

MODELLING OF GASEOUS POLLUTANT EMISSIONS FROM SAVANNAH VEGETATION FIRES

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ABSTRACT

The concentration and transport dynamics of emissions during savannah vegetation fires are not well-understood. This study aims at modelling the ground level concentrations (GLC) of gaseous pollutants on the receptor environment using the American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD). Three (3) scenarios were investigated based on the vegetation density of the savannah grasses. The model revealed that the 24-hour averaging period for CO, NO₂, SO₂ and volatile organic compounds (VOC) ranged from 50 – 5,046 µg/m³; 0.049 – 4.97 µg/m³; 0.6 – 55.9 µg/m³ and 63 – 6,253 µg/m³ for Scenario 1; 288 – 28,825 µg/m³; 0.08 – 8.31 µg/m³; 2 – 203 µg/m³ and 65 – 6,498 µg/m³ for Scenario 2; 394 and 39,435 µg/m³; 0.2 and 22.3 µg/m³; 4 – 419 µg/m³; and 118 – 11,782 µg/m³ for Scenario 3, respectively. The study revealed that the World Health Organization (WHO) guideline of 4 mg/m³ for the 24-hour concentration of CO was breached under Scenarios 2 and 3 by 150%. The findings of this study will help in the accurate estimation of emissions from the savannah fires and in the development of appropriate mitigation strategies for emission control.

Keywords: Ground level concentrations; gaseous pollutants; modelling; emissions.

1. INTRODUCTION

Vegetation fires have been identified as one of the sources of gaseous pollutants in the environment. Gaseous pollutants such as CO, SO₂, NO₂, and VOCs emitted during vegetation fires change the chemical composition of the atmosphere which has detrimental effects on the environment, human health, and climate. Savannah landscapes are noted to experience the highest frequency and intensity of fires globally (Sun *et al.*, 2019) with about 20% of nitrogen oxides (NO_x) and one-third of global CO emissions attributed to it (Andreae, 2019). Abdulraheem *et al.* (2022) reported that approximately 167 Tg of CO and 10 Tg of NO_x were emitted from savannah vegetation fires in the West Africa region between 1990 – 2019 while Akagi *et al.* (2011) disclosed that the vegetation fire is the second largest contributor of volatile organic carbons to the atmosphere.

High concentrations of gaseous pollutants in the atmosphere have adverse effects on the environment and human health when above the thresholds established by air quality regulatory bodies. The short-term Air Quality Guideline levels recently released by the WHO 2021 have replaced the 2005 levels where tolerable pollutants levels were reviewed. To ascertain the concentrations of pollutants emitted during vegetation fires on the receptor

environment, dispersion models have been employed by researchers. One of such models is the American

Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) as recommended by the United States Environmental Protection Agency (USEPA) (de Ferreyro Monticelli *et al.*, 2020). AERMOD is a near-field steady-state Gaussian Plume model that is based on planetary boundary layer (PBL) structure and scaling concepts over simple and complex terrains (Holmes and Morawska, 2006; ul Haq *et al.*, 2019). AERMOD calculates meteorological profiles with the use of measurements and similarity parameterizations to estimate adjacent vertical measurements (Cimorelli *et al.*, 2005). The model is relevant to a variety of pollutant sources in a wide range of settings such as rural, urban, flat, and complex terrain (Jampana *et al.*, 2004). The model has been used to analyze pollutant emissions in the environmental impact assessment study (Seangkiatiyuth *et al.*, 2011).

Researchers have used AERMOD models in the past for the determination of GLC of pollutants. In the study of Adeniran *et al.* (2018), air quality at the Ibese Cement factory in Ogun state Nigeria was assessed using the AERMOD model under four scenarios. The results revealed that particulates and gaseous pollutants from

simultaneous operations of all point sources of air emissions are within stipulated limits in the neighboring communities except for the 24-h concentration values of NO_x and SO₂ which breached their limits in a few locations. Afzali *et al.* (2017) predicted air pollutant concentrations from multiple sources with the use of AERMOD coupled with Weather Research Forecasting. Their findings indicated good agreement between predicted and observed concentrations. Rangel *et al.* (2018) estimated the concentrations of air pollutants emitted from the burning of sugarcane biomass using AERMOD software in Brazil. The study revealed that the highest dispersion was observed in February while April was observed to have the highest concentrations of pollutants.

