PRIORITIZE ODOR CONTROL ALTERNATIVES WITH DISPERSION MODELING

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ABSTRACT

A primary goal of odor control master planning is to identify cost effective methods to reduce offsite odor impacts from wastewater conveyance and treatment facilities. Selecting which odor abatement technology or combination of technologies to implement from the myriad of alternatives can be arduous. The various conveyance and treatment systems prone to odorous emissions can handled by numerous odor control technologies with different capacities and configurations.

Odor control projects do not add treatment capacity and can be difficult to fund. It is important to get the greatest reduction in odor impact for the money.

Odor dispersion modeling can be a helpful tool to spatially illustrate the reduction of the area of odor impact from different odor control options. An odor dispersion model illustrates how odors generated at a wastewater plant are transported to the fence line and offsite. A dispersion model predicts the intensity, frequency, and spatial extent of nuisance odors generated by the treatment facilities. It should be emphasized that the accuracy of the model results should not be considered absolute. Air dispersion model output is most useful for illustrating the differences between odor control strategies.

The American Meteorological Society (**A**MS)/Environmental Protection Agency (**E**PA) **R**egulatory **Mod**el (AERMOD) was specially designed to support the EPA's regulatory modeling programs. AERMOD is a steady-state plume dispersion model which simulates transport and dispersion of multiple point (scrubber stacks or vents), area (uncovered process units) or volume (open doors, etc.) emission sources. A combination of area and point sources are often used to simulate emissions from a wastewater treatment facility.

Field testing can be conducted prior to dispersion modeling or odorous emissions can be estimated using published literature, data collected at other similar facilities, and/or engineering judgment. Modeling can be conducted using odor units (OU) or dilutions-to-thresholds (D/T), which allows for air to be evaluated for its total impact on "odor concentrations" since numerous compounds can contribute to the odorous character of the ambient air.

Odor dispersion model output, or odor isopleths, show the extent at which specified OU levels will be perceived for a given time period in the modeled meteorological data period. The

dispersion model can also illustrate the number of exceedances modeled receptors will be impacted at specified OU levels over the meteorological period.

Dispersion model output can be exported to Google Earth or other GIS programs to present numerous model runs all within one figure. Odor dispersion modeling can be used to compare and rank potential odor control options by evaluating reduction in the area of impact for individual and/or combinations of odor control alternatives.

Dispersion modeling output and capital cost comparisons for odor evaluations from two Texas entities and an evaluation for a proposed facility in Mexico City are discussed later in this paper.

KEYWORDS

Odor control, dispersion modeling, AERMOD, odor master planning.

ODOR REGULATIONS

Odor regulation in the State of Texas falls under the authority of the Texas Commission on Environmental Quality (TCEQ) and are promulgated under Title 30 of the Texas Administrative Code (TAC).

30 TAC 112.31-32 Control of Hydrogen Sulfide states:

> *"No person may cause, suffer, allow, or permit emissions of hydrogen sulfide from a source or sources operated on a property or multiple sources operated on contiguous properties to exceed a net ground level concentration of 0.08 parts per million averaged over any 30-minute period if the downwind concentration of hydrogen sulfide affects a property used for residential, business, or commercial purposes."*

and

> *"No person may cause, suffer, allow, or permit emissions of hydrogen sulfide from a source or sources operated on a property or multiple sources operated on contiguous properties to exceed a net ground level concentration of 0.12 parts per million averaged over any 30-minute period if the downwind concentration of hydrogen sulfide affects only property used for other than residential, recreational, business, or commercial purposes, such as industrial property and vacant tracts and range lands not normally occupied by people."*

Fence line hydrogen sulfide (H_2S) readings of 0.08 or 0.12 ppm hydrogen sulfide as listed in 30 TAC 112.31-32 could lead to nuisance odor complaints. As discussed later in this paper, the H_2S detection and recognition thresholds are at much lower concentrations than required by 30 TAC 112.31-32, 0.001 and 0.005 ppm H_2S, respectively.

30 TAC 217 *Design Criteria for Domestic Wastewater Systems* sets the regulatory design requirements for wastewater collection systems and treatment plants. The regulations place a greater emphasis on nuisance odor prevention and mitigation than the previous regulations, although they do not set specific odor control design requirements for most treatment unit processes.

30 TAC 309 *Domestic Wastewater Effluent Limitation and Plant Siting* address nuisance odors from a buffer zone standpoint. Anaerobic lagoons may not be located closer than 500 feet to the nearest property line; all other treatment units many not be located closer than 150 feet to the nearest property line. If buffer zone requirements are not met, a nuisance odor prevention plan must be developed.

TYPICAL WASTEWATER ODORANTS

Although fresh, aerobic wastewater contains many odor causing compounds, the intensity and concentrations of odorants become much greater as the oxygen content decreases and anaerobic conditions occur.

