

# **Application of A Gaussian Plume Model of Odor Dispersion To Select A Site For Livestock Facilities**

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## **ABSTRACT**

The ideal separation distance between a livestock facility and the nearest neighbor to avoid an odor nuisance has not been determined and is somewhat subjective. A windows based computer program was developed to be used as an educational tool and decision aid for planning livestock facilities. The major focus is on control and dispersion of odor, with a secondary emphasis on nutrient management. The odor dispersion model, based on a Gaussian Plume model, was used to predict the level of odor downwind from the odor source. The input variables include wind speed, atmospheric stability categories, odor source strength, and one of two terrain roughness classes. The terrain classes represent a facility surrounded by a flat, open field with crop stubble, or surrounded by a forest barrier. A sensitivity analysis was performed on the primary input variables, and the results are presented in graphical and tabular form. The results provide an objective basis for the evaluation of the suitability of a site for the location of livestock production facilities. Model results indicate that the uses of a forest barrier and odor source control are the most important factors in limiting odor dispersion.

## **INTRODUCTION**

South Carolina, like other states, has experienced a growth in the number and scale of livestock and poultry facilities. Along with this growth in the animal industries has come an increase in concern by the public over the potential water and air quality impacts. This increase in concern has lead to new or expanded state regulations (e.g. SCDHEC, 1998) for animal production facilities. Regulations for animal production facilities often include specifications for the:

- sizing and construction of manure containment structures,
- calculation of land application rates based on plant nutrient requirements,
- calibration of manure spreading equipment,
- separation distances between public waters and land application areas,
- separation distances between animal production facilities and public waters,
- disposal of animal mortalities, and
- separation distances to reduce odor nuisances.

Some state regulations also require the development of a site-specific plan to control odors and vectors (flies and rodents).

The amount of odor generated from livestock or poultry operations can vary greatly from site-to-site and is often the single greatest public concern. Therefore, selection of an appropriate site for

a livestock facility, and the implementation of management practices and technologies to reduce the strength of odors is an important part of the planning and permitting process. A detailed discussion of the sources of odor from swine facilities, and measures to reduce odor are provided by Chastain (1999) and Nicolai (1995).

The odor that is detected from a livestock operation is a complex mixture of gases. Most often the odor is a result of the uncontrolled anaerobic decomposition of manure. However, feed spoilage can also contribute to the odor. The odor that is detected by the human nose can be a combination of 60 to 150 different compounds. Some of the most important types of odor causing compounds are: volatile fatty acids, mercaptans, esters, carbonyls, aldehydes, alcohols, ammonia, and amines. The odor strength of these compounds does not combine in an additive manner. That is, sometimes mixing several of these compounds can result in reduced odor by dilution of the strongest smelling compounds. In other instances, the mixture is worse than any of the individual compounds. Ammonia can create strong odors near a building, but is not a significant component of odor downwind from an animal production facility. Ammonia is highly volatile and moves upward in the atmosphere quickly where it is diluted.

For an odor to be detected downwind, odorous compounds must be: (a) formed, (b) released to the atmosphere, and (c) transported to the receptor site. These three steps provide the basis for most odor control. If any one of the steps is inhibited, the odor will diminish. Therefore, development of an understanding of the affects of odor source strength, atmospheric stability, wind speed, and roughness of the surrounding terrain on odor dispersion is an important component in the planning and location of new livestock production facilities.

A windows based computer program was developed to be used as an educational tool and decision aid for planning livestock facilities. The major focus was on control and dispersion of odor, with a secondary emphasis on nutrient management. The program was designed to offer the user information in four topic areas: (1) odor control strategies, (2) odor dispersion mapping, (3) animal, manure, and nutrient inventories, and (4) regulations. The program utilizes point and click control with limited numerical input to present data tables, text, and color-coded odor plume maps. A detailed discussion of the program features is given by Wolak et al. (1996). The topics included in the odor control section of the program are: methods to reduce odor from buildings, benefits of covering manure storages, design and management of anaerobic lagoons to minimize odor, land application methods to reduce odor emissions, site selection factors to minimize odor complaints, and use of trees and fencing as odor dispersion aids and screens.

The objectives of this paper are to: (1) describe the odor dispersion module of the program, (2) present the results of a sensitivity analysis of the primary input variables, and (3) discuss the application of model results for site selection for livestock facilities.

