Original Research Article

Background Study on the Estimate of Horizontal Dilution Potential of air Pollutants in North-Central Nigeria, Using Wind Data

Abstract

The study gives a background estimate of the dilution potential of air pollutants (SO_2, NO_2 and CO) in three selected North Central States of Nigeria. The research was carried out using wind impact area diagram, obtained by using standard deviation to calculate analysis of pollutants and other variables of spread whose concentration were determined downwind. The results indicate that Makurdi and Lafia have varying wind direction persistence (p) approximately 1.0m^2 for all the months. This can cause variation in wind directions. It also indicate unstable pattern of wind observation in this cities. For Makurdi, lowest and highest value of potential stands at M (12.15 $m^{2)}$ and (42.5 m^2) were observed in April and May accordingly. For Lafia, values obtained by potential impact stands at M (2.20m^2) and (67.50 m^2) for the months indicated. Finally, Jos has (p) equal to 1.2m^2 through all months, showing steady wind compared to two cities of Makurdi and Lafia and the predominant wind direction during the period of October 2018 to February 2019. Lowest and largest values of dilution potentials M (1.50m^2 and 113.37m^2) were obtained for February and December of the same year under review. Lowest values of m(dilution potential) indicate lower dilution potentials in these cities which indicate high concentration of inert pollutants while larger value of M predicts high volume of wind speed with a big impact area. The study showed that, dilution potential can be applied in comparing the wind data in line and space. It also portrays that wind impact diagram gives a good representation of wind along with area of high pollutants concentration as compared to wind rose. Finally, the information obtained from the research suggests air quality monitoring stations in Makurdi, Lafia and Jos for effective monitoring of air pollutants in these cities.

Keywords: Ground level concentration, horizontal pollution potential, impact area, standard deviation, wind speed and direction.

1.0 Introduction

High wind speed describes how fast the air is moving past a certain point of source resulting in lowering of air pollutant concentration. The wind direction describes the direction on a compass from which the wind emanates. The estimate can be made to quantify the horizontal spread area which indicates potential of the atmosphere (Abulkarem 2015) and Shiada M.S (2018).

The wind impact diagram and wind rose as well as impact area (m) play a vital role to environmental meteorologist studying air pollution problems. Information gotten can be used for comparing sites of different meteorology conditions thereby helping in industrial site selection. Secondly, it can also be used on determining high concentration of pollutants observed due to low dilution available downwind emission source, which has an important role in matter sampling for receptor modeling studies (Isikwe *et al.*, 2011). Analyses of wind data include determination of standard deviations of wind direction and speed. The Standard Deviation (SD) of wind direction and associated impacts can be estimated using several methods. The basic approach for estimating SD of wind direction is the use of an Analytic Estimate of Predominance (A.E.P) of wind direction also known as Wind Direction Persistence (WNP) denoted by (P). P is measured on a scale of 0 – 1.5, a value of P = 0 indicate wind direction distributed equal in all direction while P = 1 shows persistent and constant wind direction (George *et al.*, 2009).

Several studies have been carried out in some cities about the preliminary study of these dilutions of air pollutants concerning mechanism of transportation. Better understanding of these mechanisms and their expected impact area will aid to alleviate the health hazard imposed to people living in Makurdi, Lafia and Jos, North Central Nigeria.

Abdulkarem (2015) analyzed the extent of air pollution by the petroleum refineries industries using the concentration of NO_2, CO and SO_2 and total hydrocarbon. The result obtained revealed that the dispersion pattern of pollutants diffusion depends on the proximity to the source of the pollutants, wind speed and temperature. A recent study by (Shiada *et al.*, 2019) on assessment of atmospheric air quality over an emission source in Makurdi showed that emission from stack could be unsafe for the health of the people along the plume spread owing to the fact that concentration of SO_2 and NO_2 exceeded threshold limit accepted concentration by Environmental Protection Agent (NERSEA, 2018).

