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Preliminary Study on the Estimation of Horizontal Dilution Potential of Air Pollutants over Some Cities in Nigeria Using Wind Data

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ABSTRACT

Preliminary studies of the estimates of the horizontal dilution potential of air pollutants over some cities in Nigeria have been carried out using wind impact area diagrams, obtained by using standard deviation to calculate angles of spread of the pollutants, whose concentrations were thus determined downwind. The results showed that Port Harcourt and Minna have varying wind direction persistence (P), ($P < 1.0$) for all the months, thereby causing varying wind directions. This indicates unsteady pattern of winds observed in these areas. For Port Harcourt, lowest and highest values of dilution potentials, (M) ($11.14m^2$ and $41.21m^2$) were observed in April and May respectively. For Minna, lowest and highest values of M ($2.10m^2$ and $65.88m^2$) were also observed in April and May respectively. On the other hand, Makurdi had P equal 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. 2009 was south – East oriented. Lowest and largest values of M, ($1.48m^2$ and $11.37m^2$) were obtained for February and December respectively. Low values of M indicate lower dilution potential which means high concentration of inert pollutants and larger values of M indicate high nature of wind speed with a larger impact area. This study shows how horizontal dilution potential can be used for comparison of wind data in time and space. It 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. The information obtained from this study suggests periodic air quality monitoring in these towns.

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

1. INTRODUCTION

High wind speed and large wind direction variation cause pollutants to travel far away from the source, resulting in lowering of pollutant concentrations. Large variation in wind velocity indicates considerable mixing, resulting in lower pollutant concentrations and vice-versa. This estimate of dilution potential can be used to compare wind patterns in space and time. In addition, an estimate can be made for quantifying the horizontal spread area (wind impact area), which will indicate the horizontal dilution potential of the atmosphere.

The developed wind impact diagram and wind rose, as well as the quantification of the impact area (M), are useful to environmental meteorologists studying air pollution problems. The information can be used for comparing sites of different meteorology thereby helping in industrial site selection. It can also help determine when higher concentration of pollutants will be observed due to low dilution available downwind of the source, which is important for particulate matter sampling for receptor modeling studies.

Analyses of wind data include determination of standard deviations of wind direction and predominance of wind direction. The standard deviation of wind direction has been estimated using several methods. One of the simplest methods for estimating standard deviation of wind direction is the use of an analytic estimate of predominance of wind direction also called wind direction persistence (P). P is measured on a scale of 0 – 1; a value of P = 0 indicates wind direction distributed equally in all directions and P = 1 indicates a persistent and constant wind direction (George et al, 2009).

This study has been of much recent interest, as a result of the effect and desire to control air pollution. Better understanding of the mechanisms by which pollutants are transported, and their expected impact area, will aid to alleviate the health hazards imposed by pollutants.

Abdulkareem (2005) analysed the extent of air pollution by the petroleum refinery industry using the concentrations of nitrogen monoxide (NO), CO, SO_2 and total hydrocarbon. Obtained results revealed that the dispersion pattern of pollutants showed that the extent of diffusion depends on the proximity to the source of the pollutants, wind speed, and temperature.

A recent study of air pollution in Lagos, over a period of about 10 months from selected three dumpsites, three industrial estates and six heavy traffic stations using the in situ method, shows slightly high concentrations of sulphur dioxide and nitrogen oxides (Olukayode, 2005).

Apart from determination of pollutant concentrations using different methods of pollution studies, some researchers have estimated the horizontal pollution potential using the impact area of pollutants, with the application of wind data (George et al, 2009)

The work by Isikwue et al, (2010) on the estimation of horizontal pollution potential and mean ground level concentrations of air pollutants from an elevated source over Makurdi showed that the months of November and February were marked with low concentrations of pollutants, while large values of pollutants were observed in October, January and December, judging from large horizontal dilution potentials. The Sulphate compounds (SO_x) had the highest predicted average concentration of 56.7µg/m^3, while Carbon monoxide (CO) had the lowest predicted average concentration of 24.1µg/m^3 at a location of 1000m downwind the sources.

However, the aim of this work is to is to use wind data to carryout preliminary studies of the estimates of the horizontal dilution potential as well as using the angles of spread of the pollutants to estimate the ground level concentrations of some common pollutants over Port Harcourt in the south east and Minna in the north central parts of Nigeria.