## **OVERVIEW OF THE ODOR DISPERSION MODEL**

The odor mapping section of the program allows the user to perform odor dispersion calculations using a simple Gaussian Plume model to predict the level of odor downwind from the odor source. The user can input the following variables: wind speed, direction, atmospheric stability

categories odor source strengths, and one of two terrain roughness classes. The terrain classes represent a facility surrounded by a flat, open field with crop stubble, or surrounded by a forest barrier. The output of the model is a color-coded map of the odor plume. The map indicates estimates of the plume length at odor levels of 1 odor unit (OU), 2 OU, and 5 OU. One odor unit is defined as the odor detection threshold where 50% of a panel can detect the odor and 50% can not detect the odor. Therefore, 1 OU is a slight odor, 2 OU represents a mild odor level, and 5 OU is a significant odor level.

### Plume Mapping Equation

The odor prediction model was an adaptation of that reported by Smith (1993). Smith utilized a Gaussian Plume model to predict the odor concentration downwind from a ground level point sources as follows:

$$C(x,y) = (Q / \pi \sigma_y \sigma_z U) \exp (- y^2 / 2 \sigma_y^2).$$

Where:

- $C(x,y)$  = the predicted time-averaged odor concentration (OU),
- $x$  = the downwind distance (m),
- $y$  = the crosswind distance (m),
- $Q$  = the odor emission rate or source strength (OU m<sup>3</sup>/s),
- $\sigma_y$  = the horizontal dispersion coefficient (m),
- $\sigma_z$  = the vertical dispersion coefficient (m), and
- $U$  = the mean wind speed at 10 m (m/s).

Gassman (1992) reviewed atmospheric transport models and identified several shortcomings of the Gaussian plume type models. The problems include model inability to account for air drainage, poor prediction at calm wind conditions, the inability to account for effects of vegetative impacts, the lack of data regarding emission rates and the existence of non-Gaussian flow in the observed world. An attempt is made to address two of the identified shortcomings in the current computer program, namely vegetative impacts and emission rates. Model predictions in calm and non-Gaussian flow conditions are beyond the scope of this work.

### Model Parameters

In the absence of measured data, dispersion coefficients ( $\sigma_y$  and  $\sigma_z$ ) are typically estimated as a function of distance, atmospheric stability and surface roughness. Atmospheric stability is described by 6 stability classes indicated by A through F in Table 1 (Turner, 1969). Stability class A represents a very unstable atmosphere and is characterized by large mixing heights. Stability class F is the most stable atmosphere and has a small mixing height. Stability classes between A and F represent increasing levels of atmospheric stability. For example, Class D represents a neutral atmosphere, class B is moderately unstable, and class E is slightly stable. The stability classes are assigned based on the solar radiation level, amount of cloud cover, and wind speed as defined by categories 1 through 5 in Table 1. A general description of the 5 number categories in Table 1 are listed below.

- Category 1: Clear skies, solar altitude greater than 60 degrees above the horizontal, typical of a sunny summer afternoon. Very convective atmosphere.
- Category 2: Summer day with a few broken clouds.
- Category 3: A sunny fall afternoon, summer day with broken low clouds, or summer day with clear skies and solar altitude from 15 to 35 degrees above horizontal.
- Category 4: A mostly overcast night or a winter day.
- Category 5: A clear night with minimal cloud cover.

In addition, class D, a neutral atmosphere, is recommended for overcast conditions during day or night.

**Table 1 – Atmospheric stability classes and categories (Turner, 1969).**

Surface Wind Speed At 10 m (m/s)	Day			Night	
	Incoming Solar Radiation			Cloud Cover	
	Strong (1)	Moderate (2)	Slight (3)	Mostly Overcast (4)	Mostly Clear (5)
<2	A	A-B	B	E	F
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

Surface roughness or roughness length is an indicator of the resistance to airflow by the surrounding terrain. , Zannetti (1990) provided a log scale graph of roughness lengths. Tree covered, rolling or moderate relief terrain exhibits a surface roughness similar to urban conditions ( $z_o \cong 10$  m). Both tree covered and urban surface roughness are one order of magnitude higher than the values for cut grass or crop stubble ( $z_o \cong 0.1$  m).

In order to include the influence of trees and wind breaks upon model performance, urban dispersion parameters were selected to estimate odor dispersion plumes in highly forested areas or areas with significant wind breaks. The urban dispersion parameters were adopted from Briggs (1973) as reported by Zannetti (1990). Open terrain with cut grass or crop stubble dispersion parameters were utilized to predict odor dispersion in open field conditions. The open terrain dispersion coefficients presented by Smith (1993) were used.

