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Modeling the Effects of Meteorological Parameters and Sampling Frequency on PM_{10} Concentrations in Tacloban, Philippines

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ABSTRACT

According to the annual report of the Regional Environmental Management Bureau, Tacloban recorded high annual mean levels of PM_{10} concentrations in 2013 to 2015, which registered 65 µg m^{-3}, 76 µg m^{-3}, 64 µg m^{-3}, respectively. Such measurements were in exceedance of the long-term National Ambient Air Quality standard (60 µg m^{-3}). It was imperative, therefore, to simulate and predict the PM_{10} concentrations in this area through this study. A PM_{10} systems model was created to predict and analyze the effects of meteorological parameters and sampling frequencies to PM_{10} concentrations. Second-order Runge-Kutta integration method (DT=0.05) was used to run the model for a 20-year period. Using a multiple linear regression analysis, air temperature and wind speed were the key predictors to the concentrations of PM_{10}. Monsoonal winds and mesoscale phenomena may also have contributed to the PM_{10} levels in the sampling site. In terms of the effects of the sampling frequency, the 1-in-6-day sampling scheme (R = 58.0%) resulted in predicted PM_{10} values which acceptably fits the model. Other meteorological variables and transboundary transport must also be considered in the STELLA model to simulate the PM_{10} concentrations in Tacloban, Philippines.

Keywords: **M**eteorological parameters, multiple linear regression, PM_{10}, STELLA™, Tacloban

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INTRODUCTION

With the steady increase of industrialization in Tacloban City, Philippines, air pollution and its hostile environmental and health impacts became the primary concern to all its stakeholders. Air pollution has worsened due to numerous infrastructure projects, increased activity of smoke-emitting factories in the North and Central Tacloban (Jimenea, 2013), and the influx of motor vehicles in and outside the central business district was observed to increase by 76.25% from 2014 to 2015 alone (Land Transportation Office, 2015). In fact, the city was cited to have 88 airborne-related diseases (7%, nationwide) as mentioned by World Bank (Santiago, 2011). However, to address this problem, the Local Government Unit (LGU) must have access to several scientific data from which regulations, policies, and guidelines may be formulated to improve air quality.

In 2012, the Department of Environmental and Natural Resources Region VIII proposed for the establishment of Tacloban Airshed. Prior to this, the Leyte Geothermal Airshed (LGA) has been established in 2002 which quarterly monitors the ambient air, water, toxic and hazardous waste, environmental compliance certification (ECC) and solid waste management (SWM). As seen in Fig. 1, four municipalities are covered by this airshed, namely: Carigara, Capoocan, Kananga, and Ormoc City. Community areas covered by the airshed are located within the Leyte Geothermal Surface Development Block (LGSDB) of the Leyte Geothermal Reservation. Due to the regional influence of the Leyte Geothermal Powerplants, the City of Tacloban qualified to have ambient air monitoring stations through the assessment of the Environmental Management Bureau (EMB). These stations monitor the concentrations of air pollutants such as total suspended particles (TSP), PM_{10}, and $PM^{2.5}$ (Jimenea, 2013). Yet only one of the three stations measures PM_{10} – the EVSU Monitoring Station.

Particulate matter (<10 µm in size), generally referred as PM_{10}, is of most concern with regards to adverse effects to human health. It is considered as one of the five primary criteria pollutants with National Ambient Air Quality Guideline Values (NAAQGV) set at 150 µg m^{-3} and 60 µg m^{-3} for short-term and long-term guideline values, correspondingly (Philippine Clean Air Act, 1999). PM_{10} can be divided into coarse and fine particulate sizes referred to as $PM^{2.5-10}$ and $PM^{2.5}$, respectively. Additionally, particulate matter is a heterogeneous mixture of harmful chemical constituents (such as nitrates, sulfates, elemental and organic carbon, polycyclic aromatic hydrocarbons), biological components (endotoxins and cell fragments), and metals (iron, copper, nickel, zinc, and vanadium) (WHO, 2013). Consequently, both particle sizes are correlated with serious health issues since these can penetrate into the lungs up to the alveoli and into the bloodstream (Pabroa, 2011). Acute pulmonary and cardiovascular problems such as bronchitis, asthma, congestive heart failure, and ischemic heart disease were identified to be linked to PM pollution (EPA, 1997), risking elderly (greater than 65 years old) and young children (EPA, 1996; Jimoda, 2012). Reports determined an estimated daily mortality increase of 0.2% to 0.6% per 10 µg m^{-3} of PM_{10} (coarse size) in the world (WHO, 2005).

The concentration of ambient PM is controlled not only by the rate of source emission, but also by wind speed, turbulence level, air temperature, and precipitation. In reserve of numerous meteorological parameters, the most significant factors affecting PM10 concentrations in ambient atmosphere are dispersion, transformation, and removal (Lam and Cheng, 1998; Birim et al., 2023). Studies (Jo and Park, 2005; Giri et al., 2008; Nazif et al., 2019) limited to the influence of a single meteorological variable to PM lead to misinterpretations of relationships of two or more parameters. This stresses the significance of PM_{10} monitoring highlighting cross-correlations between meteorological parameters for understanding PM_{10} source-sink processes.

However, majority of the countries in the tropics are developing nations, including the Philippines. Economic limitation for extensive PM_{10} measurements is the deterring factor. Thus, low-cost solutions for PM_{10} measurement and monitoring are needed and crucial. In this study, a STELLA model is formulated to offer a cost-effective simulation framework to determine PM_{10} concentrations in the sampling site keeping acceptable confidence levels intact. Likewise, a multiple linear regression analysis was utilized to provide a cross-correlation among the meteorological parameters themselves missing out misinterpretations on their effects to PM_{10}.

