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Screening procedure for airborne pollutants emitted from a high-tech industrial complex in Taiwan

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HIGHLIGHTS

- The purpose of this study was to develop a two-stage air dispersion modeling procedure to screen out critical pollutants emitted from an industrial complex.
- The first stage was pre-creating a look-up table of dispersion factor with meteorological data. Secondly, an algorithm was developed to interpolate on the look-up table for dispersion factor with the emission data.
- A "risk strength", defined as the ratio of concentration to the site boundary standard or air quality standard, was estimated for each air toxic for the screening.
- A total of 1654 records of 21 pollutants emitted from 232 stacks for a high-tech complex site monitored in 2007–2009 were acquired to illustrate this screening method.
- A validation check using ISC3 model with the same meteorological and emission data showed an acceptable overestimate of 6.7% in the average concentration of the 10 nearby receptors.

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ABSTRACT

Despite the modernization of computational techniques, atmospheric dispersion modeling remains a complicated task as it involves the use of large amounts of interrelated data with wide variability. The continuously growing list of regulated air pollutants also increases the difficulty of this task. To address these challenges, this study aimed to develop a screening procedure for a long-term exposure scenario by generating a site-specific lookup table of hourly averaged dispersion factors (χ/Q), which could be evaluated by downwind distance, direction, and effective plume height only. To allow for such simplification, the average plume rise was weighted with the frequency distribution of meteorological data so that the prediction of χ/Q could be decoupled from the meteorological data. To illustrate this procedure, 20 receptors around a high-tech complex in Taiwan were selected. Five consecutive years of hourly meteorological data were acquired to generate a lookup table of χ/Q, as well as two regression formulas of plume rise as functions of downwind distance, buoyancy flux, and stack height. To calculate the concentrations for the selected receptors, a six-step Excel algorithm was programmed with four years of emission records and 10 most critical toxics were screened out. A validation check using Industrial Source Complex (ISC3) model with the same meteorological and emission data showed an acceptable overestimate of 6.7% in the average concentration of 10 nearby receptors. The procedure proposed in this study allows practical and focused emission management for a large industrial complex and can therefore be integrated into an air quality decision-making system.

1. Introduction

Atmospheric dispersion modeling has been extensively studied since the 1960s and is widely accepted today as an indispensable technique by many air quality managers. Although it is difficult to validate, the technique is employed by many governmental

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environmental authorities to evaluate whether emissions of air pollutants from existing or planned sources will comply with ambient air quality standards (Turner, 1994). In the case of environmental impact assessment, the health risk posed by hazardous air pollutants is often assessed. Here, air dispersion modeling provides the basis for estimating excess levels for proposed actions (U.S. EPA, 1989; TEPA, 2011; EPA, 2013c). The dispersion technique is also useful in stack design of emission height and for determination of off-gas exit velocity for worst-case scenarios. However, even with modern computerized techniques, air dispersion modeling for a study site is difficult, as it requires simultaneous input of vast amounts of data with wide variability.

In 2012, the Taiwan Environmental Protection Administration (TEPA) launched a new list of emission standards for air pollutants emitted from industrial stationary sources (TEPA, 2013). The new list consists of 486 chemicals, which are primarily hazardous air pollutants (HAPs) that are regulated by the U.S. EPA (2013a). It includes volatile and semivolatile organic chemicals, pesticides, polycyclic aromatic hydrocarbons, inorganic acids, bases, and heavy metals. Including in the items in this list are 510 regulated air pollutants from industrial sources. In addition to the difficulty of dispersion modeling, the ever-increasing number of air pollutants under regulation poses a significant challenge to both government and industries. However, a full list of assessments may be an overwhelming effort because of the substantial number of pollutants, the large variability in environmental conditions, and the numerous combinations of complex source configurations and receptors (Ma et al., 2012). To overcome these difficulties, this study aimed to develop a simplified procedure to screen air pollutants according to their site boundary standards (S_b), which are critical to the study site. The screening procedure was validated by the Industrial Source Complex of Taiwan EPA. It will be included as a new module in a decision support system of air quality management for complex sites in Taiwan and China (Chiang and Tsai, 2014).