The primary odorant of concern in wastewater is hydrogen sulfide gas. H_2S is a colorless gas with an egg salad or rotten egg odor. It can be detected and considered a nuisance at very low concentrations, and can be dangerous at the higher concentrations sometimes found inside unvented manholes and covered facilities. In clean air, people can typically detect H_2S at 1 part per billion (ppb) or less; in a typical outdoor environment the recognition threshold is around 5 ppb (0.0047 ppm).

H_2S forms when oxygen and nitrate are depleted in the wastewater. Microorganisms present in the wastewater then begin to reduce sulfate and produce hydrogen sulfide as a byproduct.

Typical wastewater odorants are listed in Table 1. In Table 1, the detection threshold is the level at which a person could typically detect an odor in clean air; the recognition threshold is the level at which the odor can be fairly well recognized.

Table 1 – Typical Wastewater Odorants

Compound Name	Formula	Detection Threshold, ppm (v/v)	Recognition Threshold, ppm(v/v)	Odor Description
Dimethyl sulfide	$(CH_3)_2S$	0.001	0.001	Decayed cabbage
Dimethyl disulfide	$(CH_3)_2S_2$	0.001	---	Decayed vegetables
Ethyl mercaptan	C_2H_5SH	0.0003	0.001	Decayed cabbage
Hydrogen sulfide	H_2S	0.0005	0.0047	Rotten eggs
Indole	$C_6H_4(CH)_2NH$	0.0001	---	Fecal, nauseating
Methyl mercaptan	CH_3SH	0.0005	0.001	Rotten cabbage
Propyl mercaptan	C_3H_7SH	0.0005	0.02	Unpleasant
Pyridine	C_5H_5N	0.66	0.74	Pungent, irritating
Skatole	C_9H_9N	0.001	0.05	Fecal, nauseating
Ammonia	NH3	0.04	5	Sharp, Ammoniacal
Trimethylamine	C_3H_9N	0.08	0.5	Ammoniacal, Fishy
Triethylamine	$C_6H_{15}N$	0.09	0.3	Ammoniacal, Fishy

Odor intensity or strength may not vary proportionally with the concentration of odorant. For example, the intensity of an odor at a concentration of 100 may only be twice as great as its intensity at a concentration of 10.

Odors from different treatment processes are not additive. For example, odor emissions from two equal sources typically do not result in double the odor impact on surrounding areas.

ODOR UNITS OR DILUTIONS-TO-THRESHOLDS

Odor units (OU) or dilutions-to-thresholds (D/T) allow for air to be evaluated for its total impact on "odor concentrations", since numerous compounds can contribute to the odorous character of the ambient air. For dispersion modeling, odor units, which are dimensionless, are assigned the pseudo-concentration of OU/m^3.

Sensitivity to odors varies from person to person and the interpretation of odors can be subjective. To account for differences among the population, odor unit testing requires from four to eight trained odor panelists and an olfactometer for diluting and dispensing the odor samples. Laboratory odor unit testing is expensive, typically in the range of $250 to $500 per sample.

During odor unit testing, each odor panelist sniffs three samples, one with a dilute sample of the odorous sample and two with odor free air. The panelist selects the sample that is odorous, even if they must guess. The dilution of the odorous sample is decreased as the testing continues, until each panelist can detect and recognize the odor. The individual thresholds of the panelists are averaged to determine the detection threshold for which 50-percent of individuals will observe the presence of an odor.

An OU of 1 is the level at which half the population can just barely detect odor in air. At an OU of 7, the ambient odor level sometimes considered a nuisance, a given volume of air must be diluted by a factor of 7 to have an odor just barely detected by half the population.

OU values can also be collected in the field using a field olfactometer, such as the Nasal Ranger by St. Croix Sensory pictured in Figure 1.

Figure 1 – Field Olfactometer by St. Croix Sensory

OU values from different source types cannot be “added” nor can they be “averaged”. Odor dispersion calculations and modeling must be conducted with caution when attempting to display the resulting impact from more than one odor source.

DISPERSION MODELING BASICS

Odor dispersion modeling can be a helpful tool to spatially illustrate the reduction of the area of odor impact to prioritize different odor control options. Odor dispersion models can be used to depict emissions of specific odorants, such as hydrogen sulfide, or more commonly in recent years, the overall odor impact, OU. Odor dispersion model output, or odor isopleths, show the extent at which specified levels will be perceived for a given time period in the modeled meteorological data period.

Two models used for regulatory dispersion modeling of contaminants, as well as for odor dispersion modeling, are the steady state model AERMOD and the non-steady state model CALPUFF. AERMOD is discussed in detail later in this section and modeling results from AERMOD are provided later in this paper.

CALPUFF is a Lagrangian puff model originally developed by the Sigma Research Corporation (SRC) in the late 1980s. CALPUFF is generally used as a long-range model for regulatory purposes, which is typically defined as transport over distances beyond 50 kilometers. CALPUFF often predicts a larger area of offsite odor impact than AERMOD. Results from CALPUFF are not provided as part of this paper.