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MATERIALS AND METHODS

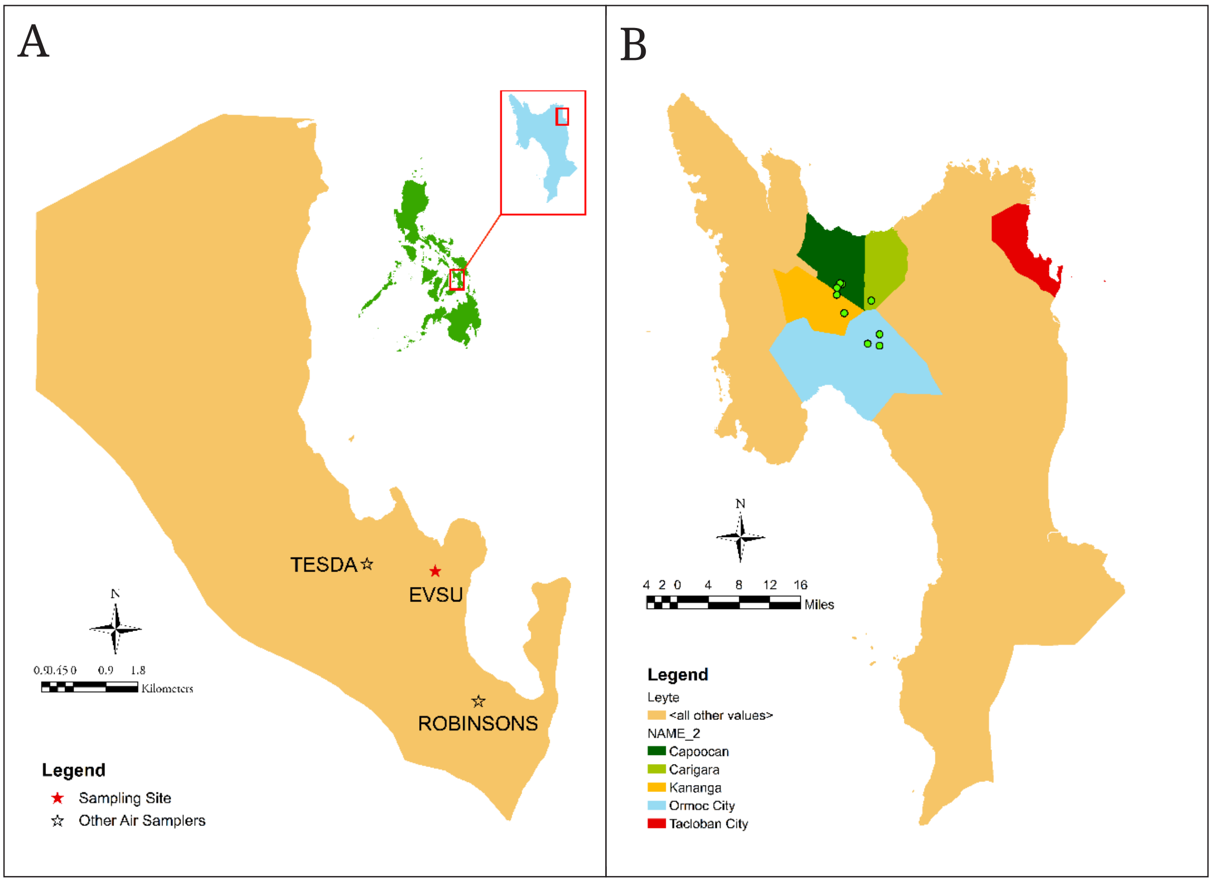

Figure 1. Map of Tacloban City Airshed and the geographic locations of DENR-EMB air samplers (A). The EVSU sampling site (11.2403° N, 124.9971° E) is located at the heart of the city center. The monitoring areas (shown by the green points) and boundaries of the Leyte Geothermal Airshed traverse the municipalities of Capoocan, Carigara, Kananga, and Ormoc City in the Northwestern portion of the Leyte Island, Philippines (B).

Software description and principles

STELLA™ (Systems Thinking, Experiential Learning Laboratory with Animation) is a visual modeling software which deals with computational and structural logic, conceptualization, equation formulation, and model analysis (Richmond, 1985). Dynamic systems are basically composed of interrelated complex components where effects over time for each are of prime concern (Sterman, 2000). As indicated in Figure 2 and Table 1, four (4) basic building blocks comprise a systems model: stock/reservoir, flow/process, converter, and connectors (Shiflet and Shiflet, 2006). Each component is well described in the PM_{10} systems model description (2.3).

Systems model is a useful tool in simulating, predicting, and interpreting the behavior of the natural environment (Deaton and Winebrake, 2000). In this study, a particulate matter (PM_{10}) systems model was created to better understand the underlying mechanisms of meteorological parameters and sampling frequencies to the PM_{10} concentrations. Besides, the model was utilized to obtain predictive values and trends of PM_{10} as provided by past and existing conditions.

Data measurement and model input

Figure 2 shows the systems entry and type of components used in the systems model, with their corresponding unit and measured values. Secondary measured data was taken from the Land Transportation Office (vehicle-related), Population Commission (population-related), and Regional Environment and Natural Resources Office (forest-related). Field validation was conducted to determine the veracity of the consolidated data.

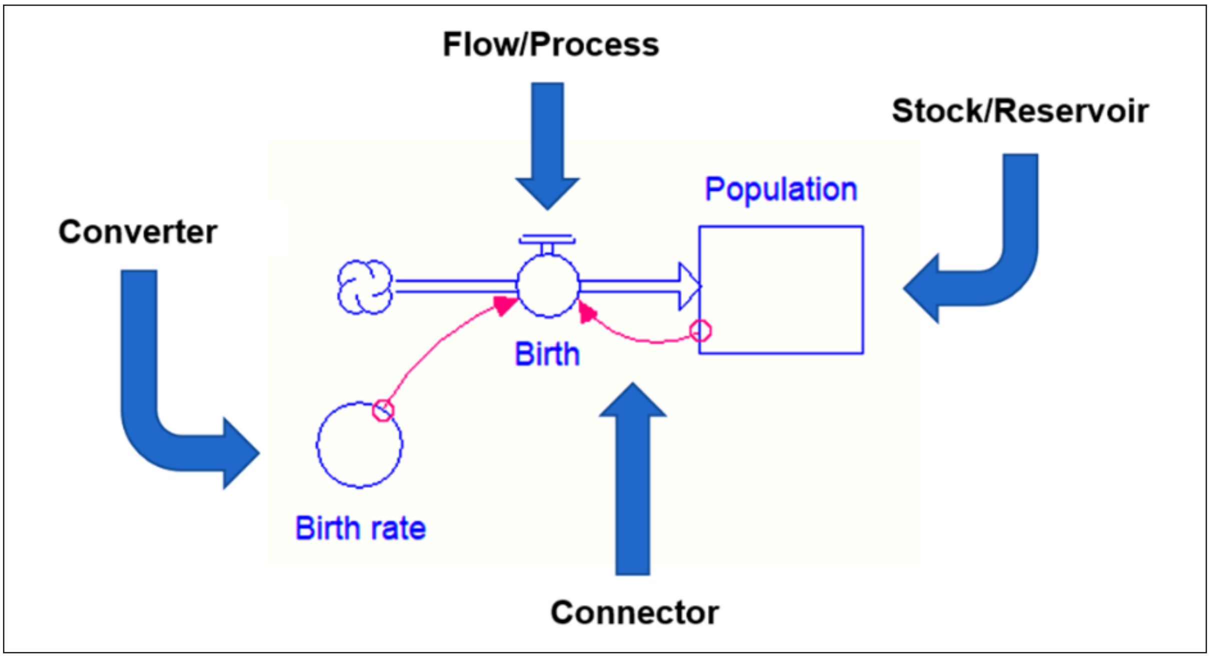

Figure 2. A simple population model consisting of building blocks of STELLA® software.

