Modelling plume dispersion pattern from a point source using spatial auto-correlational analysis

F Ujoh¹,² and D Kwabe²
¹ Department of Urban and Regional Planning, Benue State University, Makurdi, Nigeria
² Department of Geography and Environmental Management, University of Abuja, Nigeria

Email: fananujoh@gmail.com

Abstract. The main objective of the study is to estimate the rate and model the pattern of plume rise from Dangote Cement Plc. A handheld Garmin GPS was employed for collection of coordinates at a single kilometre graduation from the centre of the factory to 10 kilometres. Plume rate was estimated using the Gaussian model while Kriging, using ArcGIS, was adopted for modelling the pattern of plume dispersion over a 10 kilometre radius around the factory. ANOVA test was applied for statistical analysis of the plume coefficients. The results indicate that plume dispersion is generally high with highest values recorded for the atmospheric stability classes A and B, while the least values are recorded for the atmospheric stability classes F and E. The variograms derived from the Kriging reveal that the pattern of plume dispersion is outwardly radial and omni-directional. With the exception of 3 stability sub-classes (DH, EH and FH) out of a total of 12, the 24-hour average of particulate matters (PM₁₀ and PM₂.₅) within the study area is outrageously higher (highest value at 21392.3) than the average safety limit of 150 μg/m³-230 μg/m³ prescribed by the 2006 WHO guidelines. This indicates the presence of respirable and non-respirable pollutants that create poor ambient air quality. The study concludes that the use of geospatial technology can be adopted in modelling dispersion of pollutants from a point source. The study recommends ameliorative measures to reduce the rate of plume emission at the factory.

1. Introduction

Mining activities represent human actions that cut through the landscape, scarring and interfering with the natural habitat conditions as well as micro-climatic conditions [1]. Specifically, the environmental effects of limestone mining and cement production is known to impoverish the flora and fauna of host environment, result in sediments deposition in riverine systems, create large mining spoil mounds and deep mining lakes, result in loss of timber resources and other vegetal cover, toxification and pollution due to chemical wastes or weathering of mining spoils, cause changes in micro-climate, [2] and several others. These effects on the ecosystem are not only on-site but also off-site.

The significance of this study is premised on the fact that limestone exploitation and cement production commenced at the study area prior to the promulgation of Nigeria’s environmental impact assessment (EIA) Decree 86 of 1992, implying that no EIA was conducted at the study area. In addition, among the human activities that pose the highest threat to the conservation of biodiversity and fragile ecosystems (thereby promoting environmental degradation) is mining of mineral resources, including limestone. Additionally, findings from a recent study on cement plume rise and dispersion rate at the study area [3] reveal high concentration of pollutants from plume with negative effects arising from the release of these pollutants (from the factory) on the human, animal and plant populations of the host environment.

³ To whom any correspondence should be addressed.
Considering the observed environmental impact of the present cement plant, there is need to carry out a full scale assessment of the extent of damage on the host environment as a step in the direction of impact mitigation and prevention for future/proposed facilities. This is necessary as we hope to develop a system of resource exploitation that would not compromise the ability of future generations to cater for their needs. It is therefore, only logical to assess the status of plume rise, dispersion and concentration rates within the study area.

2. Methodology

2.1. Study area

Dangote Cement Plc is located at Yandev, near Gboko town, in Gboko Local Government Area (LGA) of Benue State in Nigeria’s north-central region. Gboko LGA is located between Latitudes 07º 08’ 16” and 07º 31’ 58”, and Longitudes 08º 37’ 46” and 09º 10’ 31”. The central location of the factory is at 7º 24’ 42.45”N and 8º 58’ 31.28”E, at about 532 feet above mean sea level (Figure 1). The study area is located within a sub-humid tropical region with mean annual temperature ranging from 23ºC to 34ºC, and with mean annual precipitation of 1,370mm. The average wind speed over the study area is about 1.50 m/s, while the average ambient air temperature is about 30ºC [4]. The area is largely covered by the pre-cambrian basement formation comprising the lower and upper cretaceous sediments, in addition to some volcanic deposits [5]. The reserves at the study area are of Cretaceous formation and in excess of 70 million tonnes [6].

