Development and Evaluation of a Dispersion Model to Predict Downwind Concentrations of Particulate Emissions from Land Application of Class B Biosolids in Unstable Conditions

Abhishek Bhat, Ashok Kumar and Kevin Czajkowski[1]
Department of Civil Engineering, The University of Toledo, Toledo,
[1]Department of Geography and Planning,
The University of Toledo, Toledo,
USA

1. Introduction

The term, biosolids, is generally used to refer to those waste products that have been stabilized by treatment of the sewage sludge for beneficial reuse through appropriate management (Davis, 2002). The agronomic and environmental benefits from the organic material and fertilizing elements contained in the biosolids are essential for maintaining soil fertility. This has been a major reason for the application of biosolids on the agricultural fields. These biosolids reused for land application on agricultural fields has potential benefits. Davis (2002) in his study described the following benefits:

1. The land application of biosolids is mainly used to improve the soil quality. The organic matter from the soil can be built. Water retention, soil stabilization, and reduced soil erosion are some of the other benefits.
2. Applied biosolids can partially or completely substitute commercial fertilizer. These biosolids contain nutrients present in conventional fertilizer including nitrogen, phosphate, and other additive elements.
3. The application of biosolids or reuse of biosolids reduces the quantity of waste required to be disposed in landfills. This reduces the pollution due to landfills, leachates, etc.

The process of land application of biosolids on agricultural land has been carried out for generations. The agricultural activities related to the land application of biosolids aerosolize particulate matter. The United States Environmental Protection Agency (US EPA) regulates particulate matter as a "criteria pollutant". The particulate matter emitted during various agricultural activities impact air quality. The particulate matter generated from agricultural activities includes dust from the fields and dust generated from agricultural activities. The particulate matter emitted from the agricultural activities can contain bioaerosols, endotoxins, and pathogens. The airborne particles consisting of or originating from the microorganism are called bioaerosols. Bioaerosols containing pathogenic bacteria and harmful microorganisms accompanied with handling and the application process could harm the public health and environment. Modeling transport and dispersion of the

particulate matter emitted during the land application of biosolids is important to predict the downwind concentrations and in turn to predict the risk.
The objective of this chapter is to model the particulate matter released during and after the application of biosolids based on the data collected during the field study. The efforts include a derivation of solution to the convective-diffusion equation incorporating wind shear.

2. Literature review

Emissions of particulate matter during the application of these biosolids were studied by various researchers. Paez-Rubio et al. (2006) studied the composition of these particulate matters and determined the emission rates due to disking activity. The researchers used arrayed samplers to estimate the vertical source aerosol concentration, which were used to calculate the plume. The different constituents of the biosolids and their emission rates were reported in the study.
Brooks et al. (2005) derived an empirical equation to estimate the bioaerosols risk infection to residents adjacent to the land that is applied with biosolids. For this study, a coliphage MS-2 and Escherichia coli organisms were aerosolized after adding them to water within a biosolids spray application truck. Then the downwind concentration of these microorganisms was measured at various distances ranging from 2 m to 70 m. The data were taken downwind of the sprayer and were used to derive an empirical equation. The limitation of this study is that the authors used a simplistic regression model to determine the transport. US EPA's SCREEN 3 dispersion model was used to predict the downwind concentrations of particulate aerosols in the study by Taha et al. (2005). The emission rates in this study were determined by the wind tunnel experiments conducted on the surface of the static compost windrows. In a similar study, Dowd et al. (2000) predicted the downwind concentration of airborne viruses from a biosolids placement site. The study incorporated a modified Gaussian equation to quantify the downwind concentrations in an area undergoing the land application of biosolids. The model was used to predict the downwind concentration of microorganisms from an area source by taking into account the length and the width of the agricultural field.
A major difference between a conventional source of particulate matter and an agricultural source is that the later is a ground level source. Conventionally the wind velocity used in the downwind concentration calculated by researchers was used as an average velocity which was assumed to be constant over the vertical stretch of the plume. In real conditions, near the ground level, the magnitude of velocity changes with the change in vertical height. A vertical shear layer is formed and the velocity varies at a rapid rate near the ground. Thus the concentrations predicted can show large variations if the wind shear is not taken into account during dispersion. Kumar and Bhat (2008) discuss a possible generic model for transport and dispersion of particulate matters incorporating wind shear (magnitude shear only) near the ground. There is a need to understand and apply the knowledge of dispersion modeling to particulate fate and transport. It is important to develop a general screening model to predict downwind concentrations. The account for wind shear near the ground needs to be studied and incorporated in the existing models. The book entitled "Micrometeorology" by Sutton (1953) gives a solution using the variable eddy diffusivity and wind speed for steady state two-dimensional convective-diffusion equation representing the diffusion from an infinite line source. Kumar and Bhat (2008) extended the