Table 1. STELLA building blocks and its meaning (Deaton and Winebrake, 2000).

Component	Description
Stock/Reservoir	A repository where something is accumulated, stored, and potentially passed to other elements in the system
Flow/Process	An ongoing activity that determines the contents of the reservoirs over time
Converter	system variable: dictates the rates at which the process operates and reservoir contents change.
Connector	transmits an input or an output; creates interrelationships between components

PM_{10} sampling station was administered and monitored by the Air Quality Division of the Regional Environmental Management Bureau in Eastern Visayas, Philippines. The station was at Eastern Visayas State University, Tacloban City, Leyte, Philippines (11.2403° N, 124.9971° E; elevation at 9 meters above sea level) which is highly populated and located at the center of the urban site. Partisol 2000H gravimetric air sampler measured the PM_{10} concentrations, with a standard 47-mm diameter quartz fiber filter mounted in an FRM-style filter cassette. The sampler registered a volumetric flow rate of 16.7 liters per minute (LPM).

The station was equipped with MSO weather sensor capable of measuring several meteorological parameters. Wind speed and direction were measured using conventional cup and vane techniques. A multi-plated radiation shield reduces solar radiation errors. The temperature sensor is a platinum RTD class 1/3B while relative humidity was determined with an accurate solid-state sensor designed to continuous exposure to extreme climates. The pressure sensor is a piezo-resistive device designed for robustness, highly accurate needs, and for long-term stability (Met One Instruments, 2013).

Air sampling was done for 24 hours every 6 days using manual method. Data from second to fourth quarters (April-October 2015) were used in the model. About 45.8% (22 samples) of the total samples were considered due to some logistic grounds such as vehicular maintenance and repairs during the first quarter of the year.

2.1. PM_{10} systems model description

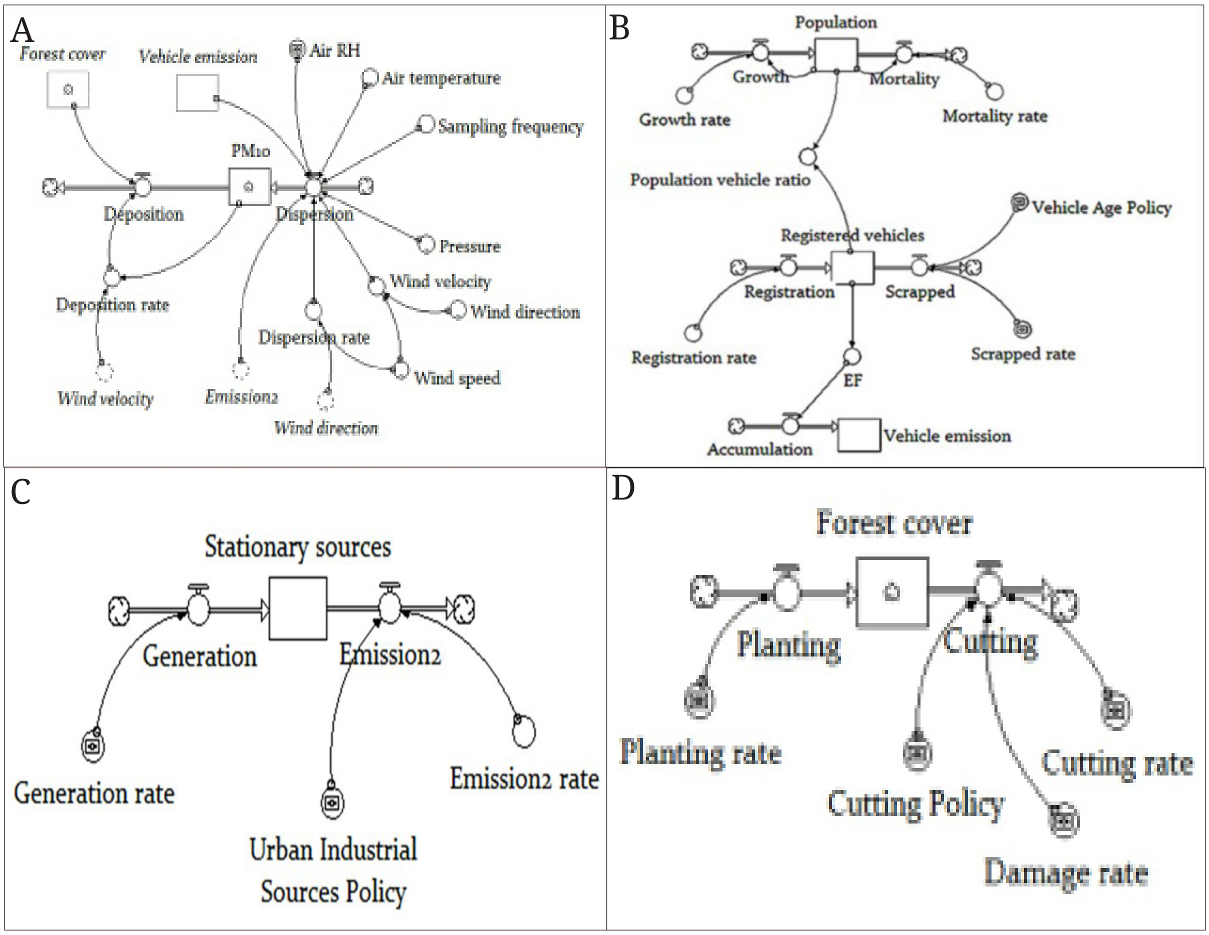

Figure 3. PM_{10} concentration systems model (A); human-vehicle population (B); stationary source submodels (C) and forest cover submodel (D).

Figure 3 shows the submodels and the PM_{10} concentration dynamic systems model used to simulate and predict the effects of meteorological parameters and sampling frequency to PM_{10} levels. The human-vehicle population submodel depicted human population and the increasing vehicle volume in the study area. In human population submodel, birth and mortality were the driving processes affecting the growth and decline of the reservoir (population). These processes were in turn dictated by birth rate (per capita per year) and mortality rate (per capita per year), correspondingly, and number of people (population). On the contrary, the number of register vehicles was influenced by registration and scrap mechanisms. The registration was dictated by the number of people registering their vehicle in a year (registration rate). The scrap process was affected by the rate at which vehicles were scrapped and by the government measures which the researcher called "vehicle age policy". To connect the number of registered vehicles to vehicular emission (reservoir), the researcher placed a converter "emission factor" (EF) which may affect the accumulation process.

