GIS-Based Modeling of Odor Dispersion from Biosolids Reuse Sites

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ABSTRACT

Wastewater biosolids applied to agricultural fields for the recycling of the nutrients can generate nuisance odors that affect the surrounding community. Communities neighboring these application sites have enacted legislation to ban the recycling of biosolids due to odors. This study is to develop a GIS-Based odor model to measure the impact of biosolids odorants in reuse fields by modeling odor dispersion from the District of Columbia Water and Sewer Authority (DCWASA) biosolids land application sites. The results show the prediction maps expressed as predicted odorant area so-called sensation area defined as the area that people could potentially detect the odor. The sensation area usually occurs during low wind speed and adverse meteorological condition especially in early morning and night. The sensation area, moreover, is also sensitive to topographic features particularly elevated terrain. This study will help biosolids manager making better decision when distributing biosolids.

1. Introduction

Wastewater biosolids are the by product from wastewater treatment process that contain nutrient-rich organic matter used in recycling and beneficial agricultural fertilization purposes. It is one of the best sources of soil conditioner and source of slow-release nutrients and microelements (Oleszkiewicz and Mavinic, 2002). Several methods of distribution, utilization, or disposal for biosolids are available including landfilling, incineration, and land application. Some methods recycle the nutrients; several do not. Land application in the United States (US) is the most widely practiced recycling method: 63% in 1998, and 70% expected in 2010 (Oleszkiewicz and Mavinic, 2002).

Nevertheless, the associated malodorous nature of land applied biosolids could upset neighboring communities even though biosolids are processed to meet the EPA Title 40 of the Code of Federal Regulations [CFR], Part 503 – the standards for the use or disposal of sewage sludge. Odor produced onsite arises from the characteristics of wastewater itself and treatment processes. Off site nuisance odors not only depends on the quality of biosolids but also site location and atmospheric conditions. Consequently, the odor problems would potentially lead to complaints and might cause public resistance to a worthwhile biosolids recycling program.

This study is to develop a GIS-Based Odor Dispersion Model to measure the effect of biosolids odor emissions in areas surrounding DCWASA's reuse sites. The United States Environmental Protection Agency (U.S. EPA)'s steady-state atmospheric dispersion model, AERMOD, and Geographic Information System (GIS) were employed to generate predicted concentration displayed as concentration prediction maps. DCWASA reuse sites data used in the study were obtained from the Maryland Environmental Service (MES).

2. Background

District of Columbia Water and Sewer Authority (DCWASA) operates Blue Plains Advanced Wastewater Treatment Plant (AWTP) that serves more than two million Washington metro area customers in the District of Columbia, portions of Montgomery and Prince George's Counties in Maryland, and portions of Fairfax and Loudoun Counties in Virginia. As the largest facility of its kind, the plant has the capacity to treat 370 million gallons per day (MGD) of wastewater. The biosolids generation process begins with removing debris and grit from the sewage and trucked to a landfill. The resulting wastewater goes to the primary sedimentation tanks where the suspended solids are separated from the liquid. The solids from the primary process then go to the tanks where the sludge solids settle to the bottom by gravity. The settled solids from the secondary process and nitrification reactors are thickened separately. The thickened solids are dewatered. Lime is added to reduce pathogens and diminish odors before applying the final biosolids product to the farm application sites in Maryland and Virginia.

More than 1,200 tons of biosolids per day produced from the plant and distributed to agricultural areas can, under certain circumstances, create odor nuisance conditions and lead to complaints. DCWASA's contractors and field inspectors periodically receive odor complaints from neighborhoods surrounding field application areas. In addition, there are some claims that biosolids odors can lead to symptoms such as headaches, nausea, eye irritation, etc. The evidence of odor nuisance can be seen from a survey near a wastewater treatment plant in 1983; one in nine respondents reported that odor had affected their quality of life (Bruvold et al, 1983). However, it is unclear when the odorant becomes a health effect for the community at large, because each individual in the community has a different point at which odor is detected. In recent years, a dramatic increase in local ordinances that attempt to ban or restrict the use of biosolids has been observed as a result of odor complaints. Therefore, the measurement of odor from wastewater treatment facilities is usually a requirement for compliance monitoring, planning, site expansion, and review of operational practices (McGinley et al, 2002).

