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*Full Length Research Paper*

# Estimation of horizontal pollution potential and mean ground level concentrations of air pollutants from an elevated source over Makurdi, Nigeria using wind data

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**This work estimates the horizontal pollution potential using wind impact area diagrams obtained by using standard deviations to calculate angles of spread of the pollutants, whose concentrations were thus determined downwind. The results showed that winds in Makurdi during the period under study were consistently south-easterly. November and February were marked with low concentrations of pollutants, while large values of pollutants were observed in October, January and December, having large horizontal dilution potentials. Sulphate compounds ($SO_x$) had the highest predicted mean concentration of 56.7 μgm$^{-3}$, while carbon monoxide (CO) had the lowest predicted mean concentration of 24.1 μgm$^{-3}$ 1000 m downwind of the sources.**

**Key words:** Horizontal pollution potential, impact area, standard deviation, wind rose, wind speed, wind direction

## INTRODUCTION

Estimation of dilution potential or atmospheric volume available for dilution of pollutants under given meteorological conditions requires measurement of three dimensions of which the plane area (horizontal plane) can be approximated using the estimated horizontal dilution potential. Visualization of this horizontal dimension is possible using the wind rose and estimated area of impact on the downwind side of pollution sources.

Wind rose diagrams have multiple uses, including studies of air pollution meteorology (George et al., 2009). In the wind rose diagram, the length of the arm represents the duration for a specific wind speed and indicates the distance up to which a pollutant can travel by advection. Many arms on the wind rose diagram represent high wind direction variation. 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 modelling studies.

Analyses of wind data include determination of standard deviations of wind direction and predominance of wind direction. The standard deviation of wind direction can be estimated using several methods (Essenwange, 1964; Nelson, 1984; Mardia, 1975; Verrall and Williams, 1982); Yamartino, 1984; Weber, 1991; Ackermann,

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1983). 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 had 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 alleviate the impact of pollutants on health hazards. The following are among some of the many attempts to measure air quality in Nigeria. Nigeria's Federal Ministry of the Environment had conducted air quality studies in several Nigerian cities to determine the perceptible high level of air pollution by vehicle fumes and found that the concentrations of particulate matters and (carbon monoxide) in these cities were much higher than the levels identified by the World Health Organization (WHO) as tolerable (African Press Agency, 2010).

Abdulkareem (2005) analysed the extent of air pollution by the petroleum refinery industry on the concentrations of nitrogen monoxide (NO), CO, $SO_2$ and total hydrocarbon. Results obtained revealed that pollutant concentrations were unacceptable compared to the Federal Environmental Protection Agency set limits. The dispersion pattern of pollutants showed that the extent of diffusion depends on proximity to the source of the pollutants, wind speed, 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). The values obtained were all higher than the Nigerian National Standards (FEPA Standards) for ambient air.

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). However, literature searches show that little research had been carried out in Nigeria despite its importance for meteorological applications and climatic predictions. Hence this work estimates the horizontal pollution potential and average ground level concentration of air pollutants from an elevated source over Makurdi (Nigeria) using wind data.

## Data sources

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 in Makurdi is short, about five months. This did not allow for a long term climatic investigation. Hence, this research serves as a preliminary investigation of the estimation of the horizontal pollution potential in this station using these data.

## METHODS

This work was conducted in three stages: Constructing of wind rose diagrams, determinations of impact area and horizontal dilution potentials (M) and the determination of the concentrations of the common pollutants from a point source emitter in the area.

Wind rose diagrams were constructed from the data of wind speeds and wind directions using the magnitude of wind speeds and the varying direction of the wind to show the length of arm in proportion to the percentage of wind blowing in a direction. 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 was determined. Impact area under different wind speed categories was summed up to obtain the total impact area. The formula was further extended to incorporate contribution 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.

### Determinations of impact area and horizontal dilution potentials (M)

The standard deviation ($\sigma_\theta$) 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 (George et al., 2009)

$$\sigma_\theta = 105.8\,(1 - p)^{0.534} \qquad (1)$$

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

The area of impact $a_j$ for each wind category down wind was calculated using the equation (George et al., 2009):

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

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 > 0.2 $ms^{-1}$ 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. Con-tribution 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 (PA). 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.

### 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 1.5 m from the ground level for five months (from October 2008 to February, 2009) measured to be 0.9 $ms^{-1}$ and mean wind direction for the period of study was south– east, as obtained from the available NECOP data..The stack is 13 m above ground level. Wind speed at that height H, was obtained using the wind profile law of Counham (1975), given as:

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

$U_1$ is the observed wind speed at height $Z_1$ = 1.5 m and $U_2$ is the inferred wind speed at height $Z_2$ = 13 m, with m the power law exponent equal to 0.28 for urban settlements. Hence wind speed at 13 m was calculated to be 1.6 m $s^{-1}$.