## SENSITIVITY ANALYSIS

A sensitivity analysis was performed on the model to develop an understanding of how the model parameters affect odor dispersion. Results that demonstrate the influence of atmospheric stability, odor source strength, terrain roughness, and wind speed are presented.

One of the greatest sources of error related to the prediction of plume lengths is the definition of the source strength,  $Q$ . In addition, the magnitude of the source strength varies from day-to-day and from farm-to-farm. For example, a dairy farm with a well-designed and managed manure handling and storage system often generates very little odor with no complaints from neighbors. However, agitation of the contents of a manure storage prior to land application can generate very strong odors.

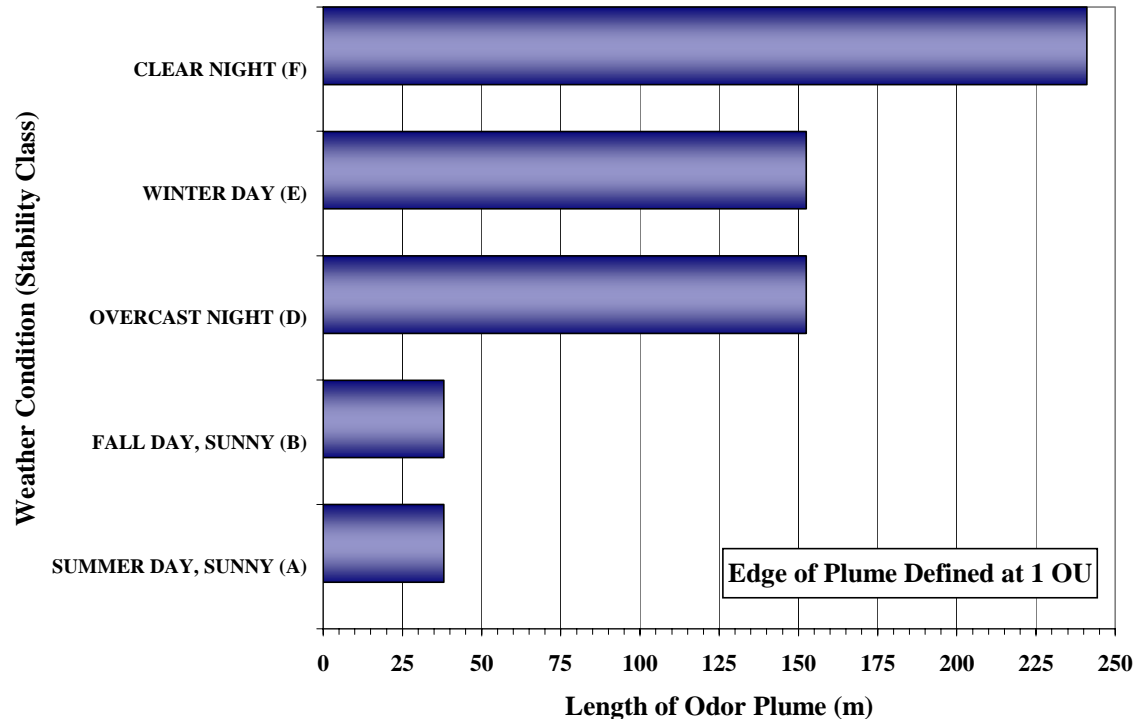
The sensitivity analysis was performed using source strength values ranging from 100 to 10,000 OU m<sup>3</sup>/s based on the information provided by du Toit (1989), Gassman (1992), and Smith (1994). It is the opinion of the authors that an odor source strength greater than 1000 OU m<sup>3</sup>/s is indicative of a livestock production facility with much greater than normal odor production. Production units with a properly designed and managed waste system, well ventilated and maintained buildings, and proper mortality disposal, should be able to maintain the odor strength at a reasonably low level (250 OU m<sup>3</sup>/s or less).

### Atmospheric Stability

The effect of atmospheric stability on the length of an odor plume is given in Figure 1 for a moderately high odor source of 500 OU m<sup>3</sup>/s, a low wind speed of 0.89 m/s, and the open flat terrain class ( $z_o \cong 0.1$  m). For this figure, the edge of the odor plume was defined as the distance required for the odor to be diluted to 1 OU. The results indicate that as the atmospheric stability class varies from very unstable, class A, to stable, class F, the length of the odor plume increases from 38 to 241 m (125 to 791 ft). Therefore, the worst case weather condition for odor dispersion is a clear night due to poor mixing in the vertical ( $z$ ) direction. The other critical weather condition is a winter day or an overcast night that is characterized by a neutral atmosphere (class D or E). The trends shown in Figure 1 are the same for larger odor emission rates.

