APPENDIX E

Determination of Ground Water Dilution Attenuation Factors

DETERMINATION OF GROUNDWATER DILUTION ATTENUATION FACTORS FOR FIXED WASTE SITE AREAS USING EPACMTP

BACKGROUND DOCUMENT

EPA OFFICE OF SOLID WASTE

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PREFACE

The work documented in this report was conducted by HydroGeoLogic, Inc. for the EPA Office of Solid Waste. The work was performed partially under Contract No. 68-W0-0029 and partially under Contract No. 68-W3-0008, subcontracted through ICF Inc. This documentation was prepared under Contract No. 68-W4-0017. Technical direction on behalf of the Office of Solid Waste was provided by Dr. Z.A. Saleem.

ABSTRACT

The EPA Composite Model for Leachate Migration with Transformation Products (EPACMTP) was applied to generate Dilution Attenuation Factors (DAF) for the groundwater pathway in support of the development of Soil Screening Level Guidance. The model was applied on a nationwide basis, using Monte Carlo simulation, to determine DAFs as a function of the area of the contaminated site at various probability levels. The analysis was conducted in two stages: First, the number of Monte Carlo iterations required to achieve converged results was determined. Convergence was defined as a change of less than 5 % in the 85th percentile DAF value. A number of 15,000 Monte Carlo iterations was determined to yield convergence; subsequent analyses were performed using this number of iterations. Second, Monte Carlo analyses were performed to determine DAF values as a function of the contaminated area. The effects of different placements of the receptor well were evaluated.

1.0 INTRODUCTION

The Agency is developing estimates for threshold values of chemical concentrations in soils at contaminated sites that represent a level of concentration above which there is sufficient concern to warrant further site-specific study. These concentration levels are called Soil Screening Levels (SSLs). The primary purpose of the SSLs is to accelerate decision making concerning contaminated soils. Generally, if contaminant concentrations in soil fall below the screening level and the site meets specific residential use conditions, no further study or action is warranted for that area under CERCLA (EPA, 1993b).

The Soil Screening Levels have been developed using residential land use human exposure assumptions and considering multiple pathways of exposure to the contaminants, including migration of contaminants through soil to an underlying potable aquifer. Contaminant migration through the unsaturated zone to the water table generally reduces the soil leachate concentration by attenuation processes such as adsorption and degradation. Groundwater transport in the saturated zone further reduces concentrations through attenuation and dilution. The contaminant concentration arriving at a receptor point in the saturated zone, e.g., a domestic drinking water well, is therefore generally lower than the original contaminant concentration in the soil leachate.

The reduction in concentration can be expressed succinctly in a Dilution-Attenuation Factor (DAF) defined as the ratio of original soil leachate concentration to the receptor point concentration. The lowest possible value of DAF is therefore one; a value of DAF=1 means that there is no dilution or attenuation at all; the concentration at the receptor point is the same as that in the soil leachate. High values of DAF on the other hand correspond to a high degree of dilution and attenuation.

For any specific site, the DAF depends on the interaction of a multitude of site-specific factors and physical and bio-chemical processes. The DAF also depends on the nature of the contaminant itself; i.e., whether or not the chemical degrades or sorbs. As a result, it is impossible to predict DAF values without the aid of a suitable computer fate and transport simulation model that simulates the migration of a contaminant through the subsurface, and accounts for the relevant mechanisms and processes that affect the receptor concentration.

The Agency has developed the EPA Composite Model for Leachate Migration with Transformation Products (EPACMTP; EPA, l993a, 1994) to assess the groundwater quality impacts due to migration of wastes from surface waste sites. This model simulates the fate and transport of contaminants after their release from the land disposal unit into the soil, downwards to the water table and subsequently through the saturated zone. The fate and transport model has been coupled to a Monte Carlo driver to permit determination of DAFs on a generic, nationwide basis. The EPACMTP model has been applied to determine DAFs for the subsurface pathway for fixed waste site areas, as part of the development of Soil Screening Levels. This report describes the application of EPACMTP for this purpose.

2.0 GROUNDWATER MODEL

2.1 Description of EPACMTP Model

The EPA Composite Model for Leachate Migration with Transformation Products (EPACMTP, EPA, 1993a, 1994) is a computer model for simulating the subsurface fate and transport of contaminants that are released at or near the soil surface. A schematic view of the conceptual subsurface system as simulated by EPACMTP, is shown in Figure 1. The contaminants are initially released over a rectangular source area representing the waste site. The modeled subsurface system consists of an unsaturated zone underneath the source area, and an underlying water table aquifer. Contaminants move vertically downward through the unsaturated zone to the water table. The contaminant is assumed to be dissolved in the aqueous phase; it migrates through the soil under the influence of downward infiltration. The rate of infiltration may reflect the combined effect of precipitation and releases from the source area. Once the contaminant enters the saturated zone, a three-dimensional plume develops under the combined influence of advection with the ambient groundwater flow and dispersive mixing.

The EPACMTP accounts for the following processes affecting contaminant fate and transport: advection, dispersion, equilibrium sorption, first-order decay reactions, and recharge dilution in the saturated zone. For contaminants that transform into one or more daughter products, the model can account for the fate and transport of those transformation products also.

The EPACMTP model consists of three main modules:

- An unsaturated zone flow and transport module
- A saturated zone flow and transport module
- A Monte Carlo driver module, which generates model input parameter values from specified probability distributions

The assumptions of the unsaturated zone and saturated zone flow and transport modules are described in Section 2.2. The Monte Carlo modeling procedure is described in Section 2.3.

2.2 Fate and Transport Simulation Modules

2.2.1 Unsaturated zone flow and transport module

Details on the mathematical formulation and solution techniques of the unsaturated zone flow and transport module are provided in the EPACMTP background document (EPA, 1993a). For completeness, the major features and assumptions are summarized below:

- The source area is a rectangular area.
- Contaminants are distributed uniformly over the source area.
- The soil is a uniform, isotropic porous medium.
- Flow and transport in the unsaturated zone are one-dimensional, downward.
- Flow is steady state, and driven by a prescribed rate of infiltration.
- Flow is isothermal and governed by Darcy's Law.