The measurement of odor impacts usually begins with assessment of odor parameters. The U.S. EPA recommends five independent factors that are required for the complete assessment: intensity or pervasiveness, character, hedonics, detectability or quality, and mass. Charles and Michael McGinley, from St.Croix Sensory Inc., present the odor parameters including odor concentration (thresholds), odor intensity (intensity referencing), odor character (standard descriptors), odor persistency (the hang time of the odor), and odor hedonic tone (subjective measure of pleasantness/ unpleasantness). The odor parameters are used to estimate the effect of odor, which usually requires field and laboratory odor testing. The laboratory odor testing requires samples that are collected and shipped overnight to an odor-testing laboratory. A field olfactometer is an instrument used to measure the effect of odor downwind of an odor source and at the property line. The olfactometry creates a series of dilutions by mixing the odorous ambient air with odor-free air. The dilution factor is defined as Dilution to Threshold, D/T that is a measure of the number of dilutions needed to make the odorous ambient air non-detectable (McGinley et al, 2005). However, a major disadvantage of olfactometry is the infeasibility of continuous or semi-continuous olfactometric measurement (Harreveld, 2004). It can only be used to measure the impact of biosolids at the certain point of time, specific location, and exact weather location. On the other hand, another method that might be considered for use in measuring odor impacts is atmospheric dispersion models. Dispersion models are widely used in the literature to measure odor impact in livestock or swine operations, but have not been widely applied to biosolids odors. The application of a dispersion model implies a need for models that take into account local flow conditions, caused by buildings, valleys and hills, and that would model fluctuations in a time-frame of seconds (Harreveld, 2004).

3. Methodology

3.1 AERMOD

This study utilized the new air quality model developed by the U.S. EPA in conjunction with American Meteorological Society (AMS) the **A**MS/**E**PA **R**egulatory **MOD**el (AERMOD). AERMOD is a steady-state plume dispersion model for assessing pollutant concentrations from a variety of sources based on the assumption of a planetary boundary layer (PBL). Typically, AERMOD is a modeling system that contains: 1) an air dispersion model, 2) a meteorological data preprocessor called AERMET, and 3) a terrain data preprocessor called AERMAP.

AERMOD requires two input files. The runstream setup file contains five control pathways representing the selected modeling options, as well as source location, receptor locations, meteorological data file, and output options. The other type of basic input data needed to run the model is meteorological data. AERMOD requires two types of meteorological data files that are provided by the AERMET meteorological preprocessor program. One file consists of surface scalar parameters, and the other file consists of vertical profiles of meteorological data.

The model simulates odor concentration values expressed as odor units per volume. One hour averaging period of concentration was selected to represent a situation when people sense the odor that is usually in a short period of time. The source location or source coordinate is input as a user-defined origin that is in horizontal (X) and vertical (Y) values. The elevation of the emitted source is taken into account and is determined by the use of the Geographic Information System (GIS) data. The area source that is typically used to model low level or ground level releases was selected responding for biosolids being applied. In addition, the other data needed to represent source characteristics involve the source emission rate, release height above ground, and the size of the area.

The Cartesian grid was selected to be the receptor network when running the model because it is more uniform than the polar grid. Unless defining type of receptor grid network in the receptor pathway, terrain elevation and hill height for each receptor can also be included to the model when applying AERMOD in complex terrain situation.

The meteorology pathway requires a minimum of two meteorological data sources: surface observation data and twice daily upper air data. Those data were generated using a meteorological preprocessor called AERMOD METEOROLOGICAL PREPROCESSOR (AERMET), which is a preprocessor for organizing available meteorological data into a format suitable for use by the AERMOD dispersion model. The minimum two types of data, National Weather Service (NWS) Integrated Surface Hourly Data (ISH), DS-3505, and NWS twice-daily upper air soundings, TD-6201, are needed as inputs for AERMET. Surface data are meteorological data that are measured at the earth's surface and include physical parameters that are measured directly by instrumentation, such as temperature, dew point, wind direction, wind speed, cloud cover, ceiling height, etc. Upper air data are meteorological data that are measured in the vertical layers of the atmosphere. Two files are written for AERMOD: a file of hourly boundary layer scaling parameter estimate which contains surface friction velocity and mixing height, and a file of multiple-level observations (profiles) of wind speed and direction, temperature, and standard deviation of the fluctuating components of the wind. These data were obtained from the National Climatic Data Center (NCDC) in Asheville, North Carolina.