analytical solution given by Sutton (1953) to predict the concentrations for ground level area sources. The new model has been evaluated using the data collected in 2009 and the regression equation given by Brooks et al. (2005) based on their field work.

3. Field sampling study

In the summer of 2009, a field study was conducted to collect particles emitted during the land application of biosolids. Particle emissions were collected for three days during the application (application), and for two days after the application (post-application) of biosolids. An agricultural field, scheduled for application of Class B biosolids in Northwest Ohio was selected for the sampling. The biosolids were applied on this field by injection method.
Particle samples were collected via the use of two GRIMM 1.108 aerosol samplers operating at airflow of 1.2 l/minute. The gravimetric data in 16 channels over the size range $0.23\ \mu m < d < 20\ \mu m$ was collected for a total of six hours every sampling day. The samplers were placed onto specially arranged tables raised to a height so that the intake nozzle was at average human breathing height of 1.5 m. Two sampling stations, one station inside the field and one outside were selected. The location of the outside sampling station at 10 m downwind from edge of the field was changed to 20 m downwind after first three hours of sampling keeping the location of the inside station same throughout the sampling. The monitors were reoriented in the direction of the wind, if needed. The weather data were collected using a portable weather station at both sampling locations inside and outside. The atmospheric parameters defining the atmospheric stability for each hour of sampling on each sampling day are presented in Table 1. The location of outside concentration monitoring station for each hour is also noted. The atmospheric stability for almost all sampling days was slightly unstable to moderately unstable. On one occasion it was slightly unstable to neutral.

Date	Time	Concentration Monitor Location from Edge	Wind Velocity (m/s)	Wind Condition	Cloud Cover (in tenth)	Daily Solar Radiation (W/m^2)	Atmospheric Stability using P-G Method*
Application August 21, 2009	09:25–10:25	@ 10 m	5.81	Very High	0	755	C
	10:25-11:25		8.56				C
	11:25-12:25		8.59				C
	12:25-13:25	@ 20 m	8.93				C
	13:25-14:25		8.85				C
	14:25-15:25		8.64				C
Application August 24, 2009	09:17–10:17	@ 10 m	0.27	Calm	4	373	B
	10:17-11:17		0.33				B
	11:17-12:17		0.25				B
	12:17-13:17	@ 20 m	0.68				B

	13:17-14:17		0.60				B
	14:17-15:17		0.41				B
Application August 26, 2009	08:00-09:00	@ 10 m	3.46	Low	8	288	C
	9:00-10:00		3.73				C
	10:00-11:00		2.94				C
	11:00-12:00	@ 20 m	2.27				C
	12:00-13:00		1.91				B
	13:00-14:00		2.39				C
Post-Application Sept. 24, 2009	08:40-09:40	@ 10 m	0.14	Calm	8	327	B
	09:40-10:40		0.14				B
	10:40-11:40		0.25				B
	11:40-12:40	@ 20 m	0.40				B
	12:40-13:40		0.32				B
	13:40-14:40		0.13				B
Post-Application Sept. 25, 2009	08:30-09:40	@ 10 m	4.07	High	5	541	C-D
	09:30-10:30		5.26				C-D
	10:30-11:30		5.87				C-D
	11:30-12:30	@ 20 m	5.45				C-D
	12:30-13:30		6.13				D
	13:30-14:30		5.78				C-D