Annual burning of vegetation is a prevalent practice in the savannah region of the country. The concentrations and transport dynamics of the pollutants emitted during this process are fairly understood and might exceed the acceptable levels stipulated by the regulatory guidelines. Therefore, this study aims at determining the GLC of pollutants emitted during savannah vegetation fires and their impacts on the receptor environment.

2. METHODOLOGY

The AERMOD model is a steady-state Gaussian dispersion model developed for air quality regulations. The gaseous pollutants emitted during the burning of savannah grasses were simulated using the AERMOD model over a flat/undulated terrain and under known meteorological conditions in three different scenarios. The impacts on receptor locations were observed under each scenario. The AERMOD model flowchart process is presented in Figure 1.

The licensed version of Lakes Environmental AERMOD View (version 8.9) was used for simulation in this study. The input data includes the source data, geological data i.e., the map of source location, and the meteorological data that are defined under various pathways.

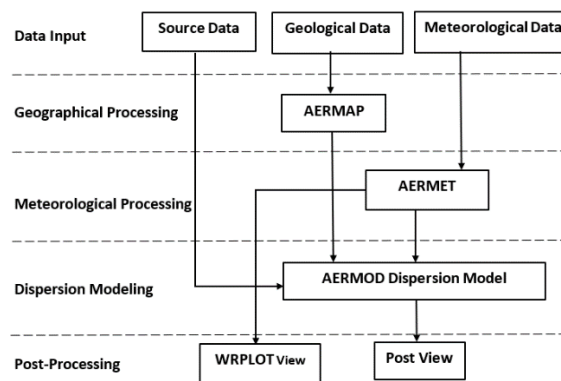


Figure 1: Process Flowchart for AERMOD model

Adapted from: Seangkiatiyuth *et al.* (2011)

The source location selected for modelling was selected based on the Moderate Imaging Spectroradiometer (MODIS) satellite observations detected by the Aqua satellite which shows the active fire hotspots. For this study, the savannah region that is susceptible to annual vegetation fires in Nigeria was used for the modelling. The area source was selected in the Mariga Local Government Area of Niger State, at a geographical location of 10.508°N and 5.853°E. Figure 2 shows the active fire hotspots detected in Niger State in the first week of January 2021 and the selected source location used for the AERMOD model.

The model input includes the air emission rate, release height, area of dimension, orientation angle, and base elevation. The air emission rate is given as:

$$AE = (EF \times FC) / t \quad (1)$$

where AE = Area emission rate ($\text{g}/\text{m}^2 \text{ s}$); EF = Emission Factor (g/kg); FC = Fuel consumption (kg/m^2) and t = average burning time (sec).

For the determination of GLC of pollutants from burning of savannah grasses using the AERMOD model, three (3) scenarios of air emission from savannah burnings were considered in this study which was based on the emission rate and grass density, they are: Low Emission - Scenario 1; Moderate Emission - Scenario 2; and High Emission - Scenario 3.

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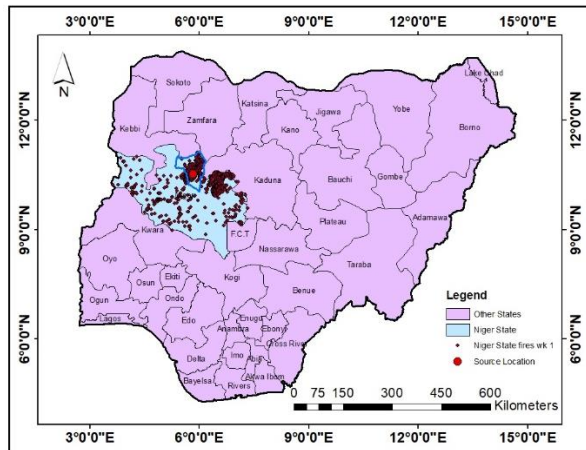


Figure 2: Map of Nigeria showing the source location used for the AERMOD model

3. RESULTS

The AERMOD air quality dispersion model was performed to predict the GLC of CO, NO₂, SO₂, and VOC around the selected burned area in Niger State, Nigeria. The GLCs CO, NO₂, SO₂, and VOC were considered for the 1-hour, 8-hour, and 24-hour averaging period using the Industrial Source Complex (ISC)-AERMOD view. The minimum and maximum GLC of the pollutants from burned vegetation were computed and compared with the NAAQS - FME_{env} and NESREA; WHO Air Quality Guidelines; and the NAAQS - USEPA to determine their level of compliance.