The following are the common pollutants emitted by industry: $SO_2$, $NO_x$ and CO, having their respective emission rates at exit velocity of 5 $ms^{-1}$ as 12.0, 7.7 and 5.1 k $gs^{-1}$ 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):

$$C_{(x,y,0)} = \frac{Q}{\pi\sigma_y\sigma_z u}\exp\left(\frac{(-y)^2}{2\sigma_y^2}\right)\left(\exp\frac{(-\mathrm{H})^2}{2\sigma_z^2}\right) \tag{4}$$

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:

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

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 appro-priate Briggs interpolation formula for urban area (Briggs, 1972) was used to obtain $\sigma_y$(m) and $\sigma_z$(m).

## RESULTS

For the five months under investigation, Table1 shows the following: Wind speed class (Vj), (which depicts the mean wind speed for each month as classified from 0.00 to 2.00 $ms^{-1}$), data in wind speed 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, and wind speed specific impact area. Figures 1 to 5 show the wind rose diagrams constructed using the wind speed and wind direction data entries for each month and the corresponding wind impact diagrams con-structed using the percentages of wind data in a specified direction for each month. Each bears the values of the estimated horizontal potential, calm wind percentage and the value of persistence area coefficient for each month. In addition, Figures 6 to 8 show the variations of distance with GLC along the centerline for $SO_2$, $NO_x$ and CO respectively.

## DISCUSSION

From calculations, it was observed that the Makurdi has a wind persistency equal to 1 throughout the period of investigation, indicating that the winds were consistent in the observed directions, which is south-easterly direction as indicated by the wind rose and the wind impact area diagrams (Figures 1 to 5).

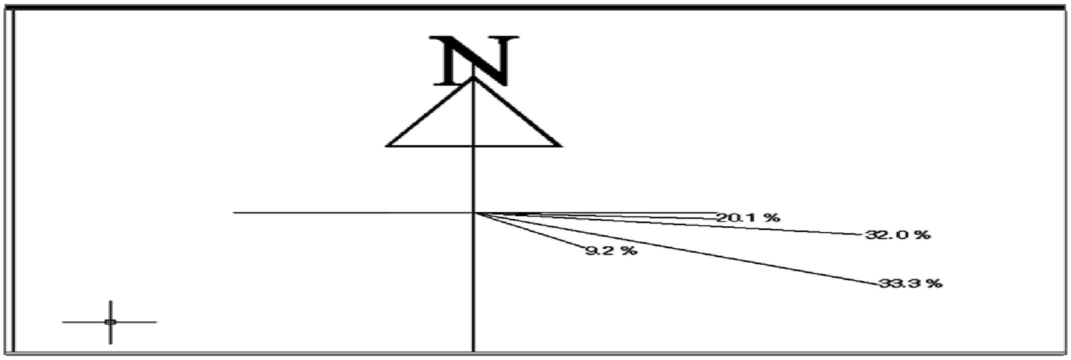
For October, 2008, in the 0 to 1 $ms^{-1}$ class, the calm winds were only about 5%, the class made up the winds which carried pollutants up to an area of 5.93 $m^2$ from the point source, as indicated by the value of M. However, the remaining 12% belonged to those winds with speeds 1.1 to 2.0 $ms^{-1}$ making an impact area of 0.38 $m^2$. On the other hand, for November, 2008, the calm winds reduced to 2%, in the range 0.00 to 1.00 $ms^{-1}$ that carried pollutants up to an area of about 1.06 $m^2$, whereas the remaining 12% belonged to those winds of 1.10 to 2.00 $ms^{-1}$ with an impact area of 0.12 $m^2$

For December, 2008, the calm winds reduced to zero, and those winds between 0 .00 to 1.00 m $s^{-1}$ category were 88% carrying pollutants up to an area of 10.78 $m^2$, but those having speeds between 1.10 to 2.00 $ms^{-1}$ were 12% with an impact area of 0.59 $m^2$. In January, 2009, the wind rose showed that most of the winds did not last long. Only two categories, (51 and 36%) lasted long. There was no calm wind, but all winds’ velocities range from 1.00 to 2.00 $ms^{-1}$ and carried pollutants up to an area of 7.58 $m^2$ from the point source. Those winds that could travel further were 25%.