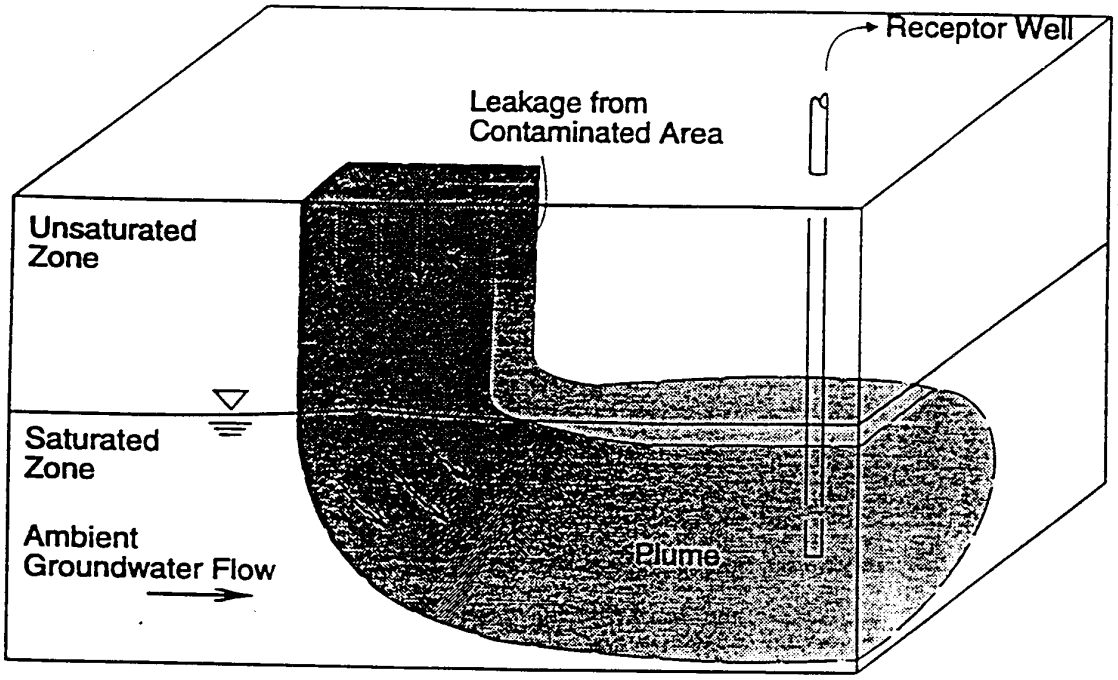


Figure 1
Conceptual View Of The Unsaturated Zone-Saturated Zone System Simulated By EPACMTP

- The leachate concentration entering the soil is either constant (with a finite or infinite duration), or decreasing with time following a first-order decay process.

- The chemical is dilute and present in solution or soil solid phase only.

- Sorption of chemicals onto the soil solid phase is described by a linear or nonlinear (Freundlich) equilibrium isotherm.

- Chemical and biological transformation process can be represented by an effective, first-order decay coefficient.

2.2.2 Saturated zone flow and transport module

The unsaturated zone module computes the contaminant concentration arriving at the water table, as a function of time. Multiplying this concentration by the rate of infiltration through the unsaturated zone yields the contaminant mass flux entering the saturated zone. This mass flux is specified as the source boundary condition for the saturated zone flow and transport module.

Groundwater flow in the saturated zone is simulated using a (quasi-) three-dimensional steady state solution for predicting hydraulic head and Darcy velocities in a constant thickness groundwater system subject to infiltration and recharge along the top of the aquifer and a regional hydraulic gradient defined by upstream and downstream head boundary conditions.

In addition to modeling fully three-dimensional groundwater flow and contaminant fate and transport, EPACMTP offers the option to perform quasi-3D modeling. When this option is selected, the model ignores either the flow component in the horizontal transverse (-y) direction, or the vertical (-z) direction. The appropriate 2D approximation is selected automatically in the code, based on the relative significance of plume movement in the horizontal transverse versus vertical directions. Details of this procedure are provided in the saturated zone background document (EPA, 1993a). The switching criterion that is implemented in the code will select the 2D areal solution for situations with a relatively thin saturated zone in which the contaminant plume would occupy the entire saturated thickness; conversely, the solution in which advection in the horizontal transverse direction is ignored is used in situations with a large saturated thickness, in which the effect of vertical plume movement is more important.

The saturated zone transport module describes the advective-dispersive transport of dissolved contaminants in a three-dimensional, constant thickness aquifer. The initial boundary is zero, and the lower aquifer boundary is taken to be impermeable. No-flux conditions are set for the upstream aquifer boundary. Contaminants enter the saturated zone through a patch source of either constant concentration or constant mass flux on the upper aquifer boundary, representing the area directly underneath the waste site at the soil surface. The source may be of a finite or infinite duration. Recharge of contaminant-free infiltration water occurs along the upper aquifer boundary outside the patch source. Transport mechanisms considered are advection, longitudinal, vertical and transverse hydrodynamic dispersion, linear or nonlinear equilibrium adsorption, first-order decay and daughter product formation. As in the unsaturated zone, the saturated zone transport module can simulate multi-species transport involving chained decay reactions. The saturated zone transport module of EPACMTP can perform either a fully three-dimensional transport simulation, or provide a quasi-3D approximation. The latter ignores advection in either the horizontal transverse (-y) direction, on the vertical (-z) direction, consistent with the quasi-3D flow solution. In the course of a Monte Carlo simulation, the appropriate 2D approximations are selected automatically for each individual Monte Carlo iteration, thus yielding an overall quasi-3D simulation.

The saturated zone and transport module is based on the following assumptions:

- The aquifer is uniform and initially contaminant-free.
- The flow field is at steady state; seasonal fluctuations in groundwater flow are neglected.
- The saturated thickness of the aquifer remains constant; mounding is represented by the head distribution along the top boundary of the modeled saturated zone system.
- Flow is isothermal and governed by Darcy's Law.
- The chemical is dilute and present in the solution or aquifer solid phase only.
- Adsorption onto the solid phase is described by a linear or nonlinear equilibrium isotherm.
- Chemical and/or biochemical transformation of the contaminant can be described as a first-order process.

2.2.3 Model capabilities and limitations

EPACMTP is based on a number of simplifying assumptions which make the code easier to use and ensure its computational efficiency. These assumptions, however, may cause application of the model to be inappropriate in certain situations.

The main assumptions embedded in the fate and transport model are summarized in the previous sections and are discussed in more detail here. The user should verify that the assumptions are reasonable for a given application.

Uniform Porous Soil and Aquifer Medium. EPACMTP assumes that the soil and aquifer behave as uniform porous media and that flow and transport are described by Darcy's law and the advection-dispersion equation, respectively. The model does not account for the presence of cracks, macro-pores, and fractures. Where these features are present, EPACMTP may underpredict the rate of contaminant movement.

Single Phase Flow and Transport. The model assumes that the water phase is the only mobile phase and disregards interphase transfer processes other than reversible adsorption onto the solid phase. For example, the model does not account for volatilization in the unsaturated zone, which will tend to give conservative predictions for volatile chemicals. The model also does not account for the presence of a second liquid phase (e.g., oil). When a mobile oil phase is present, the movement of hydrophobic chemicals may be underpredicted by the model, since significant migration may occur in the oil phase rather than in the water phase.

Equilibrium Adsorption. The model assumes that adsorption of contaminants onto the soil or aquifer solid phase occurs instantaneously, or at least rapidly relative to the rate of contaminant movement. In addition, the adsorption process is taken to be entirely reversible.

Geochemistry. The EPACMTP model does not account for complex geochemical processes, such as ion exchange, precipitation and complexation, which may affect the migration of chemicals in the subsurface environment. EPACMTP can only approximate such processes as an effective equilibrium retardation process. The effect of geochemical interactions may be especially important in the fate and transport analyses of metals. Enhancement of the model for handling a wide variety of geochemical conditions is currently underway.