Scenario 1: The minimum 1-hour averaging concentration for CO, NO₂, SO₂, and VOC are 908, 0.8, 11 and 986 µg/m³, respectively while the maximum of 90835, 84.9, 1110, and 98637 µg/m³ were observed, respectively. The minimum 8-hour averaging concentration for CO, NO₂, SO₂, and VOC are 140, 0.1, 2, and 201 µg/m³, respectively while the maximum of 14011, 11.8, 185, and 20135 µg/m³ are observed respectively. The minimum 24-hour averaging concentration for CO, NO₂, SO₂, and VOC are 50, 0.049, 0.6, and 63 µg/m³ while the maximum of 5046, 4.97, 55.9, and 6,253 µg/m³ are observed respectively. The isopleth of the 24-hour averaging of the predicted concentrations of CO in Scenario 1 is shown in Figure 3. Scenario 2: For CO, the 1-hour averaging concentration ranges from 3,761 – 376,061 µg/m³; the

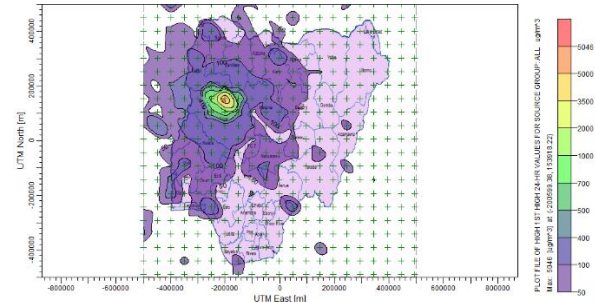


Figure 3: CO concentration profile for 24-hr averaging for Scenario 1

8-hour averaging concentration ranges from 1,242 – 124,160 µg/m³ while the 24-hour averaging concentration ranges from 288 – 28,825 µg/m³. For NO₂, the 1-hour averaging concentration ranges from 2 – 151 µg/m³; the 8-hour averaging concentration ranges from 0.3 – 25.2 µg/m³ while the 24-hour averaging concentration ranges from 0.08 – 8.31 µg/m³. For SO₂, the 1-hour averaging concentration ranges from 41 – 4,103 µg/m³; the 8-hour averaging concentration ranges from 6 – 586 µg/m³ while the 24-hour averaging concentration ranges from 2 – 203 µg/m³. For VOC, the 1-hour averaging concentration ranges from 1,495 – 149,473 µg/m³; the 8-hour averaging concentration ranges from 188 – 18,759 µg/m³ while the 24-hour averaging concentration ranges from 65 – 6,498 µg/m³. Figure 4 shows the isopleth of the 24-hour averaging of the predicted concentrations of CO in Scenario 2.

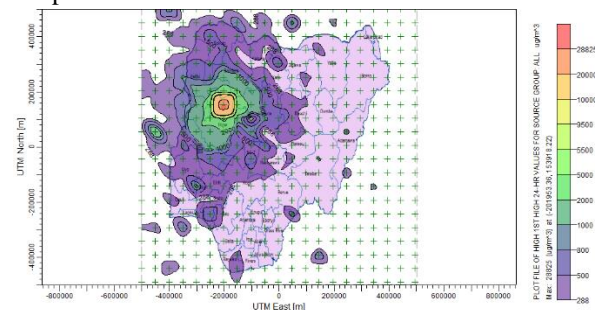


Figure 4: CO concentration profile for 24-hr averaging for Scenario 2

Scenario 3: The 1-hour, 8-hour and 24-hour averaging concentrations of CO was observed to be between 6,271 and 627,140 µg/m³; 1,045 and 104,523 µg/m³; 394 and 39,435 µg/m³, respectively. For NO₂, the 1-hour, 8-hour, and 24-hour averaging concentrations observed are between 4 and 433 µg/m³; 0.7 and 67 µg/m³; 0.2 and 22.3 µg/m³, respectively. For SO₂, the concentrations were in the range of 90 – 8,961 µg/m³; 15 – 1,493 µg/m³; and 4 – 419 µg/m³ for 1-hour, 8-hour and 24-hour averaging, respectively. Lastly, the 1-hour, 8-hour and 24-hour averaging concentration for VOC are observed to be between 2,606 and 260,555 µg/m³; 412 and 41,237 µg/m³; 118 and 11,782 µg/m³, respectively. The isopleth

of the 24-hour averaging of the predicted concentrations of CO is shown in Figure 5.

