IMPORTANT COPYRIGHT INFORMATION

The following PDF article was originally published in the *Journal of the Air & Waste Management Association* and is fully protected under the copyright laws of the United States of America. The author of this article alone has been granted permission to copy and distribute this PDF. Additional uses of the PDF/article by the author(s) or recipients, including posting it on a Web site, are prohibited without the express consent of the Air & Waste Management Association.

If you are interested in reusing, redistributing, or posting online all or parts of the enclosed article, please contact the offices of the *Journal of the Air & Waste Management Association* at

Phone: +1-412-232-3444, ext. 6027  
E-mail: journal@awma.org  
Web: www.awma.org

You may also contact the Copyright Clearance Center for all permissions related to the *Journal of the Air & Waste Management Association*: www.copyright.com.

Copyright © 2006 Air & Waste Management Association
A Robust Method for Estimating Landfill Methane Emissions

Veronica K. Figueroa, Kevin R. Mackie, Nick Guarriello, and C. David Cooper
Department of Civil, Environmental, and Construction Engineering, University of Central Florida, Orlando, FL

ABSTRACT
Because municipal solid waste (MSW) landfills emit significant amounts of methane, a potent greenhouse gas, there is considerable interest in quantifying surficial methane emissions from landfills. The authors present a method to estimate methane emissions, using ambient air volatile organic compound (VOC) measurements taken above the surface of the landfill. Using a hand-held monitor, hundreds of VOC concentrations can be taken easily in a day, and simple meteorological data can be recorded at the same time. The standard Gaussian dispersion equations are inverted and solved by matrix methods to determine the methane emission rates at hours of point locations throughout a MSW landfill. These point emission rates are then summed to give the total landfill emission rate. This method is tested on a central Florida MSW landfill using data from 3 different days, taken 6 and 12 months apart. A sensitivity study is conducted, and the emission estimates are most sensitive to the input meteorological parameters of wind speed and stability class. Because of the many measurements that are used, the results are robust. When the emission estimates were used as inputs into a dispersion model, a reasonable scatterplot fit of the individual concentration measurement data resulted.

INTRODUCTION
Methane is emitted from various natural and human sources. Natural sources of methane include wetlands, termites, oceans, freshwater bodies, and wildfires. Human-related activities that produce methane include fossil fuel production, domestic livestock ranching/farming, manure management, rice cultivation, biomass burning, and waste management. It is estimated that 60% of global methane emissions are related to human-related activities. Table 1 lists the largest sources of methane emissions in the United States from 1990 to 2003 in teragrams of CO2 equivalents.

Methane Emissions in Municipal Landfills
There are approximately 2300 active landfills in the United States. As seen from Table 1, landfills are the largest human-related source of methane in the United States, accounting for 34% of all methane emissions. In landfills, the natural process of anaerobic decomposition of biodegradable waste creates biogas. Biogas is roughly composed of 45–60% methane (CH4), 40–60% carbon dioxide (CO2), and trace species. The trace gases often are highly odorous. The amount of biogas produced in landfills is a function of the waste (quantity, type, and age), landfill moisture content, temperature, and management practices at the site.

Global climate change is predicted to produce negative global effects such as more frequent and more powerful hurricanes, rising sea level and flooding, altered rainfall patterns resulting in major changes in agriculture, more insect infestations, and loss of glaciers. Global climate change is due in large part to the emissions of human-generated greenhouse gases, mainly CO2, CH4, nitrous oxide, and chlorofluorocarbons (CFCs).

Biogas contains both CH4 and CO2; however, CH4 is more of a concern. CH4 has a global warming potential of 25 times that of CO2 over 100-yr time horizon. Because CH4 is a key greenhouse gas and landfills produce a significant amount of CH4, there is considerable interest in quantifying surficial CH4 emissions from landfills.

Existing CH4 Emission Estimation Techniques
Numerous techniques exist for the estimation of CH4 emissions from landfills. The most popular methods are the chamber techniques, either static or dynamic. Both techniques have their own advantages and disadvantages. For example, the dynamic or open flux chamber simulates field conditions better than the static or closed flux chamber; however, the open chamber may indicate artificially high fluxes because of pressure changes inside of the chamber. In contrast, the closed flux chamber is much easier to use and cheaper to operate than the open chamber; however, the closed chamber tends to underestimate the gas fluxes because of pressure buildup with time that distorts the gas flow pathways in the soil and decreases the flow into the chamber. Other drawbacks to the flux chamber method include labor and time required and getting only point measurements that often give highly...
variable results between measurements even just a few meters apart.

\( \text{CH}_4 \) production rates can be estimated by any of several biogas production models. The U.S. Environmental Protection Agency (EPA) Landfill Gas Emissions Model (LandGEM) is such an estimation tool; another is MICROGEN-MGM.\(^a\) Gas generation models rely on assumptions of waste decomposition rates and microbial growth kinetics. A major drawback is the need for precise data on waste decomposition rates and microbial growth kinetics. Also, the models do not account for how much of the \( \text{CH}_4 \) is being captured versus being emitted (although one can always assume a collection system efficiency and make a simple estimate).