The odor emission that is the physical process occurs in the atmosphere downwind of the odor source. The receptor sniffs the diluted odor. The dilution ratio is the number of dilutions needed to make the actual odor emission "non-detectable" (Detection Threshold). If the receptor detects the odor, then the odor in the atmosphere is above the detection threshold level. The detection threshold normally is determined using the "best estimate criteria" which is equal to odor concentration value of 1 gram per cubic meter calculated by the odor dispersion model (McGinley et al, 2002). A value less than 1 represents no odor or sub-threshold. In contrast, a value of greater than 1 represents odor at supra-threshold level. The result from odor dispersion model, which is, by default, micrograms per cubic meters needs to be converted to grams per cubic meters or odor units (O.U.) per cubic meters taking place of grams per cubic meters (McGinley et al, 2002). The result generated from AERMOD shows the average concentration values with relative date of concentration for selected receptor network, Cartesian grid (CAR), and selected average concentration time. In addition, if the model accounts for complex terrain situation, the result would show relative elevation values for each grid location.

3.2 Geographic Information System

The Geographic Information System especially ArcGIS 9.2 and ArcGIS Extension are used as main tools in the study. More specifically, ArcMap was used to create a map in study areas and to determine receptor elevations and used for spatial analysis. Due to the impossibility of obtaining concentration values at any location, Geostatistical Analyst is used to statistically analyze the values of concentration data and to create a prediction map of biosolids odor concentration.

By implementing the Geostatistical Analyst, the input data obtained from the result of dispersion model first need to be investigated by using Exploratory Spatial Data Analysis (ESDA) tool. To investigate the data statistically, there are three data features that need to be verified: distribution, dependency, and stationarity. Exploring tools such as histogram and normal QQ plots were used to investigate the data. Another data feature that is important when performing geostatistical data analysis is spatial dependency. Since the goal of geostatistical analysis is to predict values where no data have been collected, the tools and models of Geostatistical Analyst will only work on spatially dependent data. To check the dependency of data, several tools are available in the Geostatistical Analyst’s ESDA and Geostatistical Wizard. Moreover, the

Semivariogram/Covariance modeling in Geostatistical Wizard has more potential to allow us taking a look at more details of spatial dependency. The other important feature, stationarity, also needs to be investigated when analyzing statistical data. Stationarity means that statistical properties do not depend on location. Therefore, the mean (expected value) of a variable at one location is equal to the mean at any other location.

After exploring the data, the interpolation technique could then be employed to generate a continuous surface, or in this case a concentration plot. Typically, there are two groups of interpolation techniques: deterministic and geostatistical interpolation or "kriging" models. Kriging methods depend on mathematical and statistical models. The statistical model that includes probability separates kriging methods from the deterministic methods. Deterministic models are based on either the distance between points (e.g., Inverse Distance Weighted) or the degree of smoothing (e.g., Radial Basis Functions and Local Polynomials). Geostatistical models or kriging are based on the statistical properties of the observations and provide some measure of the certainty or accuracy of the predictions while deterministic models do not. It also tells us how good the predictions are. Theoretically, if the input data can statistically be defined as Gaussian or close to Gaussian, it makes more sense to use the geostatistical models. To generate a continuous surface of biosolids concentration, the available interpolation techniques would be carefully chosen depending on the statistical properties of the data.

4. Example Result

The example results show the odor prediction maps of the DCWASA biosolids field application site in Orange County, Virginia at the Edward Cook 1 farm. The field is located at 38.245N, 78.018W. The biosolids were applied on 10/23/2006 over an area of 8.47 acres. The emission rate per area was obtained by MES by using a flux chamber method. The dimension of receptor grid network is 2 by 2 kilometers (1 km from source) with grid spacing 200 meters. Initially, the model did not take into account of complex terrain at the site.

Using the tools and the methodology described in section 3, the odor concentration, relative date, and time of concentration for hourly averaging time were generated from the odor dispersion model (AERMOD). The concentration prediction map in Figure 2 shows the concentration filled contours with relative concentration values over topographic features of the field site such as a river, roadway, and household by census block. Concentration prediction maps were focused on the contour plots that have concentration values above the detection threshold (DT) responding to the potential of biosolids effecting to surrounding community called sensation area. The concentration values were divided into five different categories based on the odor testing in laboratory. The category 1-4 D/T represents the detection threshold. The category 4-7 D/T represents the recognition threshold, and more than 7 D/T mean the possibility of nuisance condition.

