

Airshed Models

Modeling may be necessary to estimate the changes in ambient air quality—both local and at a distance—caused by a particular set of emissions. Modeling can be appropriate for new plants and for modifications to existing plants. This chapter provides guidance on some models that may be useful in the context of typical World Bank Group projects.

Air quality is an issue of increasing concern in many countries. Projects that introduce new sources of emissions or are designed to reduce emissions require careful analysis to quantify the effects as far as possible. For many sources, this will typically require mathematical modeling of the changes in ambient concentrations that result from the new emissions. The few widely used models are reviewed in this chapter.

Air quality modeling can be a complex task, and the objectives need to be clear. The costs of a study can range from US\$10,000 to US\$500,000, depending on the complexity of the situation and the level of detail required; in many cases, costs are at the lower end of this scale. The simplest approach uses a point source dispersion model to estimate the ground-level concentrations of the pollutants of interest at some distance (typically from hundreds of meters to tens of kilometers) from a point source. More complicated models allow the examination of multiple sources, including area (nonpoint) sources. For an area containing a number of point and nonpoint sources, an air quality model can be constructed that includes all of the sources in the area. In practice, such models are rare because of the costs of development and the data required to make the model a realistic tool.

This chapter examines the application of the most commonly used air quality dispersion models for assessing the impact on air quality of key pollutants—sulfur dioxide (SO₂), nitrogen oxides (NO_x), and particulates—emitted from point sources.¹ Far-field dispersion and acid rain deposition are governed by different principles and

utilize different types of models, which are discussed elsewhere in this *Handbook*.

Although thermal power plants are often singled out as major polluting sources, nearly all industrial facilities, especially those with short stacks, have the potential to cause localized areas of unacceptable air quality. In addition, urban areas can act as diffuse sources of air pollution, particularly where poor-quality fuels are burned in household stoves. Cases of multiple point sources or area sources (or both) can often be modeled by using simplifying assumptions or by integrating the impacts of individual sources.

Use of Near-Field Dispersion Models

Typically, dispersion models have been used in developing countries only in isolated cases where air pollution had been recognized as a serious problem (e.g., Mae Moh, Thailand, and Krakow, Poland). However, with increasing pollution problems and more emphasis on air quality standards in developing countries, dispersion models are expected to be used more extensively in the future for sector- and project-level environmental assessments, as well as for assistance in establishing specific emissions requirements.

As a general guide, it is suggested that a basic analysis of possible impacts on ambient concentrations be carried out on installations that have the potential to emit annually more than 500 metric tons of sulfur dioxide or nitrogen oxides, or 50 metric tons of particulate matter or any hazardous air pollutant. In many cases, simple

calculations based on loads and air volumes may be sufficient to provide an order-of-magnitude estimate. However, the use of formal models should be considered for any project involving large new plant or significant modifications. For major sources, the modeling should include the planned source or sources, as well as existing sources in the same general area—within a radius of 10 to 15 kilometers (km)—so that the cumulative effect of all the facilities on local air quality can be assessed. In some cases, building-wake effects are important (for example, where release points such as stacks and vents are less than 2.5 times the height of nearby buildings), and more detailed modeling may be appropriate.

The models described in this document pertain to “near-field” (less than 50 km from the point source) dispersion of sulfur dioxide, nitrogen oxides, and particulates. Such models estimate the ground-level concentration of pollutants in the air, which is then compared with ambient air quality standards or guidelines.² Other models that address photochemical smog are not described in detail here.

Factors Affecting Dispersion of Pollutants

The dispersion and ground-level concentration of pollutants are determined by a complex interaction of the physical characteristics of the plant stack or other emission points, the physical and chemical characteristics of the pollutants, the meteorological conditions at or near the site, and the topographical conditions of the surrounding areas.

In general, three different calculations are needed to estimate the time-averaged concentration of pollutants at a location downwind from a plant:

- The plume rise above the stack must be established (effective stack height).
- The dispersion of the pollutants between the source and the downwind locations of interest must be mathematically modeled on the basis of atmospheric conditions.
- The time-averaged concentration at ground level must be determined.