The \( \text{CH}_4 \) emissions from an entire area source can be calculated using a ground-based optical remote sensing (ORS) method.\(^b\) The ORS method uses open-path Fourier transform infrared (OP-FTIR) spectroscopy to obtain path-integrated pollution concentration information along multiple plane-configured optical paths.\(^c\) The source emissions can be determined after processing the pollutant concentration information and wind vector information with a plane-integrating computer algorithm. Problems with ORS methods are that they are expensive, time and labor intensive, depend on good measurement of meteorological parameters, and produce only one integrated emission rate for the whole landfill. This last disadvantage may make this method questionable for use in dispersion modeling studies (such as with odors).

**CH\(_4\) Concentration Data May Already Be Available**

Many large landfills are already collecting ambient air \( \text{CH}_4 \) data. Under the 1996 EPA New Source Performance Standards and Emission Guidelines for Municipal Solid Waste Landfills (40 CFR Part 60, Subparts WWW), landfills with the potential to emit more than 50 Mg/yr of non-methane volatile organic compounds (NMVOCs; typically <1% of landfill gas [LFG] or ~2% of \( \text{CH}_4 \) emissions) must collect and combust the LFG. Combusting or flaring of LFG reduces odors, safety concerns, and \( \text{CH}_4 \) emissions.

To ensure that the LFG collection systems are operating properly, quarterly surface volatile organic compound (VOC) monitoring must be conducted according to EPA regulations (40 CFR 60.755 (c) and (d), and 40 CFR 60, Appendix A, Method 21). These regulations require air monitoring around the perimeter of and within the area of a LFG collection system to determine compliance. Readings above 500 parts per million (ppm) require remedial action and may imply that something is wrong in the gas collection system.

**Proposed \( \text{CH}_4 \) Emissions Estimation Technique**

The authors propose a \( \text{CH}_4 \) emissions estimation technique that takes advantage of the hundreds of ambient air VOC concentration measurements already being taken within many municipal solid waste (MSW) landfills. These measurement locations are set as receptors, and numerous other locations are chosen as sources. The standard Gaussian dispersion equations are inverted and solved by matrix methods to determine the best-fit \( \text{CH}_4 \) emission rates throughout the landfill. What makes this proposed method so promising is that (1) it simultaneously uses hundreds of measurements, and (2) it quickly solves the equations for the best-fit set of source emission rates without tedious trial-and-error search algorithms.

The foundation for atmospheric dispersion calculations is the Gaussian dispersion equation as shown in eq 1 written for a nonreactive gaseous pollutant from a point source.\(^d\)

\[
C = \frac{Q}{2\pi u \sigma_x \sigma_y} \exp \left( -\frac{1}{2} \frac{y^2}{\sigma_y^2} \right) \exp \left( -\frac{1}{2} \frac{(z - H)^2}{\sigma_z^2} \right) \\
+ \exp \left( -\frac{1}{2} \frac{(z + H)^2}{\sigma_z^2} \right)
\]

where \( C \) is the steady-state concentration (\( \mu \text{g}/\text{m}^3 \)) at a point \((x, y, z)\), \( Q \) is the emission rate (\( \mu \text{g}/\text{sec} \)), \( \sigma_y \) and \( \sigma_z \) are the horizontal and vertical spread parameters (m) that are functions of the downwind distance and atmospheric stability, \( u \) is the average wind speed at stack height (m/sec), \( y \) is the crosswind distance from ground level (m), \( z \) is the vertical distance above the ground (m), and \( H \) is the effective stack height (physical stack height plus plume rise) (m). Figure 1 represents the source-receptor geometry for one source \((j)\) and one receptor \((i)\) in a landfill at one particular wind angle \( \Theta \).

The \( x \) and \( y \) shown in Figure 1 are not the distances in the east \((x)\) and north \((y)\) directions; rather, they are the downwind and crosswind distances specific to this particular source-receptor combination. They are given by the following equations:

\[
x = \Delta X \sin \Theta + \Delta Y \cos \Theta
\]

Table 1. U.S. \( \text{CH}_4 \) emissions by source (Tg CO\(_2\) equivalents).\(^a\)

