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Estimating Plume Emission Rate and Dispersion Pattern from a Cement Plant at Yandev, Central Nigeria

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Abstract Cement production at Yandev, Nigeria commenced in 1980 without an environmental impact assessment to ascertain the extent of damage production activities would bring to bear on the physical conditions of the host environment. This study was carried out to provide baseline data on the rate and pattern of plume rise from the factory. Field survey was employed for primary data collation, while secondary data (climatic and factory data) were acquired from NIMET Makurdi Office and Dangote Cement Plc. Plume rate was estimated using the Gaussian (Mathematical) Model; Kriging, using Arc GIS, was adopted for modelling the pattern of plume dispersion. ANOVA and HSD's Tukey test were 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 (spatial correlational analysis) 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 (PM_{10} and $PM_{2.5}$) within the study area is outrageously higher (highest value at 21392.3) than the average safety limit of 150 μg/m^3 - 230 μg/m^3 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 environmental compliance status of Dangote Cement Plc, Yandev towards attaining sustainability for the host communities and physical environment is far from meeting the target requirement as spelt by the Millennium Development Goals No. 7. The study recommends ameliorative measures including periodic environmental audits; and adoption of technologies that would reduce the rate of plume emission.

Keywords Plume dispersion coefficients, Spatial autocorrelation, Gaussian model, Yandev- Nigeria

1. Introduction

Global attention is now focused on declining quality of the environment resulting from the rapid expansion in resources exploitation. There is an increasing need to use resources in a sustainable way, such that there is concurrent increase in production while also protecting the environment, biodiversity, and global climate systems. This type of compromise requires careful resource planning and decision-making at all levels [1].

Nigeria's environment (at urban and rural levels) has suffered an accelerated decline in quality of air, soils, biodiversity and water resources [2-12]. It is clear that sound natural resources management and planning are essential to tackling the aforementioned problems and to promote sustainable development.

Mining activities represent human actions that cut through the landscape, scarring and interfering with the natural habitat conditions as well as micro-climatic conditions [13]. Specifically, the environmental effects of limestone mining and cement production are 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, and several others. These effects on the ecosystem are not only on-site but also occur off-site as well. These, in turn, significantly alter the environmental spheres of the affected areas.

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.

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Additionally, findings from a recent study on cement plume rise and dispersion rate at the study area [14] reveal high concentration of pollutants from plume.

Presently, construction work has commenced on a second cement manufacturing plant at 'Mbatiav', within the same Local Government Area (LGA). Considering the observed environmental impact of the present cement plant, there is need to carry out a some form of assessment of the extent of damage on the host environment as a step in the direction of impact mitigation for the present facility; 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.

This study assesses the status of plume rise, dispersion and concentration rates within the study area.

2. Materials and Methods

2.1. Study Area

2.1.1. Brief History and Location

The cement factory is located at Yandev, near Gboko town, in Gboko LGA of Benue State in Nigeria. 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 and Plate 1).

2.1.2. Climate

The study area is located within a sub-humid tropical region with mean annual temperature ranging from 23ºC to 34ºC, and is characterized by two distinct seasons: the dry season and rainy season. The mean annua1 precipitation is about 1,370mm [15], with an average wind speed of 1.50 m/s [16].

2.1.3. Geology and Drainage

The study area is located within the general area of the Benue Trough, which is largely covered by Cretaceous continental and marine sediments [17] (see Figure 2). The Benue floodplain is filled with Quaternary heterogeneous sediments [18], while its geology is a combination of the pre-cambrian basement formation comprising the lower and upper cretaceous sediments, in addition to some volcanic deposits [19]. The resources are grouped into Pre-cambrian limestones, marbles and dolomites, Cretaceous and Tertiary limestones, as well as concretionary calcretes. However, the reserves at Yandev (the study area) are of Cretaceous formation and in excess of 70 million tonnes [20-22].

The most significant water bodies to be found within the study area are two streams – 'Ahungwa' and 'Oratsor'. During the construction of the Dangote Cement factory, Ahungwa stream was dammed to impound water for use by the various production processes at the factory.