The American Meteorological Society (**A**MS)/Environmental Protection Agency (**E**PA) **R**egulatory **Mod**el (AERMOD) was specially designed to support the EPA's regulatory modeling programs. AERMOD was designed for short-range dispersion, up to 50 kilometers, of air pollutant emissions from stationary industrial sources.

AERMOD is a steady-state plume dispersion model which simulates transport and dispersion of multiple point (scrubber stacks or vents), area (uncovered process units) or volume (open doors, etc.) emission sources. Typically, a combination of area and point sources are used to model odors from wastewater treatment facilities.

AERMOD incorporates air dispersion based on planetary boundary layer turbulence structure and scaling concepts, including treatment of both surface and elevated sources, and both simple and complex terrain. AERMOD requires input from three preprocessors AERMAP, AERMET, and BPIP.

The AERMOD mapping program (AERMAP) is the terrain pre-processor which is used to characterize terrain and generate receptor grids for AERMOD. Input data includes receptor terrain elevation data from the U.S. Geological Survey.

The AERMOD meteorological pre-processor (AERMET) provides AERMOD with the information it needs to construct vertical profiles of required meteorological variables. The user provides surface characteristics in the form of albedo, surface roughness and Bowen ratio.

The TCEQ Air Dispersion Modeling Team (ADMT) has processed meteorological data for all counties in Texas with minimum, average and maximum surface roughness characteristics. In 2012, the TCEQ ADMT updated the preprocessed meteorological data for each county in response to revisions made to the EPA's AERMET program. Meteorological data for each county can be downloaded free of charge from the TCEQ website at:

http://www.tceq.texas.gov/permitting/air/modeling/aermod-datasets.html

The Building Profile Input Program (BPIP) is the building dimensions pre-processor program. When one or more structures interrupt the wind flow, an area of turbulence called building downwash is created. Odors emitted from a fairly low level can be caught in this turbulence, affecting their dispersion.

AERMOD employs hourly sequential preprocessed meteorological data to estimate concentrations for averaging time from one hour to one year. Because the nose can detect odors very quickly, the averaging period of one hour can be converted to a shorter averaging period (typically 5 or 10 minutes) using the power law relationship detailed in the equation below.

$$C_{new} = C_{1\text{-hour}} (T_{1\text{-hour}}/T_{new})^{q}$$

Where: C_{new} = Concentration for the shorter time period
$C_{1\text{-hour}}$ = One hour concentration
T_{new} = Shorter average period in minutes
$T_{1\text{-hour}}$ = 60 minutes (for 1-hour average period)
q = 0.2 (power law exponent, varies from 0.16 to 0.4, dependent on atmospheric stability class)

The calculated emission peaking factor to convert between one hour and 10 minutes averaging times using a power exponent of 0.2 is a multiplier of 1.43.

Although the EPA offers AERMOD code free via the Internet, purchasing the dispersion modeling program with a windows-based interface is recommended. Lakes Environmental and Trinity Consultants Inc./Breeze offer enhanced versions of AERMOD, including streamlined graphical user interfaces and technical support.

MODELING INPUTS

The wastewater treatment processes that have been found to cause the greatest off-site odor typically include preliminary and primary treatment and solids handling. Activated sludge processes, especially trickling filters, may impact off-site if sensitive receptors are close to the fence line. The anaerobic and anoxic zones associated with biological nutrient removal have the potential to make activated sludge processes more odorous than currently perceived by our industry. Secondary clarifiers, effluent filters and disinfection typically do not impact off-site receptors.

Uncontrolled treatment processes include processes that are uncovered or covered but vented to the atmosphere without foul air treatment. Treatment processes are controlled through upstream odor control chemical addition or with cover and scrub technologies. Cover and scrub technologies involve collecting foul air by covering or enclosing an odorous treatment unit and scrubbing the captured foul air in a manufactured or constructed-in-place odor control system. It is recommended that covered areas have additional corrosion protection applied to concrete and ferrous steel surfaces to deter microbial induced corrosion. A wide range of odor scrubbing technologies are commercially available, including biofiltration, bioscrubbing, carbon and chemical scrubbing.

Typical OU emission values from potential odorous wastewater treatment processes as well as from three scrubbing odor control technologies are presented in Table 2.

Table 2 – OU Values for Potentially Odorous Treatment Units and Control Technologies

Treatment Unit	OU
Odorous Processes	
Preliminary Treatment	2,500
Activated Sludge Treatment	150
Solids Holding and Processing	1,500
Odor Control Technologies	
Bioscrubbers	400
Biofilters	200
Carbon Scrubbers	150

The OU values for Odorous Processes were derived from published geometric mean values in the Odor Threshold Emission Factors for Common WWTP Processes, McGinley, WEF Odors, 2008, as well as data collected at similar facilities and engineering judgment. The OU values for the Odor Control Technologies were derived from current performance guarantees from odor control equipment manufacturers, as well as data collected at similar facilities and engineering judgment.