<table>
<thead>
<tr>
<th>Source Category</th>
<th>1990</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landfills</td>
<td>172.2</td>
<td>130.7</td>
<td>126.2</td>
<td>126.8</td>
<td>131.2</td>
</tr>
<tr>
<td>Natural gas systems</td>
<td>128.3</td>
<td>132.1</td>
<td>131.8</td>
<td>130.6</td>
<td>125.9</td>
</tr>
<tr>
<td>Enteric fermentation</td>
<td>117.9</td>
<td>115.6</td>
<td>114.5</td>
<td>114.6</td>
<td>115</td>
</tr>
<tr>
<td>Coal mining</td>
<td>81.9</td>
<td>56.2</td>
<td>55.6</td>
<td>52.4</td>
<td>53.8</td>
</tr>
<tr>
<td>Manure management</td>
<td>31.2</td>
<td>38.1</td>
<td>38.9</td>
<td>39.3</td>
<td>39.1</td>
</tr>
<tr>
<td>Wastewater treatment</td>
<td>24.8</td>
<td>34.3</td>
<td>34.7</td>
<td>35.8</td>
<td>36.8</td>
</tr>
<tr>
<td>Other</td>
<td>45.8</td>
<td>43.5</td>
<td>41.7</td>
<td>39.6</td>
<td>39.8</td>
</tr>
<tr>
<td>Total for United States</td>
<td>605.3</td>
<td>554.2</td>
<td>546.7</td>
<td>542.3</td>
<td>544.9</td>
</tr>
</tbody>
</table>

Notes: \(^a\)Tg = 10\(^{12}\) g.
In eqs 2 and 3, \( \Delta X = (x_i - x_j) \) and \( \Delta Y = (y_i - y_j) \), where \( x_i \) and \( y_i \) are the \( x \) and \( y \) coordinates of receptor and source, respectively, and \( \Theta \) is the angle of the wind vector passing through the source, relative to the north (\( y \) axis).

For ground-level sources and receptors (\( z = 0 \) and \( H = 0 \)), eq 1 reduces to eq 4. Equation 4 can be written as eq 5 for each source-receptor pair \((j,i)\), where \( C_{i,j} \) represents the modeled concentration at receptor \( i \) due to source \( j \) in \( \mu g/m^3 \), \( Q_j \) is the source \( j \) emission rate \( g/sec \), and \( f(x, y)_{i,j} \) is the rest of eq 4 for each source-receptor pair. It contains the values of wind speed, dispersion parameters, and crosswind \( (y) \) distances between source \( j \) and receptor \( i \), as seen in Figure 1.

\[
C = \frac{Q}{\pi ud\sigma_x\sigma_y} \exp\left( -\frac{1}{2} \frac{y^2}{\sigma_y^2} \right) \tag{4}
\]

\[
C_{i,j} = f(x, y)_{i,j}Q_j \tag{5}
\]

Note that is does not matter if \( y \) from eq 3 is positive or negative because it will be squared in eq 4. If \( x \) is negative, it simply means that the receptor is upwind from the source, and for that pairing, the function \( f \) in eq 5 is set to zero during the calculations.

The horizontal and vertical dispersion spread parameters are defined by eqs 6 and 7, originally developed by Martin.10 The parameters \( a, b, c, d, \) and \( f \) are numerical curve-fit constants that are functions of downwind distance, \( x \) (in kilometers), and atmospheric stability.

\[
\sigma_y = ax^b \tag{6}
\]

\[
\sigma_z = cx^d + f \tag{7}
\]

Assuming the \( CH_4 \) background concentration is zero, the total modeled concentration \( \mu g/m^3 \), \( C_{\text{modeled}} \) at each receptor is the sum of all the modeled concentrations at receptor \( i \) due to each of the \( n \) sources as shown in eq 8.

\[
C_{i,\text{modeled}} = \sum_{j=1}^{n} C_{i,j} \tag{8}
\]

The vector containing all of the modeled concentrations \( C_{i,\text{modeled}} \) is denoted as \( \mathbf{c}_{\text{modeled}} \) and has \( m \) components. Similarly, the vector containing all of the predicted emission rates \( Q_j \) is denoted as \( \mathbf{q} \) and has \( n \) components. The sum of squares of the residuals (differences between modeled and measured concentrations) is

\[
R^2 = \sum_{i=1}^{m} (C_{i,\text{measured}} - C_{i,\text{modeled}})^2 \tag{9}
\]

One method for determining the best-fit \( CH_4 \) emission rates \( \mathbf{q} \) within a landfill involves assuming different trial sets of \( n \) \( Q_j \) values and then calculating the sum of squares of the residuals over all \( m \) receptors using eq 9. A “brute force” trial-and-error method could be used to find the optimal set of \( Q_j \), \( \mathbf{q}_{\text{trial\&error}} \), to minimize \( R^2 \), as shown in eq 10.

\[
\mathbf{q}_{\text{trial\&error}} = \arg \min_{\mathbf{q}} [R^2] \tag{10}
\]

However, with hundreds of receptors and hundreds of sources, this method would be impossibly slow and inefficient. In addition, there is no mathematical guarantee that this trial-and-error method would yield the minimum possible sum of squares of the residuals unless an infinte set of receptors and sources was used.