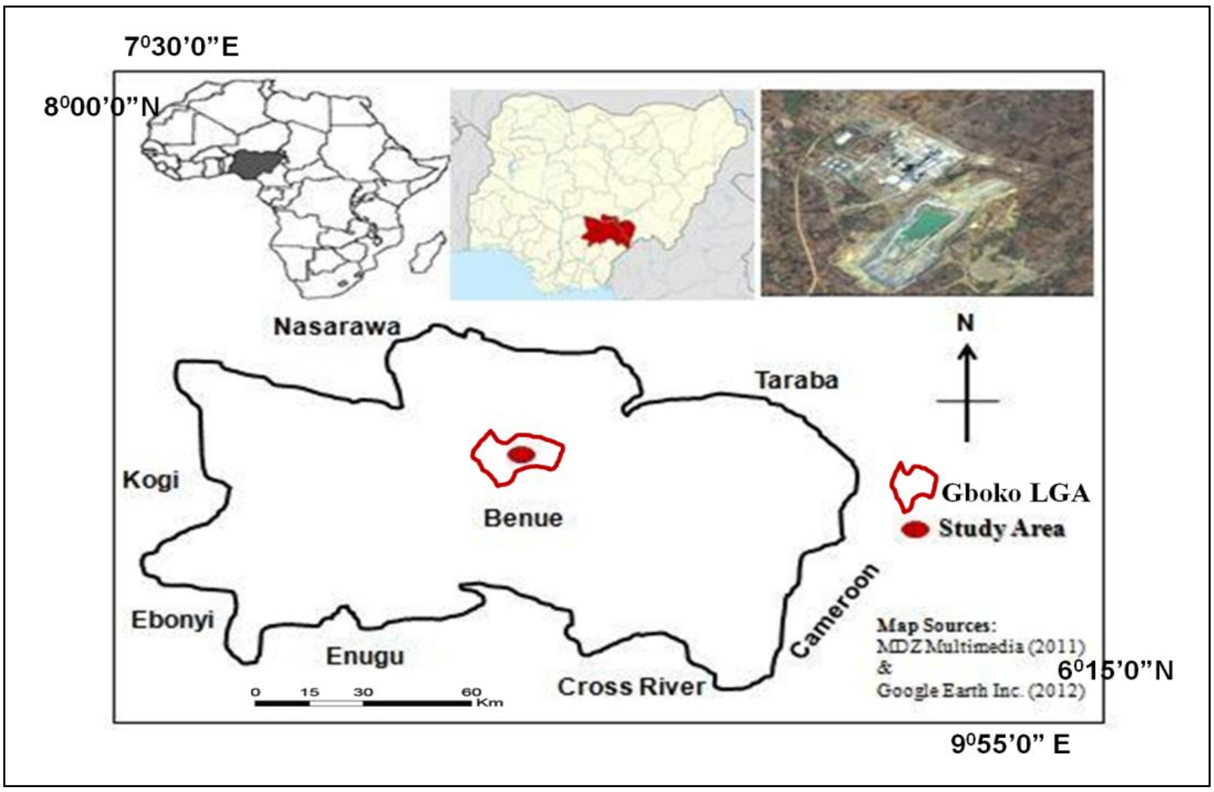

Figure 1. Locational Map of Study Area

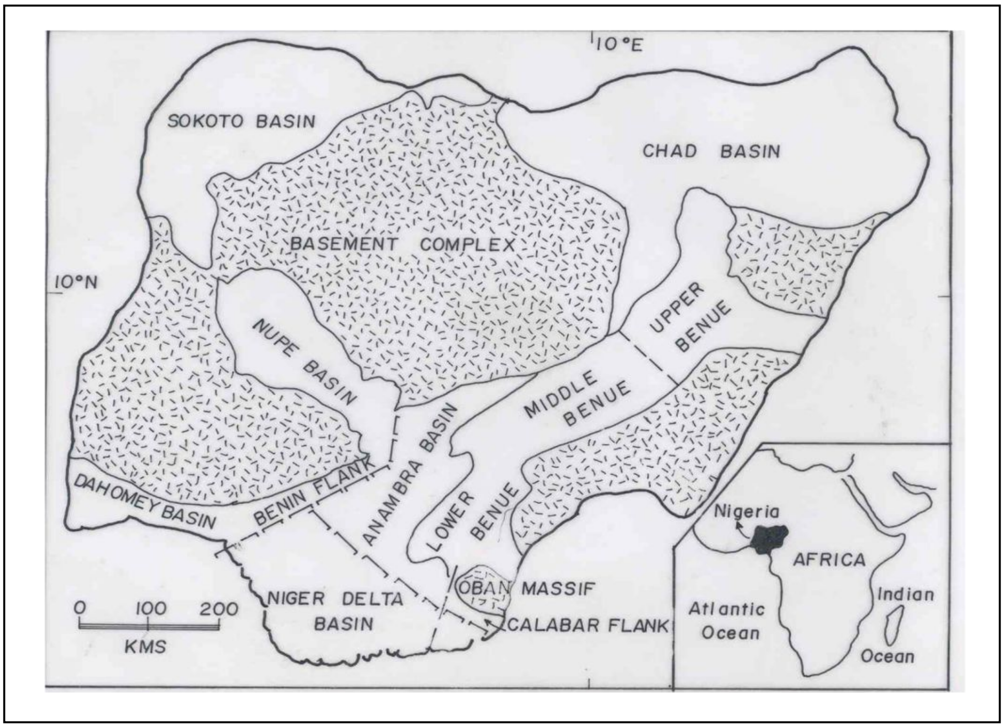

Figure 2. Geological Map of Study Area

2.1.4. Soils and Vegetation

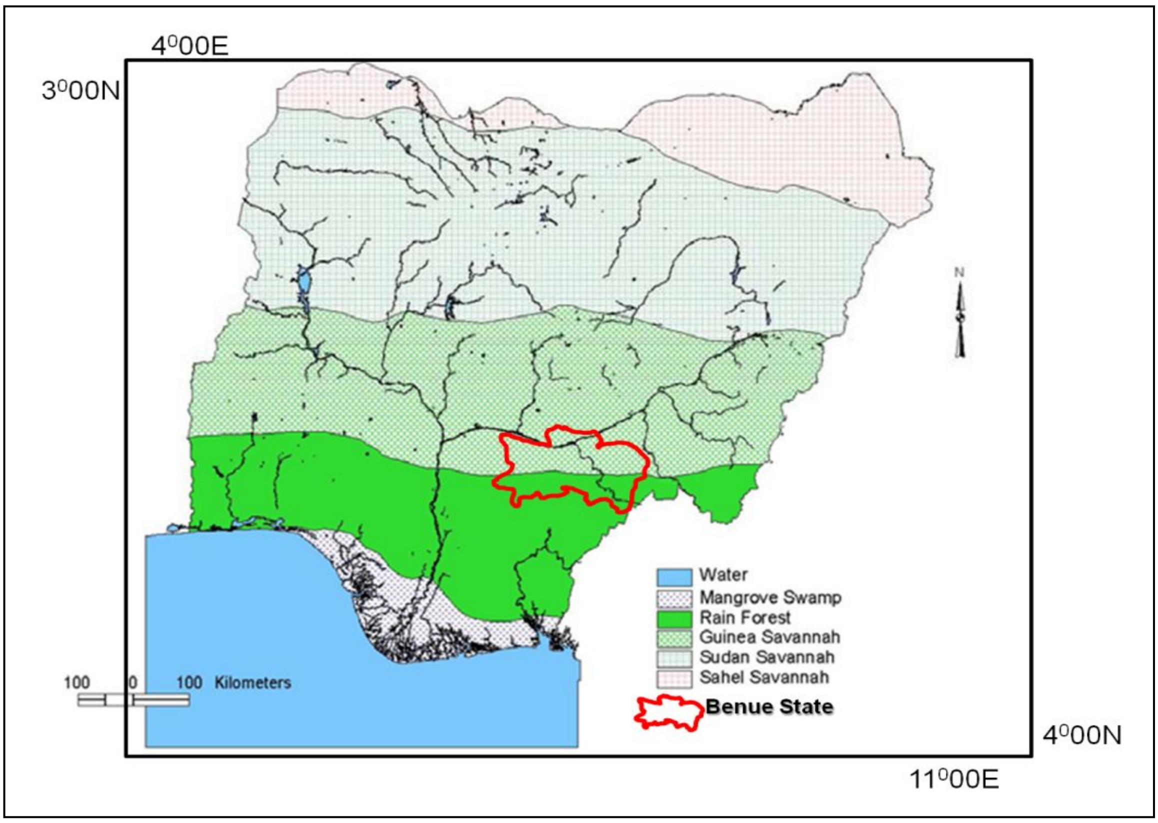

Figure 3. Vegetation Map of Study Area

The soils of the study area are classified as Acrisols (Ortic and Ferric subgroups) and Dystric Cambisols [18]. The well drained soils have predominantly low activity clay fractions (kandic property), low to medium base status and low water and nutrient retaining capacities like most other upland soils of the sub-humid region [23]. The soils are generally agriculturally rich and support high cereals and tuber produce. Naturally, the vegetation of the area was dominated by southern guinea savannah type, although at present, extensive cultivation, annual bush-burning, limestone mining and several other anthropogenic activities have transformed the vegetation into shrubs and bushes (Figure 3).

2.1.5. Population and Economy

The population of Gboko LGA is 358,936 [24], and is largely pre-occupied in subsistence agriculture and hunting. The study area is ancestral home to the *Tiv*, presumably the 4th largest ethnic group in Nigeria. However, with the establishment of cement production, a 'settler' population is expanding to provide various economic services for the business community at the factory. The most prominent communities within the study area are Tse-Kucha and Tse-Amua with proximity to the factory of distance of 1.8 km and 3.07 km, respectively from the factory.

2.2. The Point Source Gaussian Model

The Point Source Gaussian Model (also called the Mathematical Model) was applied by [14] for a similar study (using data up to the year 2006). The model provides for the determination of cement dust concentration (in μg/m^3) from cement plants using the point source plume function given below as;

$$C_{(x,y)} = \frac{Q}{\pi U_H \delta_y \delta_z}\left[\exp^{\frac{-H^2}{2\delta_z^2}}\right] \quad (1)$$

The Gaussian Plume 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 [25; 26], on a relatively flat terrain. Deriving the Gaussian dispersion equation require the assumption of constant conditions for the entire plume travel distance from the emission source point to the downwind ground level receptor. The model uses parameters such as, the stack height (h), stack diameter (d), stack exit velocity (vs), source emission rate (Q) and stack gas temperature (Ts). Other parameters like wind speed (U) and ambient air temperature (Ta) are also used.

2.2.1. Field Survey

On-site, primary data for the study was obtained through the use of a hand-held GPS unit and photographs using a Nikon Camera. Also, field surveys were conducted to collect the pre-requisite data employed for generating estimates of plume dispersion coefficients and the consequent dispersion patterns. Secondary data was collected from various sources (see Appendix 1).

2.2.2. Software

ArcGIS 9.3 and SPSS software were used for data processing and statistical analysis.

2.2.3. Atmospheric Stability Classes Definition

The determinants of the stability classes are wind speed and temperature (state of insolation and irradiation). These together affect the lapse rate, the absence or presence of convective activity, and the dynamics of the mixed layer as explained by [27]. Six atmospheric stability classes were adopted for this study (see Table 1). Classes A, B and C are conditions prevalent during daytime; D could be obtainable during daytime (under heavy cloud conditions) or at night; while E and F are mainly night time conditions [28; 29]. Table 2 provides in-depth explanation regarding the prevailing condition and time of the day.

Table 1. Atmospheric Stability Classes and Wind Profile Wind Exponent 'P'

Stability Class	Description	P
A	Very Unstable	0.15
B	Moderately Unstable	0.15
C	Slightly Unstable	0.20
D	Neutral (temperature at 0℃, it could be night or day)	0.25
E	Slightly Stable (night time with radiation inversion, and poor dispersion)	0.40
F	Stable (night time with radiation inversion, and no dispersion)	0.60

Adopted from Peterson *et al.*, 1978

Table 2. Key to Describing the Atmospheric Stability Classes

Wind Speed (m/s)	DAY			NIGHT	
	Incoming	Solar	Radiation	Amount of	Overcast
	Strong	Moderate	Slight	≥4/8 low cloud	≤3/8 low cloud
< 2.0	A	A – B	B		
2.0 – 3.0	A- B	B	C	E	F
3.0 – 5.0	B	B – C	C	D	E
5.0 – 6.0	C	C- D	D	D	D
> 6.0	C	D	D	D	D

After: Dobbins, 1979

The provisions on Table 2 imply that:

- Strong solar radiation corresponds to a solar elevation angle 600 or more, above the horizon;
- Moderate solar radiation corresponds to a solar elevation angle of between 350 – 600;
- Slight insolation corresponds to a solar elevation of 150 – 350;
- For A-B, B-C, or C-D conditions, average values are computed for each class.

2.2.4. Calculating the Dispersion Coefficients

Based on vertical and horizontal downwind dispersion coefficients, the algebraic representation of the dispersion coefficients using Table 4 is frequently expressed in terms of Power Law expression of the type:

$$\sigma_y = ax^{0.894} \tag{2}$$

(for horizontal dispersion coefficients); and,

$$\sigma_z = cx^d + f \tag{3}$$

(for vertical dispersion coefficients).

The values of the constants ***a, c, d*** and ***f*** (Table 3) are used in calculating the dispersion coefficients for distances below and above 1 kilometer. *X* in the formula is a variable that represents distance in kilometers.

This method of interpolation predicts unknown values from data observed at known locations. Using variogram, Kriging expresses the spatial variation and minimizes the error of predicted values which are estimated by spatial distribution of the predicted values.

Kriging belongs to the family of linear least squares algorithms which assumes that the mean and covariance of ***f(x)*** is known and then the Kriging predictor is the one that minimizes the variance of the prediction error. A kriging estimator is said to be linear because the predicted value $\hat{f}\left(x^*\right)$ is a linear combination that may be written as:

$$\hat{f}\left(x^*\right) = \sum_{i=1}^{n} \lambda_i\left(x^*\right) f\left(x_i\right) \tag{4}$$

The weights are solutions of a system of linear equations which is obtained by assuming that is a sample-path of a random process;

and that the error of prediction, given as,

$$\varepsilon\left(x\right) = \sum_{i=1}^{n} \lambda_i\left(x\right) F\left(x_i\right) - F\left(x\right) \tag{5}$$

is to be minimized in some sense. Hence, the so-called simple kriging assumption is that the mean and the covariance of is known and then, the kriging predictor is the one that minimizes the variance of the prediction error [30].

Table 3. Value of Constants for Calculation of Dispersion Coefficients

Stability		X ≤ 1Km			X ≥ 1Km		
Class	A	C	D	F	C	D	F
A	213.00	440.80	1.941	9.27	459.70	2.094	-9.6.
B	156.00	106.60	1.149	3.30	108.20	1.098	2.00
C	104.00	61.00	0.911	0.00	61.00	0.911	0.00
D	68.00	33.20	0.725	-1.70	44.50	0.516	-13.00
E	50.50	22.80	0.678	-1.30	55.40	0.305	-34.00
F	34.00	14.35	0.740	-0.35	62.60	0.180	-48.60

After Martin, 1976; Shiau and Tsai, 2009

Table 4. Pollutants Concentration from Plume Emitted from Stacks of Dangote Cement Plc*

Distance	Class	A	Class	B	Class	C	Class	D	Class	E	Class	F
(km)	σ_y	σ_z	σ_y	σ_z	σ_y	σ_z	σ_y	σ_z	σ_y	σ_z	σ_y	σ_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 $\mu g/m^3$

2.2.5. Determination of Buoyancy Flux Parameters

Observation of plume emitted from a stack at a temperature *Ts* above the ambient air temperature Ta shows that the plume rises above the top of the stack due to several factors prominent among which are thermal buoyancy, momentum of the exhaust gases, and the stability of the atmosphere. Hence, as described by [14], buoyancy results when exhaust gases are hotter than the ambient air, or when the molecular weight of the exhaust gas is lower than that of air (or a combination of both factors). Momentum is caused by the mass and velocity of the gases as they leave the stack. The buoyancy flux parameter (F) was determined prior to the calculation of the plume rise. The function for deriving the buoyancy flux parameter (F) is given as:

$$F = gr^2 V(1 - \frac{T_a}{T_s}) \quad (6)$$

Where:
F=buoyancy flux parameter, m^4/s^3
g=acceleration due to gravity, 10 m/s^2
V=exit velocity of plume, 10.5 m/s
r=radius, 3 m
Ta = ambient temperature, 303 K
Ts = stack gas temperature, 410 K

Thus, the buoyancy flux parameter applied in estimation of plume rise and dispersion for this study is determined as:

$$F = 10x3^2 x10.5x(1 - \frac{303}{410}) = 246.6 \, {m^4}/{s^3} \quad (7)$$

2.2.6. Statistical Analyses

Three statistical data analysis techniques were engaged to test the estimated plume dispersion coefficients. These are descriptive statistics, analysis of variance (ANOVA), and post-hoc multiple comparisons.

3. Results

3.1. Plume Dispersion Coefficients

The plume dispersion coefficients for the study area (Table 4) were calculated using the constant values in Table 3. Vertical (z) and horizontal (y) dispersion coefficient modelling was done for a distance of 1 – 10 kilometers for all atmospheric stability classes (A – F). The results show 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.

3.2. Statistical Analysis of Plume Dispersion Coefficients

Statistical analyses were conducted to test the extent of variation of the plume dispersal coefficient values between the six atmospheric stability classes (A, B, C, D, E and F). Table 5 shows that 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. Extreme variation in the standard deviation, standard error and minimum and maximum values of all 6 atmospheric stability classes was also observed, but could be explained as a function 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.