*B: Moderately Unstable; C: Slightly Unstable; D: Neutral

Table 1. Atmospheric Conditions Observed on Each Sampling Day

The concentration data collected during the application and the post-application was processed using Microsoft Office 2010 Excel sheets. Hourly average concentrations for each day were calculated. Based on the average wind velocities (u) measured, sampling days were divided into three windy conditions; low wind condition (0.5 m/s < u < 3 m/s), high wind condition (3 m/s < u < 6 m/s), and very high wind condition (u > 6 m/s) (see Table 1). The data collected at the inside station represented the emissions generated during the agricultural activities. The vertical profiles of particle dispersion inside the agricultural field during and after sludge application analyzed by Akbar et al. (2011) were used to develop a set of emission rate equations. Hourly emission rates (Q) for each sampling day were calculated using these emission rate equations. The data collected at the outside sampling stations was used as the downwind concentration (C).

4. Model development

4.1 Shear layer model development

There are different equations available in literature for the dispersion of a ground level release of a pollutant. However, none of the reported equations tackles the problem of wind shear near the ground. This part focuses on deriving the analytical solution from the convection-diffusion equation using vertical velocity profile. The following assumptions are used in deriving the equation:

1. The wind direction is always perpendicular to the field.
2. The dispersion is of the non-fumigation type.

The velocity profile with height above the ground level is assumed to be the same for all downwind distances. The magnitude of the wind velocity near the ground level changes rapidly. Therefore, for the ground level discharge of the pollutant, it is very important that the variation of the wind velocity magnitude is incorporated in the dispersion and transport equation.

The model uses the equation for C(x,z) given by Sutton (1953):

$$C(x,z) = \frac{Q}{u_1 * \Gamma(S)} * \left[\frac{u_1}{(m-n+2)^2 * K_1 * x}\right] * \exp[-u_1 * \frac{z^{m-n+2}}{((m-n+2)^2 * K_1 * x)}] \tag{1}$$

where,

C(x,z): Downwind concentration (unit/m^3)

x: Downwind distance (m)

z: Vertical distance (m)

Q: Emission rate of pollutants (unit/sec)

u_1: Wind velocity reference height Z_1 by the power law $u(z) = u_1 * \left(\frac{z}{z_1}\right)^m$ (2)

K_1: Diffusivity constant reference height Z_1 given by $K(z) = K_1 * \left(\frac{z}{z_1}\right)^n$ (3)

n: Exponent of power law velocity profile

m: Exponent of eddy diffusivity profile where, m = 1 – n

s: Stability parameter based on m and n ($s = \frac{m+1}{m-n+2}$)

Γ(s): Gamma function of s

The Equation (1) is integrated from x-(X/2) to x+(X/2) for a strip source with width X, and infinite length having the origin of x ordinate at the center of the strip to obtain the concentration from the strip. The integration gives following formulae given by Kumar and Bhat (2008).

$$C(x,z) = Q * \frac{z^{a^{S-1}}}{A} * \left[\frac{A + x^{1-S} * B * \exp\left(\frac{B}{x}\right) + D}{S-1}\right]_{x-(\frac{X}{2})}^{x+(\frac{X}{2})} \tag{4}$$

where,

$$A = \gamma(s) \tag{5}$$

$$B = -u_1 * \frac{z^a}{a^2 * K_1} \tag{6}$$

$$D = \gamma\left(s, \left(-\frac{B}{x}\right)\right) \tag{7}$$

$$a = (m - n + 2) \tag{8}$$

The total concentration of the pollutant is given by following equation after considering i number of strips in the area source.

