussian, particulate, SCREEN3.

INTRODUCTION

Natural events and human activities (anthropogenic) will emit components, whether reactive or not, to the atmosphere. Pollutant components (pollutants) can spread hundreds or even thousands of kilometres from their source depending on their physical and chemical characteristics (for example, chemical composition, water-solubility, or aerosol particle size distribution) [15].

Based on the United States Environmental Protection Agency (EPA), there are 6 (six) criteria for pollutants in the air, and particulate is one of them [26]. Based on research conducted by [19], particulate pollutants are dominated by traffic and industrial activities.

The Ciwandan District is one of the industrial zones in Cilegon City. Based on the zoning stated in the Spatial Planning of the City of Cilegon (RTRW) in 2010-2030, Ciwandan District is a zone of developing its function as a chemical and heavy industrial area non-chemical industry [20]. Central Bureau of statistics states that as many as 106 industries are in Ciwandan District, and this makes Ciwandan District the district with the highest number of industries in the City of Cilegon [3]. The industrial emissions and massive vehicles in Ciwandan District cause ambient air quality in Ciwandan District to worsen. Based on Ciwandan Public Health Centre data, 10 (ten) major diseases of during the last eight years (2011 to 2018), the most types of diseases suffered by the community in Ciwandan District are acute respiratory infections [25].

Estimating the concentration of pollutants in ambient air (atmosphere) can be done through mathematical simulations. Using an emissions dispersion model, one can predict air quality spatially, temporally, and by source category [5]. Modelling the dispersion of air pollutants can predict the effect of severe impacts on the environment and human health so that the development of various models plays a vital role for governments and researchers [15]. The Gaussian Plume Model is the most used dispersion model to estimate a pollutant's concentration at a certain point [11] [16]. The Gaussian Plume Model has analytical solutions, easy to use computationally, and has rules guidelines. The model results will be valid if the wind speed and k value (Eddy diffusion coefficient) are constant [24] [12]. The use of the Gaussian dispersion model is limited to uniform flows with homogeneous turbulence for point sources [17].

Model validation by field measurements shows the value of modelling accuracy of 14-15.5% [18]. Based on research in East Java, the highest dust dispersion in the rainy and dry season tends to accumulate near emission sources with <1000 m with a dispersion pattern following the wind direction and sensitive atmospheric stability [22]. Research conducted in Ciwandan District in 2017, resulted that the concentration of $PM_{2.5}$ and PM_{10} in Kubangsari Village (121 $\mu g/m^3$ and 157 $\mu g/m^3$) is the highest concentration of 60 sampling points in Ciwandan District [6].

The research objectives are to predict the concentration of particulate in ambient air using the Gaussian Plume Dispersion Model, compare the modelling result with SCREEN3, and simulate particulate dispersion scenarios downwind from the industrial stacks. The modelling predictions were later compared with the monitoring point (measured data).

METHODOLOGY

The study area was Ciwandan District in Cilegon City, Banten Province. The modelling was used time-series data from industrial monitoring data that was taken in January – December 2019. Stacks location and monitoring points, as measurement data, are shown in Figure 1. In achieving the research objectives, the stages carried out are described in Figure 2.

Figure 1. Stacks location and monitoring point

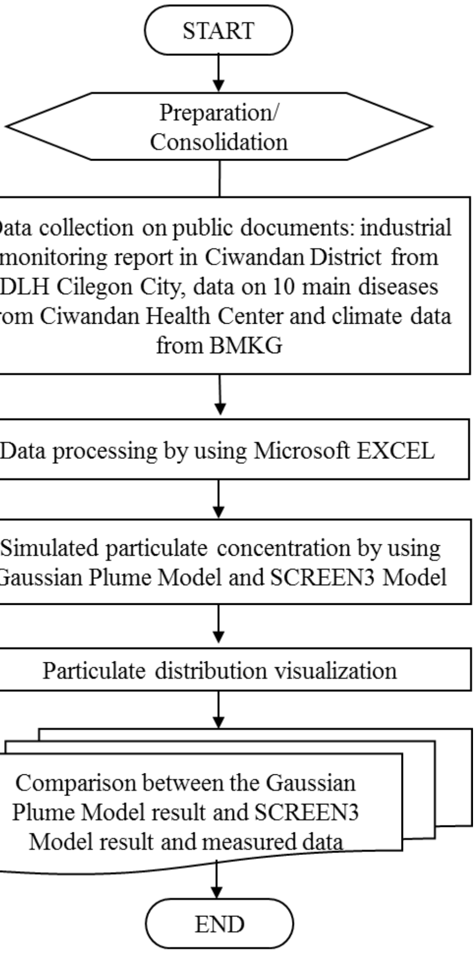

Figure 2. Flow Chart of the research

Input Parameters

In simulating particulate dispersion in the study area, emission source data, monitoring point data, and climate data are used. The data used in this study are secondary. Emission source data was obtained from monitoring reports carried out by industries in Ciwandan District in 2019 from the Environmental Office of Cilegon City. Monitoring point data were obtained from a private company located in Jakarta, and climate data were obtained from the Meteorology, Climatology, and Geophysics Agency of Serang Station for the last ten years (2009 to 2019). Ten primary diseases data from Ciwandan Health Centre were used to determine the impact of particulate in ambient on the Ciwandan District's community's health. The emission sources were used 18 stacks from 5 industries in Ciwandan District. The input of stacks emission data was shown in Table 1.