Stationary source emission was another PM contributor identified in this model. The number of stationary sources had an inflow (generation) and outflow (emission2). The former was affected by the generation rate while the latter process was by emission2 rate, and a government policy called "urban-industrial sources emission limit policy".

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Table 2. Specifications of data used with their corresponding units and baseline values.

Systems entity	Type of component	Unit	Value
Population	Reservoir	Number of individuals	221174 [a]
Registered vehicles	Reservoir	Number of registered vehicles	34281 [b]
Vehicle emission	Reservoir	Tons	2500 *
Stationary sources	Reservoir	Tons	948 [c]
Forest cover	Reservoir	Hectares	11689.47 [d]
PM_{10}	Reservoir	μg m^{-3}	64 [e]
Growth rate	Converter	Number of individuals born in a year (individuals born/year)	2.16 [f]
Mortality rate	Converter	Number of individuals die in a year (individuals die/year)	0.0099[g]
Population-vehicle ratio	Converter	Ratio of individuals in single vehicle (population/vehicle)	-
Registration rate	Converter	Number of vehicles registered in a year (registered vehicle/year)	2.5 [h]
Scrapped rate	Converter	Number of vehicles scrapped in a year (scrapped vehicle/year)	0
Vehicle-age policy	Converter	Number of vehicles to be scrapped based on its age	15*
Emission factor (EF)	Converter	(Unitless)	-
Planting rate	Converter	Number of trees planted in a year (in hectares)	260 [i]
Cutting rate	Converter	Number of trees cut in a year (in hectares)	0 [j]
Damage rate	Converter	Number of trees damaged in a year (in hectares)	131 [i]
Cutting policy	Converter	Number of trees allowed to be cut in a year (in hectares)	55 *
Generation rate	Converter	Amount of generated pollutants in a year (in tons)	500 *
Emission2 rate	Converter	Amount of emissions in a year (in tons)	79 *
Urban-industrial sources policy	Converter	Allowed volume of emissions in a year (in ug m^{-3})	150 [k]
Air relative humidity (RH)	Converter	Percent RH (%RH)	** l
Air temperature	Converter	degree Celsius (^{0}C)	** l
Air pressure	Converter	hectoPascal (hPa)	** l
Wind direction (WD)	Converter	degrees (^{o})	** l
Wind speed (WS)	Converter	Meters per second (m s^{-1})	** l
Wind velocity	Converter	Meters per second (m s^{-1})	(*WS***WD*)
Sampling frequency	Converter	Number of sampling in a week	1 [l]
Deposition rate	Converter	Amount of PM_{10} deposited in a year (ug m^{-3} yr^{-1})	-
Dispersion rate	Converter	Amount of PM_{10} dispersed in a year (ug m^{-3} yr^{-1})	-

[a]*Based on the 2010 Census of Population*
[b]*Based on 2015 LTO Comparative Tabulation of Registered MV*
[c]*Emissions inventory of Robinsons Tacloban (Generator set, boiler, evaporator, and furnace)*
[d]*Cumulative (open broadleaved forest, natural grassland, wooded land, and mangrove forests)*
[e]*Based on the 2015 PM_{10} concentrations*
[f]*Taken from 2000-2010 Census growth rates*
[g]*Taken from 2010 DOH-PHS*
[h]*Based on the 2015 LTO Registered vehicles*
[i]*Based on the data of CENRO Palo, Leyte*
[j]*Assumptive value of CENRO Palo due to a DENR Memo Circular*
[k]*Based on the DENR AON 2000-81 (Nov 2000)*
[l]*Based on the data from 2015 Annual Regional Air Quality Status Report (DENR-EMB VIII)*
**Assumptive value (Based on regional or national values)*
***See Table 2, 3, and 4*

The forest cover submodel served as an indirect natural sink in this system model affecting the dispersion process of particulate matter (Heath, 1999; Ottelé, 2010; Basu et al., 2025). Planting and cutting processes affected the area of forest cover in this sub-system. The inflow (plating) was changed by the plating rate, while the outflow (cutting) was influenced by cutting rate, cutting policy, and damage rate (during Typhoon Haiyan).

Finally, to determine the number of suspended particulates in the study site, particulate matter (PM_{10}) concentration was considered as quality indicator and reservoir. The PM_{10} concentration system model was composed of dispersion (inflow) and deposition (outflow) processes. The dispersion mechanism was affected by the following factors: vehicle emission, emission2 process (from stationary sources), meteorological parameters (air relative humidity, air temperature, air pressure, wind speed, and direction), sampling frequency, and dispersion rate. On the other hand, the deposition mechanism was affected by deposition rate (linked to PM_{10} concentration and wind speed and direction), and area of forest cover (serves as a sink of the system).

In this study, the model configuration in the STELLA software was based on the principles of choosing appropriate algorithms (STELLA and iThink, 2007) which were as follows: (1) 2^{nd} order Runge-Kutta method, (2) time step (DT) set at 0.05; (3) runtime was 20 years. Runge-Kutta is a type of integration method wherein it uses an algorithm with two flows of calculation (initialization and iteration phase) within a given time step (DT) to create an estimate for the change in a reservoir over the specified DT. This method was carried out for the systems model since it reflects a continuous and oscillatory tendency temporally. Furthermore, the selected time step achieved a good compromise between the accuracy of results and speed of simulation.

Data analysis

Simulated data were statistically treated using multiple linear regression (MLR) analysis to determine the impacts of meteorological parameters and sampling frequencies to PM_{10} concentrations, as described by Macatangay et al. (2014). This statistical tool attempts to project relationship between two (2) or more independent variables (xik) and response variables by fitting a linear equation to the observed data. The model is expressed as DATA = FIT + RESIDUAL, where FIT term is $\beta_0 + \beta_{1xi1} + \beta_{2xi2} + \ldots + \beta_{kxik}$. The RESIDUAL term shows the model deviations, ε, of the observed values y from their means μy, normally distributed with mean 0 (zero) and variance σ. In general, the model for multiple linear regression, with n observations, is given by equation (1),

$$y_i = \beta_0 + \beta_{1xi1} + \beta_{2xi2} + \ldots + \beta_{kxik} + \varepsilon_i, \qquad i = 1, 2, \ldots, n. \tag{1}$$

β_k denotes the regression coefficients and εi are the errors. The former describes the impact of available meteorological parameters to PM_{10} levels. The root-mean-square error (RMS) can assess the fit of the regression model and how will it represent the measured data, and this can be written as equation (2),

$$RMS = \sqrt{\frac{\sum_{i=1}^{n}(Y_{data,\,i} - Y_i)^2}{n}} \tag{2}$$

RESULTS

Table 3 presents the independent variables, x_{ik}, used in the multiple linear regression analysis. Only four meteorological parameters were considered in the study to determine its impact on the concentrations of ambient PM_{10} due to data constraints within the sampling station.