$$C(x,z) = \sum_1^i Q * \frac{z^{a^{S-1}}}{A} * \left[\frac{A + x^{1-S} * B * \exp\left(\frac{B}{x_i}\right) + D}{S-1}\right]_{x_i - \left(\frac{X}{2}\right)}^{x_i + \left(\frac{X}{2}\right)} \quad \text{for } z > 0 \quad \text{(9-a)}$$

$$C(x) = \sum_1^i \left[\frac{Q}{\Gamma(S) * (m+n-2)^2 * K_1} * \ln(x_i)\right]_{x_i - \frac{X}{2}}^{x_i + \frac{X}{2}} \quad \text{for } z = 0 \quad \text{(9-b)}$$

The value of x_i is calculated using

$$x_i = x_d + \frac{X}{2} \text{ (for i = 1)} \tag{10}$$

and

$$x_i = x_{i-1} + X \text{ (for i > 1)} \tag{11}$$

where, x_d is the downwind distance of monitoring station from the edge of the field.
The Equation (9-a) computes the concentration of the pollutant at chosen breathing level while the downwind concentration at the ground is computed using Equation (9-b). These Equations (9-a) and (9-b) were modeled into an Excel spreadsheet as the Shear Layer Model as part of Bioaerosols Dispersion and Risk Model spreadsheet (BDRM 1.01). The programming is done in a way so that the calculated concentrations are from the edge of the field for different downwind distances. The development of BDRM spreadsheet is discussed in Kumar and Bhat (2008).

5. Model evaluation

The evaluation of shear layer model involved two major steps: 1. the predicted concentrations from the shear layer model were compared to the measured concentration data from field study and 2. the model was evaluated using the limited data available in the literature. In each step, the predicted data were evaluated using the calculated statistical parameters.

5.1 Model evaluation using measured data

Multiple runs of the shear layer model were carried out to simulate characteristics of each sampling day. Since the shear layer model was not developed for the calm conditions, only sampling days with different windy conditions were modeled. The turbulence parameters used to simulate the atmospheric turbulence in the shear layer model are presented in Table 2. The values of n were based on urban and rural exponents used in the air quality models developed by the US EPA and K_1 was calculated using the equations compiled by Kumar (1977). The predicted concentrations and the measured concentrations were formatted into a Microsoft Excel spreadsheet to obtain average hourly concentrations. The predicted concentrations from the shear layer model were compared with the measured concentrations (Figure 1). Visible comparison were enabled by plotting the measured vs. predicted data on the same plot. It was found that the shear layer model over predicts the concentration for all windy conditions except for few data points.

Model Input	Neutral	Unstable	Stable
m	0.85	0.8	0.7
n	0.15	0.2	0.3
K_1 (m^2/sec)	8	28.43	0.993

Table 2. Input used for the Shear Layer Model

The statistical evaluation based on the work of Hanna et al. (1993), Gudivaka and Kumar (1990), Riswadkar and Kumar (1994) and Kumar et al. (2006), was used in this study. In order to determine the significance of the evaluation of the model, four statistical parameters; normalized mean square error (NMSE), fractional bias (FB), correlation coefficient (R), and geometric mean bias (MG) were calculated.