Apart from determination of pollutants using different method of studies, some researchers have estimated the horizontal pollution using the impact area of pollutants with the application of wind data (George *et al.,* 2009). The work by (Isikwe *et al.,* 2010) on the estimate of horizontal potential mean ground level concentration of air pollutants from an elevated source over Makurdi showed that the month of November and February were marked with low concentration of pollutants which larger values of these pollutants were obtained in October, January and December. Based on the findings, SO_2 had the highest predicated average concentration of 56.7ug/m^3 while CO has the lowest of 24.1ug/m^3 at a location of 100m downwind the source.

However, the aim of this work is to adopt AEP procedure and use wind data to carry out the studies to estimate horizontal dilution of potential as well as using the angle of spread of the pollutant to estimate the ground level concentration of some common pollutants in some selected States in North Central Nigeria (Makurdi, Lafia and Jos).

2.0 Methodology

The wind speed and wind direction data used for this research were obtained from the Nigeria Environmental Climate Observing Programme (NECOP). Meteorological data were also obtained from Department of Geography, Benue State University, Makurdi. NECOP has been in existence for over 9 years, designed to establish a network of meteorological and climatology observing station spatially across the North Central Zone. NECOP's objective is making real time data available for meteorological and climatological research which serves as a warning tool for decision makers involved in emergency management, natural resource management, transportation and agricultural sector.

This work basic objectives are to:

i. Determination of impact area and horizontal dilution potential (M) for Makurdi, Lafia and Jos.

ii. Determination of concentration of common pollutants from point source emitter in Makurdi using angle of spread of pollutants.

The impact area downwind of pollution source was estimated based on the formula of the sector of a circle. Daily wind speed over a period of a month was grouped into wind speed categories which determines the distance traveled by inert pollutants. The standard deviation of wind direction is considered as the lateral dimension of the impact area and thereby area of sectors was determined. Impact areas under different wind speed categories were summed up to obtain the total impact area. The formula was further extended to incorporate contributions due to calm wind. Since different wind speed group may indicate different direction of impact area, its linear summation was weighted by persistence of impact area thereby yielding dilution potential. The concentrations of the pollutants from a point source in Makurdi were carried out using the angles of spread as determined by standard deviation.

2.1 Determination of Impact Area of Horizontal Dilution Potentials (M)

The standard deviation (σ_θ) of the wind direction was estimated from the adaption of Weber's equation which is a function of wind direction persistence (p) of the estimate of predominance of wind direction as used by (George *et al.,* 2009) and (Isikwe *et al.,*2010):

$$\sigma_\theta = 105.8\ (1 - p)\ 0.534 \qquad (1)$$

P is the ratio of vector mean to scalar mean of wind speed.

The area of impact a_j for each wind category downwind was calculated using equation, (George *et al.,* 2009; Isikwe *et al.,* 2010);

$$a_j = \frac{\sigma_\theta}{2}\ \text{x}\ \left[\left(v^2_j \text{x}\ \frac{n_j}{N - N_{calm}}\right)\right] \qquad (2)$$

Where

σ_θ = angular standard deviation of a specific wind speed group; $v^2{}_j$ = mean wind speed for the specific group; n_j number of wind data in specific wind speed category and N = total number of wind data.

The above relation is considered applicable to wind speeds greater than 0.2m/s and excludes calm – wind conditions. Contribution due to calm wind to the impact area was estimated separately and added to the downwind impact area estimated in each category. Contribution due to calm wind to the downwind impact area for each wind speed category was also obtained using extracts from (George *et al.*,2010).

Total impact area was determined by summing all wind speeds and; specific wind impact areas. However, if impact areas vary in direction, their summation will mask information about horizontal spread of impact area. This was overcome by the use of direction persistence of receptor area (P_A). The persistence is inversely proportional to direction variation, the ratio of total impact area and direction persistence of wind impact area gave an estimate of horizontal dilution potential (Okorie et al, 2014).