It is critical to consider that the OU values presented in Table 2 were measured directly at the source of the odor. Odor testing often includes a flux hood, which completely contains odorous emissions from the source. OU values from air samples collected within the path of wind at wastewater treatment facilities would not be as high as the OU values in Table 2 for similar treatment processes. Figure 2 is a photograph of emissions sampling from an area source using a flux hood.

Figure 2 – Flux Hood Emissions Testing of an Area Source

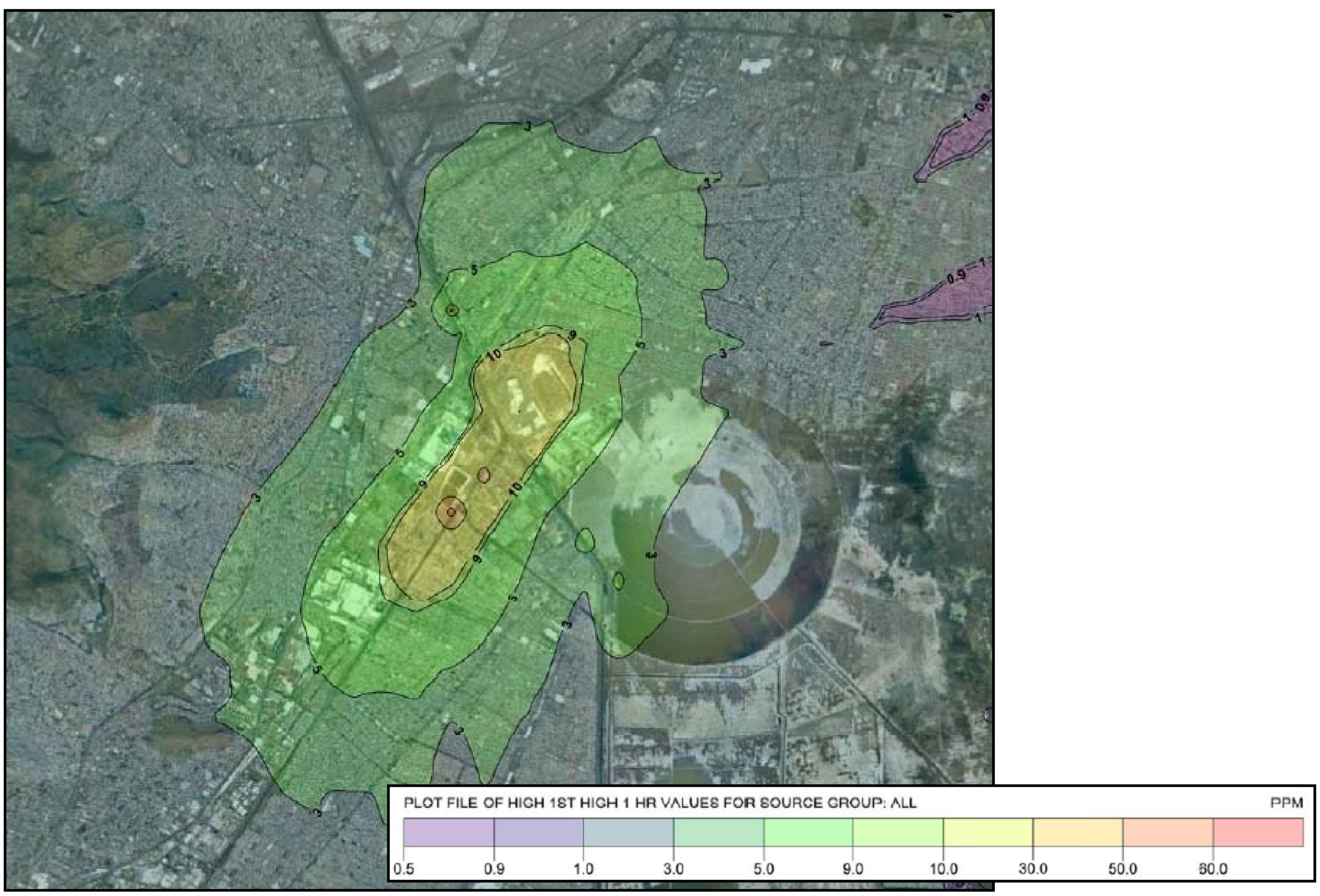
In dispersion modeling, the air flow rate for an area source is typically calculated as a ratio of the area and flux rate of the flux chamber used for sampling. For point sources, the air flow rate is equal either to the fan design capacity, or if available, the measured air flow rate in the conveyance duct or discharge stack or vent from the field.