2. Source of Data and Method of Analysis

The wind speed and wind direction data used for this work were obtained from the Nigerian Environmental Climatic Observing Programme (NECOP). NECOP is a new programme, about three years old, designed to establish a network of meteorological and climatological observing stations spatially spread across Nigeria. NECOP's main objectives include making real time data available for meteorological and climatological research which will serve as a warning tool for decision makers involved in emergency management, natural resources management, transportation and agriculture. The length of NECOP real time data obtained is short. Hence, the length of data in Makurdi is about five months; Port Harcourt is eight months and Minna is about eleven months. This does not allow for a long term climatic investigation. Hence, this research serves as a preliminary investigation of the estimation of the horizontal pollution potential using these data.

This work was analyzed in two stages: Determinations of impact area and horizontal dilution potentials (M) for Port Harcourt and Minna; and the determination of the concentrations of the common pollutants from a 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, mean wind speed of a category 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 were 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 groups 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 Determinations of Impact Area and Horizontal Dilution Potentials (M)

The standard deviation (σ_θ) of the wind direction was estimated from the adaptation 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 Isikwue et al, (2010):

σ_θ = 105.8 (1 – p) 0.534 (1)

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

The area of impact aj for each wind category down wind was calculated using the equation, (George et al, 2009 and Isikwue et al, 2010):

$$a_j = \left[\frac{\sigma_{\theta j}}{2} \times \left(v_j^2 \times \frac{n_j}{\mathrm{N} - \mathrm{N}_{calm}}\right)\right] \quad (2)$$

where:

$\sigma_{\theta j}$ = angular standard deviation of a specific wind speed group; v_j^2 = 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 0.2ms -1 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, (2009).

Total impact area was determined by summing all wind speeds and; specific wind impact areas. However, if impact areas vary in direction, their linear 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 directional variation, the ratio of total impact area and direction persistence of wind impact area gave an estimate of horizontal dilution potential. .

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° N and longitude 8.54° 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:

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

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 1.6 m s-1.

The following are the common pollutants emitted by industry: SO_2, NOx and CO, having their respective emission rates at exit velocity of 5 m s-1 as 12.0, 7.7 and 5.1 k g s-1 for capped 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:

$$C_{(x,0,0)}=\frac{Q}{\pi\sigma_y\sigma_z u}\exp\frac{(-H)^2}{2\sigma_z^2} \quad (5)$$

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

σ_y (m) = 0.22x (1 + 0.0001x)-½

and (6)

σ_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 a class of winds for each month (October, 2008 – February, 2009), 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 center line of the plume. The values of x were the used in equation (6) to calculate the GLC of SO_X, NO_X and CO.

3. RESULTS AND DISCUSSION

For the Port Harcourt, Minna and Makurdi respectively, with the months under investigation, Tables 1, 2 and 3 show the following: wind speed class (Vj), (which depicts the mean wind speed for each month as classified from 0.00-2.00 m s-1), data in wind class Nj (%) (the percentage of the 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 Port Harcourt (Feb. – Sept. 2008)

Sl. No.	Wind speed class (v_j)	Data in wind class N_j) (%)	Average wind V_{sj} (ms^{-1})	Predominant wind $A_{\theta j}$ (degree)	Standard deviation of wind σ_j (degree)	Wind specific impact area	Dillution potential M	Persistence of wind P
Feb. 2008								
1	0.00 – 1.00	85	0.7867	133	33	25.5216	27.86	1.0000
2	1.10-2.00	15	1.1361	94	4	2.3424		
March 2008								
1	0.00-1.00	75	0.8899	134	15	22.5316	31.17	0.9986
2	1.10-2.00	28	1.2424	128	29	8.5901		
April 2008								
1	0.00-1.00	82	0.7777	142	10	9.9874	11.15	0.9807
2	1.10-2.00	18	1.1308	165	7	1.7300		
May 2008								
1	0.00-1.00	79	0.8338	135	35	34.3772	41.21	0.9999
2	1.10-2.00	21	1.1611	136	20	6.8303		
June 2008								
1	0.00-1.00	84	0.7375	130	29	21.6770	24.89	0.9575
2	1.10-2.00	16	1.2109	86	4	2.1591		
July 2008								
1	0.00-1.00	86	0.8201	117	24	31.8914	36.94	1.0000
2	1.10-2.00	14	1.1734	123	31	5.0526		
August 2008								
1	0.00-1.00	85	0.7053	117	12	10.29644	11.56	1.0000
2	1.10-2.00	15	1.2220	97	2	1.2655		
Sept. 2008								
1	0.00-1.00	84	0.7695	124	24	26.3168	30.40	1.0000
2	1.10-2.00	16	1.1509	132	19	4.0900		