Table 1. Stack Characteristics

Stack Code	Stack height (H_s) (m)	Stack diameter (d_s) (m)	Stack temperature (T_s) (K)	Exit velocity (V_s) (m/s)	Total Particulate Matter (TPM) Emission Concentration (mg/m^3)
CR1	35.50	0.80	304	2.70	9
CR2	60.00	2.00	403	1.00	5
CR3	60.00	2.00	409	9.90	13
CR4	23.00	1.00	339	13.54	8
CR5	23.31	1.10	585	9.60	2
CR6	23.31	1.10	572	15.38	1
CR7	22.00	2.30	575	6.88	1
CR8	41.30	2.00	393	11.67	12
CR9	36.45	1.30	304	8.35	5
CR10	16.00	1.50	451	12.77	6
CR11	24.00	1.00	306	9.75	15
CR12	27.10	1.50	424	2.64	7
CR13	30.00	1.50	361	3.88	32
CR14	30.00	1.20	120	9.04	35
CR15	30.00	1.20	120	8.68	33
CR16	30.00	1.20	120	9.21	28
CR17	30.00	1.20	120	9.65	47
CR18	80.00	1.20	120	21.49	41

The Gaussian Plume Dispersion Model

The Gaussian Plume Model is a semi-empirical method [14]. The Gaussian plume dispersion equation calculates particulates' concentration at a specified distance. The ground-level concentrations in downwind direction are calculated by the equation shown in Equation 1 [27].

$$C(x,y,z) = \frac{Q}{2\,\pi\,u_s\,\sigma_y\,\sigma_z}\,exp\left[-\frac{1}{2}\frac{y^2}{\sigma_y{}^2}\right]\left\{exp\left[-\frac{1}{2}\frac{\left(z-Hc\right)^2}{\sigma_z^2}\right]+exp\left[-\frac{1}{2}\frac{(z+Hc)^2}{\sigma_z^2}\right]\right\} \quad (1)$$

Remark:

$C_{(x,y,z)}$ = Concentration of the gas pollutant (μg/m^3)

Q = Source pollutant emission rate (μg/s)

u_s = Horizontal wind speed along with the plume centreline (m/s)

σ_y = Dispersion parameter in the horizontal (lateral) direction (m)

σ_z = Dispersion parameter in the vertical direction (m)

Hc = Effective stack height (m)

x = Distance downwind from the source (m)

y = Crosswind direction standard deviation of the concentration distribution at downwind distance x (m)

z = Vertical direction standard deviation of the concentration distribution at downwind distance x (m)

The study location determined that the atmospheric stability class is B (moderately unstable). Several parameters are calculated using the equations below:

Wind Speed

The wind speed referred to a particular reference height (usually 10 m). The wind power law is used to adjust the observed wind speed, U_1, from a reference measurement height, Z_1, to the stack height, Z_2. The wind speed profile at altitude z (m) is calculated with the power-law [27].

$$U_2 = U_1\left[\frac{Z_2}{Z_1}\right]^p \quad (2)$$

Remark:

U_2 = Wind speed at height 2 (m/s)

U_1 = Wind speed at height 1 (m/s)

Z_2 = Height 2 (m/s)

Z_1 = height 1 (m)

p = Wind profile exponent

The value of *p* denotes the wind profile exponent, depending upon the atmospheric stability category and wind speed class. The value of *p* in rural areas is provided in Table 2. In this study, due to the atmospheric stability class was B (moderately unstable), the *p* value was 0.12.

Table 2. Value of *p* to predict wind speed profiles for rural terrain

Stability Class	*p*
A	0.11
B	0.12
C	0.12
D	0.17
E	0.29
F	0.45

Buoyancy Factor

Pollutants coming out of the stack will move up vertically caused by the initial speed that pollutants have and the ability to move up (flux buoyancy) due to high pollutant temperature and density.

$$F_B = g\,V_s d_s{}^2\left[\frac{T_s - T_a}{4\,T_s}\right] \quad (3)$$

Remark:

F_B = Buoyancy flux parameter (m^4/s^3)

g = Gravity (9.8 m/s^2)

Vs = Gas exit speed (m/s)

Ts = Temperature of the released gas (K)

Ta = Temperature of the surrounding air (K)

The Distance of Maximum Plume Rise

The maximum plume rise distance (X_f) is the downwind distance from the source where the plume has reached its maximum rise and stable. This study used the Briggs Equation (Eq.4) to determine the maximum plume distance due to buoyancy flux (F_B), less than 55 m^4/s^3 [27].