MODELING RESULTS

The Author has modeled the impact of odorous emissions of numerous operating scenarios from over ten facilities. Dispersion modeling output and capital cost comparisons for odor evaluations from two Texas entities as well as modeling output for a proposed facility in Mexico City are discussed later in this section.

A unique dispersion modeling project for a proposed wastewater treatment plant in Mexico City included sampling existing odor sources, which was conducted by another engineering firm, to illustrate the surrounding area was already impacted by odors prior to the construction and startup of a new wastewater treatment facility. Existing area odor sources included open canals partially conveying raw sewage, a chemical solvent plant and an evaporation pond. The open channels, ranging in width from 8 to 34 meters, were modeled using hydrogen sulfide emissions. Figure 3 is the H_2S isopleths resulting from the canal emissions for a one hour averaging period.

Figure 3 – H_2S Isopleths for One Hour Averaging Time



The isopleths indicate the extent at which the H_2S concentration noted will be perceived for at least one hour in one year. The modeling results illustrate the odor impacts already prevalent in the area prior to the startup of the wastewater treatment plant. The proposed treatment facility will not be the only cause of future area odors. Funds available for odor control may be better spent on controlling emissions from sources other than the proposed water reclamation plant.

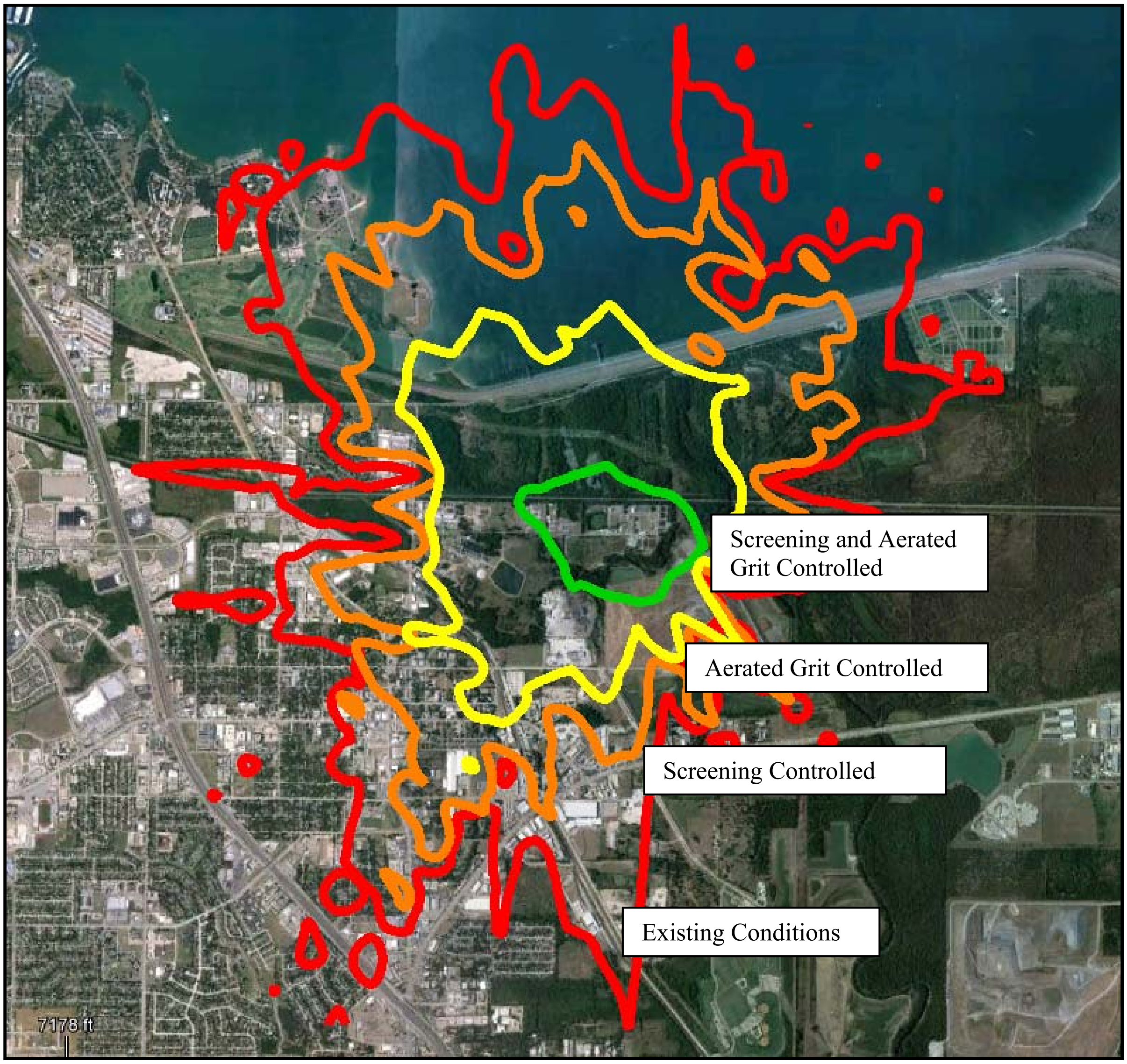
Dispersion modeling can be used to identify treatment levels required to control odors at specific locations offsite. Controlling only part of the odorous emissions from a treatment facility may not be sufficient to prevent odors from impacting sensitive receptors. Dispersion modeling can be used to identify the odorous treatment processes to control, if funds are available, to effectively reduce offsite impact.