Table 3. List of independent variables, x_{ik}, used in the multiple linear regression analysis for Tacloban site.

Independent variable, x_{ik}	Meteorological parameter	Unit of measure
x_{i1}	Relative humidity	% RH
x_{i2}	Air temperature	°C
x_{i3}	Air pressure	hPa
x_{i4}	Wind speed	m/s

Figure 4 shows a series of scatterplots indicating correlation plots and coefficients between independent variables, x_{ik}. Qualitative interpretations of correlation coefficients were staggered as follows: 0.00-0.19 (very weak); 0.20-0.39 (weak); 0.40-0.59 (moderate); 0.60-0.79 (strong); and 0.80-1.00 (very strong) (Evans, 1996). The strength and relationship of correlations, measured in r, widely varied between meteorological parameters. Very strong negative correlations (r = 0.89) were shown by the effect of relative humidity (RH) and air temperature to the concentrations of PM_{10} in the sampling site. Wind speed made moderate positive and negative correlations, in terms of its influence to PM_{10} levels, between air temperature (r =0.57) and RH (r =0.53), respectively. Contrary to these parameters, air pressure revealed weak positive and

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negative correlations with RH (r =0.35) and air temperature (r =0.38), respectively, while indicating a much weaker negative correlation with wind speed (r =0.17).

Tables 4, 5, 6 and its sub-tables depict the observed PM_{10} and meteorological parameter measurements in the sampling site which were staggered into 3 quarters (Q2: April-June; Q3: Jul-Sept; Q4: Oct) of the sampling period/year. These tables show the varying concentrations of PM_{10} in the sampling site while monitoring four (4) meteorological parameters measured using sophisticated instruments installed in the air sampling station. In Q2, the Jun 3-4 sampling week had no gathered data for wind speed and direction, pressure, air temperature, and air RH due to instruments' maintenance and logistics issue, as mentioned by the DENR-EMB Region VIII. In Q2, PM_{10} level measurements were consistently and gradually increasing. However, in Q3 and Q4, PM_{10} concentrations were fluctuating every month.

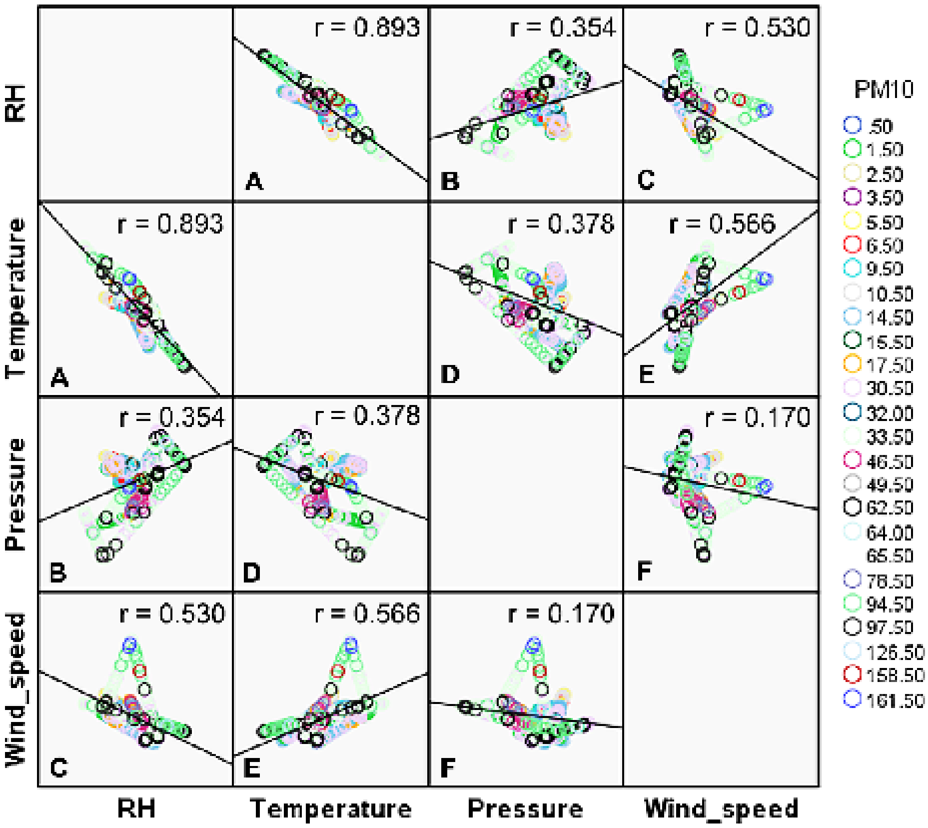

Figure 4. Correlation plots and coefficients of meteorological parameters. Down-sloping line signifies negative correlation between indicated variables. The upward-sloping line indicates positive correlation. Colored circles and values denote PM_{10} concentrations (μg m^{-3}).

Table 4. 2nd quarterly monitoring data (2015) of PM_{10} concentrations, wind speed and direction in Tacloban Sampling Site, Leyte, Philippines (*NR - No Record).

Date	PM_{10} (μg m^{-3})	WS (m s^{-1})	WD (degrees)
Apr 13-14	9.44 ± 1.83	0.7203 ± 0.02	160.87 ± 4.97
Apr 22-23	6.9 ± 3.10	0.9592 ± 0.10	143.39 ± 13.71
Apr 27-28	7.8 ± 2.65	0.802 ± 0.02	160.22 ± 5.29
May 4-5	7.72 ± 2.69	0.8132 ± 0.02	173.46 ± 1.33
May 11-12	3.14 ± 4.98	0.8554 ± 0.04	158.36 ± 6.22
May 19-20	11.51 ± 0.79	0.7573 ± 0.004	172.28 ± 0.74
May 26-27	12.48 ± 0.31	0.77 ± 0.002	164.18 ± 3.31
Jun 3-4	10.44 ± 1.33	NR*	NR*
Jun 22-23	13.84 ± 0.37	0.5294 ± 0.11797	192.23 ± 10.71

Table 4.1. 2nd quarterly monitoring data (2015) of air pressure, air temperature, and air relative humidity in Tacloban Sampling Site, Leyte, Philippines (*NR - No Record).