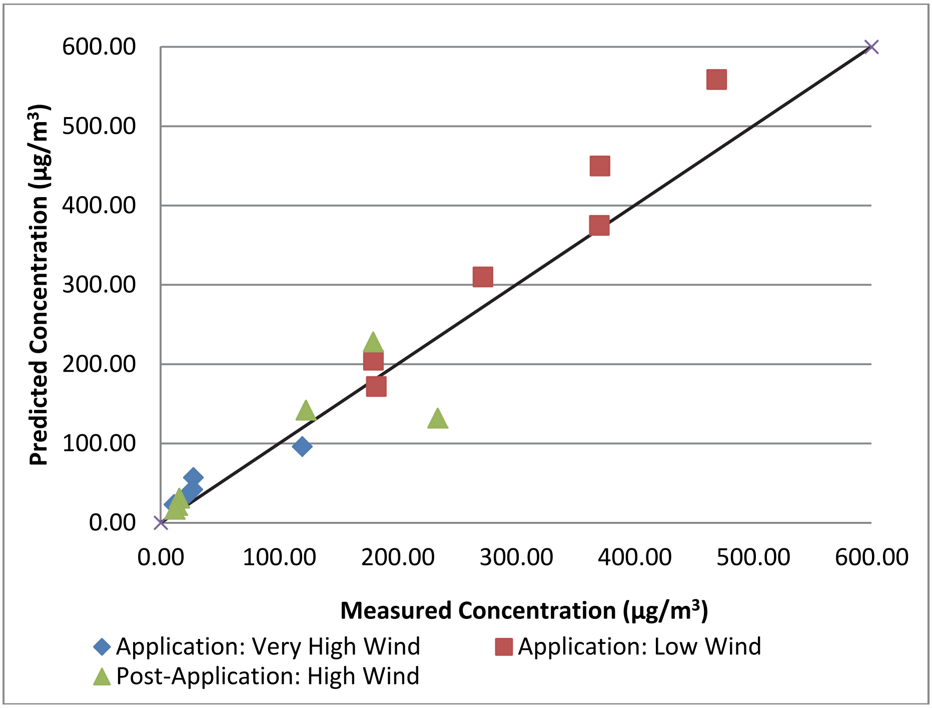

Fig. 1. Measured vs. Predicted Concentration

The normalized mean square error (NMSE) is given by the formula,

$$NMSE = \frac{(C_O - C_P)^2}{\overline{C_0} \times \overline{C_P}} \tag{12}$$

The fractional bias (FB) is given by the formula,

$$FB = 2 \times \left(\frac{\overline{C_0} - \overline{C_P}}{\overline{C_0} + C_P} \right) \tag{13}$$

The correlation coefficient (R) is given by the formula,

$$r = \frac{\overline{\left(C_0 - \overline{C_0}\right)\left(C_P - \overline{C_P}\right)}}{\sigma_{C_P} \sigma_{C_0}} \tag{14}$$

And the geometric mean (MG) bias is calculated by the formula,

$$MG = \exp\left(\overline{\ln C_0} - \overline{\ln C_P}\right) \tag{15}$$

where, C_o is observed values from regression equation and C_p is predicted. These parameters were used to further assess the predictability. The values of these statistical parameters are presented in Table 3.

Statistical Parameter	Complete Dataset	Application		Post-Application
		Low Wind	Very High Wind	High Wind
NMSE	0.17	0.31	0.017	0.21
Fractional Bias	0.23	0.41	0.09	0.21
R	0.94	0.96	0.89	0.71
MG	0.78	0.90	0.65	0.80

Table 3. Shear Layer Model Performance Using Predicted and Measured Concentrations

For a "perfect" ideal model the fractional bias and the normalized mean square error are equal to zero. The ideal values for a geometric mean bias and the correlation coefficient should be 1. As expected in the real life, the shear layer model is not a perfect model. However, the acceptable range for NMSE and FB for an air quality model suggested by Kumar et al. (1993) is given as, NMSE ≤ 0.5 and -0.5 ≤ FB ≤ 0.5. The values of NMSE and FB for shear layer model in all wind conditions were within acceptable limits.