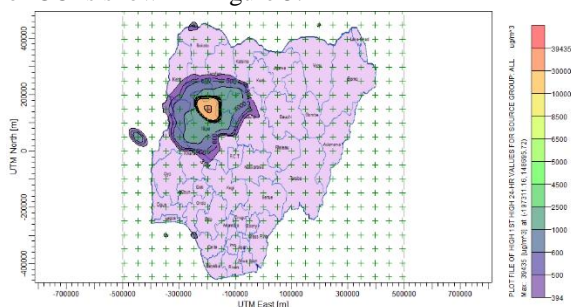


Figure 5: CO concentration profile for 24-hr averaging for Scenario 3

Table 1: The Nigerian States and their average distance from the source location

State	The average distance from the source (km)	State	The average distance from the source (km)
Kwara	197.33	Kano	272.6
Ekiti	307.62	Plateau	329.65
FCT	199.23	Kogi	261.24
Kebbi	61.93	Nasaraw	274.52

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State	The average distance from the source (km)	State	The average distance from the source (km)
Sokoto	146.76	Osun	318.43
Kaduna	41.47	Oyo	270.45
Jigawa	376.34	Ondo	334
Bauchi	326.95	Benue	408.05
Katsina	152.75	Gombe	525.8
Ogun	468.114	Yobe	568.89
Zamfar	47.75		

Table 1 presents the distances of the pollution source point to the receptor locations, i.e., the states in the country where the impacts of the burning activity were observed. Table 2 displays the minimum and maximum GLC of the selected pollutants under the three scenarios considered while the percentage increase in average concentration of CO above the statutory limits are presented in Table 3.

Table 2: Ground-level concentrations of pollutants from the AERMOD model

	Pollutant concentrations ($\mu\text{g}/\text{m}^3$)					
	Scenario 1		Scenario 2		Scenario 3	
	Min	Max	Min	Max	Min	Max
CO (1-hr)	908	90,835	3761	376,061	6,271	627,140
CO (8-hr)	140	14,011	1,045	104,523	1,242	124,160
CO (24-hr)	50	5,046	288	28,825	394	39,435
NO ₂ (1-hr)	0.8	84.9	2	151	4	433
NO ₂ (8-hr)	0.1	11.8	0.3	25.2	0.7	67
NO ₂ (24-hr)	0.049	4.97	0.08	8.31	0.2	22.3
SO ₂ (1-hr)	11	1,110	41	4,103	90	8,961
SO ₂ (8-hr)	2	185	6	586	15	1,493

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	Pollutant concentrations ($\mu\text{g}/\text{m}^3$)					
	Scenario 1		Scenario 2		Scenario 3	
	Min	Max	Min	Max	Min	Max
SO ₂ (24-hr)	0.6	55.9	2	203	4	419
VOC (1-hr)	986	98,637	1,495	149,473	2,606	260,555
VOC (8-hr)	188	18,759	201	20,135	412	41,237
VOC (24-hr)	63	6,253	65	6,498	118	11,782

Table 3: Percentage increase in average concentrations of CO above regulatory guidelines

States	WHO guideline 4 mg/m ³ (24-hr)		USEPA Standards 10 mg/m ³ (8-hr)	
	Scenario 2	Scenario 3	Scenario 2	Scenario 3
	Kebbi	150%	150%	387%
Kaduna	150%	150%	387%	191%
Zamfara	150%	138%	193%	191%

4. DISCUSSION

The distances from the source point to the receptor locations are shown in Table 1. It was observed that the dispersion of pollutants was in all directions of burned area for all the pollutants investigated. The pollutants disperse to several states in Nigeria and their concentrations depended on the distances between the source and the receptor states. The closest states to the source such as Kebbi, Zamfara, and Kaduna were observed to have the highest impacts.