Key factors that affect these calculations, and therefore the selection of dispersion models, are:

- *Topography.* The area surrounding the plant is characterized either as flat to gently rolling terrain or complex terrain (having downwind locations with elevations greater than stack height).
- *Land use.* Whether the surrounding area is urban or rural is important because urban areas typically have large structures and heat sources that affect the dispersion of pollutants. In addition, the density of the population affects the numbers potentially impacted.
- *Pollutant properties.* Physical and chemical properties of the pollutants influence their transport. For modeling sulfur dioxide within 5 to 10 km of a source, no chemical transformations are assumed to occur. Beyond this distance, an exponential decay function may be useful. Most nitrogen oxide is emitted as nitric oxide (NO), but in a matter of minutes, depending on the availability of ozone, it becomes nitrogen dioxide. The deposition of particulates is a function of particle size and travel time.
- *Source configuration.* The height and temperature of the discharge and proximity to structures affect dispersion. Effective plume height is the physical height of the stack adjusted for factors that raise the plume (as a result of buoyancy or momentum) or lower it (as a result of downwash or deflection).
- *Multiple sources.* All dispersion models assume that the concentrations at any one target site are the arithmetic sum of concentrations from each of the sources being examined. Note that it is the effects that are summed, not the emissions rates or stack parameters.
- *Time scale of exposure.* The recommended models make calculations for the basic time period of one hour. Concentrations for longer time periods, such as 8 hours or 24 hours, are the arithmetic averages of the hourly concentrations of those time periods. Annual averages are computed by averaging hourly concentrations for a full year or by using models that use a frequency distribution of meteorological events to compute an annual average. The recom-

mended models have the necessary “book-keeping” incorporated into the processing or available as postprocessor routines.

Selecting an Appropriate Model

Model selection requires matching the key characteristics of the site and the requirements of the evaluation with the capabilities of the model. Normally, expert advice is required in making a selection. As a general principle, modeling should always begin with the simplest form possible, moving to more complex approaches only where their necessity and value can be demonstrated. At the most basic level, a crude mass balance can indicate whether a new source is likely to pose a problem. Alternatively, a simple screening model, as described below, can provide a realistic estimate of the order of magnitude of the impacts of a source. Situations involving multiple sources or varying terrain may require a more sophisticated effort involving site-specific data collection and more complex models.

In some cases, more than one model may be required. For example, modeling of gaseous emissions and particulates in the Mae Moh Valley, Thailand, required the use of one model for the valley floor, where the terrain is flat, and another for the mountains that surround the valley on three sides (KBN Engineering and Applied Sciences, Inc. 1989).

Commonly Used Models

Screening Models

The preliminary scoping of the magnitude of the air pollution problem can be accomplished by the use of screening models designed to determine quickly and easily the impacts from a single source. If it is obvious that several sources are contributing to concentrations, screening is not appropriate. A useful screening model is SCREEN3 (EPA 450/4-9-006, Modeling Guideline, and EPA 454/R-92-019, Screening Procedures for Stationary Sources). This approach requires no site-specific meteorological input, as calculations are made for a spectrum of possible combinations of wind speed and atmospheric stability (using Pasquill classes). Concentrations at the downwind point of maximum impact, as

well as at other specified distances, are determined. No consideration of wind direction is required because the output represents the concentrations directly downwind. (This model is designed for average North American conditions; care should be taken in using it under different climatic conditions.)

Options in the model allow for the effects of a single dominant building and for terrain differences between the source and the receptors. To refine the estimates in complex terrain, a more sophisticated screening model is available in CTSCREEN, derived from CTDMPLUS (see below).

Although only a single source (stack) is considered, multiple nearby sources can be screened by using the sum of the emissions rates from the sources as the emissions rate for this single stack. This will yield an overestimate, since the effects of geographic separation of the sources or the points of maximum concentration will not have been included. Scaling factors to estimate concentrations for longer time averages (3 hours, 8 hours, 24 hours, and even one year) are included in the user's guide.