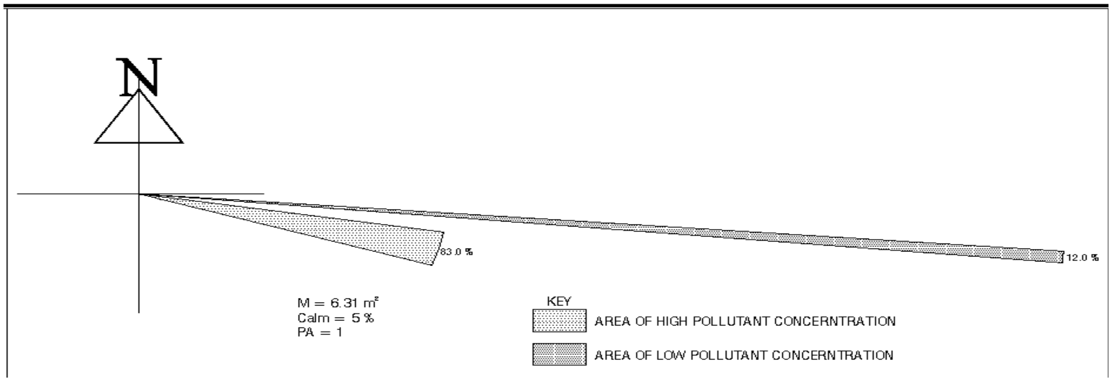
Finally, in February 2009, the wind rose showed that only two categories of winds (69 and 39%) were available. The corresponding impact area diagram showed that 61% of these winds (1.1 to 2.0 $ms^{-1}$) and 39% of the winds (0.0 to 1.0 $ms^{-1}$) could carry pollutants up to a total area of 1.48 $m^2$. The reverse trend of the

**Table 1.** Wind data analysis for estimating dilution potentials (October, 2008 – February, 2009).

| S/N | Wind speed class ($v_j$) | Data wind class $N_j$)(%) | Mean wind $V_{sj}$ ($ms^{-1}$) | Persistence of wind $P_j$ | Predominant wind $A_{\theta j}$ (degree) | Standard deviation of wind $\sigma_j$ (degree) | Wind specific impact area |
|---|---|---|---|---|---|---|---|
| | | | | **October 2008** | | | |
| 1 | 0.00-1.00 | 88 | 0.5493 | 0.9901 | 100 | 9 | 5.9338 |
| 2 | 1.10-2.00 | 12 | 1.2361 | 0.9999 | 95 | 1 | 0.3843 |
| | | | | **November 2008** | | | |
| 1 | 0.00-1.00 | 87 | 0.5217 | 0.9998 | 104 | 1 | 1.0577 |
| 2 | 1.10-2.00 | 13 | 1.1580 | 0.9999 | 107 | 1 | 0.1152 |
| | | | | **December 2008** | | | |
| 1 | 0.00-1.00 | 88 | 0.6146 | 0.9709 | 111 | 16 | 10.7783 |
| 2 | 1.10-2.00 | 12 | 1.1515 | 0.9999 | 108 | 1 | 0.5911 |
| | | | | **January 2009** | | | |
| 1 | 0.00-1.00 | 75 | 0.6844 | 0.9873 | 112 | 10 | 6.5772 |
| 2 | 1.10-2.00 | 25 | 1.2041 | 0.9989 | 114 | 3 | 1.0040 |
| | | | | **February 2009** | | | |
| 1 | 0.00-1.00 | 39 | 0.7057 | 0.9999 | 116 | 1 | 0.6574 |
| 2 | 1.10-2.00 | 61 | 1.2070 | 0.9999 | 116 | 1 | 0.8187 |