$$X_f = 49\ {F_B}^{5/8} \tag{4}$$

Remark:

X_f = Distance of maximum plume rise (m)

F_B = Buoyancy flux parameter (m^4/s^3)

Plume Rise

The plume rise formula for unstable atmospheric conditions was calculated by using the Briggs Equation (Eq.5) [27]. In this study, the plume rise calculation was used gradual plume rise equation.

$$\Delta h = \frac{1.6{F_B}^{1/3}{X_f}^{2/3}}{u_s} \tag{5}$$

Remark:

Δh = Height of plume rise (m)

F_B = Buoyancy flux parameter (m^4/s^3)

X_f = Distance of maximum plume rise (m)

u_s = Wind speed (m/s)

Effective Height (H_c)

The effective stack height is the actual stack height plus the plume centreline's rise due to the effluent buoyancy. Buoyancy forces probable that a further rise of the plume. The calculation of effective height was used the Eq.6.

$$H_c = H_s + \Delta h \tag{6}$$

Remark:

Hc = Effective stack height (m)

Hs = Stack height (m)

Δh = Plume rise (m)

The Gaussian Plume Model and SCREEN3 results were later compared with the measured data. Particulate concentrations at monitoring points are presented in Table 3.

Table 3. Concentration of particulate at the monitoring point

Monitoring Point	Concentration ($\mu g/m^3$)
TP1	27
TP2	57
TP3	11
TP4	54
TP5	134

SCREEN3

SCREEN3 is a screening air dispersion model of ISC3, Industrial Source Complex 3, developed by Lake Environment based on the document Screening Procedures for Estimating the Air Quality Impact of Stationary Sources U.S EPA [26]. SCREEN3 is the recommended tool to calculate screening-level impact estimates for stationary sources in simple terrain. Simple terrain is defined as that in which terrain elevations are lower in elevation than the top of the source's stack height being evaluated in the modelling analysis. SCREEN3 is a Gaussian plume model that provides maximum ground-level concentrations for point, area, flare, and volume sources.

The SCREEN3's input data, using the same stack data in the Gaussian model and location atmospheric condition. In SCREEN3, the fumigation and shoreline calculation were used because the stack location is within 3000 m of the sea.

SURFER

Surfer is a software that is used for contour map creation and three-dimensional modelling based on a grid. Surfer is simply a mathematical interpolation program that draws contours of best fit between data points. Surfer was used to the visualization of the simulation of particulate dispersion in the study area.

METEOROLOGY

In analysing the determination of the distribution of pollutants required supporting data, including wind direction and speed. Cilegon has a hot and humid climate on the boundary between tropical monsoon (*Am*) and savannah (*Aw*) according to the Köppen climate classification system. Despite being located relatively close to the equator, the city has distinct wet and dry seasons. In the dry season, around May-October, the dominant wind blows from the North and the Northeast. In the wet or rainy season, around November-April, the dominant wind blows from the West and a small part from the North. For annual winds, the dominant wind blows from the North, West, and a small part of the Northeast. The wind speed range from 0.3 – 4.4 m/s, and the temperature range from 23.6 – 28.8 °C. The dry season and wet season wind roses are presented in Figure 3. The annual wind rose is presented in Figure 4.