A much more efficient method for determining the optimal set uses matrix methods. Equation 11 is equivalent to eq 9 but is represented in matrix notation. It follows the form of a standard least-squares problem in which the objective is to minimize the 2-norm of the residual.

\[
\min_{\mathbf{q}} \| \mathbf{F} \cdot \mathbf{q} - \mathbf{c}_{\text{modeled}} \|^2 \tag{11}
\]

where \( \mathbf{F} \in \mathbb{R}^{mxn} \) is the (real) \( m \) by \( n \) matrix of values of the function \( f(x,y)_{i,j} \), \( \mathbf{q} \in \mathbb{R}^n \) is the (real) \( n \) vector of sources, and \( \mathbf{c}_{\text{measured}} \in \mathbb{R}^m \) is the (real) \( m \) vector of measured receptor concentrations. Equation 11 can be solved using basic linear least-squares regression theory if the number of sources is less than or equal to the number of receptors. In addition, if any downwind distance is negative, \( F_{i,j} \) must be set to zero because the receptor is upwind from the source.

The vector \( \mathbf{q} \) that minimizes eq 11 is unique if and only if \( \mathbf{F} \) has full rank. If \( \mathbf{F} \) has full rank, \( \mathbf{q} \) can be determined using the normal equations as eq 12, in which the pseudoinverse \( \mathbf{F}^+ \) is shown in eq 13.
Such a least-squares solution technique for emission prediction has previously been implemented for farm \( \text{CH}_4 \) emissions using a backward Lagrangian stochastic model.\textsuperscript{11} The study indicated that the emission results were sensitive to the condition number; however, it will be illustrated in this paper that the conditioning issues can be alleviated by better choice of source-receptor geometry and by reduction of the coefficient matrix to full rank.

In addition, the formulation in eq 12 does not guarantee that each \( Q_i \) is not negative. Therefore, a more general approach, eq 14, is necessary and requires solution of the non-negative constrained least-squares problem, where \( I \) is the identity matrix. The non-negative least-squares (NNLS) problem can be solved numerically using various available transformation, active-set, or iterative algorithms.\textsuperscript{12}

\[
\mathbf{q} = \arg\min_{\mathbf{q}} \| \mathbf{F} \cdot \mathbf{q} - \mathbf{c}_{\text{measured}} \|_2 \quad \text{subject to} \quad \mathbf{q} \geq 0
\]  

\[
\mathbf{F}^+ = (\mathbf{F}^\top \mathbf{F})^{-1} \mathbf{F}^\top
\]

\textbf{METHODOLOGY}

The following discussion outlines the authors’ methodology for determining \( \text{CH}_4 \) emission rates from a MSW landfill.

\textbf{Step 1: Obtain VOC Data and Locate Receptors}

Obtain ambient air VOC measurements (e.g., with a portable flame-ionization detector [FID], reported as \( \text{CH}_4 \)) at numerous locations within the landfill. It is noted that the ambient VOC concentrations near a MSW landfill are almost entirely composed of \( \text{CH}_4 \), so such measurements can be taken as the \( \text{CH}_4 \) concentrations. If the landfill is large enough that such measurements are required by 40 CFR Part 60, Subparts WWW, reasonable estimates of the locations of the measurements should also be made. If the landfill does not require quarterly ambient air VOC measurements, a walking survey with instruments (a portable FID and a global positioning system [GPS]) is recommended to obtain the ambient concentrations and to link each concentration with a location. Also, the local wind speed and direction and stability class must be determined during the time of the walking survey.

\textbf{Step 2: Designate Source Locations}

Use an aerial photo or plot plan to plot the locations of the concentration measurements (the receptors). Next, designate locations of numerous point sources throughout the MSW landfill. Recall the constraints previously defined: the number of sources must be less than or equal to the number of receptors. Locations of these sources should be chosen generally upwind of receptors, not too close or too far away. In this research, the authors initially used their best judgment in locating sources. This method influenced the final answers for individual source strengths and (as it turned out) the final estimate of overall emissions. This realization by the authors led to a better method for locating sources, as discussed later in this paper.

\textbf{Step 3: Formulate and Solve Dispersion Model by Matrix Inversion}

Solve the standard Gaussian dispersion equations by matrix inversion methods, as previously described, to determine the \( \text{CH}_4 \) emission rates at the various sources throughout the MSW landfill. This was done easily in MATLAB,\textsuperscript{13} commercial software that specializes in numerical computing and allows easy matrix manipulation.

\textbf{Step 4: Perform Sensitivity Studies}

Perform sensitivity studies to explore the sensitivity of results to source locations and meteorological parameters. Although not required to obtain emission estimates, it is always wise to understand the sensitivity of models to their input parameters.