2.2 Determination of the Concentrations of the Common Pollutants from a Point Source Emitter in the Area

The city of Makurdi is located at latitude 7.44^{o}N and longitude 8.54^{o}E. The meteorological data taken around the site are the mean wind speed at 1.5m from the ground level for five months (from October 2008 – February, 2009) measured to be 0.9ms^{-1} and mean wind direction for the period of study was south-east, as obtained from the available NECOP data. The stack is 13m above ground level. Wind speed at that height H, was obtained using the wind profile law of Counham (1975), given as:

$$\frac{U_2}{U_1} = \left[\frac{Z_2}{Z_1}\right]^m \quad (3)$$

Where U_1 is the observed wind speed at height Z_1 = 1.5m and U_2 is the inferred wind speed at height Z_2 = 13m, with m the power law exponent equal to 0.28 for urban settlements. Hence wind speed at 13m was calculated to be 0m/s

The following are the common pollutants emitted by industry: SO_2, NO_2 and CO having their respective emission rates at exit velocity of 5m/s as 12.0kg/s, 7.7kg/s and 5.1kg/s for sapped stacks (Dobbins, 1979). The environmental impact of most interest occurs at ground level thus the ground level concentrations C(x,y,0) of these were calculated using extracts from (Dobbin, 1979):

$$C(x,y,0) = \frac{Q}{\pi\sigma\, y^{\sigma} z^{u}} \exp\left(\frac{(-y)^2}{2\sigma_y^2}\right)\left(exp\,\frac{(-H)^2}{2\sigma_z^2}\right) \quad (4)$$

Using the "worst case" scenario, which is applicable to our study, we note that the maximum ground level concentration occurs in the x – z plane passing as it does through the plume centre-line, at y = 0. Thus, equation (4) reduces to:

$$C(x,y,0) = \frac{Q}{\pi\sigma\, y^{\sigma} z^{u}} \exp\left(exp\,\frac{(-H)^2}{2\sigma_z^2}\right) \quad (5)$$

The ability class for the atmosphere over the site of study during the period of study fall into the stability class A, with low wind speed and strong incoming radiation, (Dobbins, 1979). Hence the appropriate Bridges interpolation formula for urban area (Briggs, 1972) was used to obtain σ_y(m) and σ_z(m) thus:

$$\sigma_y(m) = 0.22x\,(1+0.0001x)^{-1/2} \quad (6)$$

and $\sigma_z(m) = 0.20x$

Where; x is the horizontal distance or extent travelled by the pollutants along the plume centre line.

Using the angle of spread as determined from the largest angle of deviation of class of winds or each month (October, 2018 – February, 2019), the respective horizontal extents, x(m) of the pollutants were estimated using the method of trigonometry, assuming that the vertical extent is 50m from the centre line of the plume. The values of x were the one used in equation (6) to calculate the GLC of SO_2, NO_2 and CO.

3.0 Results and Discussion

For Makurdi, Lafia and Jos respectively, in the months under investigation, Table 1, 2 and 3 show the following: wind speed class (V_j), (which depicts the mean wind speed for each month as classified from 0.00 – 2.00ms^{-1}, data in wind class Nj (%) (the percentage of class frequency in each wind speed category), mean wind speed in each classified category, persistence of wind direction, standard deviation of wind direction, wind speed specific impact area and dilution potential.