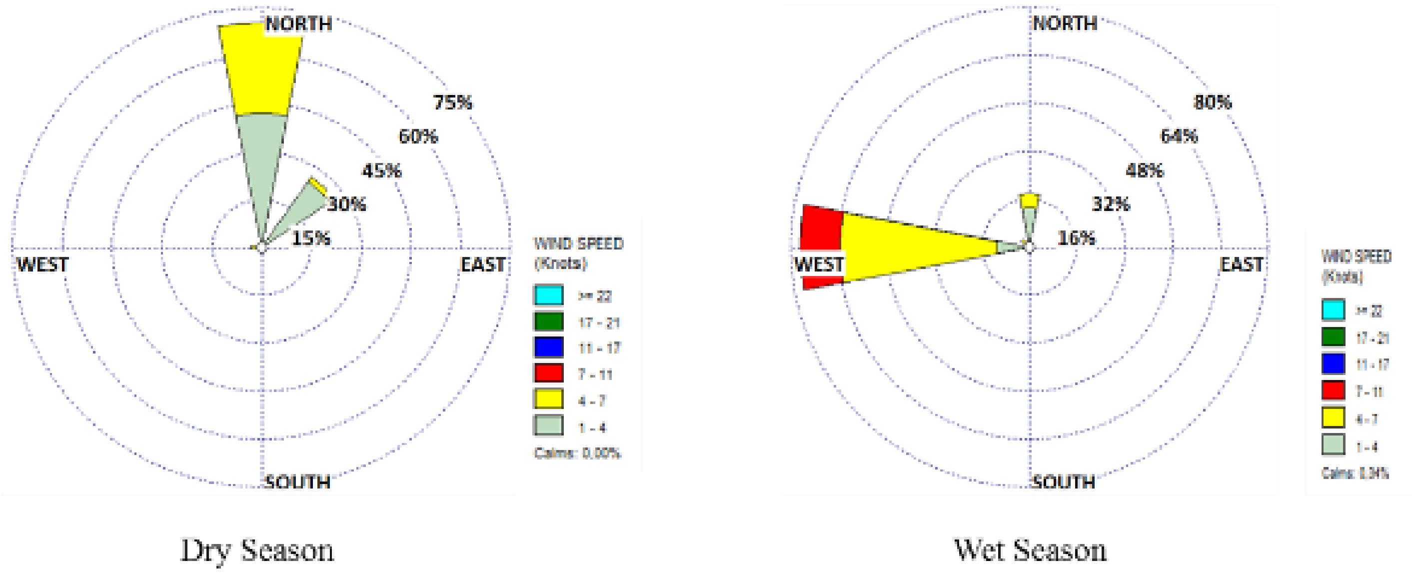

Figure 3. The wind roses of dry season and wet season

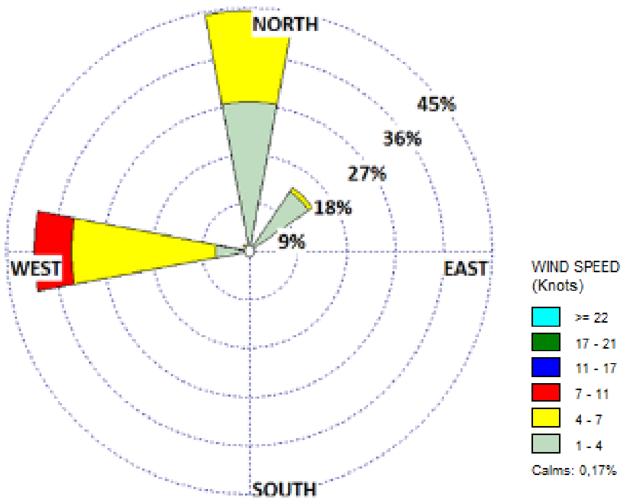

Figure 4. The annual wind rose

RESULT AND DISCUSSION

The Modelling of Particulate Concentration Prediction

The calculation of particulate concentration using the Gaussian Plume Model and SCREEN3 for each stack obtained the maximum particulate concentration at a certain distance. The maximum particulate concentration for CR1 computed by SCREEN3 was found at 500 m (0.145 µg/m^3), while the maximum particulate concentration calculated by Gaussian Plume Model was also found at 500 m (0.132 µg/m^3). Comparing the maximum particulate concentration obtained by the SCREEN3 and the Gaussian Plume model for each stack at the same distance had no significant concentration difference.

The fumigation and shoreline components in the SCREEN3 calculation result differ not significantly from the Gaussian Plume model results. A significant difference occurred when both model results were compared with the monitoring data (measurement data). The particulate concentration measured at the monitoring location at 500 m from the stack was 57 µg/m^3. The comparison of maximum particulate concentration between the SCREEN3 result and the Gaussian Plume model result is showed in Figure 5.

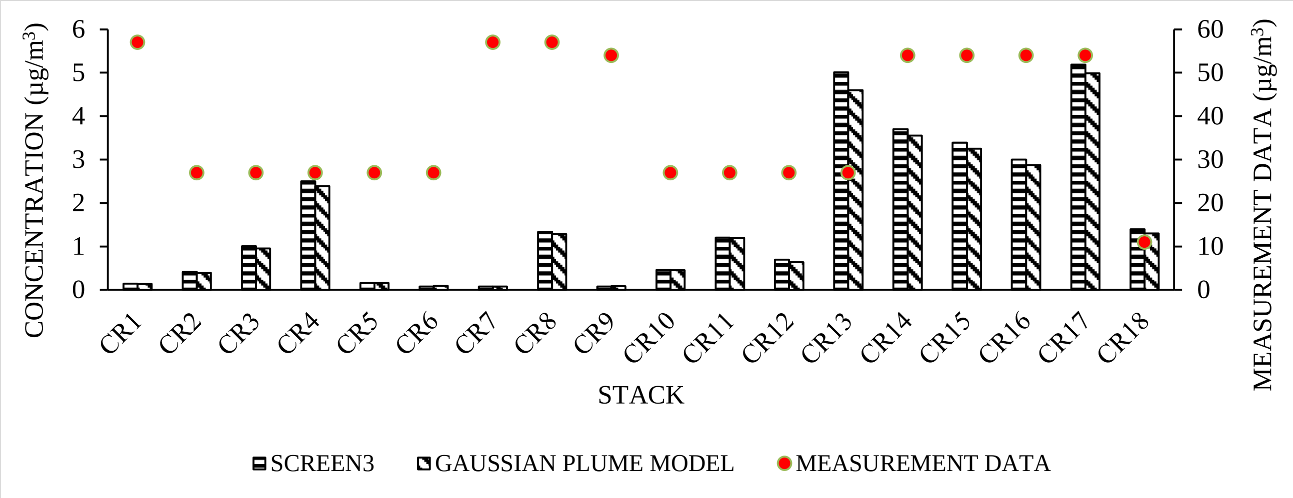

Figure 5. Comparison between simulated particulate maximum concentration by the SCREEN3 Model and Gaussian Plume Model for 18 stacks