\textbf{Step 5: Formulate Air Dispersion Model to Test Results}

After determining the best representation of \( \text{CH}_4 \) point-source emission rates from the MSW landfill, use those emission rates in a Gaussian air dispersion model, such as the Industrial Source Complex Model (ISC),\textsuperscript{14} AERMOD,\textsuperscript{15} or CALPUFF,\textsuperscript{15} to model the VOC ambient air concentrations at each receptor. (ISC was utilized in this study instead of the current EPA model, AERMOD, because the ISC model allows one to easily specify the particular hour or hours of meteorological data to model the situation during the VOC measurement period of time.) Compare the modeled receptor concentrations with the ambient air VOC measurements to test the accuracy of the predicted \( \text{CH}_4 \) emission rates. Note: Assuming that the emission rates will not change significantly over a few days, this step could be done with an independent concentration dataset from a different day with different meteorology.

\textbf{CASE STUDIES}

\textbf{Simple Scenario Test Case}

Before using the above methodology on a landfill, a simple scenario was devised as a test case to determine the accuracy of the proposed method to predict source strengths. This test case is based on a small and simplified set of receptors and sources with precisely known source locations and strengths. Figure 2 shows the test case’s source-receptor geometry.

Instead of obtaining ambient air VOC measurements, the test case relied on a modeling exercise, described as follows. Fifteen receptors and 10 sources were judiciously placed in a grid, and their \( x\)-\( y \) coordinates determined (see Figure 2). Source emission rates, \( \mathbf{q}_{\text{Assumed}} \), were assumed (see Table 2), and eqs 1–8 were solved in a spreadsheet for a specific meteorology: wind speed of 2 m/sec, wind direction from 40°, and stability class C. The calculated receptor concentrations, \( \mathbf{c}_{\text{Excel}} \), are presented in Table 3.

Because this test case solved for the concentrations’ given source strengths—a forward solution of eqs 1–8—the proposed method must be able to recover the input by backward solution to prove that it could apply to actual
MSW landfills. The concentrations and coordinates from Table 3 were entered along with the meteorology into the MATLAB\textsuperscript{13} program, and the standard Gaussian dispersion equations were solved using a NNLS algorithm to determine the best-fit emission rate at each source. The authors’ method was able to exactly reproduce the original emission rates, as expected for an accurate method given accurate data.

Central Florida MSW Landfill Case Study

The methodology was applied to an existing MSW landfill, serving a single county in the central Florida area to determine CH\textsubscript{4} emissions from the landfill. Figure 3 is an aerial photograph of the landfill showing both a closed and an active cell. This MSW landfill is a class 1 landfill, serving over 300,000 residents in 7 cities and the unincorporated county. It receives approximately 810 t of waste per day. The total disposal area is 232 acres; currently only 127 acres have been used. Typical types of received waste include residential, commercial, incinerator/waste-to-energy ash, treated biomedical, water treatment sludge, air treatment sludge, agricultural, asbestos, construction and demolition debris, shredded tires, and yard trash. The landfill has two candlestick flares that were burning the collected CH\textsubscript{4}, but recently installed four 1-MW internal combustion engines fueled by LFG to generate electricity.

Steps 2 and 3: Obtain Measurements and Locate Receptors and Sources. Initially, a copy of a recent quarterly surface monitoring report for this landfill was obtained (second quarter, 2007). Ambient air VOC concentrations at 358 locations within the landfill were read from the report. The data had been recorded in ppm as CH\textsubscript{4} using a Landtec SEM 500 FID during a walking survey. Locations of the measurements were later estimated from notes made by the technician who did the survey. The local wind speed and direction at the time of measurement were measured as 1.3 m/sec and from 40° (northeast), respectively. The stability class was estimated after the fact from records of data from a nearby airport. On the day and time of the survey, the temperature was 88 °F with scattered clouds, and class B stability conditions were estimated. Figure 4 shows the receptor locations for the 358 VOC readings. Locations for the point sources were chosen by hand on the basis of criteria discussed previously. Figure 5 shows the 356 point sources that were selected.

Step 3: Formulate Matrix Dispersion Model. The CH\textsubscript{4} emission rates throughout the landfill were determined by solving the standard Gaussian dispersion equations by matrix methods, as previously described. Figure 6 is a plot of the CH\textsubscript{4} emission isopleths. On the basis of the results, Phase I emits much less CH\textsubscript{4} than Phase II. This makes sense because Phase I is closed and has a gas collection system that appears to provide sufficient coverage. For Phase II, the areas of highest CH\textsubscript{4} emissions may identify locations where waste was recently deposited or where a temporary soil cover might not be adequately covering the waste.