Table 1: Wind data analysis for Estimating dilution potentials for Makurdi (Feb. – Sept. 2018)

SI No	Wind speed class (V_j)	Data in wind class (N_j)	Average wind V_{sj} (m^{s-1})	Predominant wind A_{0j} (degree)	Standard deviation of wind σ_j (degree)	Wind specific impact area	Dilution potential M	Persistence of wind P
Feb. 2018								
1	0.00-1.50	87	1.7867	135	34	26.5216	29.05	1.0000
2	0.00-2.00	17	2.1361	96	5	3.3424		
March 2018								
1	0.00-1.00	77	1.8899	136	16	23.5316		
2	1.50-2.00	20	2.2424	130	30	9.5901	32.47	0.9986
April 2018								
1	0.00-1.00	84	1.7777	144	11	10.9874		
2	1.10-2.00	20	2.1308	167	8	2.7300	12.25	0.9807
May, 2018								
1	0.00-1.00	81	1.8338	137	36	35.3772		
2	1.10-2.00	23	2.1611	138	21	7.8303	42.50	0.9999
June 2018								

1	0.00-1.00	86	1.7375	132	30	22.6770		
2	1.10-2.00	18	2.2109	88	5	3.1591	25.09	0.9575
July 2018								
1	0.00-1.00	88	1.8201	118	125	32.8914		
2	1.10-2.00	16	2.1734	125	32	6.0526	37.94	1.0000
August 2018								
1	0.00-1.00	87	1.7053	119	13	11.29644	12.50	1.0000
2	1.10-2.00	17	2.2220	99	3	2.2655		
Sept. 2018								
1	0.00-1.00	86	1.7695	126	25	27.3168	31.70	1.0000
2	1.10-2.00	18	2.1509	134	20	5.0900		

Table 2: Wind data analysis for estimating dilution potentials for Lafia (Feb. – Nov. 2018)

SI No	Wind speed class (V_j)	Data in wind class (N_j)	Average wind V_{sj} (m^{s-1})	Predominant wind $A_{\theta j}$ (degree)	Standard deviation of wind σ_j (degree)	Wind specific impact area	Dilution potential M	Persistence of wind P
Feb. 2018								
1	0.00-1.50	11	1.9512	134	5	2.1204		
2	1.50-2.00	18	2.5332	192	12	23.921	17.43	0.9996
3	2.10-3.00	31	3.64036	195	5	50.535		
4	3.10-4.00	40	4.3704	195	4	81.706		
March 2018								
1	0.00-1.00	16	2.0867	183.057	14	5.935		
2	1.50-2.00	84	2.4124	172.895	22	31.357	37.33	0.9987
April 2018								
1	0.00-1.00	90	2.5739	222.998	5	2.857		
2	1.10-2.00	10	3.2244	186.071	1	1.1429	2.20	0.9498
May, 2018								
1	0.00-1.00	6	2.00217	155	25	5.0052		
2	1.10-2.00	94	2.5459	202	33	7.8211	67.50	0.9991
June 2018								
1	0.00-1.00	19	1.9878	173	11	7.5780		
2	1.10-2.00	81	2.5056	216	37	54.9866	65.26	0.9736
July 2018								
1	0.00-1.00	23	1.9550	156	3	8.7580		
2	1.10-2.00	77	2.2770	187	42	47.4782	55.33	0.9736
August 2018								
1	0.00-1.00	16	1.97395	167	24	8.5353		
2	1.10-2.00	84	1.2582	177	24	39.1539	46.79	0.9976
Sept. 2018								

1	0.00-1.00	31	1.8788	185	19	13.9363		
2	1.10-2.00	69	1.9459	181.1	23	28.9519	46.79	0.9976
October 2018								
1	0.00-1.00	61	1.9204	160	27	34.0969	51.88	0.9904
2	1.10-2.00	39	2.2609	186	19	18.2900		
November 2018								
1	0.00-1.00	22	2.0452	170	59	16.9199	44.60	0.9994
2	1.10-2.00	78	2.2276	1166	7	28.908		

Table 3: Wind data analysis for estimating dilution potentials for Jos (Feb. – Oct. 2018)