Table 5. Descriptive Statistics for the 6 Atmospheric Stability Classes

Orientation	Classes	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
VDC	CLASS A	10	963.7000	487.29390	154.09586	615.1109	1312.2891	213.00	1669.00
	CLASS B	10	705.8000	356.76005	112.81743	450.5892	961.0108	156.00	1222.00
	CLASS C	10	470.4000	237.98002	75.25589	300.1594	640.6406	104.00	815.00
	CLASS D	10	307.6000	155.55935	49.19219	196.3195	418.8805	68.00	533.00
	CLASS E	10	228.5000	115.67219	36.57876	145.7531	311.2469	50.00	396.00
	CLASS F	10	153.7000	77.70893	24.57372	98.1104	209.2896	34.00	266.00
HDC	CLASS A	10	21392.3000	19556.31142	6184.24867	7402.5576	35382.0424	450.00	57069.00
	CLASS B	10	716.7000	421.50024	133.29008	415.1769	1018.2231	110.00	1358.00
	CLASS C	10	285.0000	146.28967	46.26085	180.3507	389.6493	61.00	497.00
	CLASS D	10	91.2000	34.21436	10.81953	66.7245	115.6755	31.00	136.00
	CLASS E	10	55.8000	18.10341	5.72480	42.8496	68.7504	22.00	78.00
	CLASS F	10	34.1000	10.24641	3.24020	26.7702	41.4298	14.00	46.00

VDC = Vertical Dispersion Coefficient
HDC = Horizontal Dispersion Coefficient

Table 6. ANOVA

		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			

The analysis of variance (ANOVA) result (Table 6) 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 significant variation in the mean values of plume dispersion between and within the stability classes for both VDC and HDC orientations. This is because the probability distributions of VDC and HDC (0.000) all fall below the critical level value of 0.05 set for ANOVA. Since the ANOVA results are found to be significant using the above procedure, it implies that the values of the means differ more than would be expected by chance alone.

The variation in the ANOVA results requires further detailed analysis to identify the nature of variation between the values of the means of the atmospheric stability classes. To address this, the post hoc test is applied (see Appendix 2). Values for Tukey's HSD (honestly significant difference) and Fisher's LSD (least significant difference) contains a high level of redundancy, nevertheless some key discoveries are made as specific mean values under specific atmospheric stability classes are found significant at the 0.05 alpha level. These have been flagged.

3.3. 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 variograms (Appendix 3). The variograms model the difference between the value of plume concentration at each intervalled kilometer (1 – 10), according to the distance and direction between them. As a key function in geostatistics, it is used to fit a model of the spatial correlation of the plume concentration data for this study. Therefore, the variograms also represents both structural and random aspects of the dispersion coefficients of plume within a known distance of 10 km intervalling at single km.

As shown on the variograms (Appendix 3), values increase with increasing distance of separation until it reaches the maximum (C) at a distance known as the "range" (a). If at a distance nearly equal to zero, (h 0), the variogram value is greater than zero, this value is known as the "nugget-effect" (C0). The total-sill of the variogram (S) is C+C0. Often C is also treated equal to the sill of the variogram model fitted to the experimental variograms and the nugget effect (C0). Both C0 and the sill (S) characterize the random aspect of the data, whereas the range (a) and C characterize the structural aspect of the deposit of plume. The analysis is consistent with [31] and [32].

The application of this model to this study has aided the establishment of the predictability of values at those locations across a relatively wider area affected by plume, yet not sampled by this study. Also, the technique reveals the dispersion pattern of plume under the various atmospheric stability classes (defined by prevalence of weather conditions and time of day), as well as on the basis of vertical and horizontal orientations. The weights are optimized using the variogram model (generated and shown as Appendix 3), 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 also provided within the variogram which allows for the quantification of confidence levels for all locations analysed.

Generally, for both vertical and horizontal 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. Thus, the output variograms for plume deposition at the study area exhibit an omni-directional (as against directional) orientation, and are sufficient for kriging data even as spatially irregular as the results of the plume dispersion coefficients appear. Finally, the distribution of plume on the variograms seems spatially correlated in a radial, omni-directional orientation.

4. Discussion

The environmental consequences of cement production at the study area are glaring even to a passive observer. Soil and plant texture is observed to be affected by fugitive dust and plume deposits over the years. With the installation of taller stacks (75m as against the previous 55m stacks), the 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) therefore, deposition occurring further away from the source of emission.

Furthermore, plume dispersion exhibits a seasonal pattern of variation where plume deposition is denser during the rainy season when the wind conditions are relatively stable, and more scattered during the dry windy season.

Although daily averages of plume dispersion vary across the atmospheric stability classes as well as along their vertical and horizontal orientations (Table 5), they are found generally occurring higher and denser away from the factory.

Since plume, fugitive and cement dust contains heavy metals and pollutants hazardous to the biotic environment, with adverse impact for vegetation, human and animal health and ecosystems [33, 34], the rate of concentration observed is considered unhealthy for the biotic environment.

5. Conclusions

Summary of the major findings indicate that: the highest plume dispersion coefficient values are recorded for the ‘unstable’ climatic stability class ‘A’ with least values recorded for the relatively ‘stable’ stability class ‘F’; the plume dispersion coefficients for the study area are estimated to be generally high; the ANOVA result of plume dispersion coefficients is found to be significant, implying that the values of the means differ more than would be expected by chance alone; the variograms show that plume deposition amounts increase with distance away from the emission source (the stacks at the cement factory), and is radially omni-directional in orientation. The implication is that the observed daily average values of both PM_{10} and $PM_{2.5}$ are higher than the WHO [35] permissible limits for all stability classes except for DH, EH and FH stability/orientation categories. This result spells adverse effect for both human, animal and plant population within the 10-kilometre study radius.

It is therefore, recommended that:

- Deliberate reforestation efforts using species with high pollution tolerance index such as *Azadirachta indica, Albizzia lebbek, Aegle marmelos, Annona squamosa, Bambusa bambos, Butea frondosa, Cassia fistula, Cordia myxa, Delonix regia, Ficus religiosa,* etc.;
- 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;
- Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR) systems should be adopted at the factory kilns to reduce drastically, the amount of plume emissions during production; and,
- Human, animal and agricultural populations should only be located either within the first 2 - 3 km or from 11 km away from the factory (avoiding km 4-10 which are areas of high plume deposition levels) to reduce the risk of exposure to plume from the factory.

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Appendix 1

Field Survey Data for Plume Modelling

S/No.	Parameter	Quantity	Data Source
1	Exit Velocity of Stack gas	10.5 m/s	M & P Units, Dangote Cement Plc
2	Stack Height	75.0 m	M & P Units, Dangote Cement Plc
3	Mass Rate	11.5 Kg/S = 1.15 x 10^{10} μg/S	M & P Units, Dangote Cement Plc
4	Stack Gas Temperature	137℃ = 410 K	M & P Units, Dangote Cement Plc
5	Stack Diameter	6.0 m	M & P Units, Dangote Cement Plc
6	Mean Wind Speed	1.50 ± 0.04 m/s	NIMET, Makurdi
7.	Mean Ambient Temperature	30.0℃ = 303 K	NIMET, Makurdi

Appendix 2

Post Hoc Multiple Comparisons of Atmospheric Stability Classes

Dependent Variable		(I) Constant	(J) Variables	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
							Upper Bound	Lower Bound
VDC	Tukey HSD	CLASS A	CLASS B	257.90000	124.49699	.317	-109.9238	625.7238
			CLASS C	493.30000(*)	124.49699	.003	125.4762	861.1238
			CLASS D	656.10000(*)	124.49699	.000	288.2762	1023.9238
			CLASS E	735.20000(*)	124.49699	.000	367.3762	1103.0238
			CLASS F	810.00000(*)	124.49699	.000	442.1762	1177.8238

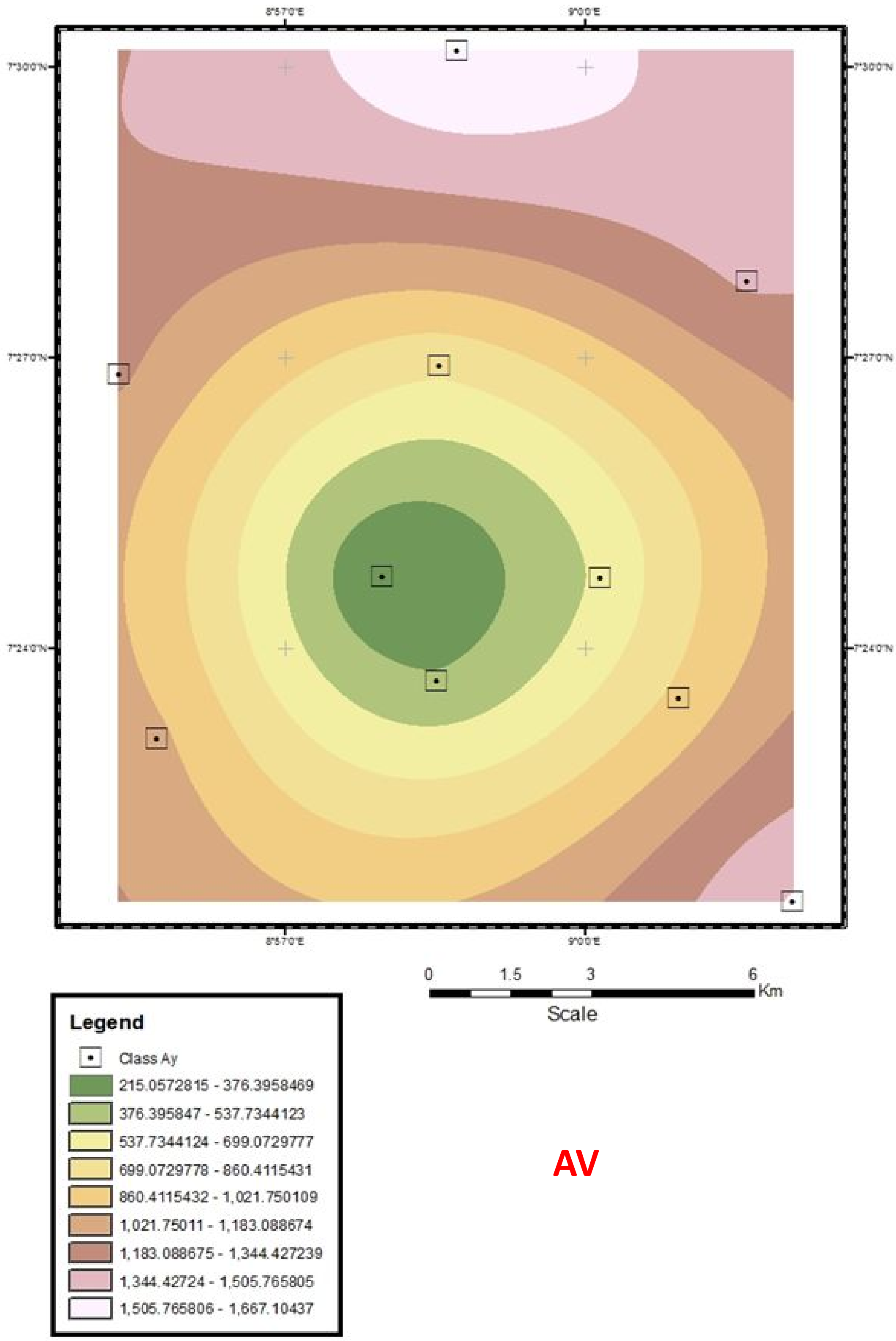
		CLASS B	CLASS A	-257.90000	124.49699	.317	-625.7238	109.9238
			CLASS C	235.40000	124.49699	.419	-132.4238	603.2238
			CLASS D	398.20000(*)	124.49699	.027	30.3762	766.0238
			CLASS E	477.30000(*)	124.49699	.004	109.4762	845.1238
			CLASS F	552.10000(*)	124.49699	.001	184.2762	919.9238
		CLASS C	CLASS A	-493.30000(*)	124.49699	.003	-861.1238	-125.4762
			CLASS B	-235.40000	124.49699	.419	-603.2238	132.4238
			CLASS D	162.80000	124.49699	.780	-205.0238	530.6238
			CLASS E	241.90000	124.49699	.388	-125.9238	609.7238
			CLASS F	316.70000	124.49699	.130	-51.1238	684.5238
		CLASS D	CLASS A	-656.10000(*)	124.49699	.000	-1023.9238	-288.2762
			CLASS B	-398.20000(*)	124.49699	.027	-766.0238	-30.3762
			CLASS C	-162.80000	124.49699	.780	-530.6238	205.0238
			CLASS E	79.10000	124.49699	.988	-288.7238	446.9238
			CLASS F	153.90000	124.49699	.817	-213.9238	521.7238
		CLASS E	CLASS A	-735.20000(*)	124.49699	.000	-1103.0238	-367.3762
			CLASS B	-477.30000(*)	124.49699	.004	-845.1238	-109.4762
			CLASS C	-241.90000	124.49699	.388	-609.7238	125.9238
			CLASS D	-79.10000	124.49699	.988	-446.9238	288.7238
			CLASS F	74.80000	124.49699	.991	-293.0238	442.6238
		CLASS F	CLASS A	-810.00000(*)	124.49699	.000	-1177.8238	-442.1762
			CLASS B	-552.10000(*)	124.49699	.001	-919.9238	-184.2762
			CLASS C	-316.70000	124.49699	.130	-684.5238	51.1238
			CLASS D	-153.90000	124.49699	.817	-521.7238	213.9238
			CLASS E	-74.80000	124.49699	.991	-442.6238	293.0238
	LSD	CLASS A	CLASS B	257.90000(*)	124.49699	.043	8.2986	507.5014
			CLASS C	493.30000(*)	124.49699	.000	243.6986	742.9014
			CLASS D	656.10000(*)	124.49699	.000	406.4986	905.7014
			CLASS E	735.20000(*)	124.49699	.000	485.5986	984.8014
			CLASS F	810.00000(*)	124.49699	.000	560.3986	1059.6014
		CLASS B	CLASS A	-257.90000(*)	124.49699	.043	-507.5014	-8.2986
			CLASS C	235.40000	124.49699	.064	-14.2014	485.0014
			CLASS D	398.20000(*)	124.49699	.002	148.5986	647.8014
			CLASS E	477.30000(*)	124.49699	.000	227.6986	726.9014
			CLASS F	552.10000(*)	124.49699	.000	302.4986	801.7014
		CLASS C	CLASS A	-493.30000(*)	124.49699	.000	-742.9014	-243.6986
			CLASS B	-235.40000	124.49699	.064	-485.0014	14.2014
			CLASS D	162.80000	124.49699	.197	-86.8014	412.4014
			CLASS E	241.90000	124.49699	.057	-7.7014	491.5014
			CLASS F	316.70000(*)	124.49699	.014	67.0986	566.3014
		CLASS D	CLASS A	-656.10000(*)	124.49699	.000	-905.7014	-406.4986
			CLASS B	-398.20000(*)	124.49699	.002	-647.8014	-148.5986
			CLASS C	-162.80000	124.49699	.197	-412.4014	86.8014
			CLASS E	79.10000	124.49699	.528	-170.5014	328.7014
			CLASS F	153.90000	124.49699	.222	-95.7014	403.5014
		CLASS E	CLASS A	-735.20000(*)	124.49699	.000	-984.8014	-485.5986
			CLASS B	-477.30000(*)	124.49699	.000	-726.9014	-227.6986
			CLASS C	-241.90000	124.49699	.057	-491.5014	7.7014
			CLASS D	-79.10000	124.49699	.528	-328.7014	170.5014
			CLASS F	74.80000	124.49699	.550	-174.8014	324.4014
		CLASS F	CLASS A	-810.00000(*)	124.49699	.000	-1059.6014	-560.3986
			CLASS B	-552.10000(*)	124.49699	.000	-801.7014	-302.4986
			CLASS C	-316.70000(*)	124.49699	.014	-566.3014	-67.0986
			CLASS D	-153.90000	124.49699	.222	-403.5014	95.7014
			CLASS E	-74.80000	124.49699	.550	-324.4014	174.8014
HDC	Tukey HSD	CLASS A	CLASS B	20675.60000(*)	3571.41420	.000	10123.9293	31227.2707
			CLASS C	21107.30000(*)	3571.41420	.000	10555.6293	31658.9707
			CLASS D	21301.10000(*)	3571.41420	.000	10749.4293	31852.7707