One advantage of the matrix solution methodology is that it automatically removes sources that do not contribute to the solution. For the predicted source emissions solution to be unique, it is necessary for F to be full rank. Numerically it is possible to determine what sources are linearly dependent and therefore causing rank deficiency. For instance, 356 point sources were chosen by the authors; however, before solving the NNLS problem, an algorithm performed row reduction on the F matrix to identify and remove all sources that were linearly dependent. It is for this reason

<table>
<thead>
<tr>
<th>Receptor Number</th>
<th>x</th>
<th>y</th>
<th>( C_{\text{Excel}} ) (( \mu g/m^2 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>800</td>
<td>500</td>
<td>33</td>
</tr>
<tr>
<td>2</td>
<td>700</td>
<td>300</td>
<td>164</td>
</tr>
<tr>
<td>3</td>
<td>600</td>
<td>100</td>
<td>93</td>
</tr>
<tr>
<td>4</td>
<td>800</td>
<td>400</td>
<td>235</td>
</tr>
<tr>
<td>5</td>
<td>900</td>
<td>500</td>
<td>649</td>
</tr>
<tr>
<td>6</td>
<td>1000</td>
<td>300</td>
<td>49</td>
</tr>
<tr>
<td>7</td>
<td>1000</td>
<td>400</td>
<td>171</td>
</tr>
<tr>
<td>8</td>
<td>1600</td>
<td>1100</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>1000</td>
<td>700</td>
<td>648</td>
</tr>
<tr>
<td>10</td>
<td>1100</td>
<td>600</td>
<td>273</td>
</tr>
<tr>
<td>11</td>
<td>800</td>
<td>200</td>
<td>199</td>
</tr>
<tr>
<td>12</td>
<td>1200</td>
<td>500</td>
<td>62</td>
</tr>
<tr>
<td>13</td>
<td>1400</td>
<td>600</td>
<td>41</td>
</tr>
<tr>
<td>14</td>
<td>1000</td>
<td>750</td>
<td>70</td>
</tr>
<tr>
<td>15</td>
<td>800</td>
<td>900</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 2. Source data for test case.
that each of the cases reported below (Cases 1–3) have a total number of sources less than 356.

**Step 4: Perform Sensitivity Studies.** First, a limited sensitivity study was performed on the numbers and locations of point sources. This part of the sensitivity testing included three cases:

- **Case 1:** Base case with 356 sources that were chosen carefully to ensure that sources were in “good” positions (e.g., upwind and not too close nor too far from receptors—an intelligent choice of locations).
- **Case 2:** All of the 356 sources from Case 1 were uniformly relocated 20 m east of their original location (an unintelligent choice of locations).
- **Case 3:** 128 sources were deleted from the initial 356 sources of Case 1, whereas the remaining 228 sources stayed at the same locations as Case 1 (a case to test robustness with regard to number of sources).

Table 4 compares the calculated landfill emission inventory for each of the above cases. As previously mentioned, before solving the NNLS problem, all sources that do not contribute or are linearly dependent are automatically removed. Table 4 shows the calculated emission inventory for each of the cases.
inventory (on the basis of ambient CH$_4$ concentration data from this one monitoring report). This table also shows the number of sources the authors input and the resulting number of sources that were determined to be linearly independent.

Table 4 illustrates that changing the number of point sources did not significantly change the total CH$_4$ emissions inventory, thus demonstrating the robustness of the proposed method. Comparing Case 3 with Case 1, the differences in the calculated CH$_4$ emissions rates were small. Table 4 also illustrates that varying the locations of the point sources can produce variations in the emission inventory.

Recall that for Case 1, source locations were chosen based on close visual inspection of where the concentration measurements had been made and using good judgment about keeping sources upwind of receptors. Comparing Case 2 with Case 1, a “less intelligent” process for locating the point sources, created a 12.5% difference in the landfill’s emission inventory. Recall that for Case 2, all of the sources from Case 1 were uniformly relocated 20 m east of their original location. Therefore, using good judgment in placing sources did make a difference.

The sensitivity to source location led to further research on techniques for automated source placement. An
approach using Voronoi diagrams and importance sampling was developed that mitigates the dependence on expert opinion for selecting source locations. This approach is briefly discussed in the following paragraphs and is described in more detail elsewhere. An importance sampling algorithm was also developed to help determine optimal placement of the sources using the input locations as a starting point. For each realization of the simulation, probability density functions that describe likely locations of the sources were sampled. These sampled locations were then evaluated using the authors’ methods described earlier to produce emission estimates.

The optimum set of sources, as defined by the minimum sum of squares of the residuals (eq 11) was found using importance sampling. Because of the computational demands of the NNLS algorithm with 356 (approximately) sources, it was only feasible to run 50–200 simulations. However, even with this relatively small number, fairly stable values of the total landfill CH$_4$ emission rate were obtained, and the result was an “automated” method using Voronoi diagrams and importance sampling that is being published separately.

The Voronoi diagram method of placing sources proved to be a significant improvement to the “good judgment” method; furthermore it was automated and thus much faster. The revised emissions estimate for the base case (data from the monitoring survey of second quarter, 2007) using the Voronoi method was 708 g/sec (vs. 970 g/sec). Two other monitoring surveys were obtained for the same landfill (fourth quarter 2006 and second quarter 2008). For all three datasets, the source placements were determined using the Voronoi diagram method, and the emissions were recalculated. The results are shown in Table 5.