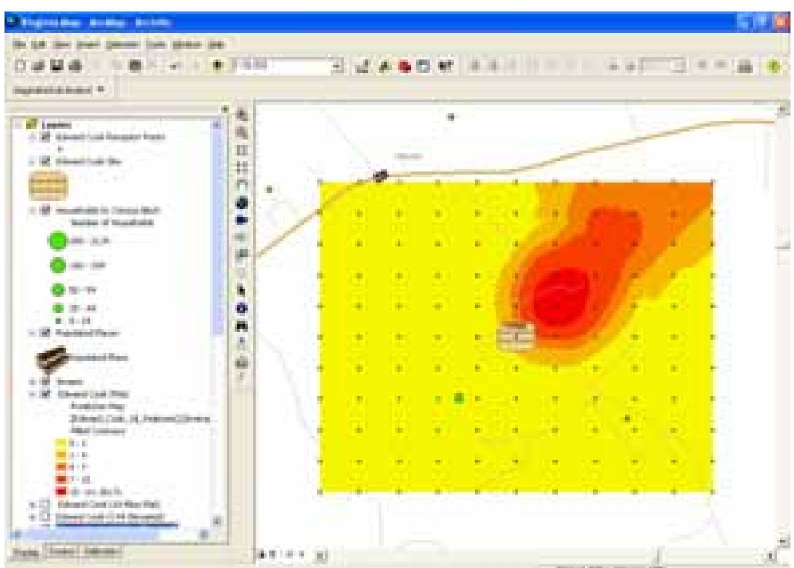

Figure 2 - Averaging One Hour Concentration Prediction Map

Because nose can detect odors very quickly, odor problems, thus, usually occur in shorter period of time. Therefore, we need to convert hourly concentration to averaging 10-Minutes concentration by using a power law. Theoretically, the concentration values of the same location over different period of times follow a power law (Karl etc, 2000). A power law as a result is suggested as possible conversion for use with single sources and averaging times of 24 hrs or less (Karl etc, 2000). Figure 3 shows the 10-Minutes concentration prediction map.

$$C_s = C_k \left[\frac{t_k}{t_s} \right]^p$$

where C_s = concentration for time t_s C_k = concentration for time t_k

t_s = longer averaging time t_k = shorter averaging time

P = power (values of p have ranged from 0.17 to 0.75; the suggested value is 0.17)

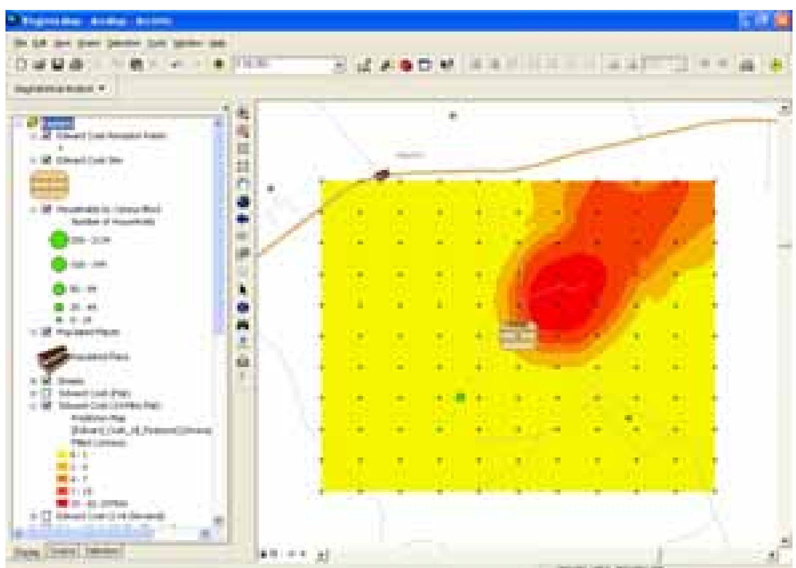

Figure 3 - Averaging 10-Minutes Concentration Prediction Map

The results shown above are based on the assumption of flat terrain situation. In fact, the terrain of a field area is not entirely flat but mostly elevated. Thus, accounting for complex terrain in the odor dispersion model would make the model more realistic. In addition, it would be useful in decision-making process when planning for distribution of biosolids to minimize an adverse affect of biosolids.