At times, activities on livestock farms will create large odor source strengths. Examples of activities that have the potential to generate strong odors include land application of poultry litter or slurry manure, and agitation of manure containment structures. Performing such tasks during periods of maximum atmospheric instability, such as the period from mid-morning to early afternoon on a sunny day, can greatly reduce the impact of the odor on neighbors and the farm residence.

**Figure 1 – Effect of Atmospheric Stability Class on Odor Dispersion,  $Q = 500 \text{ OU m}^3/\text{s}$ ,  $U = 0.89 \text{ m/s}$  (2 mph), Open Flat Terrain.**



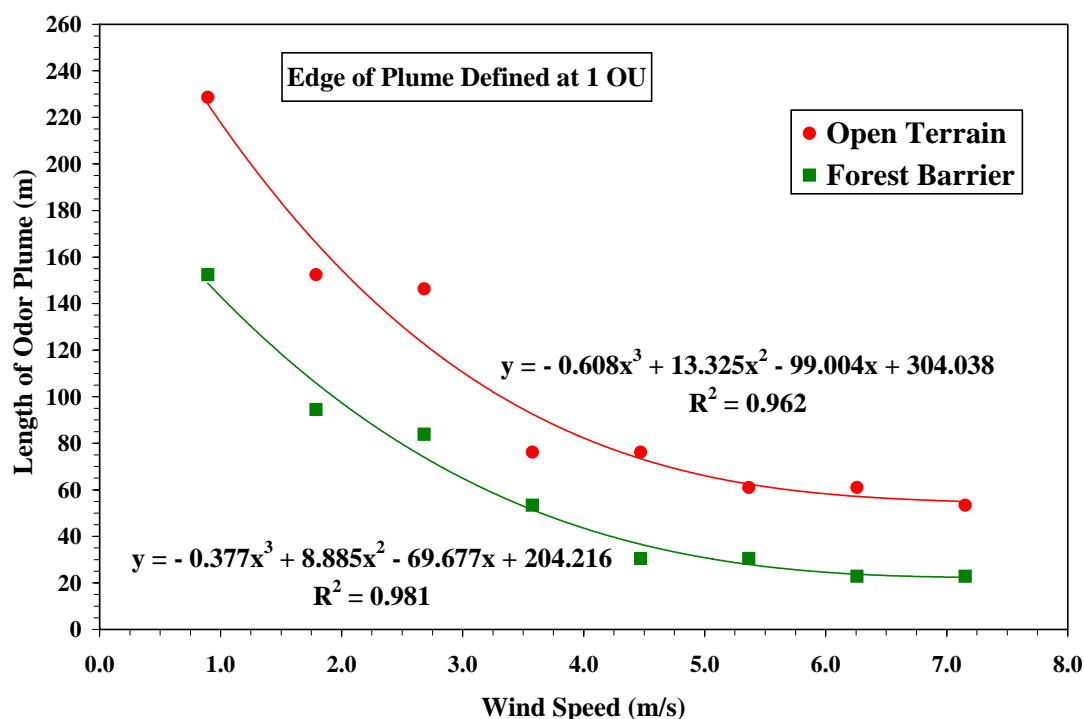
### Wind Speed and Terrain Roughness

The influence of wind speed and terrain roughness on odor dispersion from a moderately high odor source under a neutral atmosphere is shown in Figure 2. Model results were smoothed by fitting regression lines through the output values. The most important results are listed below.

- Increasing the wind speed from 0.89 to 2.68 m/s (2 to 6 mph) decreased the plume length by 36% for the open terrain class and 45% for the forested terrain class. At high wind speeds, such as 7.15 m/s (16 mph), the plume length was 55 m (180 ft) for the open terrain class and 22 m (72 ft) for the forested terrain class. The increased turbulence associated with high wind speeds enhanced vertical dispersion and decreased the plume length for both roughness classes.
- At a typical daytime wind speed of 2.68 m/s (6 mph) increasing the surface roughness by a factor of 100, forested terrain class, decreased the plume length by 40%.
- At a wind speed of 2.68 m/s the plume length for the forested terrain class was 74 m (243 ft). To achieve the same magnitude of odor dispersion for the open terrain class would require a wind speed of 4.43 m/s (9.9 mph). Therefore, the increase in atmospheric mixing associated with a forest barrier was equivalent to increasing the wind speed by a factor of 1.65.