In Table 2, the minimum and maximum GLC of the pollutants considered under the three scenarios are shown. The impacts of vegetation burning in the savannah on ambient air quality were investigated by comparing the hourly, 8-hourly, and daily maximum GLC of each of the investigated pollutants with the Nigerian NAAQS of the FMEnv and NESREA, WHO Air Quality Guidelines, and the NAAQS of the USEPA. For Scenario 1, the 1-hour, 8-hour and 24-hour maximum emission emitted for CO, NO₂, and SO₂ were within the

standards sets by the regulatory organizations. Statutory guidelines for VOCs are not available, hence GLC of VOCs was not compared.

For Scenario 2, the 1-hour, 8-hour and 24-hour maximum emissions emitted for NO₂ and SO₂ were within the standards sets by the regulatory organizations. The WHO guideline of 4 mg/m³ for the 24-hour concentration of CO was breached under this scenario by 150% in Kebbi, Kaduna, and Zamfara States whereas the USEPA standards of 9 ppm (approximately 10.3 mg/m³) for the 8-hour concentration of CO was breached by 387% in Kebbi and Kaduna states and by 193% in Zamfara State. The breakdown of the percentage increase in average concentrations of CO above the WHO and USEPA thresholds is presented in Table 3.

For Scenario 3, the 24-hour concentration of CO breached the WHO guideline of 4 mg/m³ and the 8-hour concentration of USEPA standard of 10.3 mg/m³ in the three closest states to the source location as presented in Table 3. This study observed high concentrations of CO in the 24-hour averaging concentrations in scenarios 2 and 3 which exceeded the WHO and USEPA statutory guidelines. The high concentrations of this pollutant may be attributable to the quantity of biomass burned and the season of burning i.e., dry season. The severity of biomass burning in a location is usually measured with the concentration of CO (Kganyago and Shikwambana, 2020) since CO emission is generally an indicator of biomass burning (Scholes *et al.*, 1996). CO and other non-methane volatile organic carbon are often released during the smoldering stage of a burning process whereas a significant fraction of well-oxidized species such as CO₂ or NO_x is released during the flaming stage (Manojkumar and Srimuruganandam, 2019).

The burning season in Nigeria coincides with the dry harmattan period associated with narrow planetary

boundary layer and poor mixing of air masses causing high concentrations of atmospheric gases including CO. Besides, low inversion and low wind speed usually experienced during the burning season reduce ventilation and dispersion of pollutants (Toro *et al.*, 2018) leading to their high concentrations. Increased concentrations of CO in the atmosphere may impact significantly on human health through the displacement of oxygen in the bloodstream and deprivation of the heart, brain, and other vital organs of oxygen which may lead to loss of consciousness and suffocation (Kampa and Castanas, 2008).

Smoke from wildfire plumes not only impacts the immediate environment but also has impacts on far locations at high concentrations. Alonso-Blanco *et al.* (2017) revealed that substantial concentrations of pollutants were observed in an area of Leon city in Spain, about 70km away from the source of fire due to intense subsidence inversion caused by a high-pressure system that prevented vertical dispersion. A similar observation was noted in this study, Kebbi State is approximately 62km away from the fire location and had a CO concentration of 1.5 folds of the WHO guideline for the 24-hr average concentration.

5. CONCLUSION

High concentrations of CO in the 24-hour averaging were detected from the AERMOD dispersion model in Scenarios 2 and 3. These values exceeded the WHO guideline of 4 mg/m³ for 24-hr and the USEPA standard of 10 mg/m³ for 8-hr which have negative implications on human health and the environment. The findings from this study have significantly advanced the understanding of savannah ecosystem and the characteristics of the pollutants emitted during biomass burning. The results would be useful in the estimation of emissions specific to the region and help in the development of appropriate mitigation strategies for the control.

Nomenclature

AERMOD	American Meteorological Society/Environmental Protection Agency Regulatory Model
CO	Carbon monoxide
FCT	Federal Capital Territory
FMEEnv	Federal Ministry of Environment
GLC	Ground level concentration
NAAQS	National Ambient Air Quality Standards
NESREA	National Environmental Standards and Regulations Enforcement Agency

NO	Nitric oxide
NOx	Nitrogen Oxide
USEPA	United State Environmental Protection Agency
VOC	Volatile organic compounds
WHO	World Health Organization

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