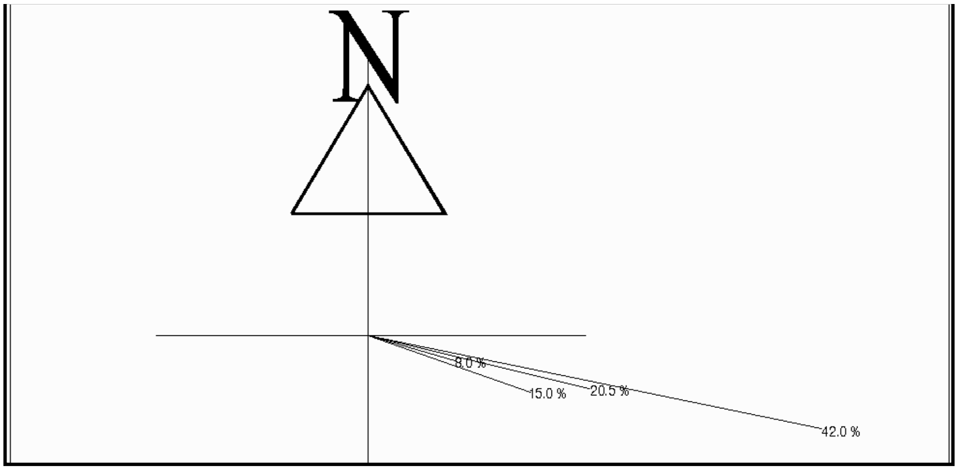


Wind rose for October, 2008

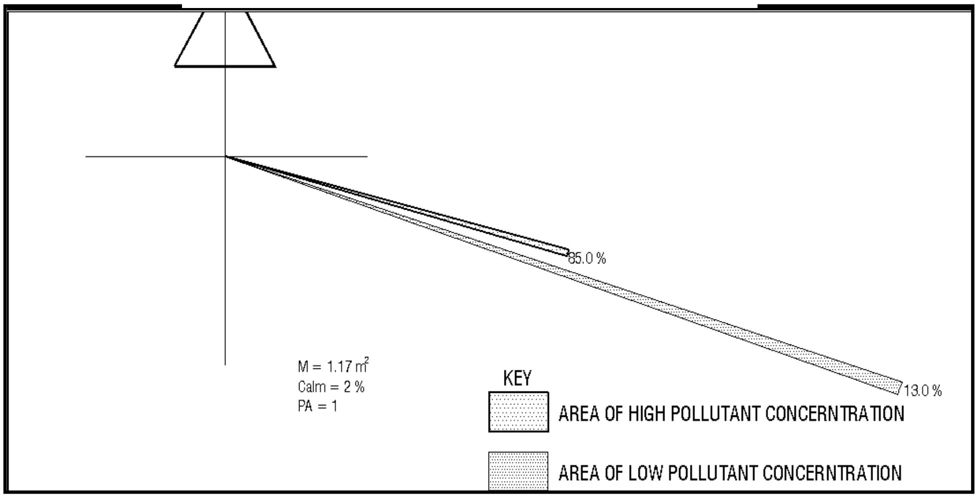


Impact area Diagram of air Pollutants for October, 2008

**Figure 1.** Comparison between Wind Rose and impact area diagram of air pollutants for October, 2008.



Wind rose for November, 2008



Impact area diagram of air pollutants for November, 2008

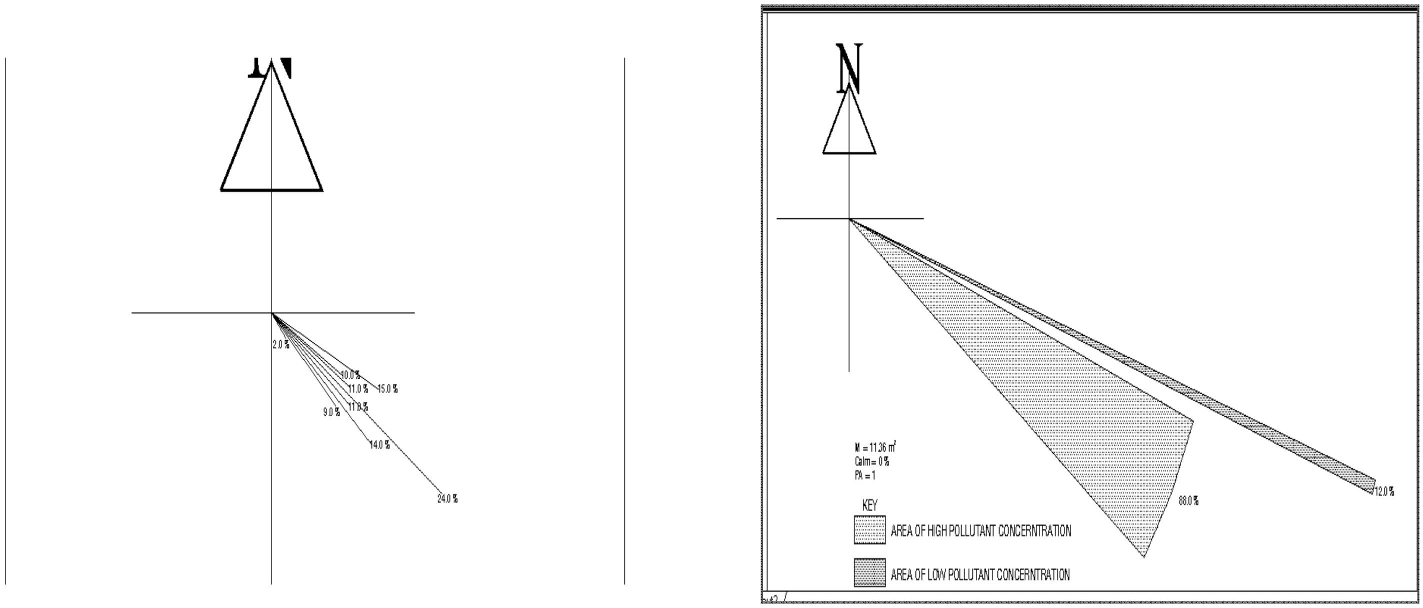
**Figure 2.** Comparison between Wind Rose and impact area diagram of air pollutants for November, 2008

February winds to the total impact area should be noted.