The odorous treatment processes at a facility in North Central Texas were sampled to quantify emissions. The odor sampling consisted of two days of sampling onsite and seven days of monitoring with OdaLog H_2S gas loggers. Continuous monitoring of H_2S gas levels using data logging instruments can verify the grab sampling for OU is conducted during time periods of representative odors.

The emissions from all odorous existing facilities were modeled to illustrate the existing offsite odor impact. The trickling filters, aeration basins, aerated digesters and solids handling facilities were found to have a relatively small odor impact. Control strategies were developed for odor sources identified as having the most offsite impact, screening and aerated grit. The dispersion model was then used to illustrate the reduction in the area of impacted by treatment plant odors when the identified odorous treatment process are controlled.

Dispersion model output was exported to Google Earth to present numerous model runs within one figure. Figure 4 illustrates the 7 OU isopleths for the existing conditions as well as for three odor control strategies. The isopleths indicate the extent at which 7 OU (OU level typically considered a nuisance) will be perceived for at least ten minutes in one year.

Figure 4 – Comparison of 7 OU Isopleths for 10-minute Averaging Time



The approximate area of odor impact at a 7 OU level is 5.2 sq. miles for the existing conditions and 0.24 sq. miles with the screening and aerated grit controlled.

The screening facility includes two structures for splitting flow to five fine screens. The opinion of probable construction cost (OPCC) for odor control at the screening facility was $ 950,000. Significant equipment and materials items included in the OPCC are a 5,400 cubic feet per minute (cfm) bioscrubber, bioscrubber foundation, drain and plant water connections, duct work, concrete coating, cover plates, and electrical and instrumentation. The additional construction cost for adding odor control to the aerated grit basins was $ 480,000.

It was decided concurrently with the odor control evaluation to convert the existing aerated grit basins to vortex grit removal basins. Switching from aerated grit to vortex grit removal technology allowed for cost savings in the odor control system by providing a smaller odor control system and reducing the area of covers and concrete coating required. The project is currently under construction with an estimated completion date of October 2015.

Dispersion modeling was recently conducted for another North Central Texas facility to illustrate the improvement in odor impact by controlling odors at the influent lift stations and solids handling facilities. The proposed odor control systems for the influent lift stations and solids handling facilities are listed in Table 3.

Table 3 – Proposed Odor Control Systems

Location	Technology	Capacity, cfm	Nominal Discharge Height, feet	Bid Type
Influent Lift Station	Bioscrubber	6,550	35	Base Bid
	Bioscrubber	6,550	35	Base Bid
	Carbon Polisher	13,100	22	Additive Alternate
Solids Handling	Carbon Adsorber	2,350	15	Base Bid
	Carbon Adsorber	7,000	19	Base Bid
	Bioscrubber	9,000	38	Base Bid
	Bioscrubber	9,000	38	Base Bid
	Carbon Polisher	18,000	25	Additive Alternate

The proposed odor control systems include two carbon polishers, which will be bid as an additive alternate. Each carbon polisher is designed to further treat the discharges from two bioscrubbers and located adjacent to the associated bioscrubbers on the same concrete foundation.

Bioscrubbers remove contaminants in foul air in the water layer surrounding the media in a packed-bed tower. Bioscrubbers effectively remove 99-percent plus H_2S, but are less effective on certain reduced sulfur compounds. Carbon systems adsorb odorous compounds into activated carbon material. When carbon media has active remaining sites for adsorption, carbon systems can remove a broad range of compounds. As listed in Table 2, the assumed OU level for the discharge of bioscrubbers, carbon adsorbers and carbon polishers are 400, 150 and 150, respectively.

Existing conditions and numerous odor control alternatives were modeled using AERMOD. The modeled output in Figure 5 includes only emissions from the proposed odor control systems listed in Table 3. The aerial map to the left in Figure 5 excludes the discharges from the two carbon polishers. The aerial map to the right excludes the discharges from the four bioscrubbers, as the bioscrubber discharges were routed to the associated downstream carbon polisher. Other odor sources were not included in the model results in Figure 5 to distinguish the difference in the modeling results with and without the carbon polishers.

Figure 5 – Comparison of Isopleths with and without Polishing Carbon

Although the carbon polishers reduce OU levels at the scrubber outlets, the discharge elevations of the carbon polishers are approximately 10 feet closer to grade than the discharge elevations of the associated bioscrubbers. The reduction in discharge elevation impacts surrounding modeled OU levels, unless stacks are extended or discharge velocities are increased.