First-Order Decay. It is assumed that the rate of contaminant loss due to decay reactions is proportional to the dissolved contaminant concentration. The model is based on one overall decay constant and does not explicitly account for multiple degradation processes, such as oxidation, hydrolysis, and biodegradation. When multiple decay processes do occur, the user must determine the overall, effective decay rate. In order to increase flexibility of the model, the user may instruct the model to determine the overall decay coefficient from chemical specific hydrolysis constants plus soil and aquifer temperature and pH.

Prescribed Decay Reaction Stoichiometry. For scenarios involving chained decay reactions, EPACMTP assumes that the reaction stoichiometry is always prescribed, and the speciation factors are specified by the user as constants (see *EPACMTP Background Document,* EPA, 1993a). In reality, these coefficients may change as functions of aquifer conditions (temperature, pH, etc.) and/ or concentration levels of other chemical components.

Uniform Soil. EPACMTP assumes that the unsaturated zone profile is homogeneous. The model does not account for the presence of cracks and/or macropores in the soil, nor does it account for lateral soil variability. The latter condition may significantly affect the average transport behavior when the waste source covers a large area.

Steady-State Flow in the Unsaturated-Zone. Flow in the unsaturated zone is always treated as steady state, with the flow rate determined by the long term, average infiltration rate through a disposal unit, or by the average depth of ponding in a surface impoundment. Considering the time scale of most practical problems, assuming steady-state flow conditions in the unsaturated zone is reasonable.

Groundwater Mounding. The saturated zone module of EPACMTP is designed to simulate flow and transport in an unconfined aquifer. Groundwater mounding beneath the source is represented only by increased head values on top of the aquifer. The saturated thickness of the aquifer remains constant in the model, and therefore the model treats the aquifer as a confined system. This approach is reasonable as long as the mound height is small relative to the saturated thickness of the aquifer and the thickness of the unsaturated zone. For composite modeling, the effect of mounding is partly accounted for in the unsaturated zone module, since the soil is allowed to become saturated. The aquifer porous material is assumed to be uniform, although the model does account for anisotropy in the hydraulic conductivity. The lower aquifer boundary is assumed to be impermeable.

Flow in the Saturated Zone. Flow in the saturated zone is taken to be at steady state. Thc concept is that of regional flow in the horizontal longitudinal direction, with vertical disturbance due to recharge and infiltration from the overlying unsaturated zone and waste site (source area). EPACMTP accounts for variable recharge rates underneath and outside the source area. It is, however, assumed that the saturated zone has a constant thickness, which may cause inaccuracies in the predicted groundwater flow and contaminant transport in cases where the infiltration rate from the waste disposal facility is high.

Transport in the Saturated Zone. Contaminant transport in the saturated zone is by advection and dispersion. The aquifer is assumed to be initially contaminant free and contaminants enter the aquifer only from the unsaturated zone immediately underneath the waste site, which is modeled as a rectangular horizontal plane source. EPACMTP can simulate both steady state and transient transport in the saturated zone. In the former case, the contaminant mass flux entering at the water table must be constant with time. In the latter case, the flux at the water table can be constant or vary as a function of time. The transport module accounts for equilibrium adsorption and decay reactions, both of which are modeled in the same manner as in the unsaturated zone. The adsorption and decay coefficients are assumed to be uniform throughout saturated zone.

2.3 Monte Carlo Module

EPACMTP was designed to perform simulations on a nationwide basis, and to account for variations of model input parameters reflecting variations in site and hydrogeological conditions. The fate and transport model is therefore linked to a Monte Carlo driver which generates model input parameter values from the probability distribution of each parameter. The Monte Carlo modeling procedure is described in more detail in this section.

The Monte Carlo method requires that for each input parameter, except constant parameters, a probability distribution is provided. The method involves the repeated generation of pseudo-random values of the uncertain input variable(s) (drawn from the known distribution and within the range of any imposed bounds) and the application of the model using these values to generate a series of model responses (receptor well concentration). These responses are then statistically analyzed to yield the cumulative probability distribution of the model output. Thus, the various steps involved in the application of the Monte Carlo simulation technique are:

(1) Selection of representative cumulative probability distribution functions for the relevant input variables.

(2) Generation of a pseudo-random number from the distributions selected in (1). These values represent a possible set of values (a realization) for the input variables.

(3) Application of the fate and transport simulation modules to compute the output(s), i.e., downstream well concentration.

(4) Repeated application of steps (2) and (3) for a specified number of iterations.

(5) Presentation of the series of output (random) values generated in step (3).

(6) Analysis of the Monte Carlo output to derive regulatory DAF values.

The Monte Carlo module designed for implementation with the EPACMTP composite model performs steps 2-5 above. This process is shown conceptually in Figure 2. Step 6 is performed as a post-processing step. This last step simply involves converting the normalized receptor well concentrations to DAF values, and ranking then for high to low values. Each Monte Carlo iteration yields one DAF value for the constituent of concern (plus one DAF value for each of the transformation products, if the constituent is a degrader). Since each Monte Carlo iteration has equal probability, ordering the DAF values from high to low, directly yields their cumulative probability distribution (CDF). If appropriate, CDF curves representing different regional distributions may be combined into a single CDF curve, which is a weighted average of the regional curves.

A simplified flow chart that illustrated the linking of the Monte Carlo module to the simulation modules of the EPACMTP composite model is presented in Figure 3. The modeling input data is read first, and subsequently the desired random numbers are generated. The generated random and/ or derived parameter values are then assigned to the model variables. Following this, the contaminant transport fate and transport simulation is performed. The result is given in terms of the predicted contaminant concentration(s) in a down-stream receptor well. The generation of random parameter values and fate and transport simulation is repeated as many times as desired to determine the probability distribution of down-stream well concentrations.