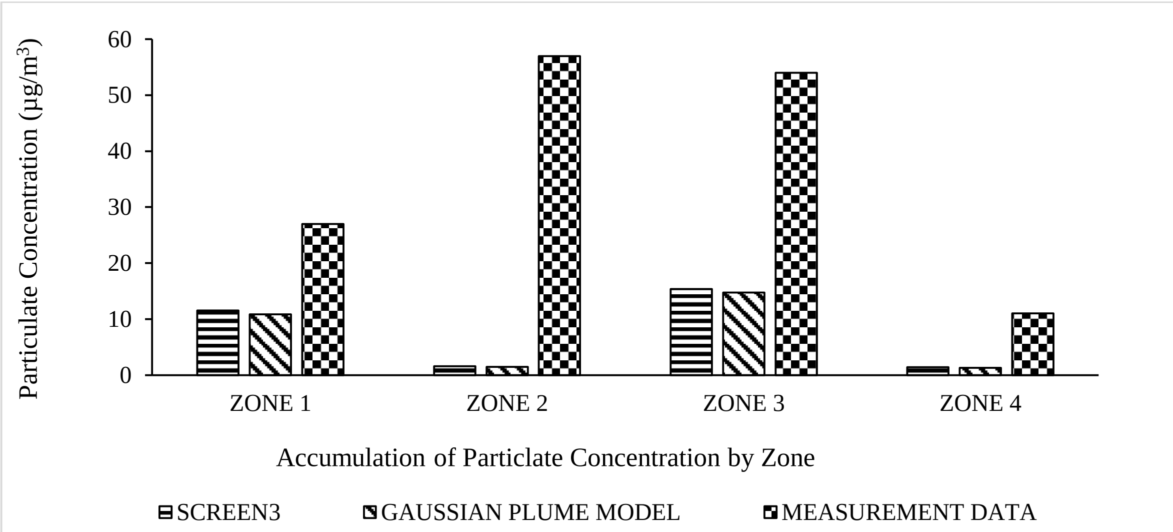

Figure 6. Comparison between particulate accumulation concentration by using the SCREEN3, Gaussian Plume Model, and measurement data

Figure 6 showed the comparison of particulate accumulation concentration obtained by the SCREEN, the Gaussian Plume model, and measurement data. The accumulated particulate concentration is divided based on the zone determined based on the distance between the maximum particulate concentration and the monitoring point (measured data). Based on these comparisons, it showed that the measured data is still higher than the modelling results.

The result indicates that the concentration of particulate in ambient air not only originates from industrial stacks. A study conducted in Cilegon city was found the five highest contributors to air pollution, which were crustal matter (40.13%), iron and steel production (22.23%), coal combustion (16.54%), biomass burning (11.83%), smelting (8.63%). Meanwhile, other sources were diesel vehicle (0.28%), sea salt (0.17%), fuel-oil combustion (0.07%), road dust (0.07%) and cement industry/construction (0.05%) [8]. Another study in Serpong, Indonesia obtained the source apportionment of particulate matter were lead industry mixed with road dust (12%), diesel vehicles (30%), oil and coal-fired power plant (26%), road dust (17%), and biomass burning mixed with road dust (15%) [23]. While a study in Peshawar revealed the source of particulate matter pollutants, which were re-suspended road/soil dust (35.9%), vehicular emission (27.4%), industrial emission (12.9%), and household combustion emission (12.8%) [1].

The Evaluation of the Model Performance

The Gaussian Plume model and the SCREEN3 (Version 4.0.1) performance was evaluated by comparing with the measured particulate concentration. The Gaussian Plume Model and SCREEN3 performance have a coefficient of determination (R^2) of 0.0345 and 0.0399, respectively. The model performance indicates that both models have a poor performance. A high correlation coefficient (r^2 = 0.98 and r^2 = 0.99) was obtained on the modelling of particulate matter dispersion from a cement plant by using the SCREEN3 model and The Gaussian Plume model [13]. A study in dispersion model evaluation of $PM_{2.5}$ from point sources in Nova Scotia, Canada using Aermod Gaussian plume air dispersion model obtained poor agreements between the model and observed data [10], R^2 of 0.65 obtained in a study at the particulate matter and its source apportionment in Peshawar, Northern Pakistan [1]. The various R^2 value in several studies showed that the model depends on the modelling times scale, domain environment, nature of the emission sources, and validation data set. The coefficient of determination of the study is presented in Figure 7.