![Figure 1. Location of study area.](image)

2.2. The point source Gaussian model

The Point Source Gaussian Model (also called the Mathematical Model) provides for the determination of cement dust concentration (in μg/m³) from cement plants using the point source plume function given below as:

$$C_{x,y} = \frac{Q}{\pi U H_\delta y \delta z} \exp \left( \frac{-h^2}{2\delta z} \right)$$  \hspace{1cm} (1)

The model is based on the approximation that the concentration downwind of a point source in the atmospheric boundary layer is also Gaussian but with unequal dispersion coefficients in the horizontal and vertical directions. It describes the atmospheric dispersion of a puff in three dimensions, or a steady-state plume from a continuous source in two-dimension [7, 8], on a relatively flat terrain. The dispersion equation assumes some constant conditions for the entire plume travel distance from the emission source point to the downwind ground level receptor. Parameters used include stack height (h), stack diameter (d), stack exit velocity (vs), source emission rate (Q), stack gas temperature (Ts), wind speed (U) and ambient air temperature (Ta). Six stability classes (A-F) are adopted for the study.
The determinants of the stability classes are wind speed and temperature (state of insolation and irradiation), which together affect the lapse rate, the absence or presence of convective activity, and the dynamics of the mixed layer as explained by [9].

2.3. Plotting the variograms

The variogram is the key function in geostatistics as it is used to fit a model of the spatial correlation of the data, according to the distance and direction between locations of interest. The variogram is the key function in geostatistics as it is used to fit a model of the spatial correlation of the data. In this study, the variograms represent both structural and random aspects of the dispersion coefficients of plume within a known distance of 10 km, graduating at a single kilometre interval. The range of the coefficients (used in plotting the variogram) represents the structural part of the variogram model. Using the locational coordinates obtained, spatial auto-correlation/plume modeling was carried out in the ArcGIS environment.

3. Results

3.1. Plume dispersion coefficients

Vertical ($z$) and horizontal ($y$) dispersion coefficient modelling were obtained for a distance of 1 – 10 kilometres for all atmospheric stability classes (Table 1). The results indicate that Class ‘A’ is the most unstable class followed by Class ‘B’. Hence, they have recorded the highest and second highest values of plume dispersion coefficients, respectively. Class ‘F’ exhibits the least values and is considered the most stable class.

Table 1. Derived Dispersion Coefficients of Plume at Study Area*.

| Distance (km) | Class A |  | Class B |  | Class C |  | Class D |  | Class E |  | Class F |  |
|--------------|---------|---|---------|---|---------|---|---------|---|---------|---|---------|---|
|              | $\sigma_y$ | $\sigma_z$ | $\sigma_y$ | $\sigma_z$ | $\sigma_y$ | $\sigma_z$ | $\sigma_y$ | $\sigma_z$ | $\sigma_y$ | $\sigma_z$ | $\sigma_y$ | $\sigma_z$ |
| 1.0          | 213     | 450    | 156     | 110    | 104     | 61     | 68     | 31     | 50     | 22     | 34     | 14     |
| 2.0          | 396     | 1953   | 290     | 234    | 193     | 115    | 126    | 51     | 94     | 34     | 63     | 22     |
| 3.0          | 569     | 4578   | 417     | 364    | 278     | 166    | 182    | 67     | 135    | 44     | 91     | 28     |
| 4.0          | 736     | 8369   | 539     | 498    | 359     | 216    | 235    | 78     | 174    | 51     | 117    | 32     |
| 5.0          | 898     | 13360  | 658     | 635    | 438     | 264    | 287    | 91     | 213    | 57     | 143    | 35     |
| 6.0          | 1057    | 19575  | 774     | 776    | 516     | 312    | 337    | 102    | 251    | 62     | 169    | 38     |
| 7.0          | 1213    | 27037  | 889     | 919    | 592     | 359    | 387    | 111    | 288    | 66     | 194    | 40     |
| 8.0          | 1367    | 35763  | 1001    | 1063   | 667     | 408    | 436    | 117    | 324    | 70     | 218    | 42     |
| 9.0          | 1519    | 45769  | 1112    | 1210   | 742     | 452    | 485    | 128    | 360    | 74     | 242    | 44     |
| 10.0         | 1669    | 57069  | 1222    | 1358   | 815     | 497    | 533    | 136    | 396    | 78     | 266    | 46     |