Table 2. Wind data analysis for estimating dilution potentials for Minna (Feb. – Nov. 2008)

Sl. No.	Wind speed class (v_j)	Data in wind class (N_j)(%)	Average wind V_{sj} (ms^{-1})	Predominant wind $A_{\theta j}$ (degree)	Standard deviation of wind σ_j (degree)	Wind specific impact area	Dillution potential M	Persistence of wind P
Feb. 2008								
1	0.00 – 1.00	11	0.9512	163	4	1.1204		
2	1.10-2.00	18	1.5332	191	11	22.921	15.43	0.9996
3	2.10-3.00	31	2.64036	194	4	49.535		
4	3.10- 4.00	40	3.3704	194	3	80.706		
March 2008								
1	0.00-1.00	16	1.0867	182.057	13	4.935	35.33	0.9987
2	1.10-2.00	84	1.4124	171.895	21	30.357		
April 2008								
1	0.00-1.00	90	1.5739	221.998	4	1.857	2.10	0.9498
2	1.10-2.00	10	2.2244	185.071	0	0.1429		
May 2008								
1	0.00-1.00	6	1.00217	154	24	4.0052	65.89	0.9991
2	1.10-2.00	94	1.5459	201	32	61.8211		
June 2008								
1	0.00-1.00	19	0.9878	172	10	8.5780	64.26	0.9736
2	1.10-2.00	81	1.5056	215	36	53.9866		
July 2008								
1	0.00-1.00	23	0.9550	155	2	7.7580	54.33	0.9736
2	1.10-2.00	77	1.2770	186	41	46.4782		

Continue Table 2…..

Sl. No.	Wind speed class (v_j)	Data in wind class (N_j)(%)	Average wind V_{sj} (ms^{-1})	Predominant wind $A_{\theta j}$ (degree)	Standard deviation of wind σ_j (degree)	Wind specific impact area	Dillution potential M	Persistence of wind P
August 2008								
1	0.00-1.00	16	0.97395	168	23	7.5353	45.79	0.9976
2	1.10-2.00	84	1.2582	176	23	38.1539		
Sept. 2008								
1	0.00-1.00	31	0.8788	184	18	12.9363	45.79	0.9976
2	1.10-2.00	69	0.9459	180.1	22	27.9519		
Oct. 2008								
1	0.00-1.00	61	0.9204	159	26	33.0969	50.88	0.9904
2	1.10-2.00	39	1.2609	185	18	17.2900		
Nov. 2008								
1	0.00-1.00	22	1.0452	169	58	15.9199	43.57	0.9994
2	1.10-2.00	78	1.2276	165	6	27.3908		

Table 3. Wind data analysis for estimating dilution potentials for Makurdi (Oct. 2008–Feb. 2009)

Sl. No.	Wind speed class (v_j)	Data in wind class N_j)(%)	Average wind V_{sj} (ms^{-1})	Predominant wind $A_{\theta j}$ (degree)	Standard deviation of wind σ_j (degree)	Wind specific impact area	Dillution potential M	Persistence of wind P
Oct. 2008								
1	0.00-1.00	88	0.5493	100	9	5.9338	6.31	1.0000
2	1.10-2.00	12	1.2361	95	1	0.3843		
Nov. 2008								
1	0.00-1.00	87	0.5217	104	1	1.0577	1.88	1.0000
2	1.10-2.00	13	1.1580	107	1	0.1152		
Dec. 2008								
1	0.00-1.00	88	0.6146	111	16	10.7783	11.36	1.0000
2	1.10-2.00	12	1.1515	108	1	0.5911		
Jan. 2009								
1	0.00-1.00	75	0.6844	112	10	6.5772	1.48	1.0000
2	1.10-2.00	25	1.2041	114	3	1.0040		
Feb. 2009								
1	0.00-1.00	39	0.7057	116	1	0.6574	1.48	1.0000
2	1.10-2.00	61	1.2070	116	1	0.8187		

Table 1 presents the analyses of the wind behavior in Port Harcourt from February to November 2008. It is observed that Port Harcourt had more high winds as indicated by Nj. The values of P show that the persistence of wind pattern in Port Harcourt during the period was considerably inconsistent, having the value between 1 and 0.575. In this consistency however, varying wind directions (North – East direction towards the South) could be discerned as can be ascertained from the values of Aөj.