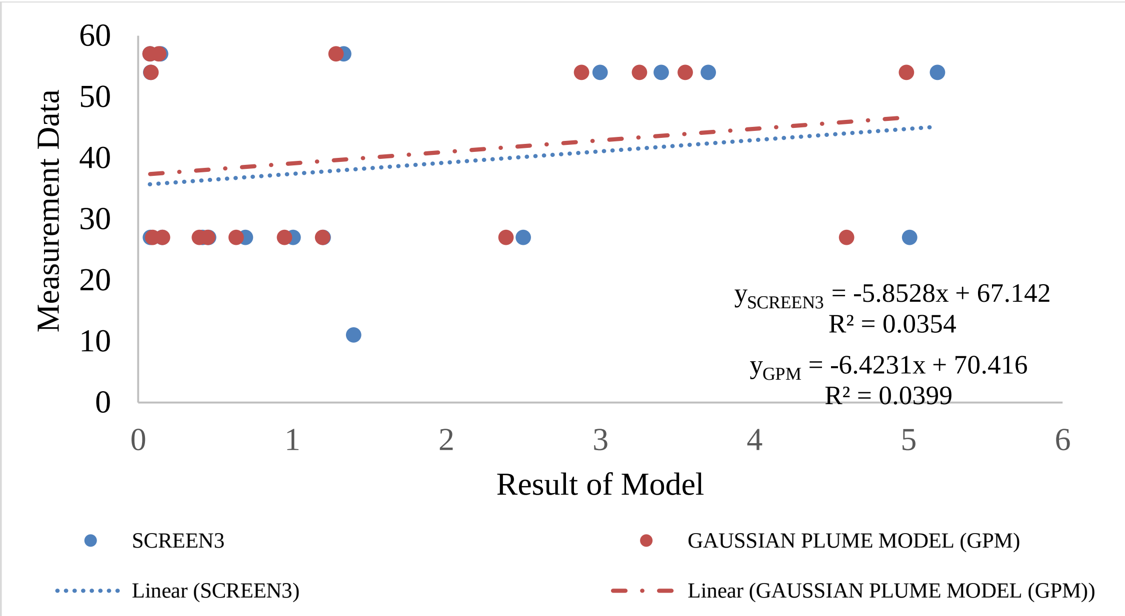

Figure 7. Coefficient of determination (R^2) for model and measurement data

In addition to the R^2 value, each model's error value is also calculated against the measured data. The error value of the models is shown in Figure 8 and Figure 9. Figure 8 to Figure 12 showed that the error between the models and measurement data is very high varied from 80–100%. This result indicates that the deviation of the models and measurement data occurred by several things.

In a study, the Gaussian Plume model's theoretical and experimental study in a small scale system obtained the error of all configurations was always less than 7% [7]. The tracer emission's dislocation not only generates random errors that were caught by the variations of the results between the different measurements transects [2]. It also has a strong potential to generate a bias in the computations since the measurements were taken in a relatively narrow range of sources. The observed location was in the downwind of another particulate emission source. Therefore, the emission rate was overestimated because of vertical atmospheric diffusion.