As can be seen from Table 5, the three estimates of total CH$_4$ emissions from this landfill showed significant variability, with the 2006 and 2007 datasets giving relatively close estimates (609 and 708 g/sec, respectively), and the 2008 data yielding a significantly higher number (1233 g/sec). Possible explanations for the higher number in 2008 were that waste deposits into the landfill increased significantly during that time frame, disturbances in the surface cover had occurred, rainfall patterns had affected the emissions, the barometric pressure had changed significantly the day of the sampling, or that the meteorological parameters had been incorrectly estimated. For example, the authors had estimated the stability class for the 2008 dataset as Class B. Choosing stability Class C instead would have resulted in an emissions estimate of 766 g/sec. This last bit of information led the authors to explore in more detail the sensitivity of the results to the meteorological input parameters. For each sampling event, the local wind speed and direction were measured at the site one time (before the start of sampling). However, the stability class was estimated after the fact on the basis of National Weather Service data that had been originally recorded on the same date and time of the monitoring event at an airport approximately 10 mi away from the landfill.

In the sensitivity testing of the meteorological parameters, the authors used the second quarter 2007 monitoring data modeled using the Voronoi approach as the base case. The wind speed, wind direction, and stability class were each varied one at a time, and the emissions model was run for each case. The emissions estimates are sensitive to each of these parameters as shown in Table 6 and as discussed below.

In the base case, the wind speed was estimated to be 1.34 m/sec from airport data. If in fact the wind speed at the site was actually 2 m/sec, a 49% increase above the base case, the emissions estimate would have been 49% higher. If we had wrongly estimated the stability class by one class, it would introduce an error in the input of 16.6% (one of six classes). As can be seen from Table 6, missing the stability class by one would result in a larger error in the emissions estimate. Furthermore, the size of the error would depend

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Second Quarter, 2007 (hand-picked sources)$^a$</th>
<th>Second Quarter, 2007 (Voronoi sources)$^b$</th>
<th>Fourth Quarter, 2006 (Voronoi sources)$^b$</th>
<th>Second Quarter, 2008 (Voronoi sources)$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind angle (degrees)</td>
<td>40</td>
<td>40</td>
<td>130</td>
<td>150</td>
</tr>
<tr>
<td>Wind speed (m/sec)</td>
<td>1.34</td>
<td>1.34</td>
<td>0.89</td>
<td>2.24</td>
</tr>
<tr>
<td>Stability class</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Background concentration (ppm)</td>
<td>0.0</td>
<td>2.4</td>
<td>3.1</td>
<td>1.8</td>
</tr>
<tr>
<td>Total emissions (g/sec)</td>
<td>970</td>
<td>708</td>
<td>609</td>
<td>1233</td>
</tr>
</tbody>
</table>

Notes: $^a$Not adjusted for background; $^b$Adjusted for background.
on whether the actual stability class was more stable or more unstable. An error in input wind direction was divided by 180° to obtain its percent change. The emissions estimate was not as sensitive to wind direction as it was to stability class or wind speed. However, it was concluded that it is very important to obtain good data for the on-site meteorology during such sampling events.

The emission rates obtained in this study were compared with independent flux measurements taken by another researcher on the same landfill. Using flux measurements taken only in the active area in 2007 by Nalamothu,

we calculated a total emission rate of between 40 and 80 g/sec, depending on how one handles the readings below the detection limit. Clearly in this case there was a dramatic difference between the emissions as estimated from previous flux measurements compared with those estimated from our inverse modeling methods. Such large differences are difficult to explain, but possible reasons include the following:

- There may be errors in the estimates of stability class or wind speed (thus overestimating emissions)—our method is very sensitive to these parameters.
- The flux chamber operator may have missed the biggest “hot spots” in the landfill (thus underestimating emissions).
- The actual emissions may well fluctuate significantly from day to day, and by chance the flux chamber data were taken on a day with very low emissions, and the modeling results were based on a day with very high emissions.

In any case, such differences suggest the need for a future study in which independent measurements of emission rates can be taken simultaneously with ambient CH₄ concentrations and meteorological data.

The estimated CH₄ emissions rate based on the authors’ methods was compared with several other landfills in the United States. Table 7 shows that the estimated total CH₄ emissions from the central Florida landfill is of the same order of magnitude (considering the amount of waste emplaced) as from several other U.S. landfills.

Step 5: Run an Air Dispersion Model. The predicted CH₄ emission rates from Case 1 were input into ISC to determine modeled ambient CH₄ concentrations at the same receptors. The details of this modeling are presented elsewhere. Figure 7 is a scatterplot that compares the ambient air VOC measurements to ISC’s modeled concentrations.