* All values in $\mu$g/m$^3$

Table 2 presents details of variations in the values of dispersion coefficients obtained for all 6 atmospheric stability classes. For the Vertical Dispersion Coefficient (VDC), the highest and lowest mean values are recorded from Classes A and F, respectively, while for the Horizontal Dispersion Coefficient (HDC), the highest and lowest mean values are recorded from Classes A and B, respectively. The results also reveal extreme variations in the standard deviation, standard error and minimum and maximum values of all 6 atmospheric stability classes. The variations is attributable to variation of prevailing weather conditions and time of the day which together are determining factors controlling the pattern of plume dispersion and eventual rate of deposition at various points within the study area.

The analysis of variance (ANOVA) result (Table 3) is the key table because it shows whether the overall $F$ ratio for the ANOVA is significant. The ANOVA F-distribution function is used to determine how significantly variable the data from the atmospheric stability classes are. The goal is to test if plume dispersion results for the 6 atmospheric stability classes are equal (or otherwise), i.e., whether; VDC = HDC = 0. The ANOVA results reveal that variation in the mean values of plume dispersion between and within the stability classes are significant for both VDC and HDC orientations.
as the probability distributions of VDC and HDC = 0.000. This implies that the values of the means differ more than would be expected by chance alone.

Table 2. Descriptive Statistics Results for Dispersion Coefficients of Plume at Study Area.

| Orientation | Classes | N   | Mean    | Std. Deviation | Std. Error | Lower Bound | Upper Bound | Minimum | Maximum |
|-------------|---------|-----|---------|----------------|------------|-------------|-------------|---------|---------|
| VDC         | CLASS A | 10  | 963.700 | 487.29390      | 154.09586  | 615.1109    | 1312.2891   | 213.00  | 1669.00 |
|             | CLASS B | 10  | 705.800 | 356.76005      | 112.81743  | 450.5892    | 961.0108    | 156.00  | 1222.00 |
|             | CLASS C | 10  | 470.400 | 237.98002      | 75.25589   | 300.1594    | 640.6406    | 104.00  | 815.00  |
|             | CLASS D | 10  | 307.600 | 155.55935      | 49.19219   | 196.3195    | 418.8805    | 68.00   | 533.00  |
|             | CLASS E | 10  | 228.500 | 115.67219      | 36.57876   | 145.7531    | 311.2469    | 50.00   | 396.00  |
|             | CLASS F | 10  | 153.700 | 77.70893       | 24.57372   | 98.1104     | 209.2896    | 34.00   | 266.00  |
| HDC         | CLASS A | 10  | 21392.300| 19556.31142    | 6184.24867 | 7402.5576   | 35382.0424  | 450.00  | 57069.00|
|             | CLASS B | 10  | 716.700 | 421.50024      | 133.29008  | 415.1769    | 1018.2231   | 110.00  | 1358.00|
|             | CLASS C | 10  | 285.000 | 146.28967      | 46.26085   | 180.3507    | 389.6493    | 61.00   | 497.00  |
|             | CLASS D | 10  | 91.200  | 34.21436       | 10.81953   | 66.7245     | 115.6755    | 31.00   | 136.00  |
|             | CLASS E | 10  | 55.800  | 18.10341       | 5.72480    | 42.8496     | 68.7504     | 22.00   | 78.00   |
|             | CLASS F | 10  | 34.100  | 10.24641       | 3.24020    | 26.7702     | 41.4298     | 14.00   | 46.00   |