If the concentrations determined by using a screening model are within the relevant guidelines, no additional modeling should be necessary. If concentrations exceed the guidelines, more refined modeling should be done. Since the simplifying assumptions made in the screening model tend to overestimate impacts, refined modeling nearly always yields somewhat lower estimates of concentration.

Screening is straightforward and does not require difficult decisions as to the relevance and representativeness of meteorological data. It may be carried out by competent local specialists, perhaps with some expert assistance.

Refined Models

More refined modeling of near-field dispersion can be carried out with one of several simple Gaussian plume models. These models predict the dispersion patterns of nonreactive pollutants such as sulfur dioxide, nitrogen oxides, and particulates within 50 km of the emissions source and are generally expected to produce results within a factor of 2 of the measured values. Most such dispersion models are similar in design and

performance and do not attempt to account for complex situations such as long-range transport and highly reactive chemical emissions.

What distinguishes the various models is their capability to handle different settings. Some of the models (such as ISC3 and CTDMPLUS, described below) are characterized as “*preferred models*” by organizations such as the USEPA because they meet certain minimum technical criteria, have undergone field testing and have had extensive peer review. This does not make the nonpreferred models less suitable for an application, but it does mean there is a documented experience base for the preferred models, which may add more credibility to the analysis or eliminate the need for model validation. Two of the most commonly used models for assessment of pollutant dispersion are from the USEPA.

- The ISC3 (Industrial Source Complex) model is used for point (stack), area, and volume sources in flat or complex terrain. The complex terrain analysis does not employ a sophisticated algorithm. There are two versions: ISCST3, for averaging periods of 24 hours or less, and ISCLT3, for averaging periods of 30 days or longer.
- The CTDMPLUS (Complex Terrain Dispersion) model is for use in complex terrain. A screening version of this model, CTSCREEN, provides estimates if only one or two stacks affect high terrain.

Other commonly used models are:

- UK-ADMS, the United Kingdom Meteorological Office Atmospheric Dispersion Modeling System

- PARADE, developed by Electricite de France
- PLUME 5, developed by Pacific Gas & Electric Co., San Ramon, Calif., and applicable to both urban and rural areas with complex terrain
- The German TA Luft procedures.

Table 1 provides the key characteristics of the commonly used air quality dispersion models. More details on these, as well as on other dispersion models (e.g., ERTAQ, COMPTER, MPSDM, MTDDIS, MULTIMAX, LONGZ, SHORTZ, SCSTER, 3141 and 4141), are provided in USEPA (1993).

These models have been developed and used mainly in industrial countries, but they are suitable for developing countries, as demonstrated by their use in, for example, the projects in Mae Moh, Krakow, and Sri Lanka mentioned below. However, they may require some adaptation to or calibration for topography and weather patterns that are not common in industrial countries. For example, dispersion models have not been subject to a comparison of model calculations of existing sources with monitored air quality data in tropical weather conditions.

ISC3 and CTDMPLUS Models

The Industrial Source Complex (ISC) model is a steady-state Gaussian plume model used to assess pollutant concentrations from a wide variety of industrial sources. It accounts for settling and dry deposition of particulates; wake effects stemming from building obstruction; plume rise as a function of downwind distance; and multiple but separate point, area, and volume

Table 1. Key Characteristics of Commonly Used Dispersion Models

	Terrain				Pollutant		Source configuration			Time scale	
	Flat/ gently rolling	Com- plex/ rough	Land use		So _x / No _x	Parti- culate	Point	Elev- ated point	Mul- tiple point	Short- term exposure	Long- term exposure
SCREEN3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No
ISCLT	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ISCST	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No ^a
PLUME5	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
CTDMPLUS	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No

Note: All of the above models except PLUME 5 are available through NTIS, Springfield, Va. 22161. PLUME 5 is available through Pacific Gas and Electric Co, San Ramon, Calif.

a. “Yes,” if all hours for the time period are averaged (e.g. 8,760 hours in a 365-day year).

sources. It has the ability to analyze concentrations in any type of terrain, and it can estimate hourly to annual pollutant concentrations. This model is recommended for both urban and rural areas.