Date	Pressure (hPa)	Air temp (°C)	Air RH (% RH)
Apr 13-14	1010.57 ± 0.76	29.06 ± 0.16	74.87 ± 0.33
Apr 22-23	1011.34 ± 1.14	29.57 ± 0.09	68.22 ± 2.99
Apr 27-28	1010.44 ± 0.69	29.28 ± 0.05	73.38 ± 0.41
May 4-5	1009.03 ± 0.01	29.29 ± 0.05	71.56 ± 1.32
May 11-12	1010.99 ± 0.97	30.09 ± 0.35	72.04 ± 1.08
May 19-20	1010.62 ± 0.78	30.59 ± 0.60	70.19 ± 2.01
May 26-27	1010.3 ± 0.62	30.57 ± 0.59	68.62 ± 2.79
Jun 3-4	NR*	NR*	NR*
Jun 22-23	1009.63 ± 0.29	28.94 ± 0.22	79.03 ± 2.41

Table 5. 3rd quarterly monitoring data (2015) of PM_{10} concentrations, wind speed and direction in Tacloban Sampling Site, Leyte, Philippines.

Date	PM_{10} (μg m^{-3})	WS (m s^{-1})	WD (degrees)
July 14-15	16.79 ± 1.85	0.90 ± 0.07	199.76 ± 14.48
July 21-22	25.06 ± 5.98	0.55 ± 0.11	167.38 ± 1.71
Aug 3-5	9.92 ± 1.59	0.72 ± 0.02	169.47 ± 0.67
Aug 19-20	10.37 ± 1.36	0.80 ± 0.02	178.82 ± 4.01
Aug 24-25	22.51 ± 4.71	1.43 ± 0.33	170.04 ± 0.38
Sep 1-2	13.46 ± 0.18	0.65 ± 0.05	159.69 ± 5.56
Sep 7-8	11.34 ± 0.88	0.55 ± 0.11	189.98 ± 9.59
Sep 17-18	9.61 ± 1.74	0.58 ± 0.09	170.21 ± 0.30
Sep 21-22	7.08 ± 3.01	0.61 ± 0.07	167.61 ± 1.60

Table 5.1. 3rd quarterly monitoring data (2015) of air pressure, air temperature, and air relative humidity in Tacloban Sampling Site, Leyte, Philippines.

Date	Pressure (hPa)	Air temp (°C)	Air RH (% RH)
July 14-15	1006.16 ± 1.45	29.35 ± 0.02	73.62 ± 0.29
July 21-22	1011.28 ± 1.11	27.73 ± 0.83	77.82 ± 0.181
Aug 3-5	1006.61 ± 1.22	28.86 ± 0.26	76.31 ± 1.05
Aug 19-20	1005.45 ± 1.80	30.91 ± 0.76	67.55 ± 3.33
Aug 24-25	1008.88 ± 0.09	30.19 ± 0.40	74.05 ± 0.08
Sep 1-2	1009.84 ± 0.39	28.96 ± 0.21	79.24 ± 2.52
Sep 7-8	1008.32 ± 0.37	29.02 ± 0.18	76.64 ± 1.22
Sep 17-18	1010.23 ± 0.59	28.48 ± 0.45	80.10 ± 2.95
Sep 21-22	1007.44 ± 0.81	28.93 ± 0.23	78.09 ± 1.94

Table 6. 4th quarterly monitoring data (2015) of PM_{10} concentrations, wind speed and direction in Tacloban Sampling Site, Leyte, Philippines.

Date	PM_{10} (μg m^{-3})	WS (m s^{-1})	WD (degrees)
Oct 2-3	37.41 ± 12.16	0.7010 ± 0.0322	176.62 ± 2.91
Oct 5-6	9.46 ± 1.82	0.6341 ± 0.0656	178.13 ± 3.66
Oct 16-17	7.15 ± 2.97	0.8473 ± 0.0410	174.26 ± 1.73
Oct 18-19	24.71 ± 5.81	0.8761 ± 0.0554	159.87 ± 5.47

Table 6.1. 4th quarterly monitoring data (2015) of air pressure, air temperature, air relative humidity in Tacloban Sampling Site, Leyte, Philippines.

Date	Pressure (hPa)	Air temp (°C)	Air RH (% RH)
Oct 2-3	1013.56 ± 2.25	28.51 ± 0.44	79.60 ± 2.70
Oct 5-6	1010.53 ± 0.74	27.03 ± 1.18	85.70 ± 5.75
Oct 16-17	1002.34 ± 3.36	30.42 ± 0.52	67.97 ± 3.12
Oct 18-19	1006.49 ± 1.28	31.40 ± 1.01	63.69 ± 5.26

Table 7 indicates the regression coefficients, β_k, of each predictor variables and β_0, calculated using multiple linear regression for Tacloban site. Air temperature (β_2) and wind speed (β_4) were the predictor variables that may have a significant effect in PM_{10} concentrations considering the frequency of sampling within a week. In 1-in-6-day sampling interval β_2 and β_4 depicted regression coefficients of 4.68 and 88.06, respectively. Surprisingly, higher regression coefficients (β_2 = 6.62; β_4 = 206.28) were observed in the 1-in-12 sampling interval. These results may be attributed to the aggregate of data collected in a longer period of sampling.

Table 7. List of regression coefficients, β_k, calculated from the multiple linear regression from Tacloban site. Root mean-square (RMS) error is also given. Bold and italicized values are the predictor variables with highest magnitude (β_0 is excluded) regression coefficients.

Regression coefficients	1-in-6-day sampling interval	1-in-12-day sampling interval
	Tacloban (RMS = ±22.49 μg m^{-3})	Tacloban (RMS = ±66.72 μg m^{-3})
β_0	3495.30	1578.99
β_1	4.55	4.01
β_2	**4.68**	**6.62**
β_3	-3.98	-2.20
β_4	**88.06**	**206.28**

Figure 5 shows scatterplots of predicted PM_{10} concentrations over a 20-year period because of calculated regression coefficients from the MLR analysis. Data used were generated from the STELLA model using 1-in-6-day and 1-in-12-day sampling frequencies. The higher regression coefficient for the 1-in-6-day sampling frequency (R = 0.580) suggests that this sampling frequency has a stronger relationship with PM_{10} concentrations compared to 1-in-12-day sampling frequency (R = 0.409). This means that more frequent sampling (1-in-6-day) provides a more significant contribution to the PM_{10} prediction model. Furthermore, the shorter sampling frequency may likely capture more variability and short-term fluctuations in PM_{10} levels compared to less frequent sampling; thus, increasing the sampling frequency could improve accuracy of PM_{10} predictions by capturing more data points and reducing uncertainty. However, the 1-in-12-day sampling frequency was used by the EMB Region VIII due to resource and logistic issues. This may still provide useful data, though with potentially reduced sensitivity to short-term pollution events.