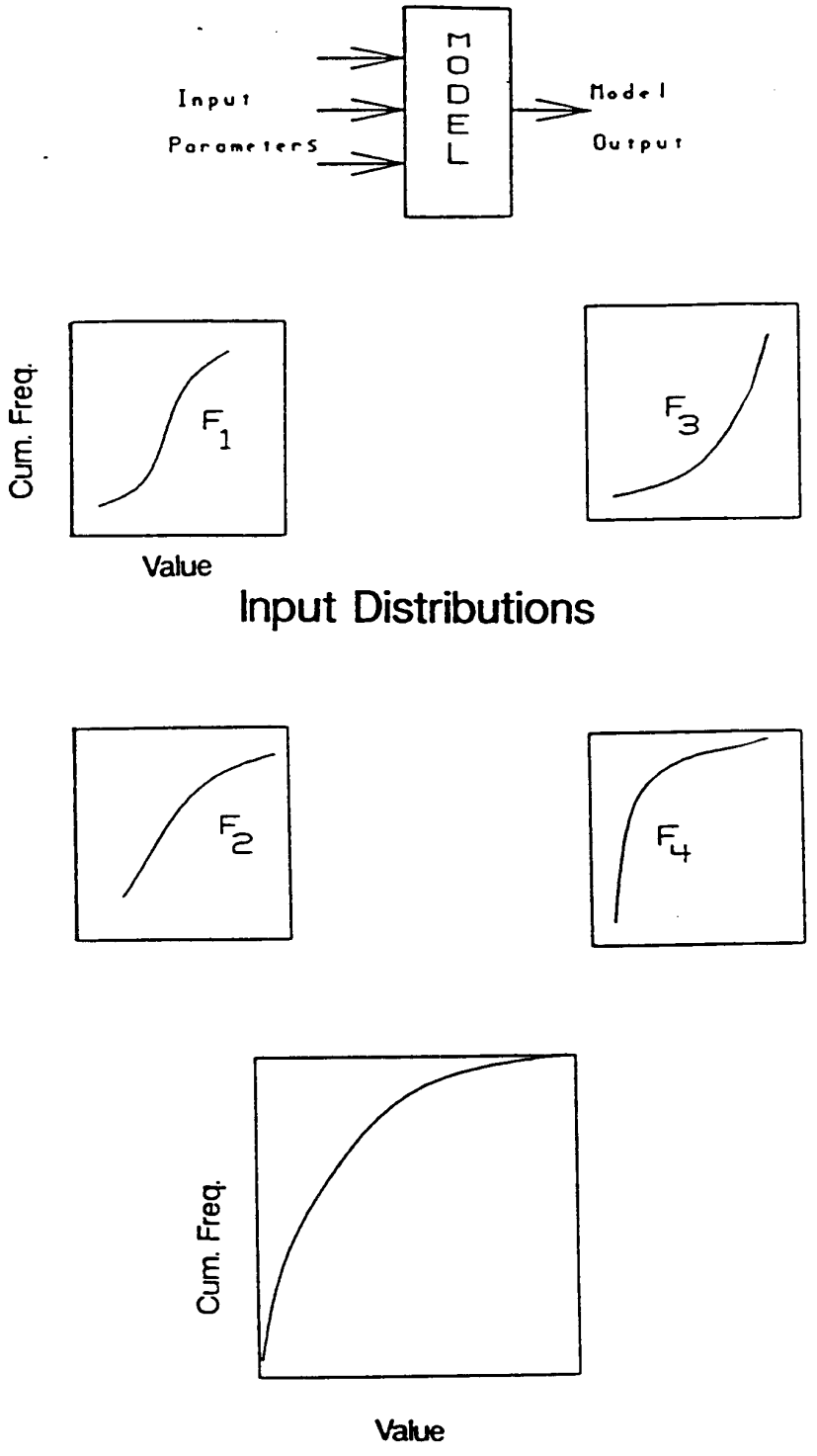


Figure 2
Conceptual Monte Carlo Framework For Deriving Probability Distribution Of Model Output From Probability Distributions Of Input Parameters

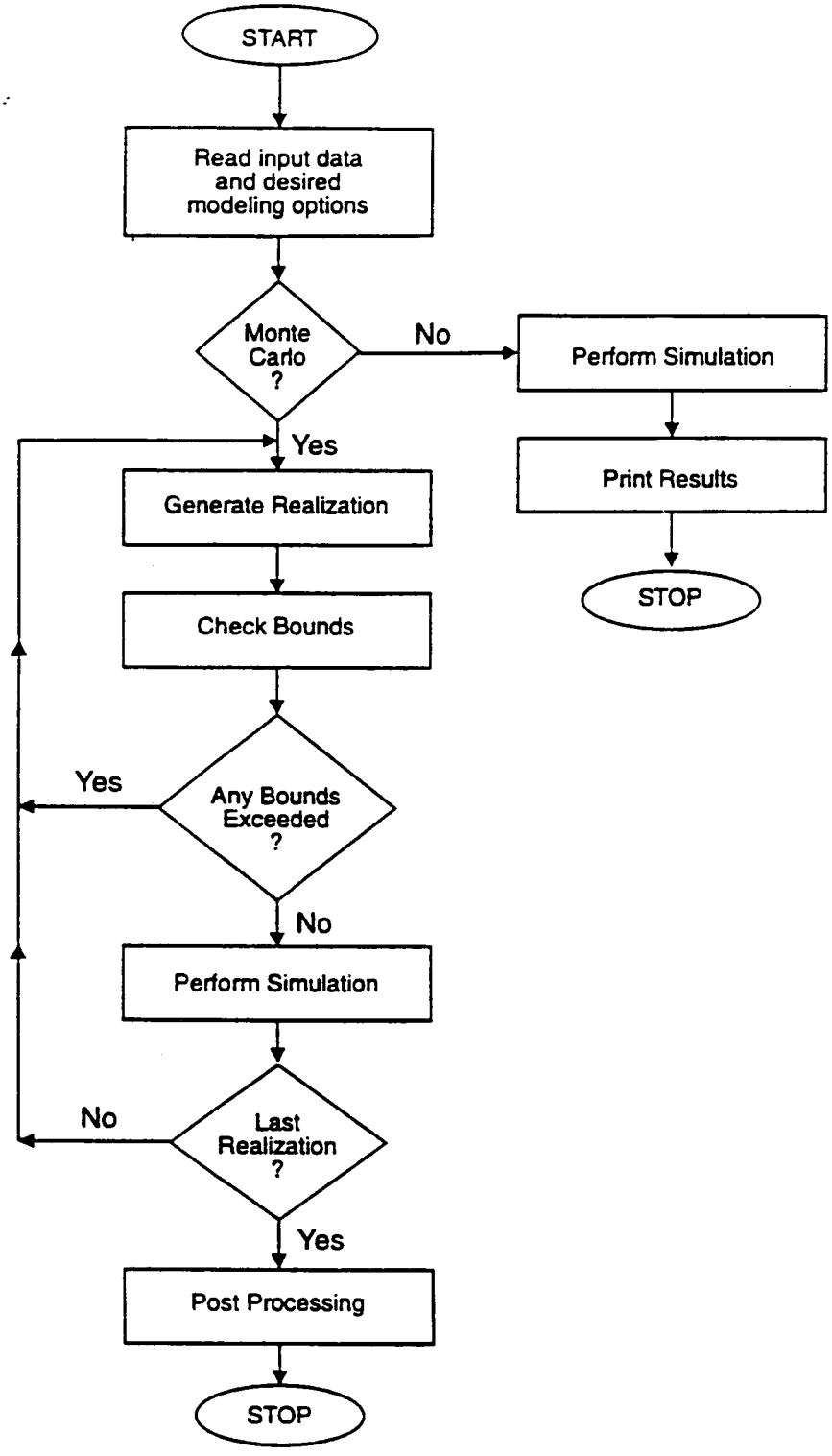


Figure 3
Flow Chart Of EPACMTP For Monte Carlo Simulation

2.3.1 Capabilities and Limitations of Monte Carlo Module

The Monte Carlo module in EPACMTP is implemented as a flexible module that can accommodate a wide variety of input distributions. These include: constant, normal, lognormal, exponential, uniform, $\log_{10}$ uniform, Johnson SB, empirical, or derived. In addition, specific upper and/or lower bounds can be provided for each parameter. The empirical distribution is used when the data does not fit any of the other probability distributions. When the empirical distribution is used, the probability distribution is specified in tabular form as a list of parameter values versus cumulative probability, from zero to one.