Table 3. ANOVA.

| Orientation | Classes | Sum of Squares | Df | Mean Square | F     | Sig. |
|-------------|---------|----------------|----|-------------|-------|------|
| VDC         | Between Groups | 4840675.083 | 5  | 968135.017  | 12.492 | .000 |
|             | Within Groups  | 4184865.100 | 54 | 77497.502   |       |      |
|             | Total          | 9025540.183 | 59 |             |       |      |
| HDC         | Between Groups | 3732987870.683 | 5 | 746597574.137 | 11.707 | .000 |
|             | Within Groups  | 3443849844.300 | 54 | 63774997.117 |       |      |
|             | Total          | 7176837714.983 | 59 |             |       |      |

3.2. Spatial autocorrelation of plume dispersion coefficients

The spatial autocorrelation of plume dispersion is applied in this research to interpolate the gathered data and establish the values from point to point within the study area, resulting in a graph known as variogram. The variograms model the difference between values of plume concentration at kilometres 1 through to 10 around the factory site (Figure 2). It represents both structural and random aspects of the dispersion coefficients of plume within a known distance of 10 km, graduating at a single kilometre interval. As shown on the variograms (Figure 2), values increase with increasing distance of separation until it reaches the maximum (C) at a distance known as the “range” (a). The analysis is consistent with [10] and [11]. The technique has aided predictability by revealing the dispersion pattern of plume under the various atmospheric stability classes, and on the basis of y and z orientations.
Figure 2. Variograms showing plume distribution in $x$ and $y$ orientations for all stability classes.

The weights are optimized using the variogram model, the location of the samples and all the relevant inter-relationships between known (and even unknown) values for specified (and even unspecified) locations within the study area. A "standard error" function is provided within the variogram which allows for the quantification of confidence levels for all locations analysed. Generally, for dispersion coefficients in all atmospheric stability classes, the rate of plume dispersion is shown to be outwardly increasing, while the direction of plume travel is determined by the prevailing condition of winds at any given time of the day. The distribution of plume on the variograms appears spatially correlated in a radial, omni-directional orientation.
4. Conclusion and recommendation

The replacement of taller stacks (75m as against the older 55m) at the factory recently has resulted in declined plume deposits close to the factory as effective stack height is increased at which point the plume exits at a higher buoyancy level and travels farther down wind (depending on the prevailing weather conditions). Seasonal pattern of variation of plume concentration (dense during rainy seasons and scattered during dry seasons) was also observed during field survey period.

The study finds the use of the Gaussian model in estimating plume rise at a point source very useful. Similarly, it has been shown that plume modeling over a relatively wide area can be achieved by using coordinates (collected from a handheld GPS) and by manipulation in an ArcGIS environment. In Nigeria where data is poor and often unavailable, this digital approach holds the promise of providing baseline data for similar studies. Summarily, the study reveal that: highest plume dispersion coefficient values are recorded for the ‘unstable’ class ‘A’ with least values recorded for the relatively ‘stable’ class ‘F’; ANOVA result is significant; the variograms show that plume deposition rates increase with distance away from the emission source, and is radially omni-directional in orientation. For all classes, daily average values of PM$_{10}$ and PM$_{2.5}$ are higher than the WHO [12] permissible limits except for DH, EH and FH stability/orientation categories. In addition to fugitive dust from other production-related activities at the factory, the result spells adverse effect for human, animal and plant population within, especially within kilometres 4-10 of factory. Thus, the study recommends the following:

- Deliberate reforestation efforts be adopted using species with high pollution tolerance index;
- Consistent and periodic inquiry into the environmental status of the area is suggested to ensure sustainability in the face of cement production at the factory;
- Appropriate technologies (e.g. SCR, SNCR, etc.) should be installed at the kilns to reduce amount of plume emission from the factory; and,
- Human and animal populations be located either within the first 2-3 km or from 11 km away from the factory site (avoiding km 4-10, which are areas of high plume deposition).

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