The values of calculated horizontal dilution potential (M) showed that the months of November and February had low values of 1.88 and 1.48 m$^2$ respectively, implying low areas of coverage for the pollutants. On the other hand, the large values of 6.31, 7.58 and 11.37 m$^2$, calculated for October, January and December, respectively, could imply higher concentrations of pollutants near the point of release as a result of high percentage of low winds (0.0 to 1.0 m s$^{-1}$) which could not carry pollutants farther away from the source.

Figures 6 to 8 showed that the mean concentrations of pollutants decreased as they moved away from the source along the centre line. Hence, of three pollutants, $SO_x$ had the highest predicted mean concentration of 56.7 μgm$^{-3}$ at 1 km downwind of the elevated source, while CO had the lowest predicted mean concentration of 24.1 μgm$^{-3}$ at 1 km downwind from the source. This could be attributed to the emission rate, physical stack height, prevalent wind speed and the densities of the different pollutants.

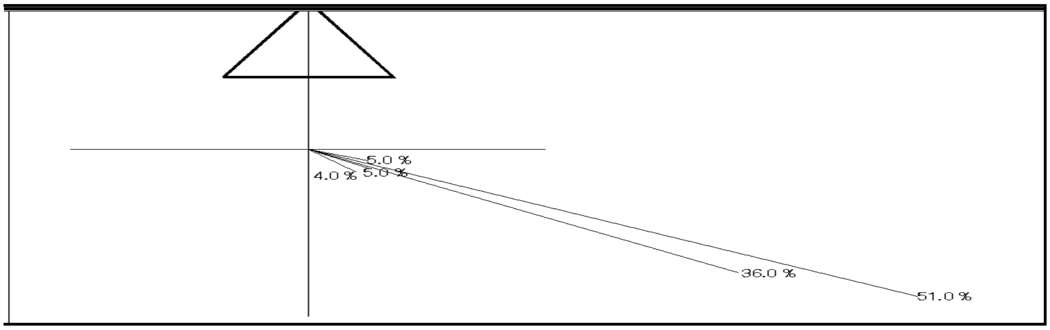
Thus, the higher the emission rate, the higher the concentration of pollutants near the sources. This could have been facilitated by the rate of diffusion and the mean wind speed which reduced the concentrations to 0.23 μg m$^{-3}$ for $SO_x$, 0.15 μg m$^{-3}$ for $NO_x$ and 0.09 μgm $^{-3}$ for CO at a distance of 20 km. Hence, as the pollutants tend to move further, the effect of the emission rate reduced which gives rise to the dominance of dispersion at far points in the windward direction.