The result also shows that April had the lowest dilution potential (M = 11.14) and the highest value (M = 41.21) was obtained in May. On the other hand, the month of May was also marked with higher wind specific impact area (34.3772m^2), whereas April had the lowest specific impact area (9.9874 m^2). 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.

Minna on the other hand was marked by more percentage of high winds than low winds in most of the months under study, except for April and October (Table 2). For instance, 40% of the winds had speeds ranging between 3.1 – 4.0 ms -1in February and 94% of the winds had speed range of 1.1 – 2.0 ms-1 in May. Unlike in Port Harcourt where large impact areas were identified with low winds (0.00 – 1.00 ms -1), for Minna, impact areas were identified with high winds (1.10 – 2.00 ms -1), with the largest impact area (80.706 m2) obtained for the wind class 3.10 – 4.00 ms -1 in February. This could imply that these winds could carry pollutants to such a large area. Minna had varying wind persistence 1.0000 - 0.9498 as can be seen from the value of P. The values are less than one in all the cases except September. Hence the predominant wind direction varied from South to South – West, indicating the unsteady wind patterns observed in the area.

The lowest dilution potential (M = 2.10) was observed in April and the highest dilution potential (M = 65.89) was observed in May. This could imply that April 2008 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, 2008 produced high presence of inert pollutants in Minna due to low dilution compared to other months in the same year.

Table 3 gives the analyses of the wind behavior with respect to pollution in Makurdi between October 2008 and February 2009. Slow winds were more prevalent than high winds. The values of wind persistence (P = 1) shows that the winds were concentrated in the South – East direction as can also be observed from the values of Aөj. From the values of dilution potential, M, February had the lowest value of 1.48 and December had the largest value of 11.37. This implies low mixing in February. Hence, in Makurdi station in 2008, high concentration of pollutants would have been observed in February, 2008 due to low dilution potential (Isikwue et al, 2010).

On the other hand, Figure1 shows the wind direction and the estimation of the horizontal distances travelled by the pollutants using the angle of spread of the pollutants from the impact area diagrams of the pollutants in Makurdi. Letters A_1 to A_5 depict the winds in particular directions while the letters B_1 to B_5 depict the corresponding estimation of the horizontal distances travelled by the pollutants. The results of the calculated ground level concentrations (GLC) of SO_X, NO_X and CO from an elevated stack in Makurdi are given in Table 4.