In regions where timber production is common, as is true in the Southeastern US, locating livestock facilities in areas surrounded by forestland may be an effective strategy for reducing odor dispersion.

**Figure 2 – Effect of Wind Speed and Terrain Roughness on Odor Dispersion With a Neutral Atmosphere (Winter Day, Category 4, and  $Q = 500 \text{ OU m}^3/\text{s}$ ).**

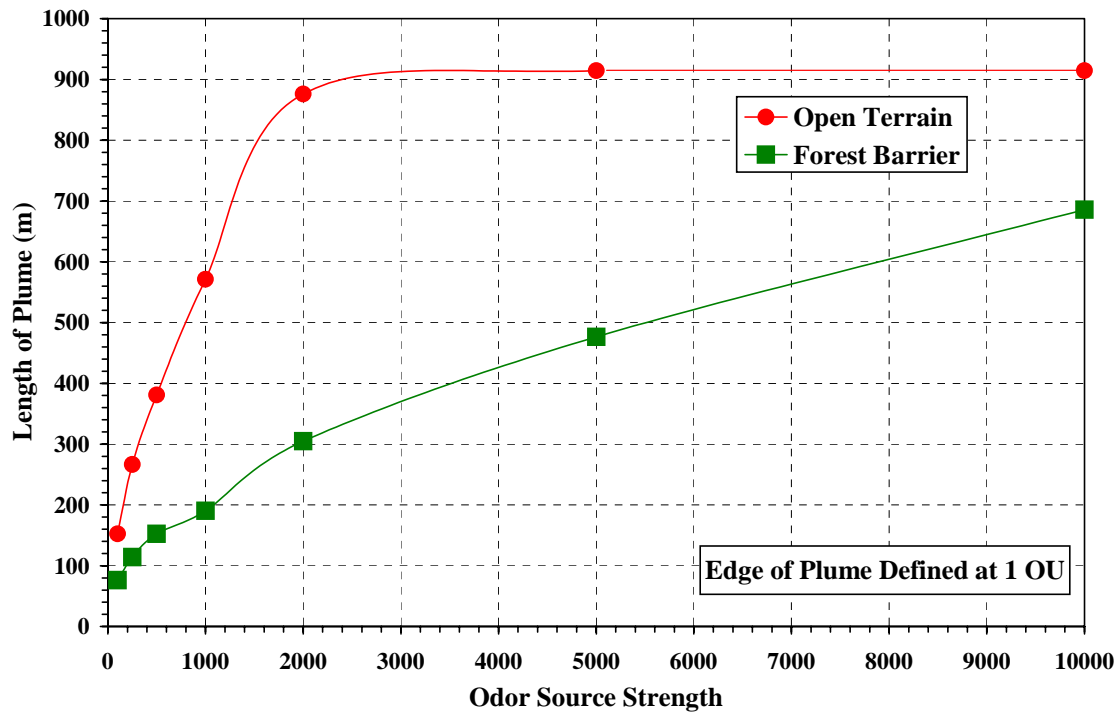


### Odor Source Strength

The results presented in Figures 1 and 2 clearly indicate that the worst case for odor dispersion is under stable atmospheric conditions (clear night) and minimal wind (0.89 m/s). Estimates of plume lengths, defined at 1 OU, are presented in Figure 3 for source strengths ranging from 100 to 10,000  $\text{OU m}^3/\text{s}$ . For the open terrain class the plume length increased dramatically from 152 m (500 ft) at  $Q = 100 \text{ OU m}^3/\text{s}$  to 876 m (2,875 ft) at  $Q = 2,000 \text{ OU m}^3/\text{s}$ . The maximum plume length of 914 m (3,000 ft) occurred at a source strength of 5,000  $\text{OU m}^3/\text{s}$  and remained constant to 10,000  $\text{OU m}^3/\text{s}$ .