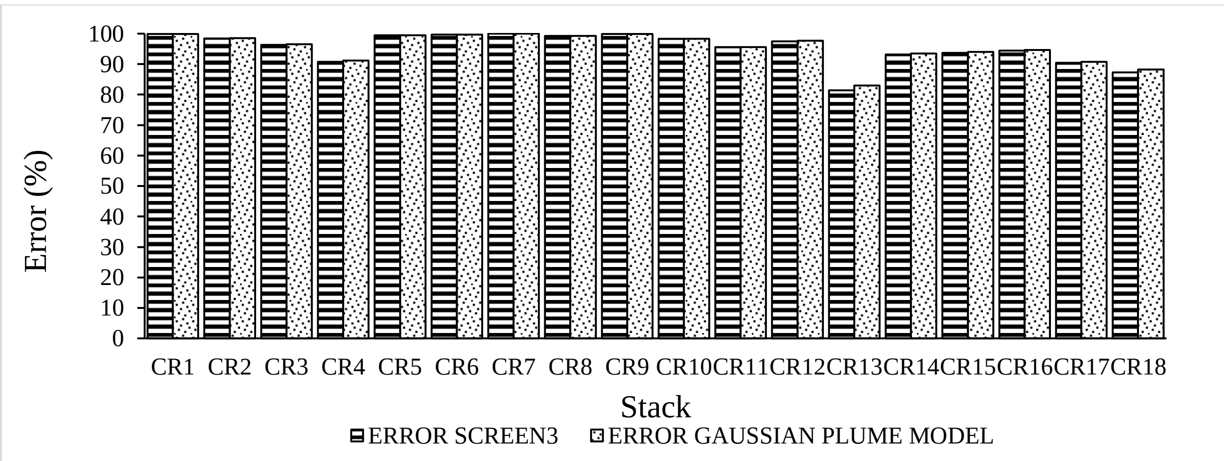

Figure 8. Comparison of Model Error

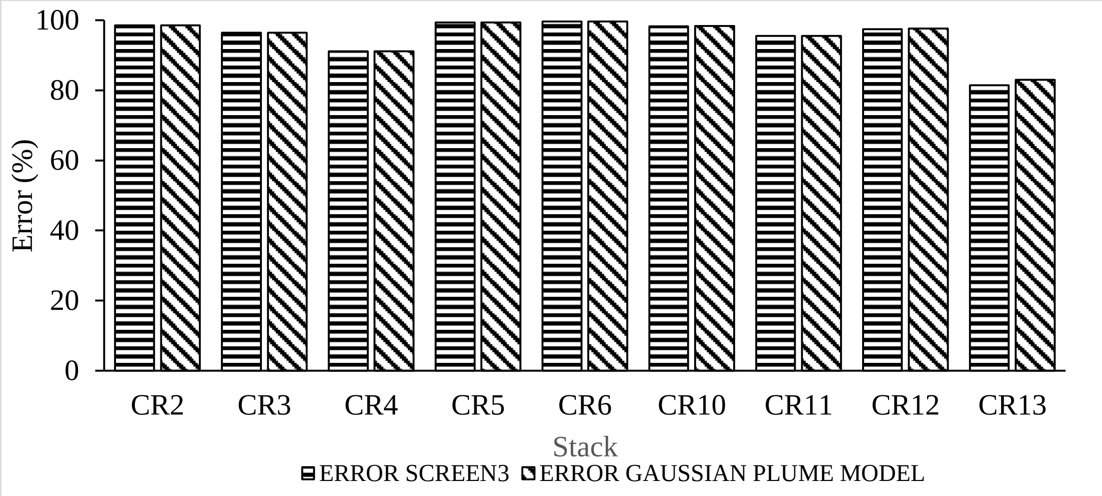

Figure 9. Comparison of Model Error to TP1

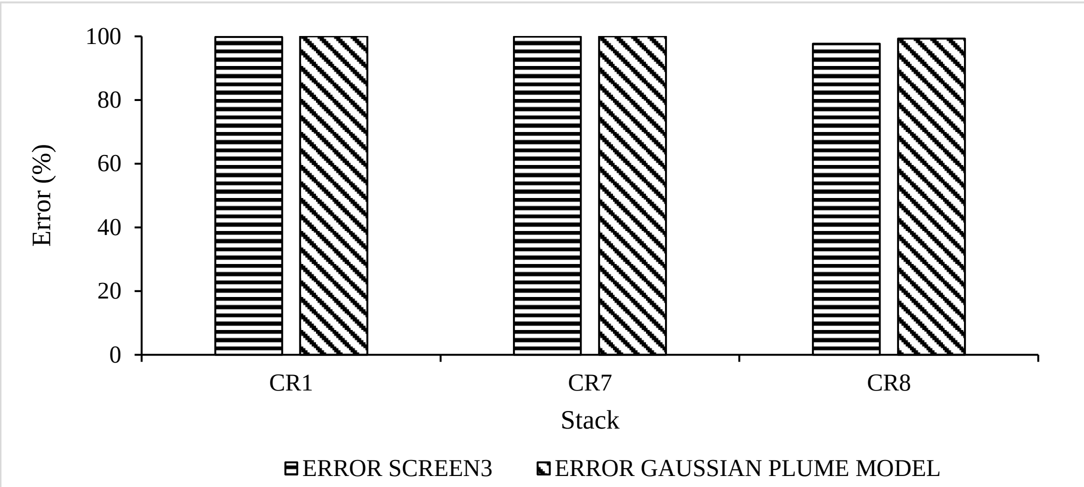

Figure 10. Comparison of Model Error to TP2

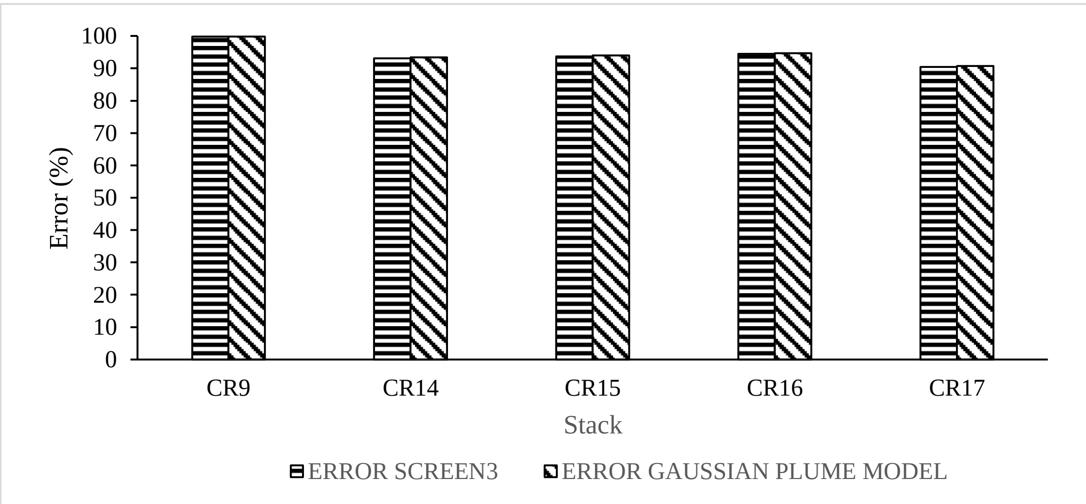

Figure 11. Comparison of Model Error to TP3

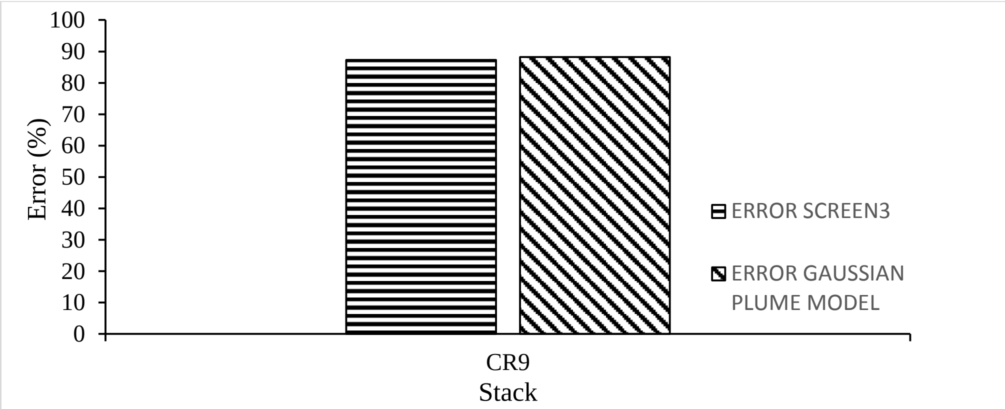

Figure 12. Comparison of Model Error to TP4

The Particulate Dispersion

The particulate dispersion predicted is shown in Figure 13. Dispersion simulation at various downwind distances shows that particulate dispersion's dominant direction was toward the southern part of the study area. The particulate distribution direction spreads based on the dominant wind direction and the vehicle movement greatly contributes to pollutant dispersion [28].

Based on the particulate concentration calculation by modelling, the smaller the particulate concentration away from the emission source. A study in West Java showed the same result [21]. The southern part of the study location is mostly in hilly areas. Based on the study area boundaries, the dispersion direction also reaches community settlements, especially in the southwest of the study location.

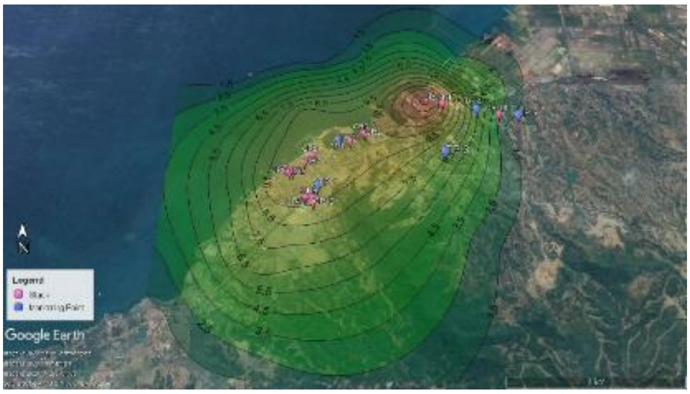

Figure 13. Visualization of the simulation particulate dispersion.

CONCLUSION

We obtained the prediction of particulates' concentration in distances about 500-5000 m from each stack based on this study. The accumulation and maximum concentration were obtained using the Gaussian Plume Model and SCREEN3 below the government's quality standard. The dispersion of particulates in ambient air using the Gaussian equation and SCREEN3 is decreasing in concentration with increasing distance from the source of emissions. The Gaussian Plume Model and SCREEN3 performance have a coefficient of determination (R^2) of 0.0345 and 0.0399, respectively. That indicates that both models have a poor agreement. By using Surfer and Google Earth, the simulation of particulate concentration dispersion was visualized. Simulated dispersion at various downwind distances shows the dominant direction of particulate dispersion toward the southern part of the study area. The particulate distribution direction spreads based on the dominant wind direction. The model's particulate concentration was smaller than the particulate concentration at the monitoring points based on comparing the modelling results and the monitoring points (measured data).

Based on the modelling results, the high level of ISPA incident in The Ciwandan district is not only affected by particulate emissions from the industrial stack but also from crustal matter, coal combustion, biomass burning, diesel vehicle, sea salt, fuel-oil combustion, re-suspended road/soil dust, and household combustion emission. Finally, the readily available tools and data combined with a dispersion model provide a more accurate representation of the air quality.

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