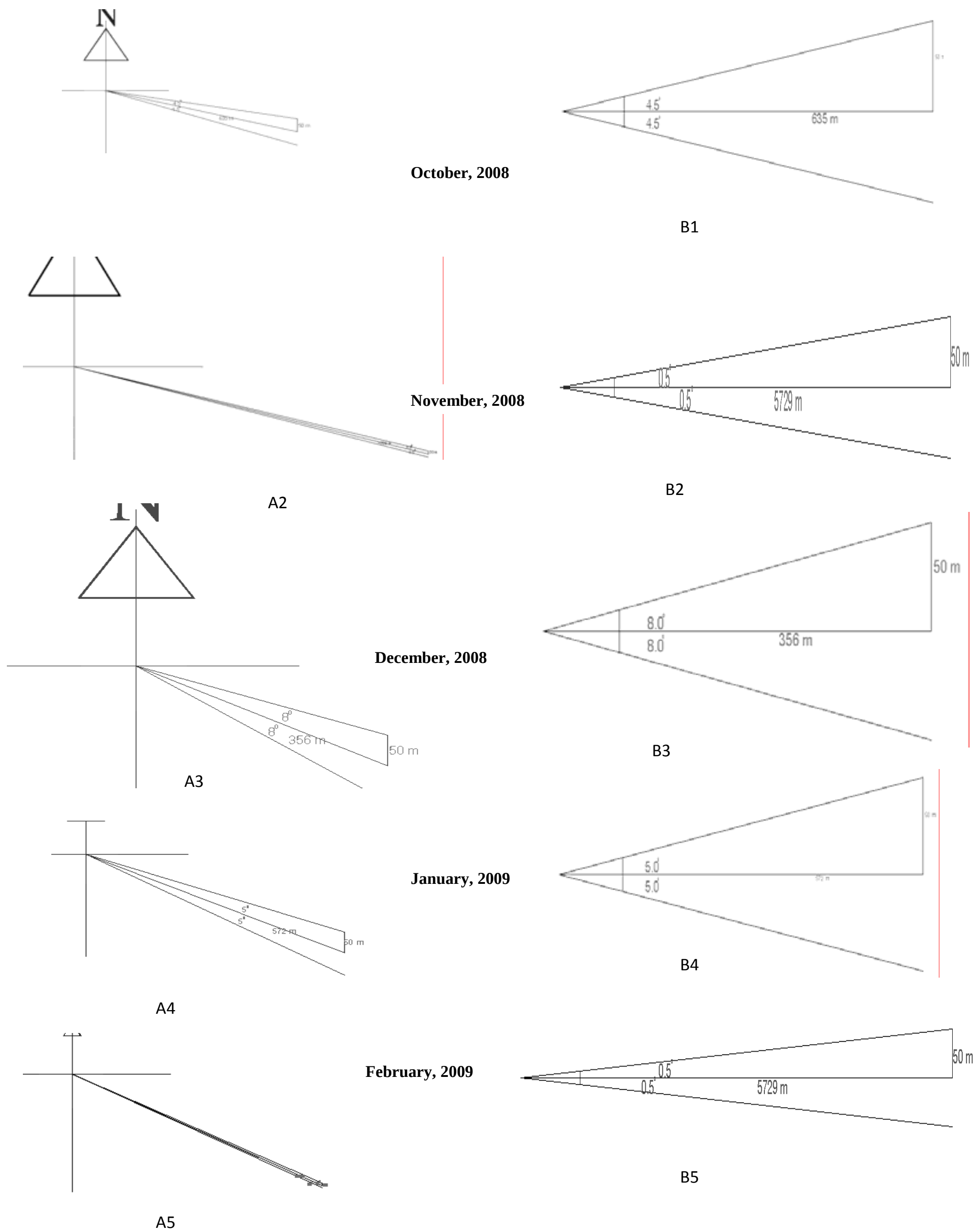

Fig. 1. Wind direction and the estimation of the horizontal distances of Pollutants along the centre line of a Plume from an elevated source in Makurdi

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

Pollutants	Y (m)	X (m)	H (m)	δ_y (m)	δ_z(m)	GLC ($\mu g/m^3$)
October, 2008						
SO_x	50	635	13	144	127	129.80
NO_x	50	635	13	144	127	83.29
CO	50	635	13	144	127	55.16
November, 2008						
SO_x	50	5729	13	1581	1146	1.32
NO_x	50	5729	13	1581	1146	0.85
CO	50	5729	13	1581	1146	0.56
December, 2008						
SO_x	50	356	13	79.70	71.20	415.14
NO_x	50	356	13	79.70	71.20	266.38
CO	50	356	13	79.70	71.20	176.43
January, 2009						
SO_x	50	572	13	129	114	161.28
NO_x	50	572	13	129	114	103.49
CO	50	572	13	129	114	68.55
February, 2009						
SO_x	50	5729	13	1581	1146	1.32
NO_x	50	5729	13	1581	1146	0.85
CO	50	5729	13	1581	1146	0.56

It could be observed that the month of December, 2008 had the largest angle of spread and the lowest distance from the source, hence, the largest concentration. This could be attributed to large number of calm winds which cause the large concentration of pollutants (Isikwue et al, 2010), thus, larger impact area near the source; therefore, 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 and 176.43μgm^{-3} respectively for SOx; NOx and CO) at larger angles of spread (16°) 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.

4. CONCLUSION

The following inferences can be drawn from this study:

- The results showed that Port Harcourt and Minna have varying wind direction persistence (P), (P < 1.0) for all the months, thereby causing varying wind directions. This indicates unsteady pattern of winds observed in these areas.
- For Port Harcourt, lowest and highest values of dilution potentials, (M) (11.14m^2 and 41.21m^2) were observed in April and May respectively. For Minna, lowest and highest values of M (2.10m^2 and 65.88m^2) were also observed in April and May respectively.
- On the other hand, Makurdi had P equal 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. 2009 was south – East oriented. Lowest and largest values of M, (1.48m^2 and 11.37m^2) were obtained for February and December respectively.

- 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
- Low values of M indicate lower dilution potential which means high concentration of inert pollutants and larger values of M indicate high nature of wind speed with a larger impact area.
- This study shows how horizontal dilution potential can be used for comparison of wind data in time and space. It 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.
- 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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