In order to account for the complex terrain situation, AERMOD allows users to manually input the terrain data through the receptor pathway (RE). The elevation and hillshade values were obtained by performing spatial analysis in the GIS and were input to the dispersion model. Using the same runstream file but adding the elevation, the results in complex terrain situation were generated and are shown in Figure 4 and 5 with the results of flat terrain situation also shown in order to compare the difference.

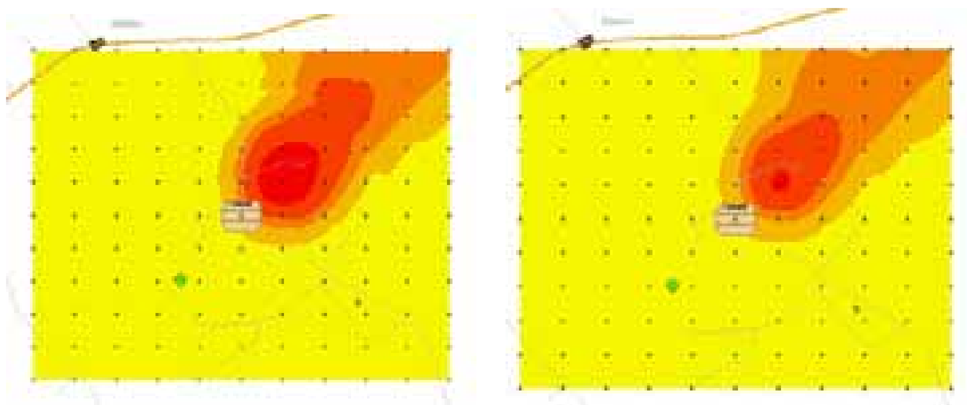

Figure 4 - 1-Hr Concentration of Flat (left) & Complex Terrain (right)

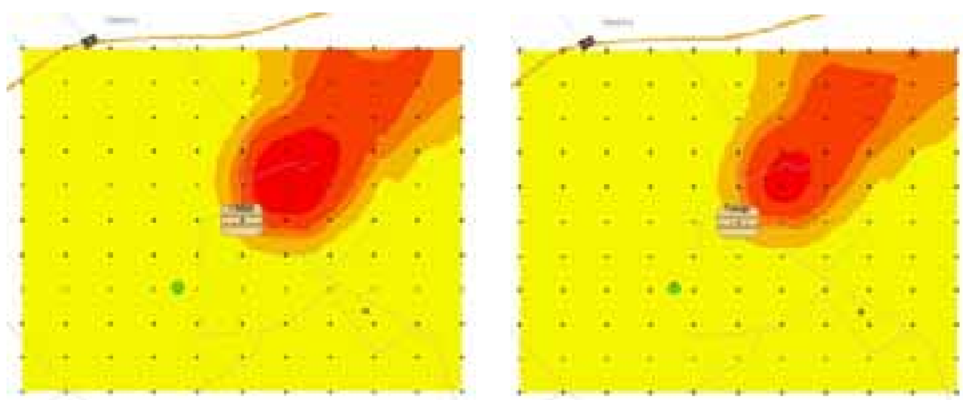

Figure 5 - 10-Minutes Concentration of Flat (left) & Complex Terrain (right)

By considering the prediction maps of flat and complex terrain situation, we can see that the dispersion directions of the complex terrain situations are almost exactly the same as with flat terrain, but slightly different sensation area, predicted odor dispersion that above the detection threshold (DT) especially in more concentrated area, concentration above 7 D/T. The interpretation of the results obviously might be that in the complex terrain situation the change in elevation would effect the change of concentration by reducing the intensity of the odor and then potentially effects to sensation area.

From the results shown above, it is easy to distinguish that there is a certain direction that biosolids odor is dispersed. In fact, it appears that the biosolids odor is dispersed in the southwest-northeast direction from the source. This occurrence was hypothesized by the effect of weather conditions, especially wind direction and wind speed on that particular date and time. To investigate that issue, we first need to know the date and time of concentration produced and its wind condition.