The scatterplot shows a positive, linear correlation between the modeled and the measured VOC concentrations. The best-fit equation has a slope of 1.36, showing a slight tendency toward overprediction. The correlation coefficient, R², is 0.89, indicating a very good relationship between the modeled and measured concentrations; for example, 89% of the variability in the data is accounted for by the modeling. Ideally, for a strong correlation, the R² value should be 0.80 or greater.

Most of the points lie within the 1:2 and the 2:1 slope lines.

CONCLUSIONS AND RECOMMENDATIONS

The authors conclude the following:

1. As shown by the test case, the authors’ approach can accurately solve for source strengths when provided with a sufficient number of accurate ambient concentrations along with accurate meteorological data.

Table 7. Order-of-magnitude comparisons of three landfills in the United States.

<table>
<thead>
<tr>
<th>Landfill</th>
<th>Year</th>
<th>Waste in Place (t)</th>
<th>Estimated CH₄ Emissions (g/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>This landfill in Central Florida</td>
<td>2007</td>
<td>6,456,000</td>
<td>708³</td>
</tr>
<tr>
<td>Outer Loop, Kentucky⁴</td>
<td>2003</td>
<td>1,930,825</td>
<td>38⁸</td>
</tr>
<tr>
<td>Outer Loop, Kentucky⁵</td>
<td>2003</td>
<td>384,000</td>
<td>160⁵</td>
</tr>
<tr>
<td>Kenosha, Wisconsin⁹</td>
<td>2003</td>
<td>5,720,000</td>
<td>899⁴</td>
</tr>
<tr>
<td>Central Landfill, Rhode Island²⁰</td>
<td>1996</td>
<td>5,916,400</td>
<td>194⁴</td>
</tr>
</tbody>
</table>

Notes: ³As calculated in this study. ⁴These cells are operated as a facultative landfill biofilter (FLB). Emissions estimated using optical methods, and complete capture of the plume was likely not achieved. ⁵These cells are operated as an aerobic-anaerobic landfill biofilter (AALB). Emissions estimated using optical methods, and complete capture of the plume was likely not achieved. ⁶This landfill is a traditional MSW landfill with no gas collection assumed. ⁷For this landfill, a gas generation rate of 1293 g/sec was calculated with the LandGEM model, and an 85% collection efficiency was assumed for the gas collection system, leaving a calculated emission rate of 194 g/sec as reported by the authors of that study.
(2) Variations in the number and locations of the sources used to model the central Florida landfill produced relatively small variations in the landfill’s predicted CH₄ emission inventory. This demonstrates the robustness of the methodology.

(3) The total CH₄ emission rate for a real MSW landfill calculated by our method using the data from one monitoring event compared reasonably well with the rate obtained by using one other dataset from another quarter. This demonstrates the potential accuracy of our method. However, data from another quarter showed a significantly different emission rate. This, combined with the sensitivity testing, suggests that one or more of the meteorological parameters were not determined accurately and points to the need to measure the meteorological data accurately during the ambient monitoring to produce accurate emission estimates.

(4) As evidenced by Figures 6 and 7, our methodology shows promise for predicting spatial variation in emission rates from landfills, from which dispersion models can be used to predict VOC and odor concentrations around landfills (or other area sources) with reasonable accuracy. This methodology is still a work in progress. More quarters of measured data should be assessed for this landfill, and more landfills should be assessed. A significant monitoring/modeling study is needed to test the accuracy of this method. However, once the methodology is refined, this technique offers much promise to the solid waste industry. First, the calculation of a MSW landfill’s carbon footprint can be made with very little extra effort if on-site monitoring data are already available (as will be the case for many landfills). Local and national greenhouse gas inventories will improve by more accurately calculating CH₄ fugitive emissions from a landfill. The ability to check the efficiency of existing gas collection systems will be enhanced by determining the emissions at a variety of points within a MSW landfill and identifying areas of greater than normal losses. This should also improve the design and maintenance of LFG collection systems. The ability to assess potential health and odor impacts will increase, thus encouraging more effective land use management near landfills.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the Hinkley Center for Solid and Hazardous Waste Management, as well as the in-kind cooperative efforts of personnel at the county landfill located in central Florida from which the data were gathered.

REFERENCES


About the Authors
Veronica Figueroa, M.S., recently completed her master’s degree in environmental engineering at the University of Central Florida (UCF) and is currently working for SCS Engineers in Tampa, FL. Kevin Mackie, Ph.D., is an assistant professor in the Civil, Environmental, and Construction Engineering (CECE) department at UCF. Nick Guarriello is a graduate student in environmental engineering at UCF. C. David Cooper, Ph.D., PE, QEP, is a professor of environmental engineering in the CECE department at UCF. He is also a fellow of the Air & Waste Management Association. Please address correspondence to C. David Cooper, Department of Civil, Environmental, and Construction Engineering, University of Central Florida, Orlando, FL 32816-2450; phone: +1-407-823-2388; fax: +1-407-823-3315; e-mail: cooper@mail.ucf.edu.