SI No	Wind speed class (V_j)	Data in wind class (N_j)	Average wind V_{sj} (m^{s-1})	Predominant wind A_{0j} (degree)	Standard deviation of wind σ_j (degree)	Wind specific impact area	Dilution potential M	Persistence of wind P
Oct. 2018								
1	0.00-1.50	88	1.5493	101	10	5.9338		
2	0.00-2.00	12	2.2361	96	2	0.3843	6.33	1.0000
Nov. 2018								
1	0.00-1.00	87	1.5217	105	2	1.0577		
2	1.50-2.00	13	2.1580	108	2	0.1152	1.87	1.0000
Dec. 2018								
1	0.00-1.00	88	1.6146	112	2	10.7783		
2	1.10-2.00	12	2.1515	109	2	0.5911	13.37	1.0000
Jan. 2018								
1	0.00-1.00	75	1.6844	113	11	6.5772	1.50	
2	1.10-2.00	25	2.2041	115	4	1.0040		1.0000
Feb. 2018								
1	0.00-1.00	39	2.7057	117	2	0.6574	1.51	1.0000
2	1.10-2.00	61	2.2070	117	2	0.8187		

Table 4: The ground level concentrations of common pollutants at a vertical extent fo 50 m from the center of the plume over an elevated stack in Makurdi

Pollutants	Y(m)	X(m)	H(m)	δ_y(m)	δ_z(m)	GLC ($\mu g/gm^3$)

October, 2018						
SO_2	50	653	13	144	127	129.80
NO_2	50	653	13	144	127	83.29
CO	50	653	13	144	127	55.16
November, 2018						
SO_2	50	5729	13	1581	1146	1.32
NO_2	50	5729	13	1581	1146	0.85
CO	50	5729	13	1581	1146	0.56
December, 2018						
SO_2	50	356	13	79.70	71.20	415.14
NO_2	50	356	13	79.70	71.20	266.38
CO	50	356	13	79.70	71.20	176.43
January, 2019						
SO_2	50	572	13	129	144	161.28
NO_2	50	572	13	129	144	103.49
CO	50	572	13	129	144	68.55
February, 2019						
SO_2	50	5729	13	1581	1146	1.32
NO_2	50	5729	13	1581	1146	0.85
CO	50	5729	13	1581	1146	0.56

Table 1 presents the analyses of the wind behaviour in Makurdi from February to November 2018. It is observed that, Makurdi had more high winds as indicated by N_j. The values of P show that the persistence of wind pattern in Makurdi during the period was considerably inconsistent, having the value between 1.0m^2 and 0.9 m^2 as compare to Lafia a close city with aw constant persistent wind of 0.9 m^2. In this consistency however, varying wind directions could be discerned as can be ascertained from the values of $A_{\theta j}$.

The result also shows that April had the lowest dilution potential (m = 12.45) and the highest value m (42.51m^2) was obtained in May while Lafia has the lowest dilution potential of 2.2 and the highest 65.2 in June. On the other hand, the month of May was also marked with higher wind specific impact area (35.372m^2), where April had the lowest specific impact area (10.9874m^2) as compare to Jos with 13.3 and 1.5 respectively This could imply that irrespective of the high impact area in May, the pollutants could easily be diluted, while the reverse is the case in April. These may cause as result of high air temperature and activities of local industries in both cities.

Lafia on the other hand was marked by more percentage of high than low winds in most of the months under study, except for April and October (Table 2). For instance, 40% of the winds have seeds ranging between 3.1 – 4.0 m/s in February and 94% of the winds had speed range of 1.1 – 2.0 m/s in May. Unlike Makurdi where large impact areas were identified with low winds (0.00 – 1.50m/s), for Lafia, impact areas were identified with high winds (1.50 – 2.00m^2), with the largest impact area (81.706m^2) obtained for the wind class 3.10 - 4.00m/s in February. This implies that these winds could carry pollutants to such a large area. Lafia had varying wind persistence 1.000 – 0.9498m^2 as can be seen from the value of p. the values are less than those in all the cases except September. Hence the predominant wind direction varied from North – to East indicating the unsteady wind patterns observed in the area. this may cause hazard to the people living in these areas.