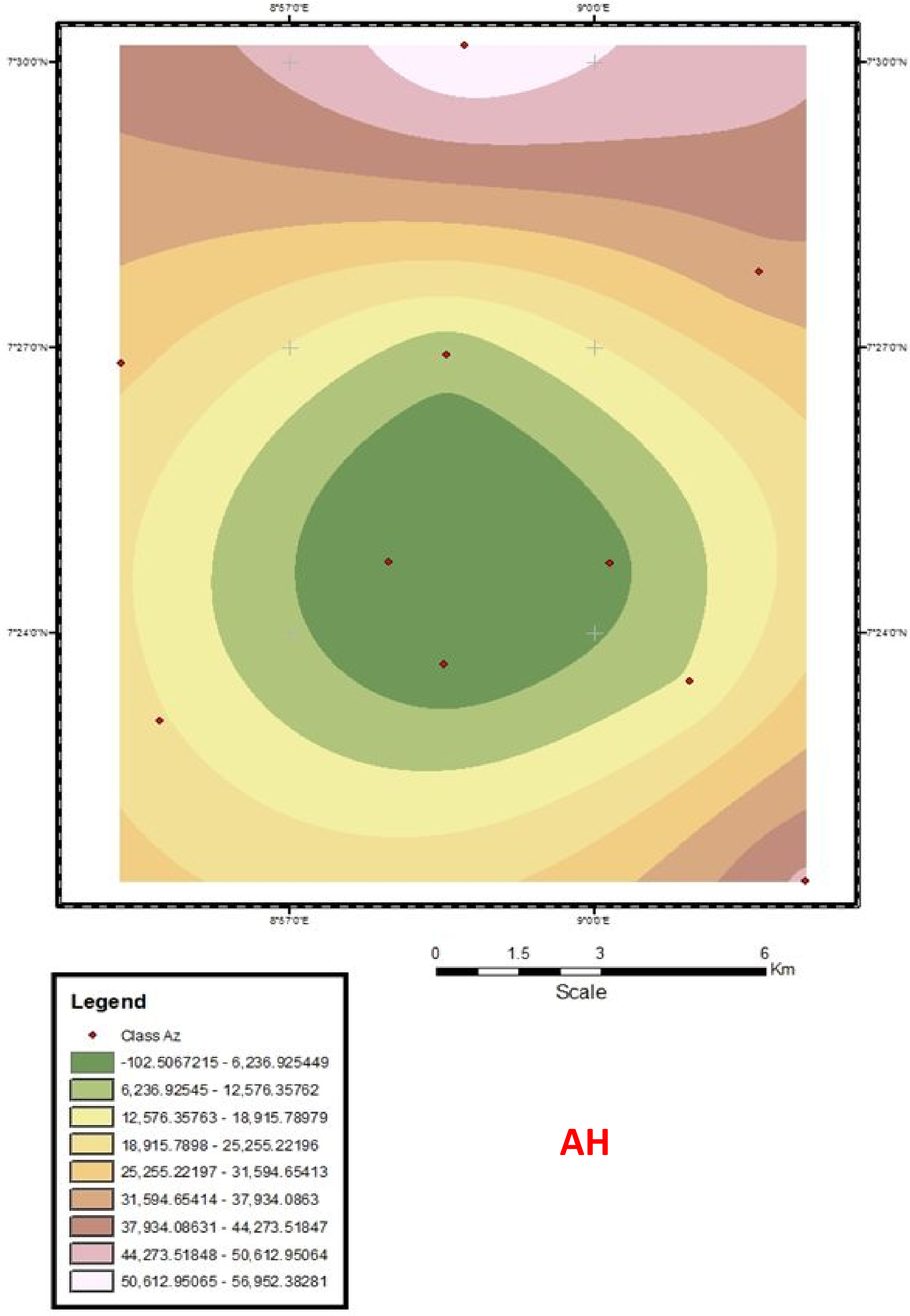
		CLASS E	21336.50000(*)	3571.41420	.000	10784.8293	31888.1707
		CLASS F	21358.20000(*)	3571.41420	.000	10806.5293	31909.8707
	CLASS B	CLASS A	-20675.60000(*)	3571.41420	.000	-31227.2707	-10123.9293
		CLASS C	431.70000	3571.41420	1.000	-10119.9707	10983.3707
		CLASS D	625.50000	3571.41420	1.000	-9926.1707	11177.1707
		CLASS E	660.90000	3571.41420	1.000	-9890.7707	11212.5707
		CLASS F	682.60000	3571.41420	1.000	-9869.0707	11234.2707
	CLASS C	CLASS A	-21107.30000(*)	3571.41420	.000	-31658.9707	-10555.6293
		CLASS B	-431.70000	3571.41420	1.000	-10983.3707	10119.9707
		CLASS D	193.80000	3571.41420	1.000	-10357.8707	10745.4707
		CLASS E	229.20000	3571.41420	1.000	-10322.4707	10780.8707
		CLASS F	250.90000	3571.41420	1.000	-10300.7707	10802.5707
	CLASS D	CLASS A	-21301.10000(*)	3571.41420	.000	-31852.7707	-10749.4293
		CLASS B	-625.50000	3571.41420	1.000	-11177.1707	9926.1707
		CLASS C	-193.80000	3571.41420	1.000	-10745.4707	10357.8707
		CLASS E	35.40000	3571.41420	1.000	-10516.2707	10587.0707
		CLASS F	57.10000	3571.41420	1.000	-10494.5707	10608.7707
	CLASS E	CLASS A	-21336.50000(*)	3571.41420	.000	-31888.1707	-10784.8293
		CLASS B	-660.90000	3571.41420	1.000	-11212.5707	9890.7707
		CLASS C	-229.20000	3571.41420	1.000	-10780.8707	10322.4707
		CLASS D	-35.40000	3571.41420	1.000	-10587.0707	10516.2707
		CLASS F	21.70000	3571.41420	1.000	-10529.9707	10573.3707
	CLASS F	CLASS A	-21358.20000(*)	3571.41420	.000	-31909.8707	-10806.5293
		CLASS B	-682.60000	3571.41420	1.000	-11234.2707	9869.0707
		CLASS C	-250.90000	3571.41420	1.000	-10802.5707	10300.7707
		CLASS D	-57.10000	3571.41420	1.000	-10608.7707	10494.5707
		CLASS E	-21.70000	3571.41420	1.000	-10573.3707	10529.9707
LSD	CLASS A	CLASS B	20675.60000(*)	3571.41420	.000	13515.3456	27835.8544
		CLASS C	21107.30000(*)	3571.41420	.000	13947.0456	28267.5544
		CLASS D	21301.10000(*)	3571.41420	.000	14140.8456	28461.3544
		CLASS E	21336.50000(*)	3571.41420	.000	14176.2456	28496.7544
		CLASS F	21358.20000(*)	3571.41420	.000	14197.9456	28518.4544
	CLASS B	CLASS A	-20675.60000(*)	3571.41420	.000	-27835.8544	-13515.3456
		CLASS C	431.70000	3571.41420	.904	-6728.5544	7591.9544
		CLASS D	625.50000	3571.41420	.862	-6534.7544	7785.7544
		CLASS E	660.90000	3571.41420	.854	-6499.3544	7821.1544
		CLASS F	682.60000	3571.41420	.849	-6477.6544	7842.8544
	CLASS C	CLASS A	-21107.30000(*)	3571.41420	.000	-28267.5544	-13947.0456
		CLASS B	-431.70000	3571.41420	.904	-7591.9544	6728.5544
		CLASS D	193.80000	3571.41420	.957	-6966.4544	7354.0544
		CLASS E	229.20000	3571.41420	.949	-6931.0544	7389.4544
		CLASS F	250.90000	3571.41420	.944	-6909.3544	7411.1544
	CLASS D	CLASS A	-21301.10000(*)	3571.41420	.000	-28461.3544	-14140.8456
		CLASS B	-625.50000	3571.41420	.862	-7785.7544	6534.7544
		CLASS C	-193.80000	3571.41420	.957	-7354.0544	6966.4544
		CLASS E	35.40000	3571.41420	.992	-7124.8544	7195.6544
		CLASS F	57.10000	3571.41420	.987	-7103.1544	7217.3544
	CLASS E	CLASS A	-21336.50000(*)	3571.41420	.000	-28496.7544	-14176.2456
		CLASS B	-660.90000	3571.41420	.854	-7821.1544	6499.3544
		CLASS C	-229.20000	3571.41420	.949	-7389.4544	6931.0544
		CLASS D	-35.40000	3571.41420	.992	-7195.6544	7124.8544
		CLASS F	21.70000	3571.41420	.995	-7138.5544	7181.9544
	CLASS F	CLASS A	-21358.20000(*)	3571.41420	.000	-28518.4544	-14197.9456
		CLASS B	-682.60000	3571.41420	.849	-7842.8544	6477.6544
		CLASS C	-250.90000	3571.41420	.944	-7411.1544	6909.3544
		CLASS D	-57.10000	3571.41420	.987	-7217.3544	7103.1544
		CLASS E	-21.70000	3571.41420	.995	-7181.9544	7138.5544