The date/time, wind direction, and wind speed generated from surface and profile data of concentration values above the detection threshold (DT) are listed in Table 1. The number 01 in hour represents one o’clock in the morning and the number 24 represents twelve o’clock at night (12 PM). Wind speed (WSPD) values vary from 1.5 m/s to 4.6 m/s that mostly fall in between wind speed category 1 to 3 defined by the model.

Table 1 Date/Time Values Exceed DT

Year	**Month**	**Date**	**Hours**	**WDIR (Degree)**	**WSPD (m/s)**
2006	10	23	02	235	1.5
2006	10	23	06	223	1.5
2006	10	23	07	252	1.5
2006	10	23	15	255	3.1
2006	10	23	22	246	3.1
2006	10	23	24	264	2.6

The direction of dispersion is actually consistent with the wind direction data on the date biosolids applied. Thus, from the example shown above, we can observe that the odor dispersion followed the assumption of the AERMOD that is a steady-state dispersion model assuming steady-trajectory flow and followed the assumption that receptors living near the reuse sites detect biosolids odors from downwind direction. This assumption can be applied to the other prediction maps of both flat terrain situation and complex terrain situation. However, the wind directions only affect to the direction of odor dispersion but not to how intense the odor could be. Therefore, it is assumed that there might be another factor that really affects the concentration; wind speed should be taken into account because its ability might potentially create nuisance condition by increasing level of concentration to surrounding area of biosolids applied. In reality, it makes sense that wind direction effects which neighbors or receptors will perceive the odors, but it is not easy to predict how strong of wind speed would create malodorous condition. Generally, under moderate atmospheric stability (e.g., partly sunny, wind speed 8-12 mph, moderate turbulence), on flat terrain area, source odorants undergo fairly rapid dilution as the distance from the source increase. As such, concentrations of odorants will likely not be objectionable to neighbors, if the biosolids are reasonably well stabilized with low odor. Conversely, the pervasive odorant of poorly stabilized biosolids can be detected at considerable distances from the source.

As the meteorological conditions can change with the season, day to day, and even with the time of day, it is necessary to investigate the issue of time when odor incident occur. It is known from the literature that odorants emitted from ground-level source will remain most concentrated during periods of high atmospheric stability, such as occur with air temperature inversions and low wind speeds at night and very early morning (EPA, 2000-Guide to Field Storage). The results of this study, Table 1, also show that the possible odor incidents, the location that the concentration above the DT, usually occur at nighttime and in the morning.

5. Conclusion

Biosolids distributed to reuse fields can potentially create nuisance conditions for people in surrounding communities and sometimes lead to odor complaints. Consequently, the anticipation of nuisance odor from land application and the public's lack of understanding can limit the implementation of a biosolids reuse program. Similar to odorants from the liquid process in the wastewater treatment facility, the odor problem in reuse fields depends on the factors such as atmospheric condition, topographic features, etc. The existing method used to measure the impact from biosolids odor such as the olfactometer lacks continuity as it could be only used generate instantaneous values (at a certain point of time, specific location, and exact weather condition).

The study utilized existing tools such as the atmospheric dispersion model and the Geographic Information System (GIS) to generate the predicted concentration and display it as a concentration prediction map to visualize the odor impact from the biosolids. The United States Environmental Protection Agency (U.S. EPA) regulatory air quality steady-state plume model called AERMOD was employed as the main tool to generate the predicted concentration. The result produced from the AERMOD was the concentration values in odor unit per cubic meters for the selected receptor locations and relative time and date occurred. Using the Geostatistical Analyst, the prediction maps were generated focusing on the areas that have concentration values above the detection threshold or one odor unit per cubic meters so-called sensation area. The sensation area is defined as the potential area that people could detect the odor and is basically caused by many factors. Some of them are critical such as pollutant emission and meteorological conditions such as wind condition which represent source and transport characteristics respectively. Besides the factors mentioned above, however, receptor location is also important since the odor incident occurs if people detect the odor. This study has shown the preliminary results for measuring biosolids odor impact to communities surrounding DCWASA reuse fields by using the dispersion model. The model accounts for steady-state flow condition. There is a need to collect more emission rate data in order to produce more accurate results. The calibration between the model output and the measurement from the field records also needs further investigation.

6. Future Work

The future direction of this study is to validate the results obtained from the odor dispersion model with the results from the field measurements to find a more reliable method for biosolids odor impact assessment. The GIS-based biosolids risk analysis would be developed for improving decision-making processes for biosolids managers.

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