The increased roughness associated with a forest barrier decreased the plume length by 50% at a  $Q$  of 100  $\text{OU m}^3/\text{s}$  and 67% for an odor source of 1000  $\text{OU m}^3/\text{s}$  (191 m vs. 572 m). However, the plume length was reduced by the forest barrier by only 25% for the most extreme odor source included in the analysis (10,000  $\text{OU m}^3/\text{s}$ ). These results agree with field studies that indicate that forest barriers can increase vertical dispersion (Bowers et al., 1989). However, control of source strength on the farm is also critical since the effectiveness of the forest barrier diminishes for extremely high source strengths.

**Figure 3 – Variation of Odor Plume Length as a Function of Source Strength (OU m<sup>3</sup>/s) for Worst Case Odor Dispersion (Clear Night, Category 5,  $U = 0.89$  m/s (2 mph)).**



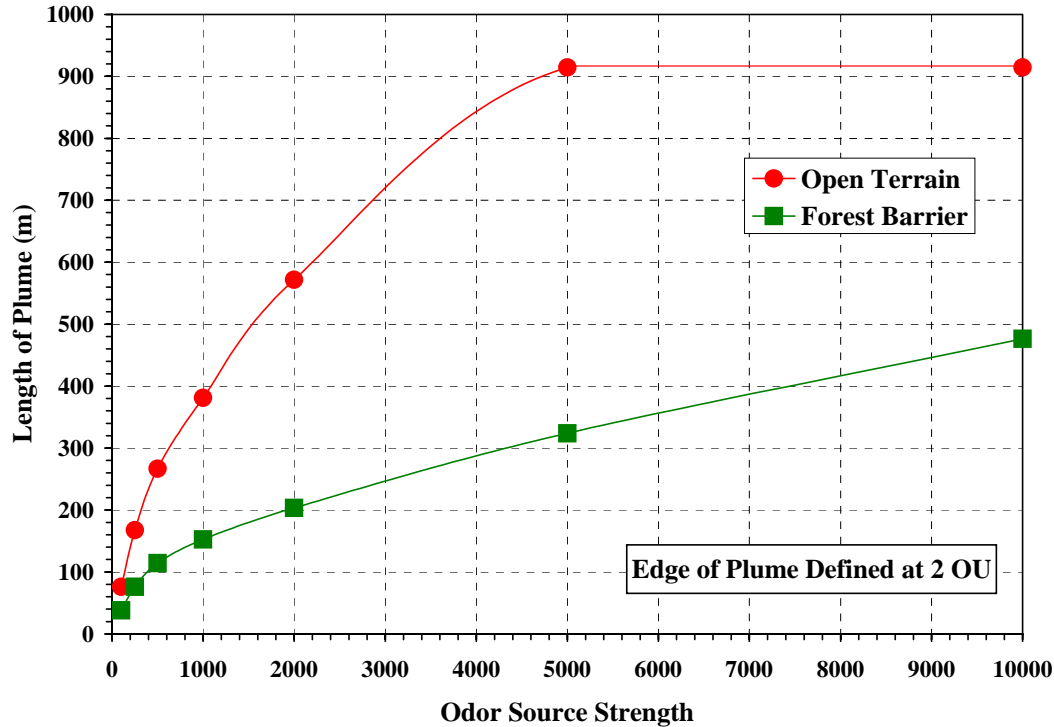
### Comparison With Field Observations

Very few field observations of odor plumes from livestock facilities are available in the literature. In 1989, du Toit made field observations of the odor plume from a poorly managed outdoor swine feedlot under nighttime conditions (presented by Gassman, 1992). It was determined that the odor source strength was 19,200 OU m<sup>3</sup>/s and the plume was observed to extend 850 m (2,789 ft). The terrain was open and flat. The results for the current model predict a plume length of 914 m (3,000 ft) for the same stability class and wind speed.

### Selection of Plume Length

Up to this point, the plume length has been defined as the downwind distance at which the odor has been reduced to 1 OU. However, by definition, 1 OU is a level that would be expected to be detected by only half of the population. The length of the odor plume can also be defined at 2 OU, which represents a slight odor that could be detected by most people. Results for worst case odor dispersion for a plume edge defined at 2 OU are presented in Figure 4.

**Figure 4 – Variation of Odor Plume Length Defined at 2 OU as a Function of Source Strength (OU m<sup>3</sup>/s) for Worst Case Odor Dispersion (Clear Night, Category 5,  $U = 0.89$  m/s (2 mph)).**



Comparison of the results presented in Figures 3 and 4 indicate that:

- Defining the plume edge at 2 OU versus 1 OU had no effect on potential siting specifications for source strengths of 5,000 to 10,000 OU m<sup>3</sup>/s for the open terrain class,
- Defining the plume edge a 2 OU instead of 1 OU reduced the plume length by 30 to 33% for values of  $Q$  ranging from 500 to 1,000 OU m<sup>3</sup>/s for the open terrain class of roughness, and
- The reduction in plume length for the forested terrain class ranged from 20 to 25% for source strengths in the range of 500 to 1,000 OU m<sup>3</sup>/s and 31% for  $Q = 10,000$  OU m<sup>3</sup>/s.