* The mean difference is significant at the .05 level.
VDC = Vertical Dispersion Coefficient
HDC = Horizontal Dispersion Coefficient

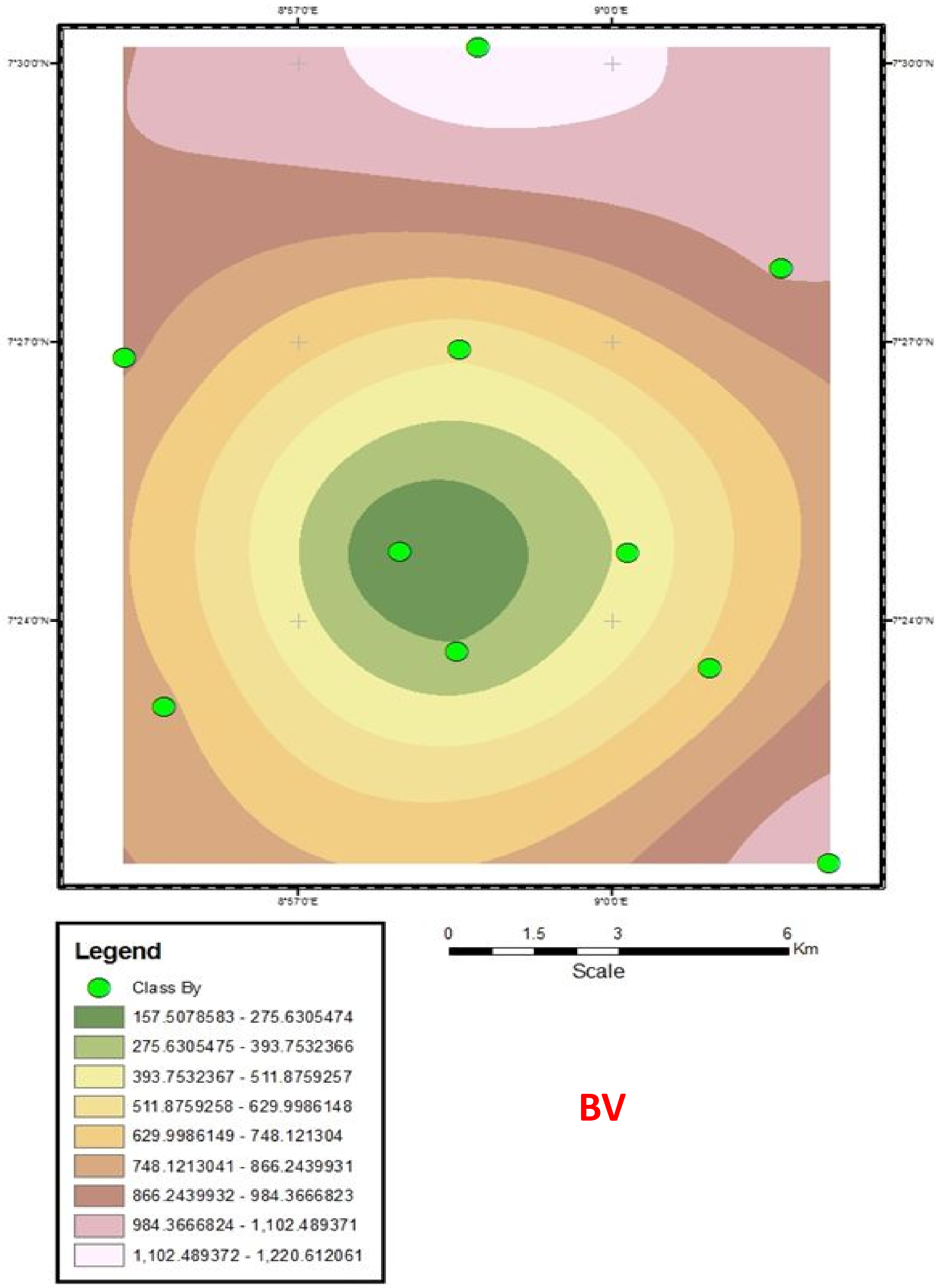
Appendix 3

Variograms showing plume distribution in *x* and *y* orientations for all stability classes.