Wind Rose for December, 2008

Impact area diagram of air pollutants for Dec.2008

**Figure 3.** Comparison between wind rose and impact area diagram of air pollutants for Dec. 2008.



Wind Rose for January, 2009

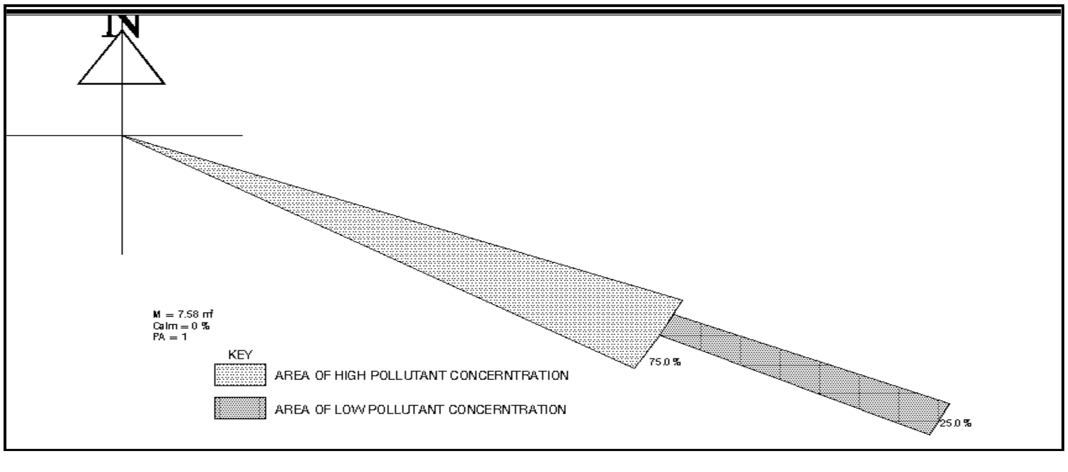
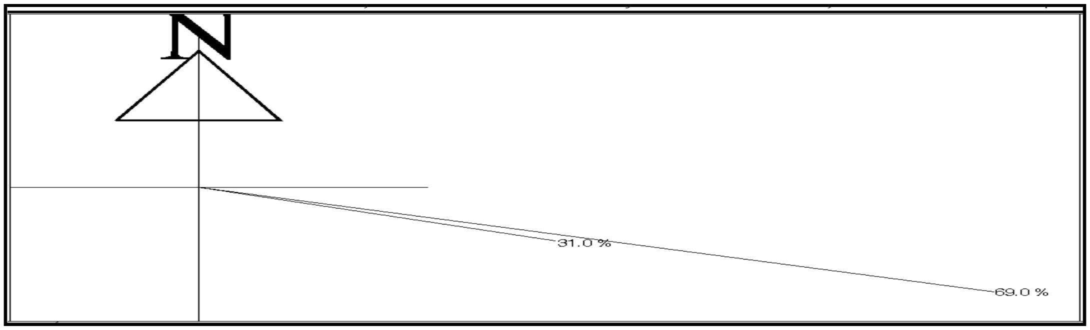
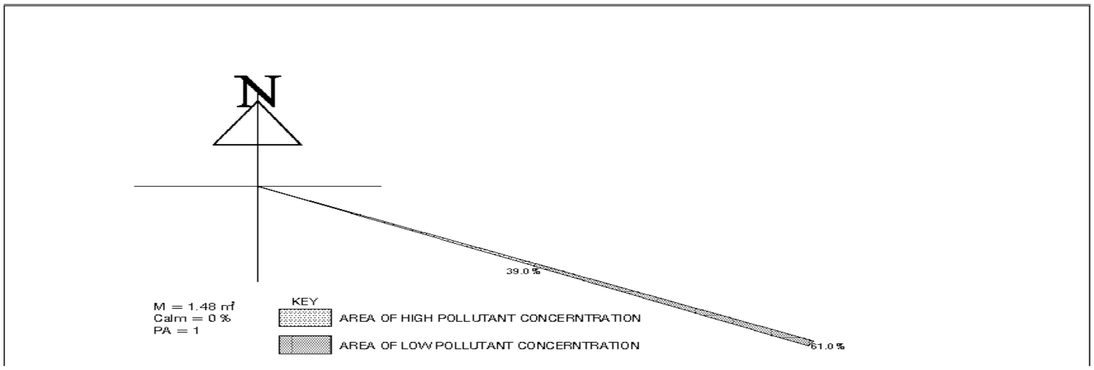