It is important to realize that the Monte Carlo method accounts for parameter variability and uncertainty; it does, however, not provide a way to account or compensate for process uncertainty. If the actual flow and transport processes that may occur at different sites, are different from those simulated in the fate and transport module, the result of a Monte Carlo analysis may not accurately reflect the actual variation in groundwater concentrations.

EPACMTP does not directly account for potential statistical dependencies, i.e., correlations between parameters. The probability distributions of individual parameters are considered to be statistically independent. At the same time, EPACMTP does incorporate a number of safeguards against generating impossible combinations of model parameters. Lower and upper bounds on the parameters prevent unrealistically low or high values from being generated at all.

In the case of model parameters that have a direct physical dependence on other parameters, these parameters can be specified as derived parameters. For instance, the ambient groundwater flow rate is determined by the regional hydraulic gradient and the aquifer hydraulic conductivity. In the Monte Carlo analyses, the ambient groundwater flow rate is therefore calculated as the product of conductivity and gradient, rather than generated independently. A detailed discussion of the derived parameters used in the model is provided in the *EPACMTP User's Guide* (EPA, 1994).

3.0 MODELING PROCEDURE

This section documents the modeling procedure followed in determining the groundwater pathway DAF values for the Soil Screening Levels. Section 3.1 describes the overall approach for the modeling analysis; section 3.2 describes the model options used and summarizes the input parameter values.

3.1 Modeling Approach

The overall modeling approach consisted of two stages. First, a sensitivity analysis was performed to determine the optimal number of Monte Carlo repetitions required to achieve a stable and converged result, and to determine which site-related parameters have the greatest impact on the DAFs. Secondly, Monte Carlo analyses were performed to determined DAF values as a function of the size of the source area, for various scenarios of receptor well placement.

3.1.1 Determination of Monte Carlo Repetition Number and Sensitivity Analysis

The criterion for determining the optimal number of Monte Carlo repetitions was set to a change in DAF value of no more than 5 percent when the number of repetitions is varied. A Monte Carlo simulation comprising 20,000 repetitions was first made. The results from this simulation were analyzed by calculating the 85th percentile DAP value obtained by sampling model output sequences of different length, from 2,000 to the full 20,000 repetitions. The modeling scenario considered in this analysis was the same as that in the base case scenario discussed in the next section, with the size of the source area set to 10,000 m^2.

The sensitivity analysis on site-related model parameters was performed by fixing one parameter at a time, while remaining model parameters were varied according to their default, nationwide probability distributions as discussed in the *EPACMTP User's Guide* (EPA, 1993b).

For each parameter, the low, medium, and high values were selected, corresponding to the 15th, 50th, and 85th percentile, respectively, of that parameter's probability distribution. As a result, the sensitivity analysis reflects, in part, the width of each parameter's probability distribution. Parameters with a narrow range of variation will tend to be among the less sensitive parameters, and vice versa for parameters that have a wide range of variation. By conducting the sensitivity analysis as a series of Monte Carlo simulations, any parameter interactions on the model output are automatically accounted for. Each of the Monte Carlo simulations yields a probability distribution of predicted receptor well concentrations. Evaluating the distributions obtained with different fixed values of the same parameter provides a measure of the overall sensitivity and impact of that parameter. In each case the model was run for 2,000 Monte Carlo iterations. Steady-state conditions (continuous source) were simulated in all cases.

In a complete Monte Carlo analysis, over 20 different model parameters are involved. These parameters may be divided into two broad categories. The first includes parameters that are independent of contaminant-specific chemical properties, e.g., depth to water table, aquifer thickness, receptor well distance, etc. The second category encompasses those parameters that are related to contaminant-specific sorption and biochemical transformation characteristics. This category includes the organic carbon partition coefficient, but also parameters such as aquifer pH, temperature and fraction organic carbon. The sensitivity of the model to the first category of parameters has examined, by considering a non-degrading, non-sorbing contaminant. Under these conditions, any parameters in the second category will have zero sensitivity. In addition, all unsaturated zone parameters can be left out of the analysis, since the predicted steady state contaminant concentration at the water table will always be the same as that entering the unsaturated

zone. The only exception to this is the soil type parameter. In the nationwide Monte Carlo modeling approach, different soil types are distinguished. Each of the three different soil types (sandy loam, silt loam or silty clay loam) has a different distribution of infiltration rate, with the sandy loam soil type having the highest infiltration rates, silty clay loam having the lowest, and silty loam having intermediate rates. The effect of the soil type parameter is thus intermixed with that of infiltration rate. Table 1 lists the input 'low', 'medium' and 'high' values for all the parameters examined.

Table 1
Parameter input values for model sensitivity analysis.

Parameter	Low	Median	High
Source Parameters			
Source Area (m^2)	$4.8x10^4$	$2.8x\ 10^5$	$1.1\ x10^6$
Infiltration Rate (m/yr)	$6.0x10^{-4}$	$6.4x10^{-3}$	$1.7x10^{-1}$
Recharge Rate (m/yr)	$6.0x10^{-4}$	$8.0x10^{-3}$	$1.5x10^{-1}$
Saturated Zone Parameters			
Saturated Thickness (m)	15.55	60.8	159.3
Hydraulic conductivity (m/yr)	$1.9\ x\ 10^3$	$1.5\ x\ 10^4$	$5.5\ X\ 10^4$
Regional gradient	$4.3\ x\ 10^{-3}$	$1.8\ x\ 10^{-2}$	$5.0\ X\ 10^{-2}$
Ambient groundwater velocity (m/yr)	53.2	404.0	2883.0
Porosity	0.374	0.415	0.455
Longitudinal Dispersivity (m)	4.2	12.7	98.5
Transverse Dispersivity (m)	0.53	1.59	12.31
Vertical Dispersivity (m)	0.026	0.079	0.62

3.1.2 Analysis of DAF Values for Different Source Areas

Following completion of the sensitivity analysis discussed above, an analysis was performed of the variation of DAF values with size of the contaminated area. The sensitivity analysis, results of which are presented in Section 4.1, showed that the size of the contaminated source area is one of the most sensitive parameters in the model. For the purpose of deriving DAF values for the groundwater pathway in determining soil screening levels, it would therefore be appropriate to correlate the DAF value to the size of the contaminated area.

The EPACMTP modeling analysis was designed to determine the size of the contaminated area that would result in DAF values of 10 and 100 at the upper 85th, 90th, and 95th percentile of probability, respectively. Since it is not possible to directly determine the source area that results in a specific DAF value, the model was executed for a range of different source areas, using a different but fixed source area value in each Monte Carlo simulation. The 85th, 90th, and 95th percentile DAF values were then plotted against source area, in order to determine the value of source area corresponding to a specific DAF value.