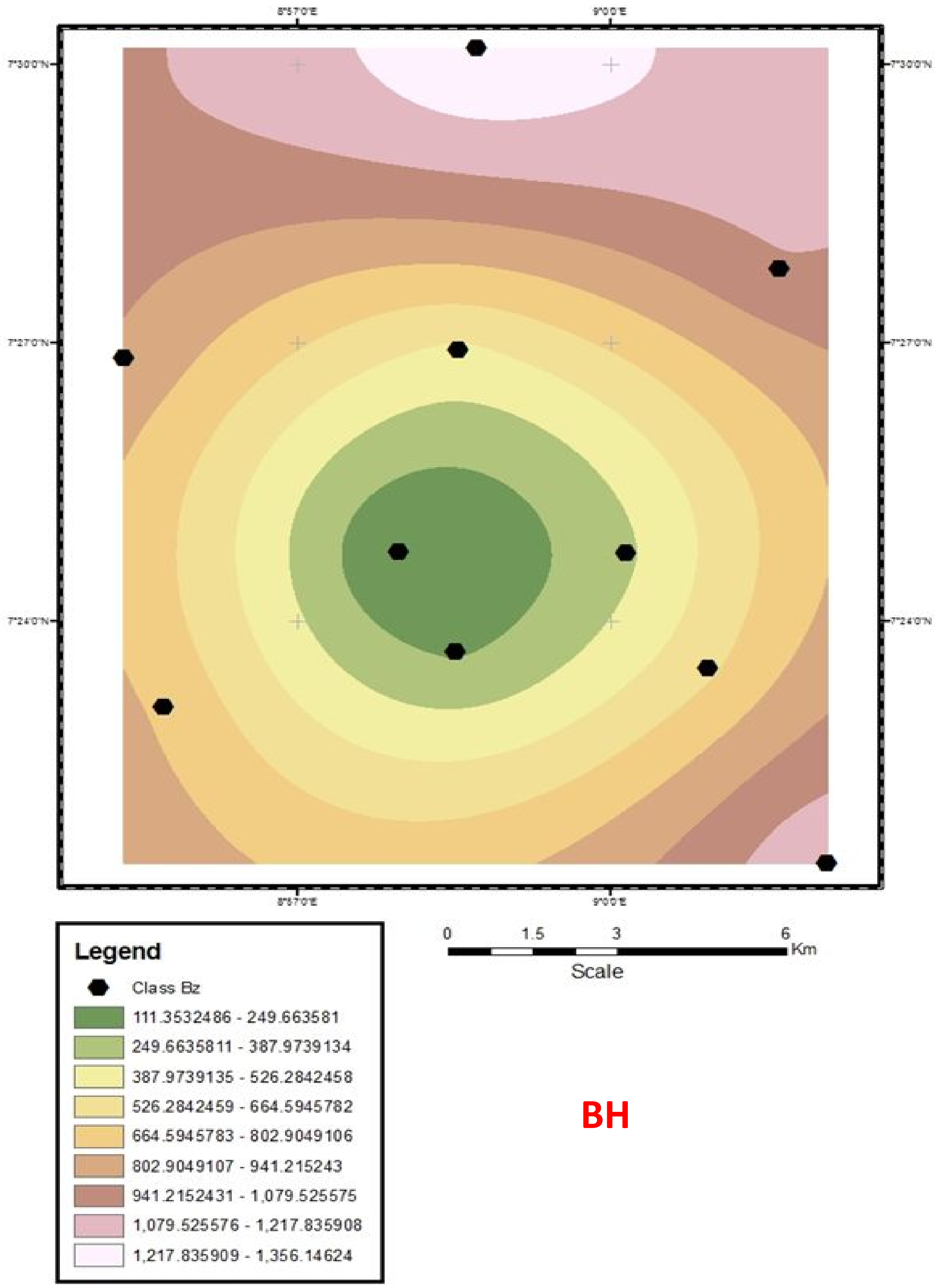


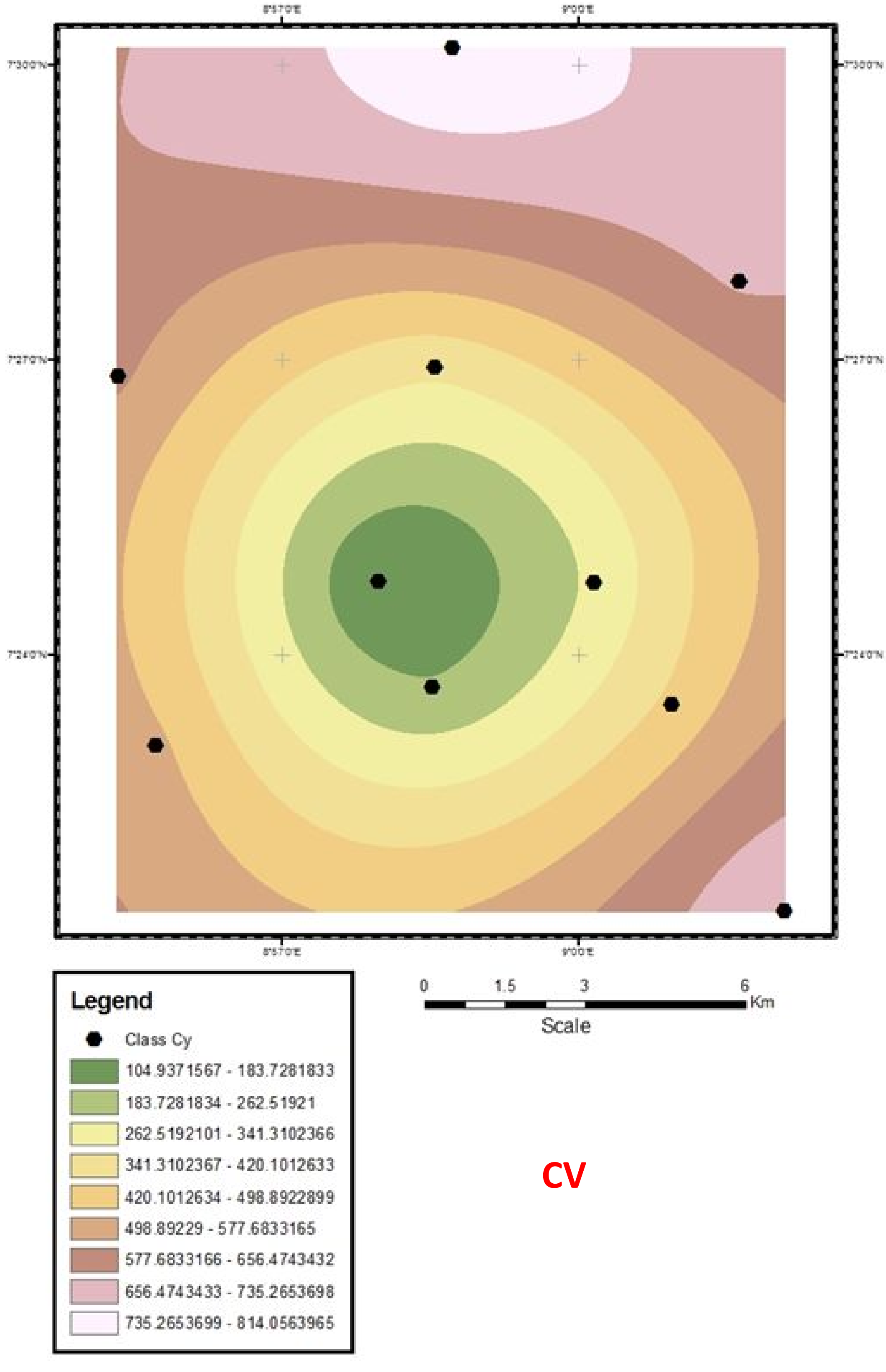

8°57'0"E
9°0'0"E
7°30'0"N
7°27'0"N
7°24'0"N
0
1.5
3
6
Km
Scale
Legend
Class Az
-102.5067215 - 6,236.925449
6,236.92545 - 12,576.35762
12,576.35763 - 18,915.78979
18,915.7898 - 25,255.22196
25,255.22197 - 31,594.65413
31,594.65414 - 37,934.0863
37,934.08631 - 44,273.51847
44,273.51848 - 50,612.95064
50,612.95065 - 56,952.38281

AH

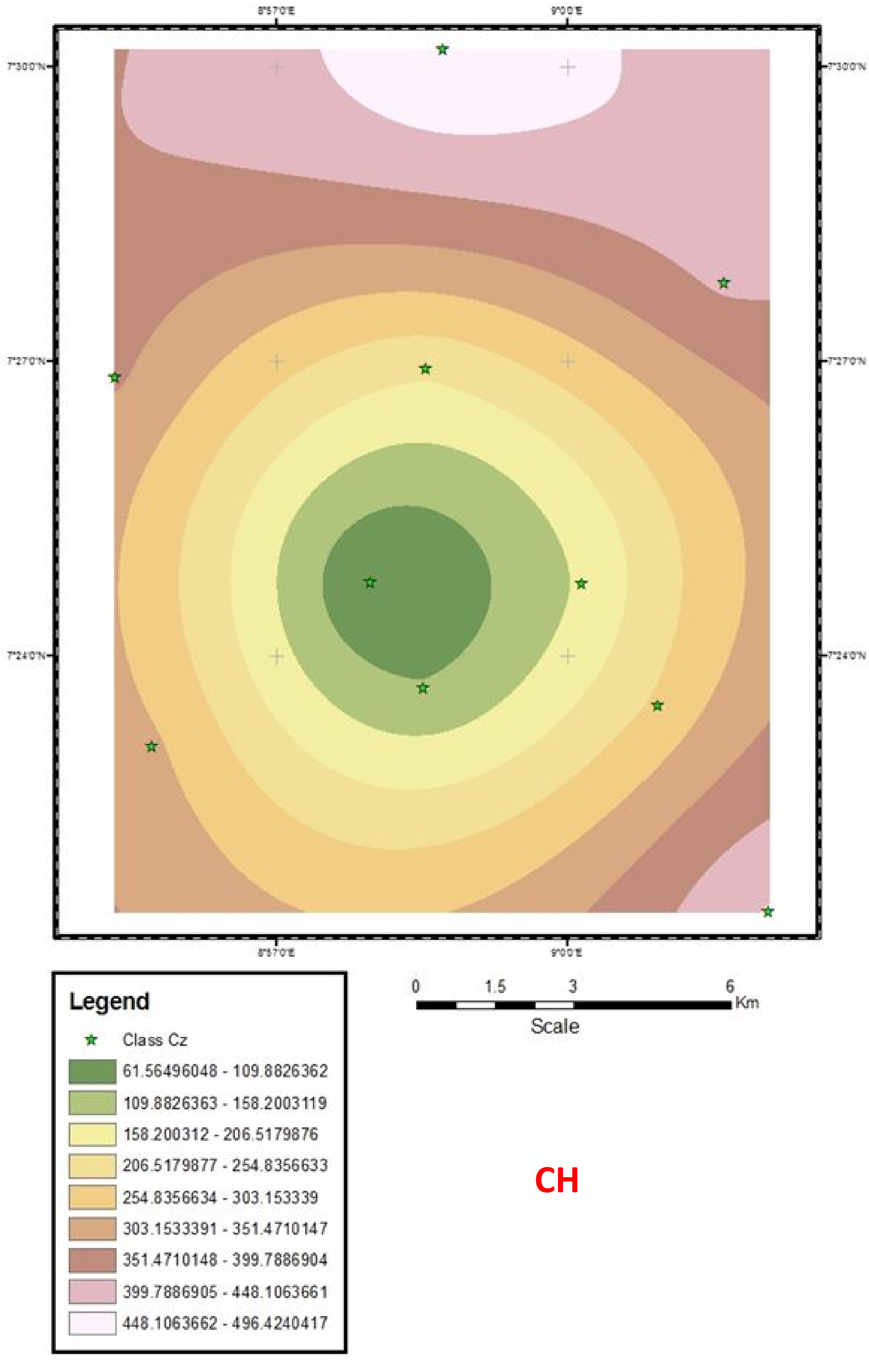

8°57'0"E
9°0'0"E
7°30'0"N
7°27'0"N
7°24'0"N
Legend
Class By
157.5078583 - 275.6305474
275.6305475 - 393.7532366
393.7532367 - 511.8759257
511.8759258 - 629.9986148
629.9986149 - 748.121304
748.1213041 - 866.2439931
866.2439932 - 984.3666823
984.3666824 - 1,102.489371
1,102.489372 - 1,220.612061
0 1.5 3 6
Km
Scale