The geometric mean bias is a function of a logarithmic mean of the predicted and observed data. Geometric mean bias values of 0.5-2.0 can be thought as "factor of two" over predictions and under predictions in the mean respectively (Hanna et al., 1993). Thus the geometric mean range for the acceptable model is given as 0.5 ≤ MG ≤ 2.0. When a data set contains pairs of data 10 or less, then the logarithmic forms are appropriate, so that the under predictions and the over predictions receive equal weight. The values of MG for each condition are better representation of the behavior of a model to assess whether a model is over predicting or under predicting in a particular situation. From Table 5 it was observed that the shear layer model over predicts the concentrations under almost all the conditions. This may be due to the factors such as the use of concentrations measured at 1.5 m as ground level concentrations, the concept of eddy diffusivity for atmospheric turbulence in the new model, and the assumptions made for other model inputs. It was also observed that during the low wind conditions the predictions were closer to reality (MG=0.90) than during other wind conditions.

5.2 Model evaluation using literature data

To evaluate the model based on the literature data, an evaluation case was developed based on Brooks et al. (2005) study. The paper gives a regression equation based on the data collected downwind of the application site. For this evaluation purpose a constant emission rate of 4.13 particles/ m^2/sec as given in the paper was used. Wind velocity was 2.29 m/s at 10 m height. Based on the atmospheric conditions described in the literature, the slightly stable to near neutral stability condition was assumed for the simulation. The input values for the stability parameters used for shear layer model were used from Table 2.
The predicted concentrations were plotted along with the concentrations obtained from the regression equation for various downwind distances (See Figure 2). The comparison of predicted concentration with the observed concentration from regression equation was plotted (See Figure 3). It was observed from the figures that shear layer model under predicts the concentration for shorter downwind distance (x < 15 m) closer to the field, but for the higher downwind distances (x > 20 m) the model over predicts the concentrations. As a result, the shear layer model, again, was observed to over predict the downwind concentrations.

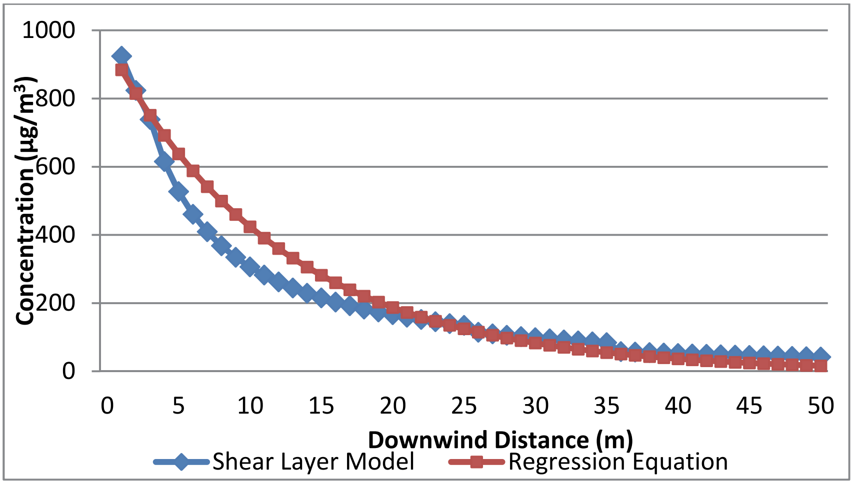

Fig. 2. Comparison of Concentrations predicted using the Shear Layer Model and Regression Equation by Brooks et al. (2005)