The selection of the odor level criterion for definition of plume length can have a significant impact on the development of siting specifications. The acceptable odor level at the plume edge will depend on the proposed location of the facility. If the facility is proposed in a rural agricultural area the 2 OU limit may be appropriate. However, people who live and work in towns and cities are often intolerant of any type of odor from agriculture. If the proposed livestock facility and land application areas would be near a town the 1 OU criterion may be needed.

## **APPLICATION OF MODEL RESULTS FOR SITE SELECTION**

Sensitivity analysis of an odor dispersion model is sufficient to demonstrate the influence of input parameters on the length of an odor plume. However, the input parameters are not well defined. Input variables such as the dispersion coefficients, roughness heights, and in particular the source strength of the odor are at best order-of-magnitude estimates. Even the assumption of Gaussian flow is not always true in the environment. Therefore, policy makers, regulators, and designers of livestock facilities must use caution in the interpretation of model results. An easy approach would be to assume the greatest odor source strength and worst case of odor dispersion for all cases and not allow livestock facilities to locate within 914 m (3,000 ft) of the nearest neighbor. While this would be an easy regulation to write and enforce very few locations, even in agricultural communities, would be deemed suitable for animal production. This would prove detrimental to the maintenance of the inexpensive and abundant food supply that is enjoyed in the United States. It would also impose on the rights of landowners to conduct the business of their choice. A more rational approach would be to begin by considering the economic importance of the livestock industry for a defined community, town, or state. In rural agricultural areas some odor of short duration may be tolerable since most people are or have engaged in agriculture as a vocation. On the other hand, few city dwellers are familiar with any type of agricultural operation and would oppose any facility that would impact air quality near their home or place of work. In short, separation specifications should take into account the current land use situation and the life style expectations of the people who live there.

The model results presented can provide objective guidance for the development of siting criteria for livestock production units. However, answers to the following questions must be developed early on in the process.

- What odor source strengths should be considered?
- What allowances should be made if a livestock producer intends to implement technologies and practices that are known to reduce the strength of odors (i.e. siting within a forest opening, direct injection of slurries, aeration of liquid manure, or anaerobic digestion)?
- Should worst case or typical weather criteria be used?
- What odor level should be used to define the plume length for a particular location or community?

### **Tables for Site Selection**

In most cases, odor source strengths in the range of 250 to 1,000 OU m<sup>3</sup>/s are the most descriptive of the levels that can be generated on livestock and poultry farms. Odors stronger than these would be infrequent. Stable atmospheric conditions, common at night and in the early morning hours, are common and should receive the greatest attention in the development of specifications for the location of animal facilities. In South Carolina, it has been estimated that stable or near stable conditions occur almost 300 days per year (Linvill, 1997). The sensitivity analysis results also clearly indicated that the greatest plume lengths occur at low wind speeds. A wind speed of 0.89 m/s (2 mph) is the lowest value used in the model. However, typical nighttime wind speeds are around 1.78 m/s (4 mph) in many areas of the US and should be considered. Model results for stable conditions and wind speeds of 0.89 and 1.78 m/s (2 to 4

mph) are given in Tables 2 and 3. Worst case odor dispersion for a forest barrier is given in Table 4. Plume lengths defined at 1, 2 and 5 OU are also presented for comparison.

**Table 2 - Estimates of plume lengths under stable atmospheric conditions (category 5, clear night) and a wind speed of 0.89 m/s (2 mph) in open terrain.**

Odor Level Used to Define Plume Length	Odor Source Strength, OU m <sup>3</sup> /s		
	1,000	500	250
	---- Distance Downwind, m (ft) ----		
1 OU (Detectable by 1/2 of the population)	572 (1,875)	381 (1,250)	244 (800)
2 OU (Mild, detectable by most everyone)	381 (1,250)	244 (800)	152 (500)
5 OU (Significant odor level)	229 (750)	152 (500)	76 (250)