3.1.2.1 *Model Options and Input Parameters*

Table 2 summarizes the EPACMTP model options used in performing the simulations. Model input parameters used are summarized in Table 3. The selected options and input parameter distributions and values are consistent with those used in the default nationwide modeling, and are discussed individually in the *EPACMTP User's Guide (EPA,* 1994). Exceptions to this default modeling scenario are discussed below.

Table 2
Summary of EPACMTP modeling options.

Option	Value Selected
Simulation Type	Monte Carlo
Number of Repetitions	15,000
Nationwide Aggregation	Yes
Source Type	Continuous
Unsat. Zone Present	Yes
Sat. Zone Model	Quasi-3D
Contaminant Degradation	No
Contaminant Sorption	No

Source Area

In the default, nationwide modeling scenario, the waste site area, or source area, is treated as a Monte Carlo variable, with a distribution of values equal to that of the type of waste unit, e.g. landfills, considered. In the present modeling analyses, the source area was set to a different but constant value in each simulation run.

Receptor Well Location

In the default nationwide modeling scenario, the position of the nearest downgradient receptor well in the saturated zone is treated as a Monte Carlo variable. The position of the well is defined by its x-, y-, and z-coordinates. The x-coordinate represents the distance along the ambient groundwater flow direction from the downgradient edge of the contaminated area. The y-coordinate represents the horizontal transverse distance of the well from the plume centerline. The x-, and y-coordinate in turn can be defined in terms of an overall downgradient distance, and an angle off-center (EPA, 1994). The z-coordinate represents the depth of the well intake point below the water table. This is illustrated schematically in Figure 4, which shows the receptor well location in both plan view and cross-sectional view.

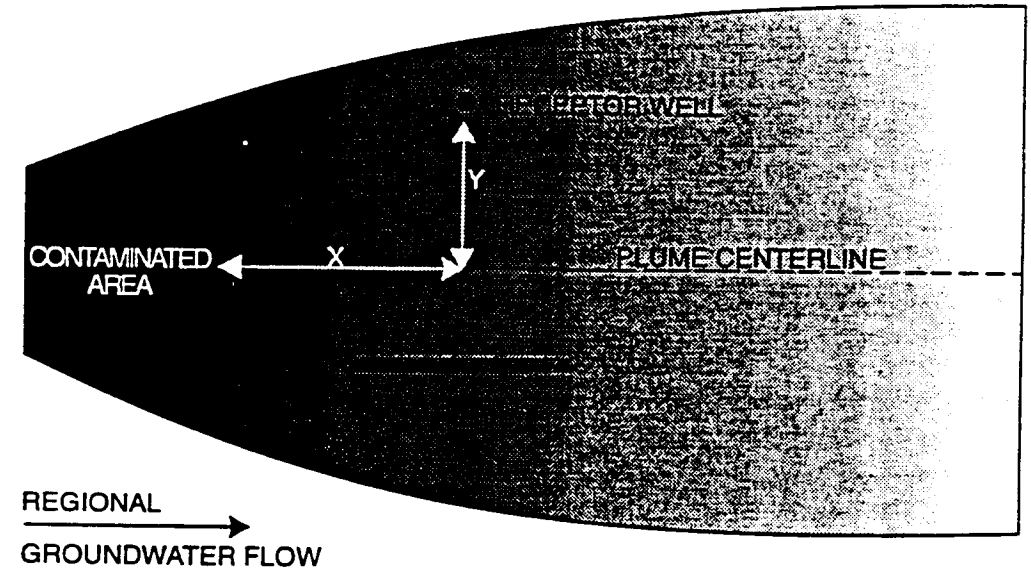
In the default nationwide modeling scenario, the x-, and z-coordinates of the well are determined from Agency surveys on the distance of residential wells from municipal landfills, and data on the depth of residential drinking water wells, respectively. The y-coordinate value is determined so that the well location falls within the approximate areal extent of the contaminant plume (see Figure 4).

For the present modeling analysis, a number of different receptor well placement scenarios were considered. These scenarios are summarized in Table 4.

Table 3
Summary of EPACMTP input parameters.

Parameter	Value or Distribution Type	Comment
Source-Specific		
Area	Constant	Varied in each run
Infiltration Rate	Soil-type dependent	default
Recharge Rate	Soil-type dependent	default
Leachate Concentration	= 1.0	default
Chemical-Specific		
Hydrolysis Rate Constants	= 0.0	Contaminant does not degrade
Organic Carbon Partition Coeff.	= 0.0	Contaminant does not sorb
Unsaturated Zone Specific		
Depth to Water Table	Empirical	default
Dispersivity	Soil-depth dependent	default
Soil Hydraulic Properties	Soil-type dependent	default
Soil Chemical Properties	Soil-type dependent	default
Saturated Zone Specific		
Sat. Zone Thickness	Exponential	default
Hydraulic Conductivity	Derived from Part. Diam.	default
Hydraulic Gradient	Exponential	default
Seepage Velocity	Derived from Conductivity and Gradient	default
Particle Diameter	Empirical	default
Porosity	Derived from Part. Diam	default
Bulk Density	Derived from Porosity	default
Longitudinal Dispersivity	Distance-dependent	default
Transverse Dispersivity	Derived from Long. Dispersivity	default
Vertical Dispersivity	Derived from Long. Dispersivity	default
Receptor Well x-coordinate	= 25 feet	Set to fixed value
Receptor Well y-coordinate	Within plume	default
Receptor Well z-coordinate	Empirical	default

Note: 'Default' represents default nationwide Monte Carlo scenario as presented in *EPACMTP User's Guide* (EPA, 1994).