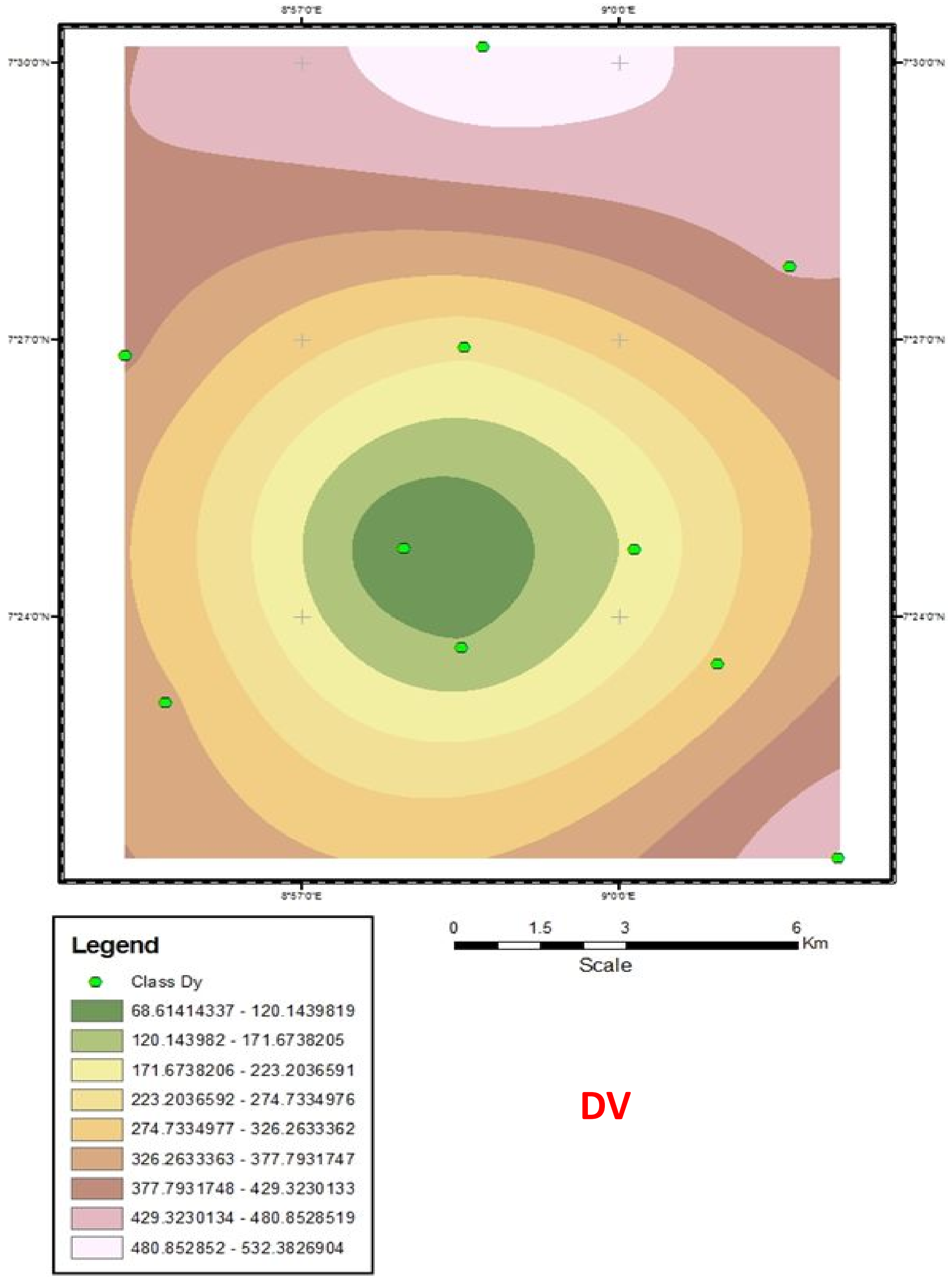
BV

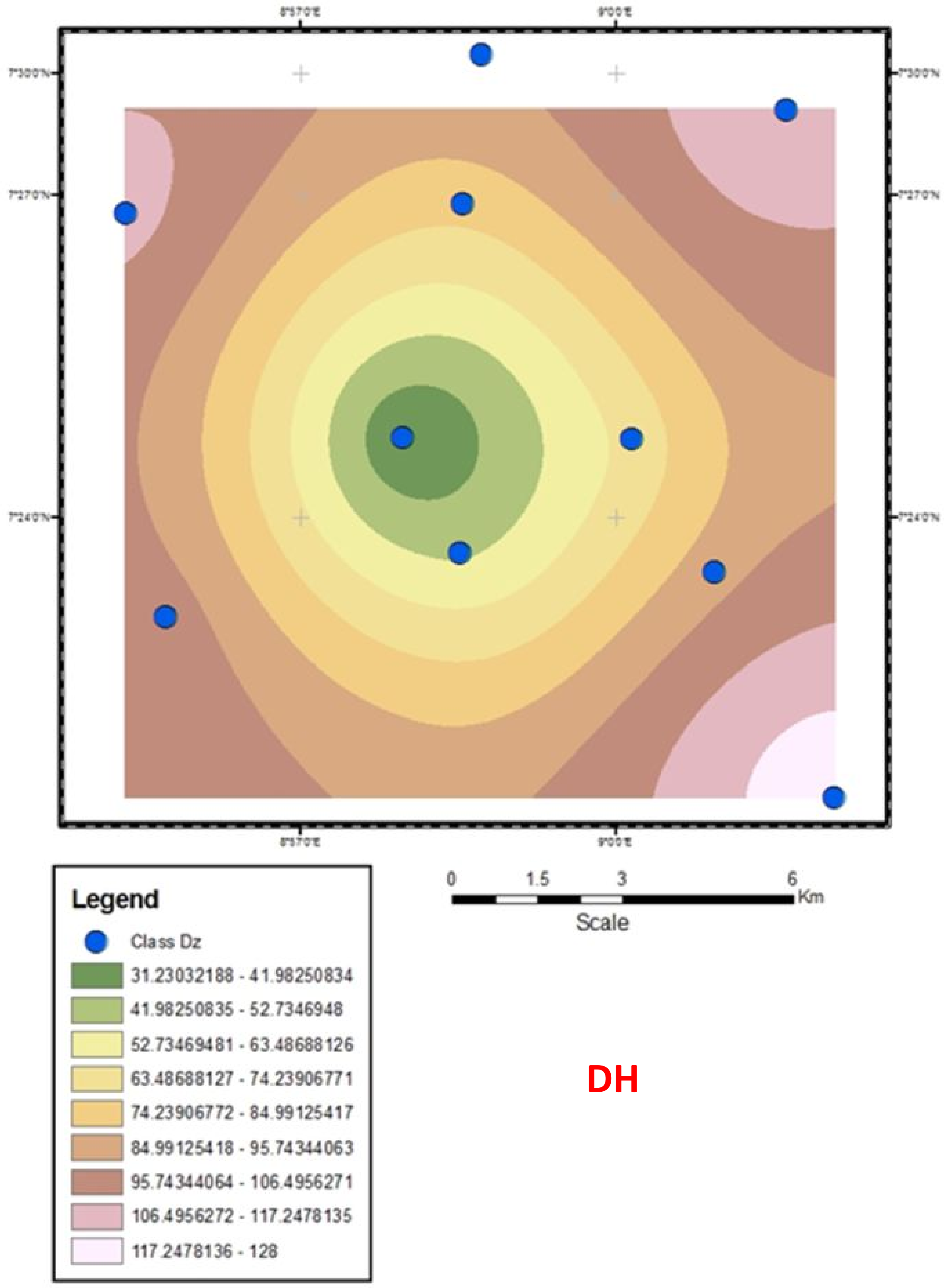

8°57'0"E
9°0'0"E
7°30'0"N
7°27'0"N
7°24'0"N
Legend
Class Bz
111.3532486 - 249.663581
249.6635811 - 387.9739134
387.9739135 - 526.2842458
526.2842459 - 664.5945782
664.5945783 - 802.9049106
802.9049107 - 941.215243
941.2152431 - 1,079.525575
1,079.525576 - 1,217.835908
1,217.835909 - 1,356.14624
0 1.5 3 6 Km
Scale
BH


Legend
Class Cy
104.9371567 - 183.7281833
183.7281834 - 262.51921
262.5192101 - 341.3102366
341.3102367 - 420.1012633
420.1012634 - 498.8922899
498.89229 - 577.6833165
577.6833166 - 656.4743432
656.4743433 - 735.2653698
735.2653699 - 814.0563965
0 1.5 3 6 Km
Scale

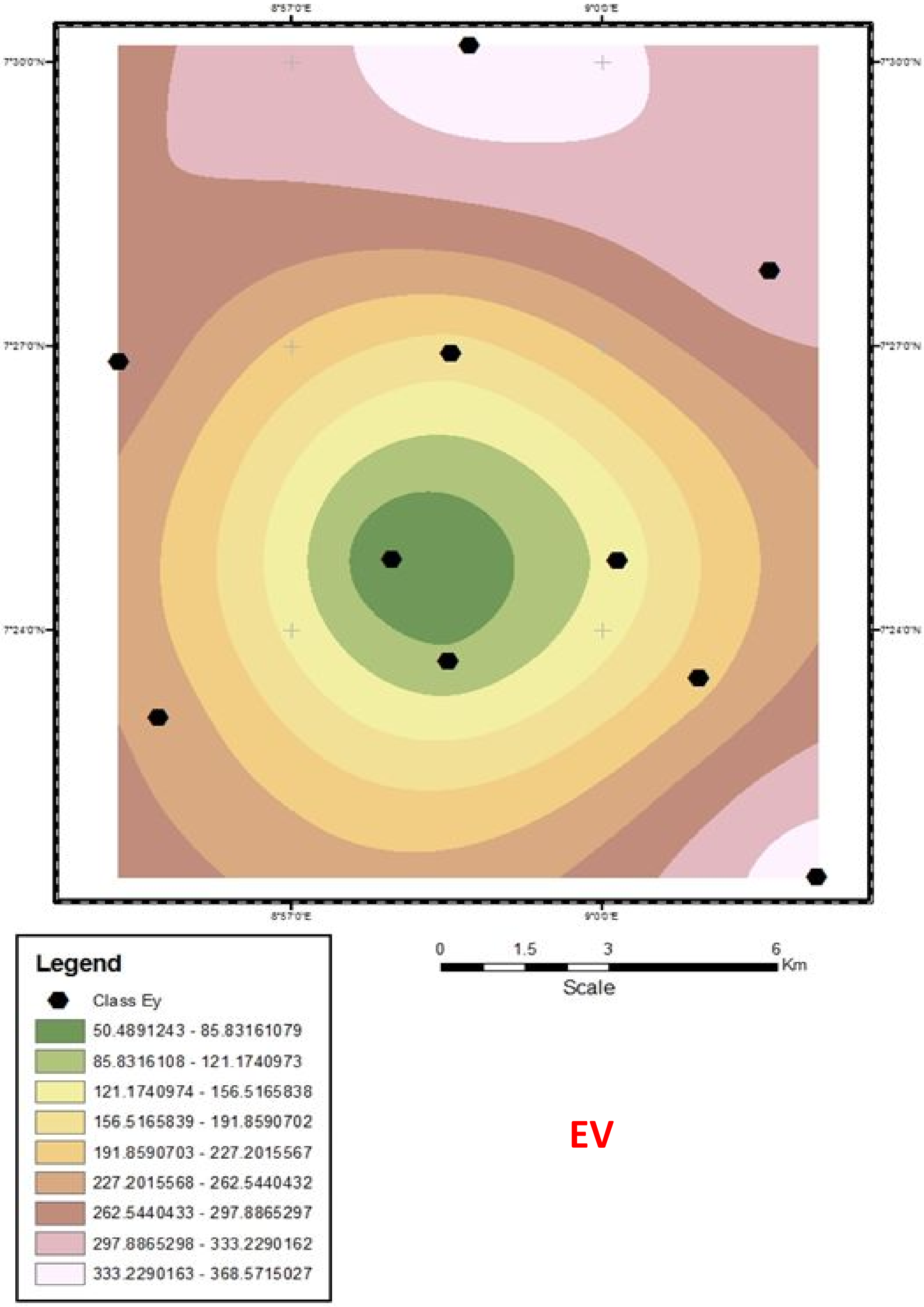
CV


8°57'0"E
9°0'0"E
7°30'0"N
7°27'0"N
7°24'0"N
Legend
Class Cz
61.56496048 - 109.8826362
109.8826363 - 158.2003119
158.200312 - 206.5179876
206.5179877 - 254.8356633
254.8356634 - 303.153339
303.1533391 - 351.4710147
351.4710148 - 399.7886904
399.7886905 - 448.1063661
448.1063662 - 496.4240417
0
1.5
3
6
Km
Scale
CH