An earlier version of the ISC model has been used in a number of World Bank projects such as Mae Moh, Thailand (KBN Engineering and Applied Sciences, Inc. 1990), Krakow, Poland (Adamson et al. 1996), and Sri Lanka (Meier and Munasinghe 1994).

Several private firms offer enhanced versions of the EPA models (see, for example, Scholze 1990). The enhancements include user-friendly data input, the capability of easily plotting the output, custom output summaries, and technical support. Some of these firms offer training in the use of models, both in the United States and overseas.

Addresses for obtaining further information on the USEPA and German models are given at the end of this chapter.

Other Models

In addition to the above-mentioned models, there are models that are not used widely but that may be the most suitable for specific locations because they have been developed by local institutions and have taken into account local requirements. For example, a World Bank study in Krakow, Poland (Adamson et al. 1996) utilized a model developed by the Warsaw University of Technology.

For a facility within 200 km of an urban center that has a smog problem, one may wish to examine the effects of photochemical reactions between volatile organic compounds (VOCs) and nitrogen oxides, if the new source contributes more than 1–2% to the total emissions of these compounds in the airshed. This analysis requires an enormous amount of data, takes highly skilled modeling personnel, and is generally quite expensive. Commonly used models for such an assessment are the USEPA Urban Air Quality Model (UAM) and the Regional Oxidant Model (ROM).

Use of Refined Models

Models such as ISCST3 are more sophisticated in their structure and capabilities than the simple

screening models, but they can be applied in a basic manner when the necessary data are difficult to obtain or in order to determine the value of collecting further data. For example, in a complex airshed with several sources and differing meteorological conditions, it may be appropriate to calculate the impacts of each major source individually, using simplified meteorology for that source. The impacts from all the sources can then be summed, producing estimates that are not as precise as a multisource model but that may give a reasonable indication of the overall impact.

In complex situations, significant effort and professional judgment are often necessary for estimation of the emissions inventory (defining all the sources to be included), for collection of local meteorological data, and for selection of the specific combinations of conditions to be modeled. For example, in an industrial city, it may be appropriate to group the sources into different types, such as major sources, smaller industrial or municipal sources, and indeterminate residential emissions. Identification of sources and estimation of the emissions inventory for use in the model would be significant tasks. For the major sources, site-specific details should be obtained. Smaller industrial sources might be handled by aggregating them into groups or by defining typical characteristics. Residential sources would have to be partitioned in accordance with some estimates of population density or housing type. Efforts would have to be made to understand the local meteorology in some detail, addressing variability across the area, patterns of inversions, and perhaps day/night variations to reflect patterns of residential emissions.

Credible modeling in such complex situations requires significant effort and resources. Collection and interpretation of the data required as input can take a large part of the overall resources—perhaps 50% or more.

Data Requirements

The data requirements of dispersion models fall into three categories:

- *Source data*, including location of stacks and other sources (coordinates), physical stack height and inside diameter, stack exit gas velocity and tem-

perature, and pollutant release rate. The latter is usually given as the time-weighted average (per 1 hour, 24 hours, or year).

Some dispersion models may require additional inputs such as point source elevation, building dimensions (e.g., average building width and space between buildings), particle size distribution with corresponding settling velocities, and surface reflection coefficients.

- *Meteorological data* are required for predicting the transport, dispersion, and depletion of the pollutants. Most models accept hourly surface weather data that include the hourly Pasquill stability class, wind direction and speed, air temperature, and mixing height. Ideally, a year of meteorological data would be available. In cases where some long-term data are available in the region (typically, readings taken at an airport), shorter-term local observations may allow the long-term records to be transferred to the site under examination. Where appropriate, a local meteorological station can be established (estimated cost, about US\$30,000–\$40,000 for setup and one year of operation of one automated site).
- *Receptor data*, meaning identification of all key receptors (e.g., areas of high population or expected maximum ground-level concentration). Usually, receptors are specified by their coordinates and elevation.