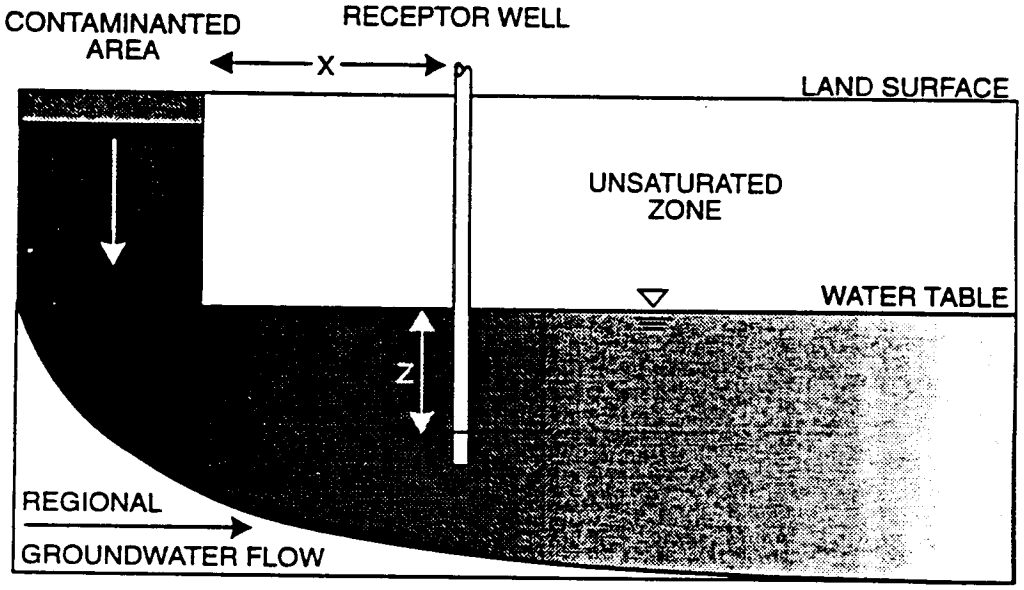


Figure 4
Plain View And Cross-Section View Showing Location Of Receptor Well

Table 4
Receptor Well Location Scenarios

Scenario	Xwell	Ywell	Zwell
1 (Base Case)	25 ft from edge of source area	Monte Carlo within plume	Nationwide Distribution
2	Nationwide Distribution	Monte Carlo within plume	Nationwide Distribution
3	0 ft from edge of source area	Monte Carlo within half-width of source area	Nationwide Distribution
4	25 ft from edge of source area	Monte Carlo within half-width of source area	Nationwide Distribution
5	100 ft from edge of source area	Monte Carlo within half-width of source area	Nationwide Distribution
6	25 ft from edge of source area	Width of source area + 25 ft	25 ft below water table

Xwell = Downgradient distance of receptor well from edge of source area.
Ywell = Horizontal transverse distance from plume centerline.
Zwell = Depth of well intake point below water tablet

The base case scenario (scenario 1) involved setting the x-distance of the receptor well to 25 feet from the edge of the source area. Nationwide default options were used for the receptor well y- and z-coordinates. The y-coordinate of the well was assigned a uniform probability distribution within the boundary of the plume. The depth of the well intake point (z-coordinate) was assumed to vary within upper and lower bounds of 15 and 300 feet below the water table, reflecting a national sample distribution of depths of residential drinking water wells (EPA, 1994).

In addition to this base case scenario, a number of other well placement scenarios were investigated also. These are numbered in Table 4 as scenarios 2 through 6. Scenario 2 corresponds to the default, nationwide Monte Carlo modeling scenario in which the x, y, and z locations of the well are all variable. In scenarios 3, 4 and 5, the distance between the receptor well and the source area is varied from zero to 100 feet. In these scenarios, the ycoordinate of the well was constrained to the central portion of the plume. In scenario number 6, the x-, y-, and z-coordinates of the receptor well were all set to constant values. These additional scenarios were included in the analysis in order to assess the sensitivity of the model results to the location of the receptor well.

Aquifer Particle Size Distribution

In the default Monte Carlo modeling scenario, the aquifer hydraulic conductivity, porosity, and bulk density are determined from the mean particle diameter. The particle diameter distribution used is based on data compiled by Shea (1974). In the present modeling analyses for fixed waste site areas, the same approach and data were used, but the distribution was shifted somewhat to assign more weight to the smallest particle diameter interval. The result is that lower values of the hydraulic conductivity values generated, and also of the ambient groundwater seepage velocities, received more emphasis. Lower ambient groundwater velocities reduce the degree of dilution of the incoming contaminant plume and therefore result in lower, i.e. more conservative, DAF values. Table 5 summarizes the distribution of particle size diameters used in both the default nationwide modeling scenario and in the present analyses.

Table 5
Distribution of aquifer particle diameter.

Nationwide Default		Present Analyses	
Particle Diameter (cm)	Cumulative Probability	Particle Diameter (cm)	Cumulative Probability
$3.9\ 10^{-4}$	0.000	$4.0\ 10^{-4}$	0.100
$7.8\ 10^{-4}$	0.038	$8.0\ 10^{-4}$	0.150
$1.6\ 10^{-3}$	0.104	$1.6\ 10^{-3}$	0.200
$3.1\ 10^{-3}$	0.171	$3.1\ 10^{-3}$	0.270
$6.3\ 10^{-3}$	0.262	$6.3\ 10^{-3}$	0.330
$1.25\ 10^{-2}$	0.371	$1.25\ 10^{-2}$	0.440
$2.5\ 10^{-2}$	0.560	$2.5\ 10^{-2}$	0.590
$5.0\ 10^{-2}$	0.792	$5.0\ 10^{-2}$	0.790
$1.0\ 10^{-1}$	0.904	$1.0\ 10^{-1}$	0.880
$2.0\ 10^{-1}$	0.944	$2.0\ 10^{-1}$	0.910
$4.0\ 10^{-1}$	0.946	$4.0\ 10^{-1}$	0.940
$8.0\ 10^{-1}$	1.000	$7.5\ 10^{-1}$	1.000

4.0 RESULTS

This section presents the results of the modeling analyses performed. The analysis of the convergence of the Monte Carlo simulation is presented first, followed by the parameter sensitivity analysis, and thirdly the analysis of DAF values as a function of source area for various well placement scenarios.

4.1 Convergence of Monte Carlo Simulation

Table 6 summarizes the results of this convergence analysis. It shows the variation of the 85th percentile DAF value with the number of Monte Carlo repetitions, from 2,000 to 20,000. The variations in DAF values are shown both as absolute and relative differences. The table shows that for this example, the DAF generally increases with the number of Monte Carlo repetitions. It should be kept in mind that the results from different repetition numbers as presented in the table, are not independent of one another. For instance, the first 2,000 repetitions are also incorporated in the 5000 repetition results, which in turn is in the 10,000 repetition result, etc. The rightmost column of Table 6 shows the percentage difference in DAF value between different repetition numbers. At repetition numbers of 14,000 or less, the percentage difference varies in a somewhat irregular manner. However, for repetition numbers of 15,000 or greater, the DAF remained relatively constant, with incremental changes of DAF remaining at 1 % or less. Based upon these results, a repetition number of 15,000 was selected for use in the subsequent runs with fixed source area.

4.2 Parameter Sensitivity Analysis

Results of the parameter sensitivity analysis are summarized in Table 7. The parameters are ranked in this table in order of relative sensitivity. Relative sensitivity is defined for this purpose as the absolute difference between the "high" and "low" DAF at the 85th percentile level, divided by the 85th percentile DAF for the "median" case.

The table shows that the most sensitive parameters included the rate of infiltration, which is a function of soil type, the saturated thickness of the aquifer, the size of source area, the groundwater seepage velocity, and the vertical position of the receptor well below the water table. The least sensitive parameters included porosity, downstream distance of the receptor well in both the x- and y-directions, the horizontal transverse dispersivity, and the areal recharge rate. To interpret these results, it should be kept in mind that the rankings reflect in part the range of variation of each parameter in the data set used for the sensitivity analysis. The infiltration rate was a highly sensitive parameter since, for a given leachate concentration, it directly affects the mass flux of contaminant entering the subsurface. The size of the source would be expected to be equally sensitive, were it not for the fact that in the sensitivity analysis, the source area had a much narrower range of variation than the infiltration rate. The "high" and "low" values of the source area, which were taken from a nationwide distribution of landfill waste units, varied by a factor of 23, while the ratio of "high" to "low" infiltration rate was almost 300.