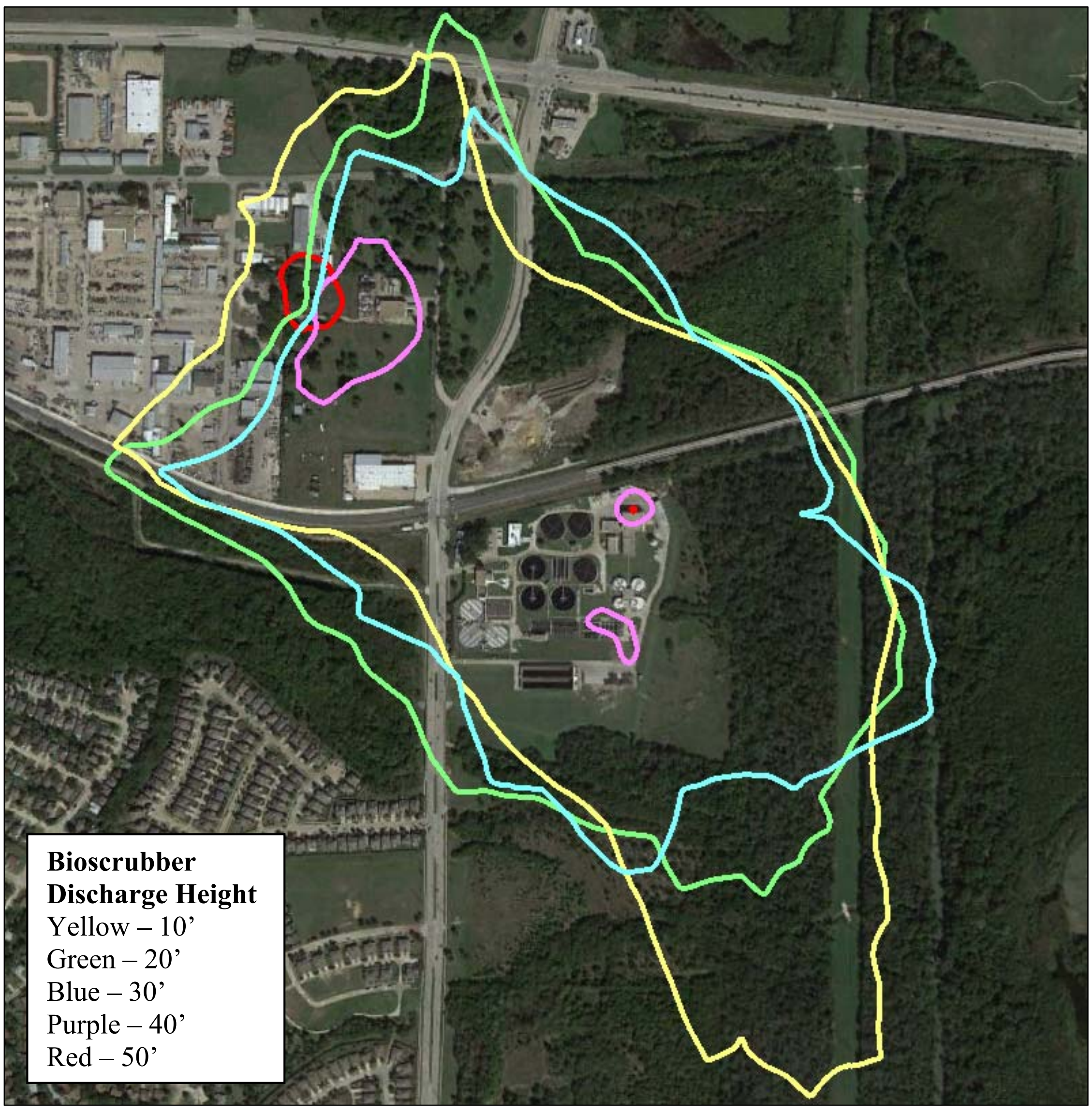
The OPCC for odor control at the influent lift stations without carbon polishers was $ 1,580,000. Significant equipment and materials items included in the OPCC for odor control at the lift stations are two 6,550 cubic feet per minute (cfm) bioscrubbers, foundation, drain and plant water connections, duct work, and electrical and instrumentation. The OPCC for odor control at solids handling without carbon polishers was $ 4,180,000. Significant equipment and materials items included in the OPCC for odor control at solids handling are two 9,000 cubic feet per minute (cfm) bioscrubbers, one 2,350 cfm carbon adsorber, one 7,000 cfm carbon adsorber, associated foundations, drain and plant water connections, duct work, and electrical and instrumentation. The OPCC for the 13,100 cfm and 18,000 cfm additive alternate carbon polishers and associated foundations, drains and duct work is $ 980,000.