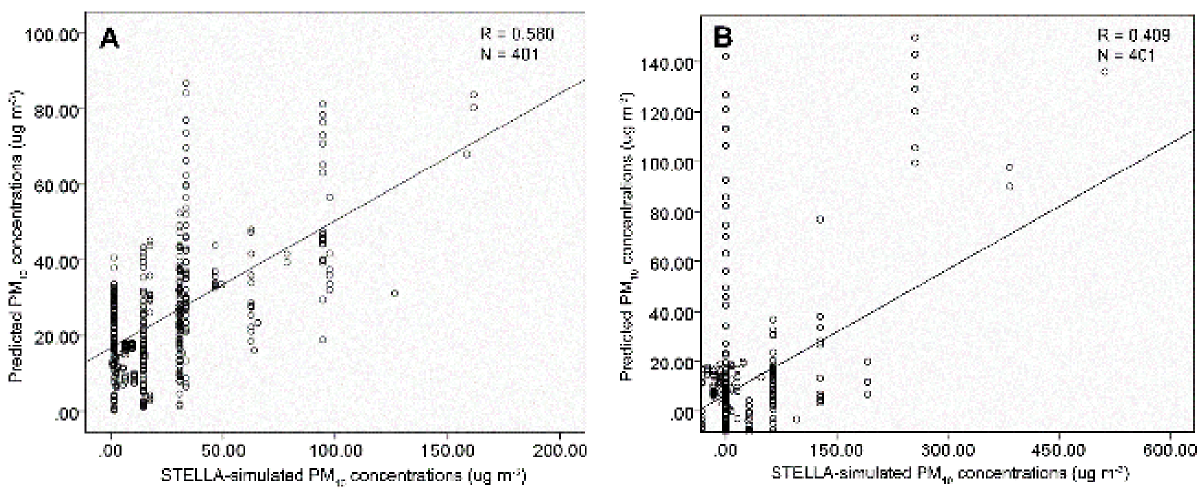

Figure 5. Predicted PM_{10} concentrations were calculated using the regression coefficients (Table 4) derived from the multiple linear regression analysis from sampled data which used (A) 1-in-6-day, and (B) 1-in-12-day sampling frequencies.

Table 8 and Figure 6 elaborate the annual average PM_{10} concentrations for both STELLA and MLR models. The study utilized STELLA and Multiple Linear Regression (MLR) models to predict PM_{10} concentrations, averaging the predicted values annually (N = 20) due to the large dataset (N = 40). The National Environmental Management Bureau (EMB) sets an annual PM_{10} guideline of 60 µg m^{-3}, and exceeding this threshold may indicate potential air quality concerns requiring intervention. The regression coefficient (R = 0.78) suggests a strong correlation between predicted and actual PM_{10} concentrations, indicating reliable model performance while acknowledging some unexplained variability. Annual averaging helps identify long-term trends but may smooth out short-term pollution spikes. While both models effectively estimate PM_{10} levels, incorporating higher-frequency monitoring could improve accuracy. If predicted values surpass the regulatory limit, stricter air quality measures may be necessary to mitigate pollution and protect public health.

Table 8. Annual average of PM_{10} concentrations (ug m^{-3}) as predicted by STELLA and MLR.

Year	STELLA	MLR
2016	9.07	11.18
2017	4.35	12.40
2018	6.05	17.16
2019	7.35	17.35
2020	18.10	11.40
2021	11.85	2.47
2022	16.05	11.33
2023	20.05	33.99
2024	26.95	24.51
2025	20.20	22.41
2026	13.40	27.67
2027	51.95	54.49
2028	54.70	58.36
2029	15.00	24.76
2030	26.60	22.36
2031	24.15	30.21
2032	19.80	27.12
2033	58.00	35.56
2034	60.65	41.42
2035	41.75	19.79

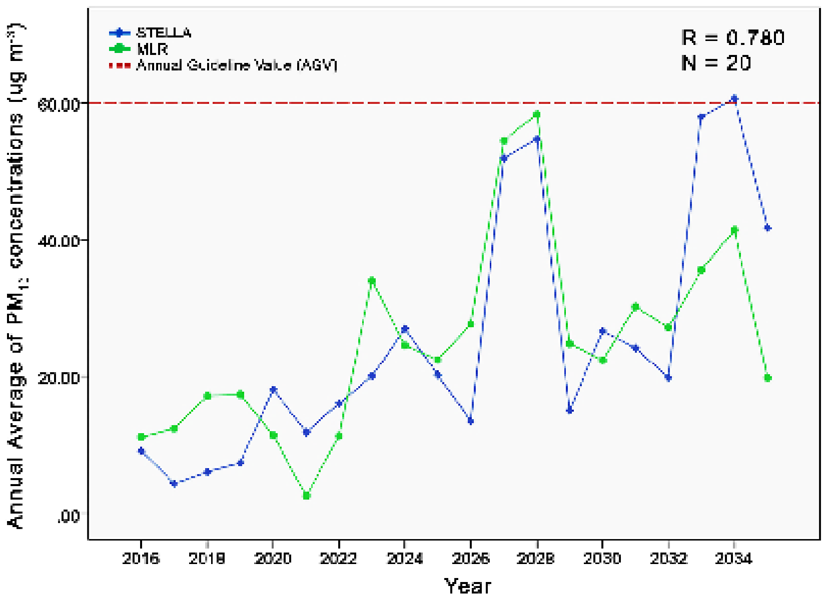

Figure 6. STELLA and MLR predicted values were averaged (annual; N = 20) due to the enormity of datasets from the models (N = 40). The annual guideline value set by the National Environmental Management Bureau for PM_{10} is at 60 ug m^{-3}.