The lowest dilution potential (M = 2.20m^2) was observed in April while the highest dilution potential (M=67.50m^2) was observed in May. This implies that April 2018 was marked by high concentration of pollutants due to lowest mixing, while the mixing of pollutants in that year was obtained in May due to the highest dilution available this result also shows that the months of February to April, 2018 produced high presence of inert pollutants in Lafia due to low dilution compared to other months in the same year. This pollutants if not check will have high effects on man and other livings within the area of discharge

Table 3 gives the analyses of the wind behaviour with respect to pollution in Jos between October, 2018 and February, 2019. Slow winds were more prevalent than high winds. The values of wind persistence (P = 1) shows wind were more prevalent than high winds. The values of wind persistence (P = 1) shows that the wind were concentrated in South – East direction as observed from the values of $A_{\theta j}$. From the values of dilution potential, M, February had the lowest value of $1.50m^2$ and December had the lowest value of $13.37m^2$. This implies low mixing in February. Therefore Jos station has high concentration of pollutants which have been observed in February, 2018 due to low dilution potential (Isikwue *et al.,* 2010) and (Isikwue *et al.,* 2019). It is as a result of low air temperature with the area of study as monthly rainfall and clouds dropped.

On the other hand, the wind direction and the estimation of the horizontal distances travelled by the pollutant using the angle of spread of the pollutants from the impact area diagrams of the pollutants in Makurdi. The result of the ground level concentrations (GLC) of SO_2, NO_2 and CO from an elevated stack in Makurdi are given in table 4.

It is observed that the month of December, 2018 had the largest angle of spread and the lowest distance from the source, hence, the largest concentration of the pollutants reduced. This could be attributed to large number of calm winds which cause the large concentration of pollutants reduced. Thus, the large impact area near the source, the shorter distances travelled by the pollutants from the source along the centre line. This could be the reason for the observed larger concentrations of these common pollutants in December 415.14; $266.38\mu g/m^3$ and $176.43\mu g/m^3$ respectively for SO_2, NO_2) at larger angles of spread (16^o) as compared to other months. Therefore, the angle of spread of pollutants from an elevated source varies directly to the concentrations and inversely with the distances travelled by the pollutants along the centre line (Osang, 2013).

4.0 Conclusion

The following conclusions are drawn from this study: they are;

i. The result showed that Makurdi and Lafia have varying wind direction persistence (p), ($p<1.22$) for all the months, thereby causing varying wind directions. This indicates unsteady pattern of winds observed in these areas.

ii. For Makurdi, lowest and highest values of dilution potentials, M($12.14m^2$ and $42.31m^2$) were observed in April and May respectively. For Lafia lowest and highest values of M ($2.20m^2$ and $67.50m^2$) were also observed in April and May respectively.

iii. On the other, Makurdi had persistence of windequal to 1 through all the months, showing that Makurdi had more steady winds compared to the other two stations and the predominant wind direction during the period of Oct. 2008 – Feb. 2019. Lowest and largest values of M, ($1.50m^2$ and $13.37m^2$) were obtained for February and December respectively.

iv. The larger impact area of the pollutants were mainly caused by large amount of slow winds which brought about low dilution of the pollutants and more hazardous to the inhabitants of such areas.

v. Low values of M indicate lower dilution potential which means high concentration of inert pollutants and large values of M indicate high nature of wind speed with a large impact area.

vi. That horizontal dilution potential can be used for comparison of wind data in time and space. The study also portrays that wind impact area diagram gives a better representation of winds along with zone of high pollutant concentration as compared to wind rose.

vii. The information obtained from this study suggests periodic air quality monitoring in these towns. Hence in pollution studies, apart from the emission rate, dispersion rate, ambient wind speed and direction, the angle of spread of pollutants are also important factors to be considered for the concentration of pollutants along the centre line of the plume.

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