2. Method and mathematical derivation

This study was designed to evaluate the relative impact of various airborne stack emissions and to screen out critical pollutants. Some of the basic assumptions in the development of such a screening method are as follows:

- The predicted concentration of different dispersed chemicals could be normalized by their associated references of regulatory standards or by their threshold limits for cross-pollutant comparison;
- each emission is assumed to originate from a point source and to be continuous;
- all emitted pollutants are inert toward other pollutants during transport.

2.1. Normalization for different pollutants

To develop the screening methodology, the dimensionless risk strength (r_s) is defined as follows:

$$r_s \equiv \frac{\chi}{\chi_{ref}} \tag{1}$$

where

χ = predicted airborne pollutant concentration at the location of concern (mg/m^3);

χ_{ref} = reference airborne concentration of the pollutant (mg/m^3);

r_s is conceptually equivalent to a toxicity-based index such as the hazard quotient (HQ) (EPA, 2013a). The χ_{ref} value could be any well-established value, e.g., inhalation reference concentration (RfC) (EPA, 2013b), HAP (EPA, 2013a), or regulatory standard of an air pollutant. It is designed as a normalized measure in order to compare the relative hazards among different pollutants. When a regulatory standard is used for the, χ_{ref}, r_s may not be directly related to health risk, but it could be linked to the relative importance of regulatory concerns.

With a predetermined dispersion factor (χ/Q), the excess airborne pollutant concentration (mg/m^3) attributed to emission sources can be calculated through the expression

$$\chi = \left\langle \frac{\chi}{Q} \right\rangle Q \tag{2}$$

where

$\left\langle \frac{\chi}{Q} \right\rangle$ = dispersion factor (s/m^3) = concentration per unit of emission rate;

Q = emission rate of airborne pollutant (mg/s).

With Eq. (1), the r_s value of a pollutant i at location k can be expressed as follows:

$$r_s^{\langle i,k\rangle} = \sum_j \frac{\chi^{\langle i,j,k\rangle}}{\chi_{ref}^{\langle i\rangle}} = \sum_j \frac{\left(\frac{\chi}{Q}\right)^{\langle j,k\rangle} Q^{i,j}}{\chi_{ref}^{\langle i\rangle}} \tag{3}$$

where

$\chi^{\langle i,j,k\rangle}$ = concentration of pollutant i released from stack j and received at location k (mg/m^3);

$\left(\frac{\chi}{Q}\right)^{\langle j,k\rangle}$ = dispersion factor from stack j to location k (s/m^3);

$Q^{\langle i,j\rangle}$ = emission rate of pollutant i from stack j (mg/s);

$\chi_{ref}^{\langle i\rangle}$ = reference concentration of pollutant i (mg/m^3).

Eq. (3) conceptually implies two steps of computation: (1) calculating the r_s value for pollutant i received at location k from stack j and (2) superimposing r_s values from all stacks. The stack-summed r_s value for pollutant i received at location k can then be ranked according to the r_s value; hence, critical pollutants can be screened out for further study.

2.2. Dispersion factor

For years, air dispersion modeling based on the Gaussian plume theory has been widely used to assess the impact of toxic air emissions on air quality, especially for regulatory compliance. For a ground-level receptor from an elevated release with a defined mixing layer height (z_m), the χ/Q value can be calculated by the classical Gaussian plume formula (Turner, 1994; Napier et al., 2011):

$$\begin{aligned}\frac{\chi}{Q}(x,y,0) &= \frac{1}{\pi u_e \sigma_y \sigma_z} e^{-\frac{y^2}{2\sigma_y^2}} \left\{ \cdots + e^{\frac{-(h_e-2z_m)^2}{2\sigma_z^2}} + e^{\frac{-(h_e+0z_m)^2}{2\sigma_z^2}} + e^{\frac{-(h_e+2z_m)^2}{2\sigma_z^2}} + \cdots \right\} \\ &= \frac{1}{\pi u_e \sigma_y \sigma_z} e^{-\frac{y^2}{2\sigma_y^2}} \sum_{j=-\infty}^{\infty} e^{\frac{-(h_e+2jz_m)^2}{2\sigma_z^2}}\end{aligned} \tag{4}$$

where

x = downwind distance (m);

y = crosswind position (m);

u_e = wind speed at effective release height (m/s);

σ_y = horizontal dispersion coefficient (m);

σ_z = vertical dispersion coefficient (m);

h_e = effective release height (m) = stack height (h_s) + plume rise (Δh) + elevation difference (Δz);