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DISCUSSIONS

PM_{10} and meteorological parameters

Based on the multiple linear regression analysis, two (2) meteorological parameters significantly contributed to the concentrations of PM_{10} in Tacloban, Philippines. Without considering the leading regression coefficient, β_0, air temperature (β_1) and wind speed (β_4) were the main predictors influencing PM_{10} concentrations in the sampling site. In typical atmospheric conditions, the air temperature peaks during afternoon. The maximum daily temperature, brought by radiative heating, pauses as a result that the ground surface requires to warm the adjoining atmosphere, generally occurring during noontime in the tropical regions (Macatangay et al., 2014). This atmospheric inversion generates perturbation and convection of warm air, alongside with moisture, heat, aerosols including particulate matter, causing deep planetary boundary layer (PBL) mixing in effect. This leads to higher PM_{10} concentrations (Odat, 2009), especially during heavy traffic (Giri et al., 2008). Notably, monsoon winds, during transition period of southwest monsoon (June to October; local term: "Habagat") and northeast monsoon (November to February; "Amihan"), bring large volume of precipitation which washout air pollutants from the atmosphere if combined with high relative humidity (Seinfeld and Spyros, 1998; Youn, 2016), compromising the hygroscopic capability of near submicro-particulate matter.

PM_{10} concentrations were greatly affected by wind speed within the sampling site. The average wind speed recorded was 0.76 0.07 m $s^{-1.}$ Due to the absence of anemometer in the station, wind direction data from the Philippine Atmospheric Geophysical and Astronomical Services Administration (PAGASA) in Tacloban was used to determine the average wind direction. Throughout the year, wind direction changes depending on the apparent monsoonal wind. In between mid-October to end of June, cool and dry eastern winds were mostly prominent. In early July to October, the average wind direction is blowing from the west, bringing hot and humid weather and frequent heavy rainfall. During the onset of intense rain, land surface temperature and sensible heat flux drops drastically. Within monsoon seasons, latent heat release basically dominates the atmospheric heat content (Levermann et al., 2009). Therefore, thermal energy is transported out of the landmass via large-scale advection (horizontal wind movement) and synoptic processes. Moreover, the release of latent heat due to intense rainfall over land enhances the temperature difference between land and ocean, thus driving stronger winds from the ocean to land. This, coupled with convection of warm air, critically affects PM_{10} levels. Other factors associated with wind speed and air temperature may have also been attributed to PM_{10} concentrations in the sampling site.

Mesoscale phenomena, such as mountain-gap wind and land-sea breeze, play a vital role in the PM_{10} concentrations in Tacloban City due to the 1-kilometer proximity of the station to Cancabato Bay (north) and 5-kilometer distance from San Pedro Bay or Leyte Gulf (east) directly facing the Pacific, with minimal vertical obstructions such as high-rise buildings around the sampling station. Also, the historic Strait de San Juanico (between Samar and Leyte islands), crammed by Mt. Danglay (NE) and Mt. Naga-Naga (SW), contributes to the gap winds in Tacloban. With these meteorological features, Tacloban site may be thought of as a good "mixing bowl", combined with perfect ingredients, increases the levels of airborne particulate matter. A corpus of studies (Wang et.al, 2015; Giri et.al, 2008; Tian et.al, 2008) indicated similar correlation between wind velocity/speed and PM_{10} concentrations.

PM_{10} and sampling frequency

Based on the regression coefficients (Table 7) from the MLR analysis, predicted PM_{10} concentrations were calculated (Fig. 5). Fifty-eight (Fig. 5a) and forty-one percent (Fig. 5b) of the predicted values fit the model using a 1-in-6-day and 1-in-12-day sampling schemes, respectively. Ensuing standard sampling method of air particulate matter requires following widely accepted strategies to warrant the quality of gathered data. In this study, a proposal to change the sampling scheme from 6 days to 12 days was presented by Papp and Camalier (2005). Particularly, the importance of the 75 percent-completeness rule, with acceptable levels of confidence, should be attained. In Tacloban site where air sampling has been an issue for years, changing to the new scheme (1-in-12-day) may provide practical reasons (such as lesser cost for filters and maintenance). However, as seen on Fig. 5, changing the sampling scheme may greatly affect the credibility of the sampled data. Increasing the days for sampling can in turn decrease the sample size, compensating for initial data loss resulting from the reduction of collated sample frequency. Generally, changing the sampling frequency to 1-in-12-day will have an adverse effect on the precision estimates.

Predicted annual average of PM_{10} concentrations

Due to the nature of the datasets predicted and calculated by STELLA and MLR, values from both models were averaged to an annual term, as prescribed by the National Ambient Air Quality Index, which sets 60 ug m^{-3} as the guideline value for PM_{10}. As seen from Fig. 6, all predicted and calculated values were within the acceptable range set by the national standard. Most of the values, except in the year 2034 (STELLA), slightly exceeded (n = 60.65 ug m^{-3}) the annual guideline value (AGV). Moreover, seventy-eight percent (78%) of the values explain the models. Needless to say, the absence of historical data for meteorological parameters and PM_{10} concentrations cannot establish a scientific explanation for the trend in PM_{10} for the next 20 years. It was only in 2013 when the Environmental Management Bureau started PM_{10} sampling in the site and achieves below 75% data capture consistently due to logistic issues. As indicated in the MLR analysis, comparing the historical data for air temperature (β_2) and wind speed (β_4) may give scientific insights for the model trend.

CONCLUSION

The main purpose of this study was to simulate, predict, and analyze the effects of meteorological parameters and sampling frequency to PM_{10} concentrations in Tacloban, Philippines using a STELLA model. Among the four meteorological parameters, air temperature and wind speed were the key predictors for determining PM_{10} levels in the sampling site based on the MLR analysis. Granting the effects of these meteorological parameters to PM_{10} concentrations, other factors may have played a role in the variations of this pollutant. Monsoonal winds and mesoscale features (gap winds and land-sea breeze) are weather systems commonly observed in the tropical regions. Also, changing the sampling scheme was considered in this study. Notably, the 1-in-6-day sampling frequency yielded acceptable results of predicted values. Otherwise, precision estimates were affected critically.

Such preliminary study is not thus far adequate to explain the present condition of PM pollution in the Tacloban sampling site. A more improved STELLA model, together with other factors such as type of fuel, age of vehicle, other meteorological variables, and transboundary transport should be considered. Historical data for meteorological parameters (air temperature and wind speed) shall also be considered to establish possible influence on PM_{10} concentrations. Finally, conducting a source apportionment study is needed to determine the sources and quantify their contributions to the PM_{10} concentration in Tacloban City.

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CONFLICT OF INTEREST

The authors confirm that there are no conflicts of interest associated with this publication and that there has been no financial or personal relationship that could have influenced the research.

AUTHOR CONTRIBUTIONS

Conceptualization, FBC and JRS; Methodology, FBC and JRS; Data analysis: FBC and JRS; Manuscript drafting, FBC; Reviewing and Editing, FBC and JRS; Preparation of article, FBC. All authors have read and agreed to the publication of this manuscript.

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