**Table 3 - Estimates of plume lengths under stable atmospheric conditions (category 5, clear night) and a wind speed of 1.78 m/s (4 mph) in open terrain.**

Odor Level Used to Define Plume Length	Odor Source Strength, OU m <sup>3</sup> /s		
	1,000	500	250
	---- Distance Downwind, m (ft) ----		
1 OU (Detectable by 1/2 of the population)	381 (1,250)	244 (800)	152 (500)
2 OU (Mild, detectable by most everyone)	244 (800)	152 (500)	91 (300)
5 OU (Significant odor level)	152 (500)	76 (250)	61 (200)

**Table 4 - Effect of a forest barrier on plume length estimates under stable atmospheric conditions (category 5, clear night) and a wind speed of 0.89 m/s (2 mph).**

Odor Level Used to Define Plume Length	Odor Source Strength, OU m <sup>3</sup> /s		
	1,000	500	250
	---- Distance Downwind, m (ft) ----		
1 OU (Detectable by 1/2 of the population)	229 (750)	152 (500)	114 (375)
2 OU (Mild, detectable by most everyone)	152 (500)	114 (375)	76 (250)
5 OU (Significant odor level)	76 (250)	76 (250)	38 (125)

Some activities on livestock farms can generate strong odors over a short period of time. As was stated previously, these tasks should be scheduled when the atmosphere is neutral or unstable to provide for more vertical mixing. Estimates of plume lengths under neutral conditions are considered to represent the worst case for odor dispersion during the day. A comparison of model results for neutral conditions is provided in Table 5.

**Table 5 - Estimates of plume lengths under neutral atmospheric conditions (stability class D, category 4) and a wind speed of 2.68 m/s (6 mph) in open terrain.**

Odor Level Used to Define Plume Length	Odor Source Strength, OU m <sup>3</sup> /s		
	10,000	1,000	500
	---- Distance Downwind, m (ft) ----		
1 OU (Detectable by 1/2 of the population)	287 (940)	91 (300)	76 (250)
2 OU (Mild, detectable by most everyone)	192 (630)	38 (125)	****
5 OU (Significant odor level)	114 (375)	****	****

\*\*\*\* = too small to distinguish.

### Air Drainage

A Gaussian plume model can not be used to describe the effects of air drainage on odor transport. Air drainage is a factor to consider when constructing a new facility in hilly areas. During calm summer evenings the air near the ground begins to cool and drifts down-slope since cool air is heavier than warm air. If a livestock building or waste storage is located uphill from a town or cluster of houses the cool air will flow past the livestock facility, may pick up unpleasant odors, and may create a nuisance around dwellings in its path. This pattern of cold air drainage will be repeated at regular intervals throughout the year. It is important to avoid placing an odor generator in the path of an air drainage stream. As a result, it is best to choose a site that is not up-slope from close neighbors.

### Illustrative Example

The use of Tables 2 through 5 can be best demonstrated by a hypothetical example. In state X it was determined that site selection criteria would be developed for livestock production facilities in rural agricultural communities. Based on the results of discussion groups with rural residents, it was agreed that: (1) an acceptable odor level would be 2 OU, (2) most new, modern livestock production units will have emission rates of 500 OU or less, (3) the worst case odor dispersion scenario would be used to develop the criteria, and (4) allowances would be made for sites that can take advantage of a forest barrier to enhance odor dispersion. The resulting criteria for the location of new livestock or poultry production facilities are listed below.

1. The minimum separation distance from a new livestock or poultry facility and the nearest rural neighbor will be 1000 ft.

2. The separation distance can be reduced to 450 ft if the new facility is surrounded by a forest.
3. All operations that will generate greater than average amounts of odor must be performed between 8:00 am and 3:00 p.m.
4. No facility shall be located where air drainage could carry odors into a residential area, or onto the campus of a church or school.

## SUMMARY

A windows-based computer program was written to be used as a decision aide and educational tool for planning and locating livestock production facilities. The results of a sensitivity analysis clearly indicated that odor plume lengths are the greatest during the stable atmospheric conditions common at night. Neutral conditions during the day presented the next most critical period for odor dispersion. The extra vertical mixing provided by a significant increase in wind speed or the roughness associated with a forest barrier greatly reduced the distance that odor would travel. Information was also provided to provide objective guidance concerning the development of site selection criteria for a state, town, or rural community. The economic importance of livestock, the tolerances of odors, and other social factors will vary by state and community and should be part of the development of site selection specifications.

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