Values of input parameters can be determined by direct measurement, sampling, or estimates based on sound engineering principles. The literature may provide data or empirical correlations that can be used for estimating dispersion model inputs.

Interpretation of Results

The results of dispersion modeling are typically maps showing the concentration of the considered pollutants (usually sulfur dioxide, nitrogen oxides, and particulates) throughout the immediate area surrounding the facility. The map consists of the computed concentrations at each site and a plot of the isopleths (lines of constant concentrations). Since plotting results in “smoothing,” the actual computed data should be evaluated. The maps need to be evaluated (typi-

cally by an expert) to compare them with local ambient air quality standards and identify “hot spots”—areas where pollutant concentration is above desirable levels.

It should be emphasized that mathematical modeling of complex atmospheric processes involves a significant level of uncertainty, which can be made worse when data are lacking or unreliable. Model results must therefore be treated with care when using them in formal decision-making. The presentation of results should normally include a discussion of the probable variability and the confidence limits.

For decisionmakers, the results need to be summarized in a clear, understandable way. Table A.1, which sets out the key findings from a modeling study of a proposed power plant, is an example of such a presentation.

Resource Requirements for Dispersion Studies

Information on screening models is generally readily available. The costs of acquiring the model, some training, and the actual study should be less than US\$10,000. Local consultants can rapidly acquire skill with the screening models. Where refined modeling is required, the necessary skill level increases sharply.

Air quality monitoring and model validation can have significant costs. In the United States, air quality analysis costs for power plants have ranged from US\$100,000 to US\$2 million. The lower end of this range corresponds to the case of readily available meteorological data and flat terrain in a rural area. The high end of the range includes ambient air quality monitoring costs and, in some cases, the cost of demonstrating the inappropriateness of a model approved by the regulatory agency or of validating a model not approved by the regulatory agency. Although these costs are based on experience from industrial countries, costs in other countries are expected to be similar. Some cost reductions could be achieved by maximizing the utilization of local consultants, particularly if the local consultant has the opportunity to carry out four or five such projects annually. Unless there is frequent use of dispersion modeling, it may not be worthwhile to acquire the skill because of the rapid changes in the models themselves and in the com-

Annex. Example of Summary Output from an Airshed Model

Table A.1. Air Pollution Characteristics of a Proposed Thermal Power Plant

A. AIR QUALITY PROJECTIONS
(all units are $\mu\text{g}/\text{m}^3$)

Reference values	<i>World Bank guidelines</i>			<i>National standards</i>								
Annual average												
Daily maximum												
Annual maximum												
Background levels	<i>Monitoring point 1</i>			<i>Monitoring point 2</i>			<i>Monitoring point 3</i>			<i>Monitoring point 4</i>		
Annual average												
Daily maximum												
Annual maximum												
Design coal: background plus two 600 MW units	<i>Monitoring point 1</i>			<i>Monitoring point 2</i>			<i>Monitoring point 3</i>			<i>Monitoring point 4</i>		
Annual average												
Daily maximum												
Annual maximum												
Design coal: background plus four 600 MW units	<i>Monitoring point 1</i>			<i>Monitoring point 2</i>			<i>Monitoring point 3</i>			<i>Monitoring point 4</i>		
Annual average												
Daily maximum												
Annual maximum												
Check coal: background plus two 600 MW units	<i>Monitoring point 1</i>			<i>Monitoring point 2</i>			<i>Monitoring point 3</i>			<i>Monitoring point 4</i>		
Annual average												
Daily maximum												
Annual maximum												
Check coal: background plus four 600 MW units	<i>Monitoring point 1</i>			<i>Monitoring point 2</i>			<i>Monitoring point 3</i>			<i>Monitoring point 4</i>		
Annual average												
Daily maximum												
Annual maximum												