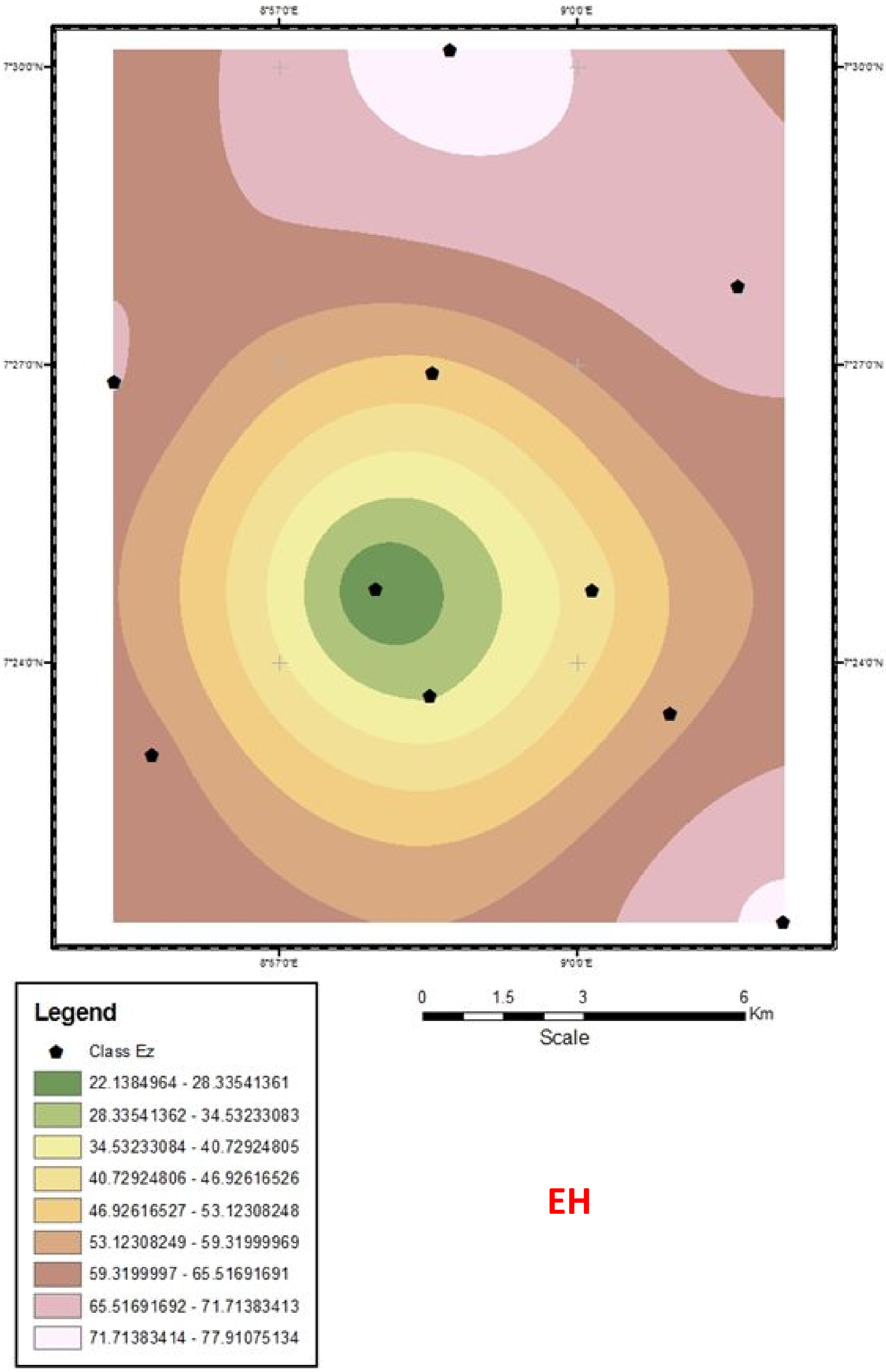

8°57'0"E
9°0'0"E
7°30'0"N
7°27'0"N
7°24'0"N
Legend
Class Dy
68.61414337 - 120.1439819
120.143982 - 171.6738205
171.6738206 - 223.2036591
223.2036592 - 274.7334976
274.7334977 - 326.2633362
326.2633363 - 377.7931747
377.7931748 - 429.3230133
429.3230134 - 480.8528519
480.852852 - 532.3826904
0 1.5 3 6
Km
Scale
DV

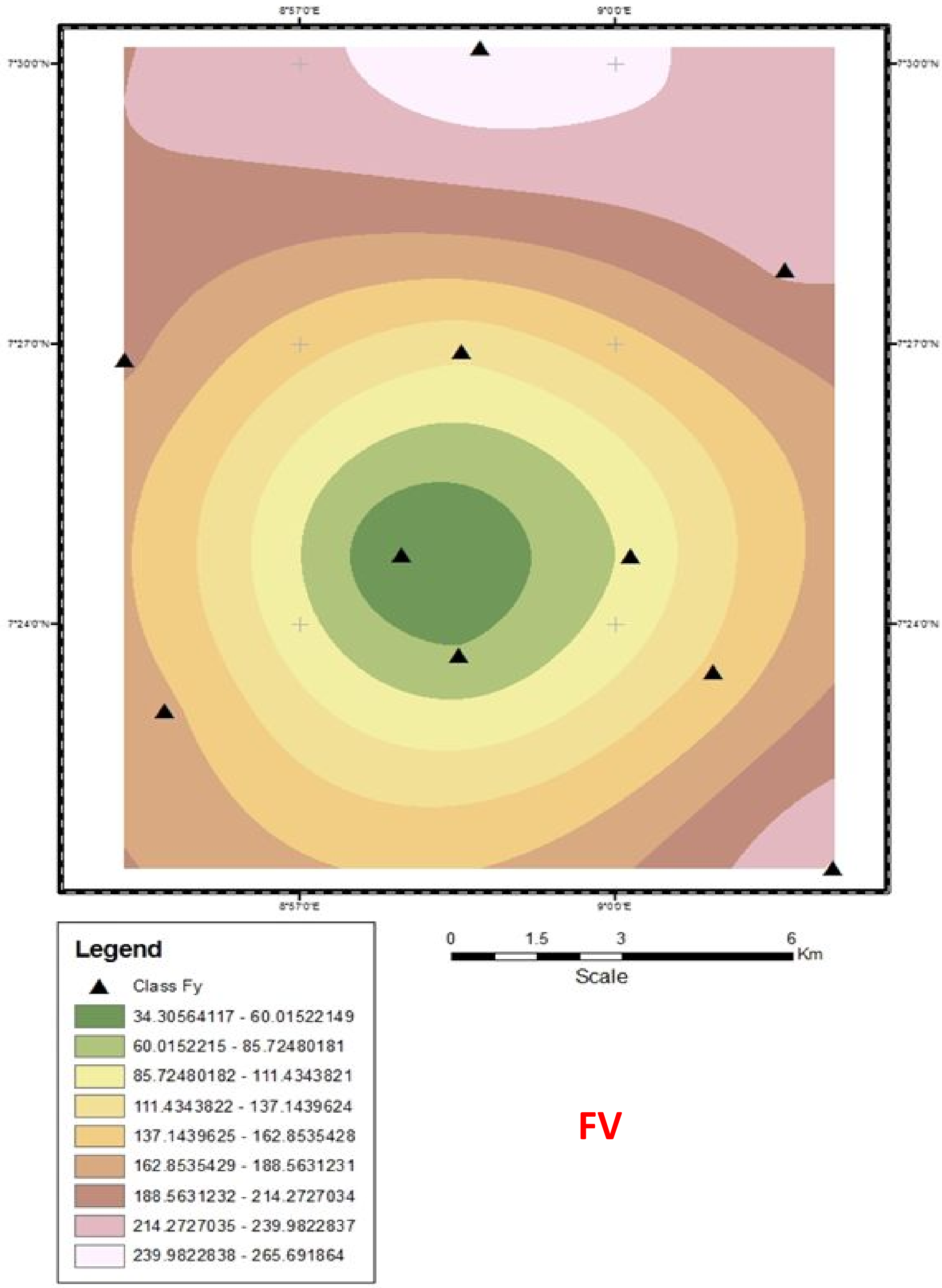

Legend
Class Dz
31.23032188 - 41.98250834
41.98250835 - 52.7346948
52.73469481 - 63.48688126
63.48688127 - 74.23906771
74.23906772 - 84.99125417
84.99125418 - 95.74344063
95.74344064 - 106.4956271
106.4956272 - 117.2478135
117.2478136 - 128
0 1.5 3 6 Km
Scale

DH


8°57'0"E
9°0'0"E
7°30'0"N
7°27'0"N
7°24'0"N
Legend
Class Ey
50.4891243 - 85.83161079
85.8316108 - 121.1740973
121.1740974 - 156.5165838
156.5165839 - 191.8590702
191.8590703 - 227.2015567
227.2015568 - 262.5440432
262.5440433 - 297.8865297
297.8865298 - 333.2290162
333.2290163 - 368.5715027
0 1.5 3 6 Km
Scale

EV


8°57'0"E
9°0'0"E
7°30'0"N
7°27'0"N
7°24'0"N
Legend
Class Ez
22.1384964 - 28.33541361
28.33541362 - 34.53233083
34.53233084 - 40.72924805
40.72924806 - 46.92616526
46.92616527 - 53.12308248
53.12308249 - 59.31999969
59.3199997 - 65.51691691
65.51691692 - 71.71383413
71.71383414 - 77.91075134
0 1.5 3 6
Km
Scale
EH


8°57'0"E
9°0'0"E
7°30'0"N
7°27'0"N
7°24'0"N
Legend
Class Fy
34.30564117 - 60.01522149
60.0152215 - 85.72480181
85.72480182 - 111.4343821
111.4343822 - 137.1439624
137.1439625 - 162.8535428
162.8535429 - 188.5631231
188.5631232 - 214.2727034
214.2727035 - 239.9822837
239.9822838 - 265.691864
0 1.5 3 6 Km
Scale

FV

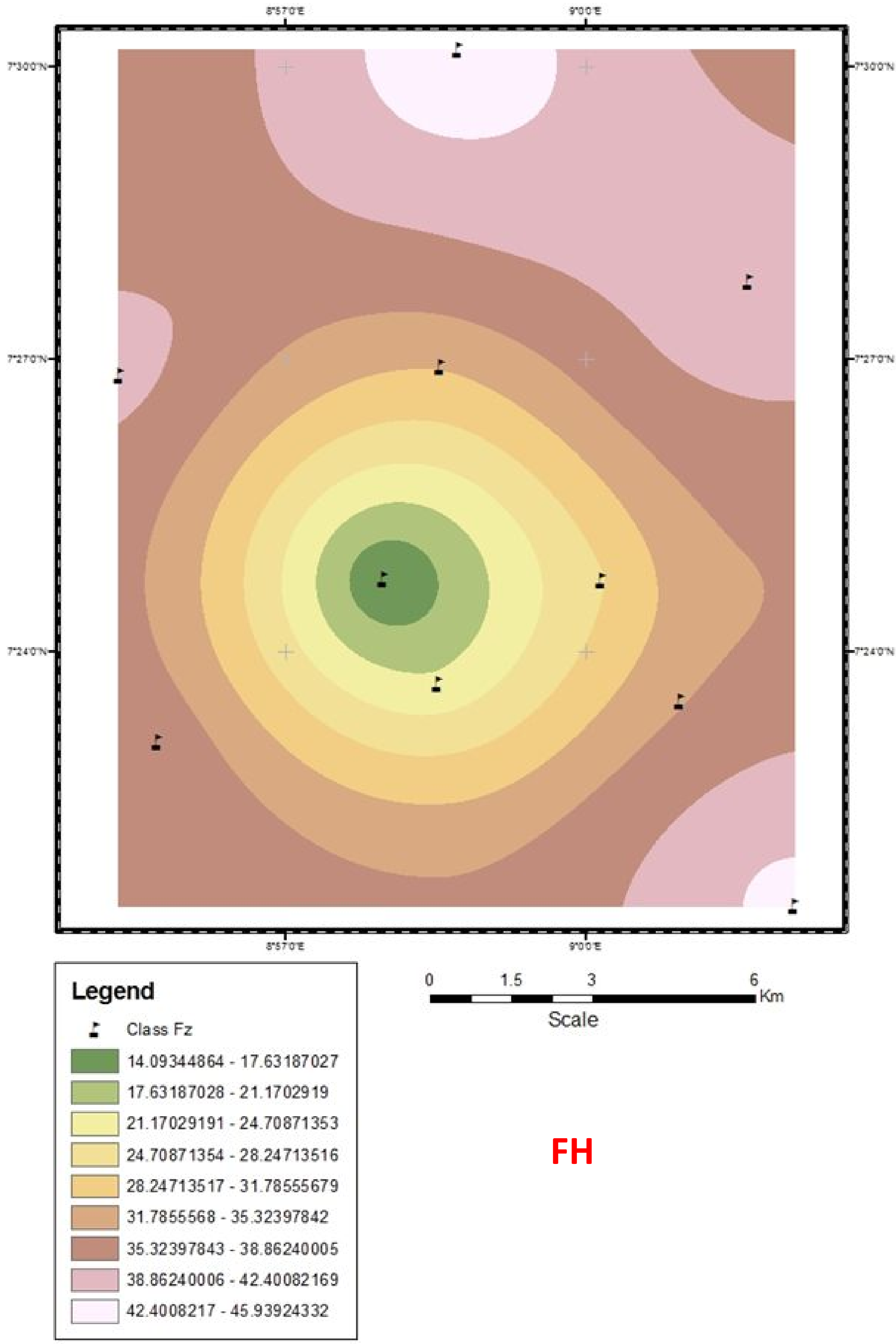


Figure 4. Variograms showing plume distribution in *x* and *y* orientations for all stability classes

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