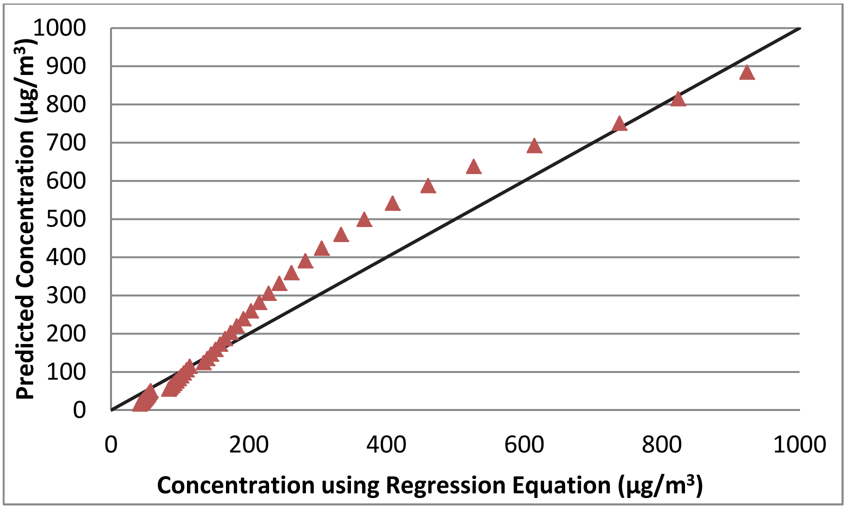

Fig. 3. Concentration using Regression Equation vs. Predicted Concentration from the Shear Layer Model

Again, performance measures were calculated from the modeled and the observed concentrations. The statistical parameter NMSE, FB, correlation coefficient, and geometric mean (MG) were calculated using the previously stated equations (See Table 4). It was determined from these performance measures that even though the shear layer model was not a perfect model, the parameters were within the acceptable range for a good fit model. The geometric mean bias indicates that the shear layer model over predicts the downwind concentrations for this data set.
As seen from the model evaluation figures and statistical evaluation, the model produced consistently good performance in simulating the downwind concentration from the application and the post-application. The model performance was also good in varying wind conditions. From the performance measures it was determined that the model over predicts the concentrations in most cases. This evaluation was performed using the limited measured and literature data available at the time of the research.

Statistical Parameter	Value
NMSE	0.14
Fractional Bias	-0.1
R	0.95
MG	0.89

Table 4. Statistical Parameter Calculated for Evaluation of the Shear Layer Model based on Regression Equation

6. Conclusion

The objective of this chapter was to develop and evaluate a dispersion model for particulate matter associated with biosolids application on a farm field. The following observations were made:

1. An analytical solution to convective-diffusion equation (the shear layer model) to incorporate wind shear near the ground was presented to predict the downwind concentration of total particulate matter. The shear layer model was evaluated using limited field study data. The model was observed to over predict the concentration for the low wind conditions during the application. For the high wind conditions during the post-application, the model was under predicting the concentration. The statistical parameters revealed that the shear layer model is a good fit to the measured data.
2. The concentrations predicted were compared to the observed regression concentrations from the literature. The results showed that shear layer model under predicts at the lower downwind distances whereas it over predicts at higher downwind distances. Again the statistical parameters revealed shear layer model to fit the literature data.

A generic screening model was derived, and can be used to predict the downwind concentrations of particulate matter emitted from the land application of biosolids. It was observed that the model over predicts the downwind concentrations in unstable conditions. Future work should focus on performing field studies to collect data under different atmospheric conditions.

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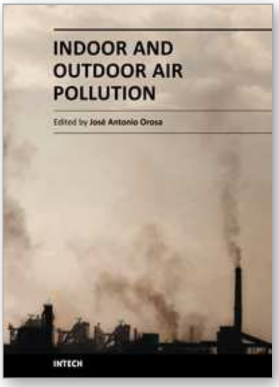

Indoor and Outdoor Air Pollution
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Air pollutants are continuously released from numerous sources into the atmosphere. Several studies have been carried out on the quantification of pollutants and their consequences on public health. Identification of the source characteristics of air pollution is an important step in the development of regional air quality control strategies. Air quality is a measure of the degree of ambient atmospheric pollution. Deterioration and damage to both public health and environment due to poor air quality have been recognized at a legislative and international level. In consequence, indoor and outdoor air quality must also be considered. This book tries to reveal different points of view of the wide concept of air quality in two different sections. In this context, there will be an initial introductory chapter on the main concepts of air quality, following which there will be real case studies on outdoor and indoor air quality with an aim to provide a guideline for future standards and research works.