B. ASSUMPTIONS

1. Sulfur content

Design value: 0.31%

Check value: 0.92%

2. Ash content

Design value: 15.5%

Check value: 28.4%

3. Stack height

4. ESP efficiency

C. PROJECTED EMISSIONS

		<i>World Bank guidelines</i>	<i>National standards</i>	<i>Two 600 MW units</i>	<i>Four 600 MW units</i>
<i>SO₂ (t/d)</i>	Design				
	Check				
<i>TSP (mg/m³)</i>	Design				
	Check				
<i>NO_x (ng/J)</i>	Design				
	Check				

Note: SO₂, sulfur dioxide; TSP, total suspended particulates; NO_x, nitrogen oxides; MW, megawatt; ESP, electrostatic precipitator; mg/m³, milligrams per cubic meter; ng/J, nanograms per joule; t/d, metric tons per day.

puter technology needed to effectively use the models.

When Should the Modeling Be Done?

Dispersion modeling should be part of the initial environmental assessment for a power project, for example. It is recommended that the dispersion modeling be carried out early in project preparation (e.g., as part of the feasibility study) before the plant location and the detailed design have been finalized.

Additional Resources: For Further Information on the Models

- USEPA (U.S. Environmental Protection Agency). "ISC Dispersion Model User's Guide: Volumes 1 and 2." EPA 454/B-95-003, a, b, and c. Office of Air Quality Planning and Standards, Research Triangle Park, N.C.
- USEPA. "CTDMPLUS Model User's Guide." EPA 600/8-89/041. "Terrain Processor." EPA 600/8-88/003. Office of Air Quality Planning and Standards, Research Triangle Park, N.C.

All USEPA models are available from the EPA SCRAM bulletin board free of charge.

Tel: 919/541-5742

e-mail: TTNBBS.RTPNC.EPA.GOV

In addition all EPA models are available for a fee from the National Technical Information Service (NTIS), Springfield, Va. 22161.

- Germany, Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety. 1992. "Manual of Ambient Air Quality Control in Germany." Berlin.
- Germany, Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety. 1992. "Air Pollution Control: Manual of Continuous Emission Monitoring." Berlin.

Notes

1. *Dispersion* refers to the movement of parcels of gases, whether vertically or horizontally, and their simultaneous dilution in the air.

2. *Standards* pertain to the environmental requirements of the country or the local authority; *guidelines* are practices suggested by organizations such as WHO and the World Bank.

References and Sources

Adamson, Sebron, Robin Bates, Robert Laslett, and Alberto Pototschnig. 1996. *Energy Use, Air Pollution, and Environmental Policy in Krakow: Can Economic Incentives Really Help?* World Bank Technical Paper 308. Washington, D.C.

Electric Power Research Institute. 1986. "Estimating the Cost of Uncertainty in Air Quality Modeling." EA-4707. Palo Alto, Calif.

KBN Engineering and Applied Sciences, Inc. 1989. "Mae Moh Air Quality Update: Units 1-11." Prepared for the Survey and Ecology Department of the Electricity Generating Authority of Thailand. Bangkok.

KBN Engineering and Applied Sciences, Inc. 1990. "Sulfur Dioxide Air Quality Impact Analysis for Mae Moh: Units 1-13." Prepared for the Survey and Ecology Department of the Electricity Generating Authority of Thailand. Bangkok.

Meier, Peter, and Mohan Munasinghe. 1994. *Incorporating Environmental Concerns into Power Sector Decisionmaking: A Case Study of Sri Lanka*. World Bank Environment Paper 6. Washington, D.C.

Scholze, R. H. 1990. "Dispersion Modeling Using Personal Computers." *Atmospheric Environment* 24A(8): 2051-57.

USEPA (U.S. Environmental Protection Agency). 1993. "Selection Criteria for Mathematical Models Used in Exposure Assessments: Atmospheric Dispersion Models." EPA/600/8-91/038. Washington, D.C.