**Figure 4.** Comparison between Wind Rose and impact area diagram of air pollutants for January, 2009.



Wind rose February, 2009



Impact area Diagram of air Pollutants for February, 2009

**Figure 5.** Comparison between Wind Rose and impact area diagram of air pollutants for February, 2009.

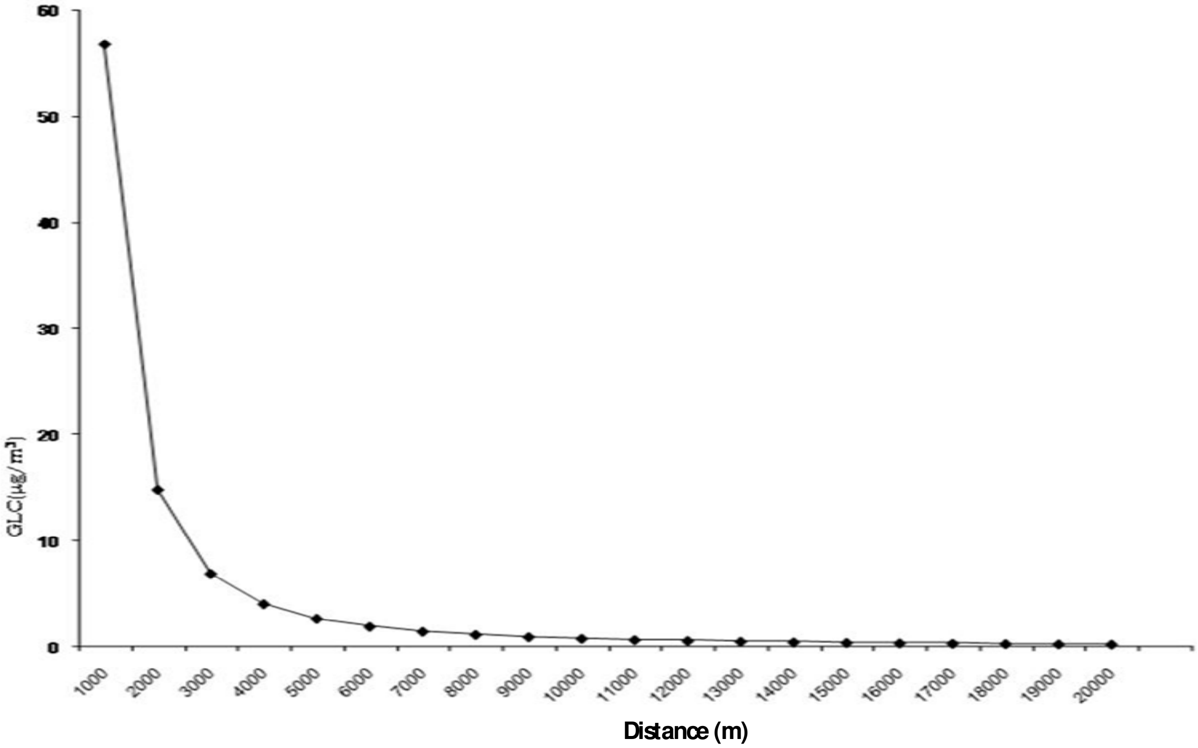


**Figure 6.** The variation of distance with GLC of SOX along the center line.

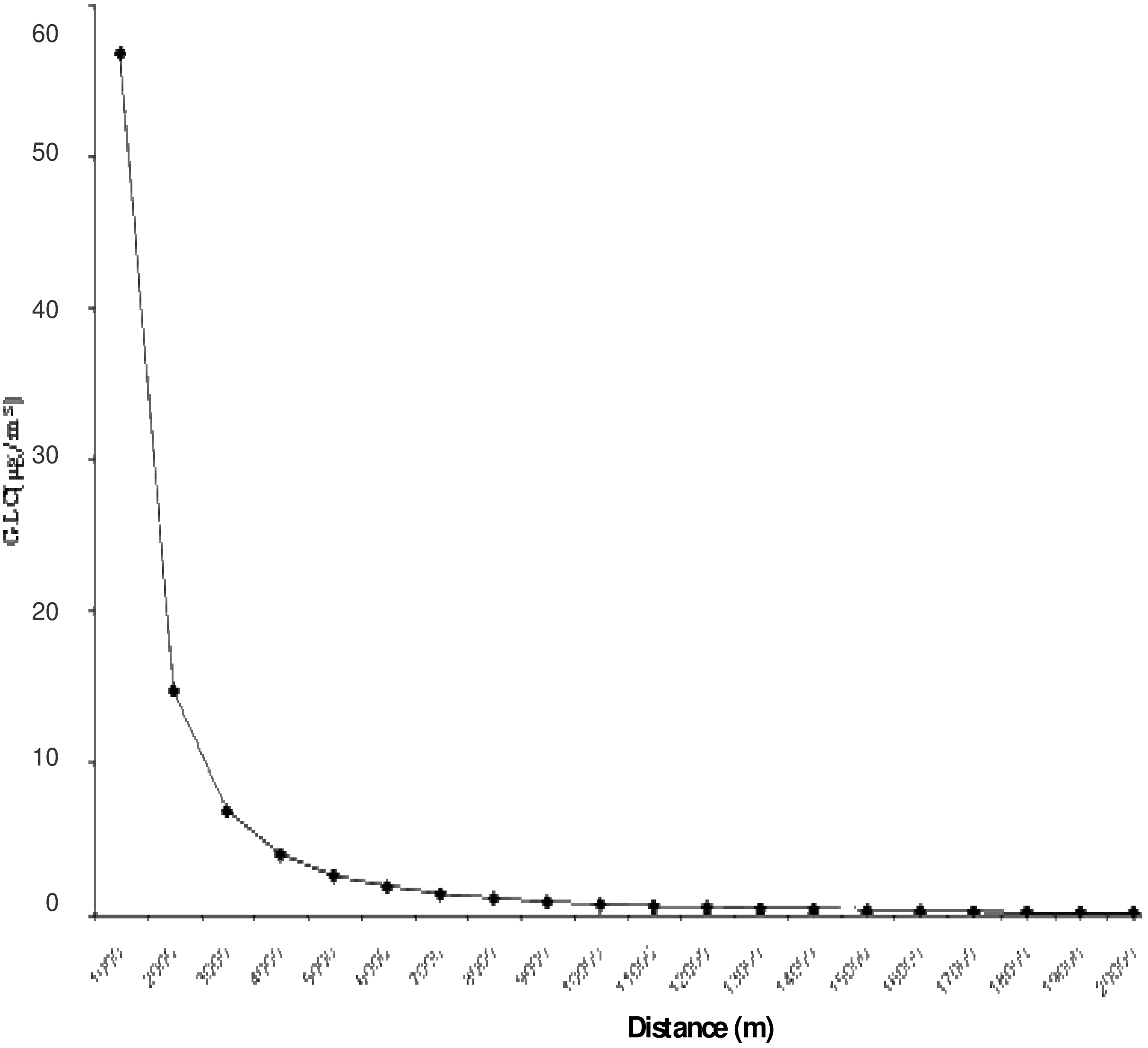


**Figure 7.** The variation of distance with GLC of NOX along the center line.

## Conclusions

Winds in Makurdi during the study period were consistently south-east as indicated by the wind rose and wind impact area diagrams.

Observations showed that the months of November and February were marked by low concentrations of pollutants, while large values of pollutants were observed in October, January and December, having large horizontal dilution potentials (M). This shows the relationship between the wind impact area and the concentrations of pollutants downwind. On the other hand, the corresponding wind rose diagrams which were not indicated with respect to standard deviations gave only the directions (in terms of angles) in which the wind travelled without specifying the area of coverage.

$SO_x$ had the highest predicted mean concentration of 56.7 µg $m^{-3}$ 1000 m downwind from the sources, while CO has the lowest predicted mean concentration of 24.1 $\mu gm^{-3}$ 1000 m downwind from the sources.

We note here that this work is continuous in estimating the horizontal pollution potential of the pollutants in Nigeria using more years of wind data.

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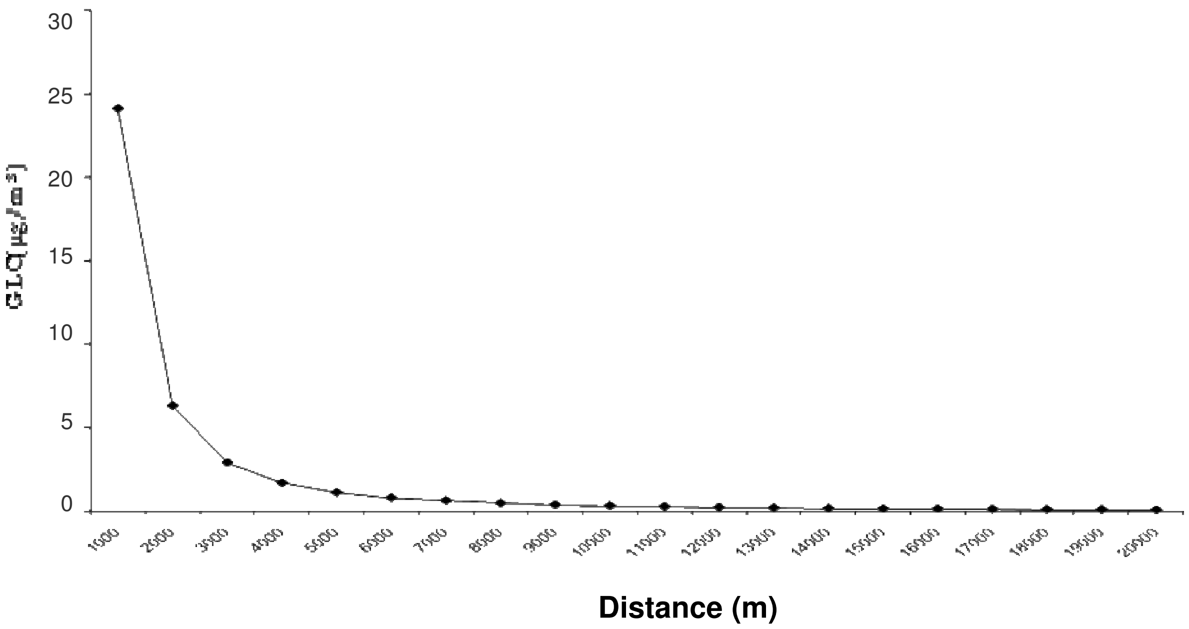

**Figure 8.** The variation of distance with GLC of CO along the center line.

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