The project is anticipated to bid in Spring 2015. The Owner will use the dispersion modeling results to assist with the decision whether or not to select the additive alternate carbon polishers.

For three recent projects, variations of the dispersion model were conducted at different structure and discharge stack elevations. The dispersion model indicates the lower discharges have larger odor impacts than similar discharges at higher release elevations. For sources at ground level and slightly elevated, as typically found in WWTPs, odorants tend to stay close to the ground in a stable atmosphere. For sources with a high release height, odorants tend to disperse before reaching receptors at grade.

Figure 6 is one example of model results generated by varying the discharge elevations of four bioscrubbers from 10 to 50 feet above grade. Figure 6 indicates the higher the discharge stacks, the lower the odor impacts.

Figure 6 – Comparison of 3 OU Isopleths for Decreasing Bioscrubber Discharge Heights

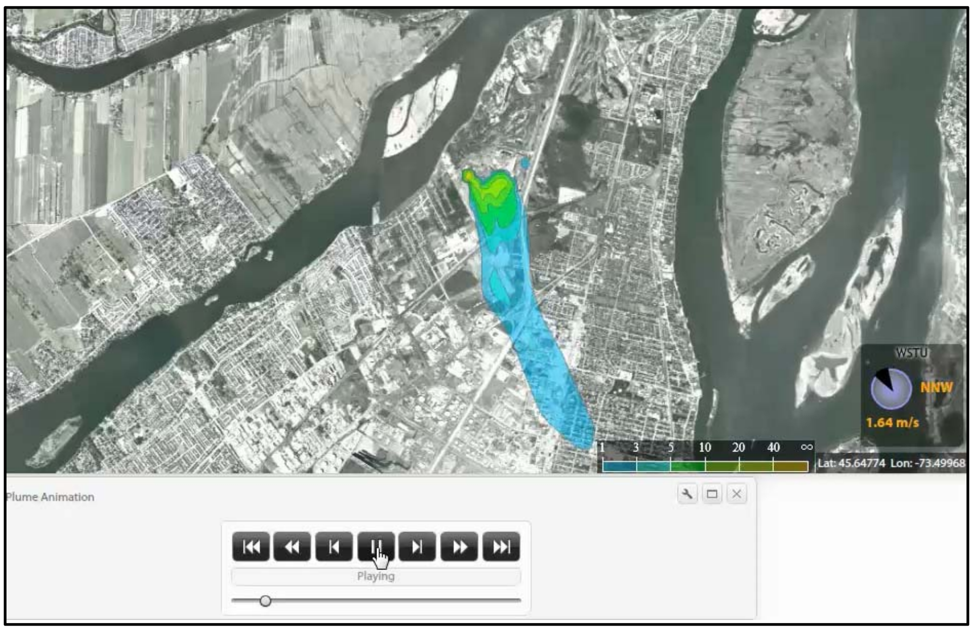


If susceptible, odor complaints often occur during inversion conditions. On damp, cold days, odors may collect in low lying areas adjacent to conveyance and treatment facilities and impact offsite receptors as a pocket of odorous air.

REAL-TIME DISPERSION MODELING

Continuous monitoring systems are available, which display odor isopleths in real-time. The real-time odor models use onsite monitors that correlate continuous measurements to OU and an onsite weather station as input to calculate the resulting odor plume. The number of OU monitors depends on the size of the facility and available budget. Figure 7 is a screen shot from a real-time odor model in Brussels using the Kruger OdoWatch® odor monitoring system.

Figure 7 – Screen Shot of Real-Time Odor Modeling System



The odor monitoring systems can be programmed to alarm when a situation could result in odor complaints. The early warnings enable Operators to make process adjustments to potentially reduce offsite odor impacts.

CONCLUSIONS

A dispersion model predicts the intensity, frequency, and spatial extent of nuisance odors generated by the treatment facilities. The accuracy of the model results should not be considered absolute. The air dispersion model output is most useful for illustrating the differences between odor control strategies.

Factors that impact odor dispersion include:

- Odor intensity of sources
- Flux and discharge air flow rates
- Meteorological conditions (wind speed, wind direction and atmospheric stability)
- Surrounding topography and building obstructions
- Water surface elevations and stack heights and discharge velocities

Odor dispersion modeling can be used to prioritize odor control and other improvements projects by spatially illustrating the reduction in offsite impact with implementing each control option. The costs of odor control projects can be compared to reductions in the area affected or to the number of persons, businesses and/or households impacted.

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REFERENCES

McGinley, M.A. and C.M. McGinley. (2008) *Odor Emission Factors for Common WWTP Processes*, Water Environment Federation/Air & Waste Management Association Specialty Conference: Odors and Air Emissions.

U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. (2004) User's Guide for the AMS/EPA Regulatory Model – AERMOD, EPA-454/B-03-001.

U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. (2009) AERMOD Implementation Guide.