In the simulations performed for the sensitivity analysis, no constraint was imposed on the vertical position of the well. The well was modeled as having a uniform distribution with the well intake point located anywhere between the water table and the base of the aquifer. The aquifer saturated thickness and vertical position of the well were both among the sensitive parameters, with similar effects on DAF values. Increasing either the saturated thickness, or the fractional depth of the receptor well below the water table, increases the likelihood that the receptor well will be located underneath the contaminant plume and sample uncontaminated groundwater, leading to a

Table 6
Variation of DAF with number of Monte Carlo repetitions

No. of Repetitions	85-th Percentile DAF	Difference	Relative Difference (%)
2,000	347.8		
		-10.9	-3.1
5,000	336.9		
		+17.3	+5.1
10,000	354.2		
		+5.0	+ 1.4
11,000	359.2		
		+28.2	+7.9
12,000	387.4		
		-18.1	-4.7
13,000	369.3		
		-0.2	-0.05
14,000	369.1		
		+ 18.2	+4.9
15,000	387.3		
		+0.1	+0.03
16,000	387.4		
		+0.6	+0.15
17,000	388.0		
		-0.7	-0.18
18,000	387.3		
		+2.9	+0.75
19,000	390.2		
		+2.6	+0.67
20,000	392.8		

Table 7
Sensitivity of model parameters.

Parameter	85% DAF Value			Relative Sensitivity*	Rank
	Low	Median	High		
Infiltration Rate	4805.4	418.8	11.6	11.4	1
Saturated Thickness	25.3	198.5	2096.9	10.4	2
G.W. Velocity	7.6	97.7	816.3	8.3	3
Source Area	357.1	85.2	35.6	3.8	4
Hydr. Conductivity	19.8	180.4	660.1	3.5	5
Vertical Well Position	49.1	206.1	491.4	2.1	6
G.W. Gradient	32.4	168.3	383.0	2.1	7
Long. Dispersivity	182.6	104.2	78.8	1.0	8
Vert. Dispersivity	179.6	114.9	66.6	1.0	9
Porosity	41.3	49.9	79.7	0.8	10
Receptor Well Distance	163.9	117.9	84.5	0.7	11
Transv. Dispersivity	156.7	156.3	173.5	0.1	12
Receptor Well Angle	127.3	130.8	113.6	0.1	13
Ambient Recharge	108.3	100.0	114.4	0.06	14

* Relative Sensitivity = l High-Low l /Median

high DAF value. The dilution-attenuation factors were also sensitive to the groundwater velocity, and the parameters that determine the groundwater velocity, i.e., hydraulic conductivity and ambient gradient. Table 7 shows that a higher groundwater velocity results in an increase of the dilution-attenuation factor. Since a conservative contaminant was simulated under steady-state conditions, variations in travel time do not affect the DAF. The increase of DAF with increasing flow velocity reflects the greater mixing and dilution of the contaminant as it enters the saturated zone in systems with high groundwater flow rate. Porosity also directly affects the groundwater velocity, but was not among the sensitive parameters. This is a reflection of the narrow range of variation assigned to this parameter.

The off-center angle which determines the y position of the well relative to the plume center line would be expected to have a similar effect as the well depth, but is seen to have a much smaller sensitivity. This was a result of constraining the y-location of the receptor well to be always inside the approximate areal extent of the contaminant plume. The effect is that the relative sensitivity of the off-center angle was much less than that of the vertical coordinate of the well. The low relative sensitivity of recharge rate reflects the fact that this parameter has an only indirect effect on plume concentrations.

Overall, the Monte Carlo results were not very sensitive to dispersivity and downstream distance of the receptor well. The probable explanation for these parameters is that variations of the parameters produce opposing effects which tended to cancel one another. Low dispersivity values will produce a compact plume which increases the probability that a randomly located receptor well will lie outside (underneath) the plume. Higher dispersivities will increase the chance that the well will intercept the plume. At the same time, however, mass balance considerations dictate that in

this case average concentrations inside the plume will be lower than in the low dispersivity case. Similar reasoning applies to the effect of receptor well distance. If the well is located near the source, concentrations in the plume will be relatively high, but so is the chance that the well does not intercept the plume at all. At greater distances from the source, the likelihood that the well is located inside the plume is greater, but the plume will also be more diluted. In the course of a full Monte Carlo simulation these opposing effects would tend to average out. The much lower sensitivity of transverse dispersivity, α_T, compared to α_L and α_V can be contributed to the imposed constraint that the well must always be within the areal extent of the plume.

The results of the sensitivity analysis show that the site characteristic which lends itself best for a classification system for correlating sites to DAF values is the size of the contaminated (or source) area. In the subsequent analyses, the DAF values were therefore determined as a function of the source area size. These results are presented in the following section.

4.3 DAF Values as a Function of Source Area

This section presents the DAF value as a function of source area for various well location scenarios. The results for each of the scenarios examined are presented in tabular and graphical form. Figure 5 shows the variation of the 85th, 90th, and 95th percentile DAF with source area for the base case scenario. The source area is expressed in square feet. The figure displays DAF against source area in a log-log graph. The graph shows an approximately linear relationship except that at very large values of the source area, the DAF starts to level off. Eventually the DAF approaches a value of 1.0. As expected, the curve for the 95th percentile DAF always shows the lowest DAF values, while the 85th percentile shows the highest DAFs. The DAF versus source area relationship for the other well placement scenarios are shown in Figures 6 through 10. The numerical results for each scenario are summarized in Tables Al through A6 in the appendix.

Inspection and comparison of the results for each scenario indicate that the relationship follows the same general shape in each case, but the magnitude of DAF values at a given source area can be quite different for different well placement scenarios. In order to allow a direct comparison between the various scenarios analyzed, the DAF values obtained for a source area of 150,000 ft^2 (3.4 acres) are shown in Table 8 as a function of the receptor well location scenario.

Inspection of the DAF values shows that the default nationwide scenario for locating the receptor well results in the highest DAF values, as compared to the base case scenario and the other scenarios, in which the receptor well location was fixed at a relatively close distance from the waste source. In the default nationwide modeling scenario, the well location is assigned from nationwide data on both the distance from the waste source and depth of the well intake point below the water table. In the default nationwide modeling scenario, the receptor well is allowed to be located up to 1 mile from the waste source. In the base case (Scenario 1) the well is allowed to be located anywhere within the areal extent of the contaminant plume for a fixed x-distance of 25 feet. This allows the well to be located near the fringes of the contaminant plume where concentrations are relatively low and DAF values are correspondingly high. In contrast, in Scenarios 3, 4, and 5, the well location was constrained to be within the half-width of the waste source. In other words, the well was always placed in the central portion of the contaminant plume where concentrations are highest. As a result, these scenarios show lower DAF values then the base case scenario. The results for Scenarios 3, 4, and 5, which differ only in the x-distance of the receptor well, show that placement of the well at either 25 or 100 feet away from the waste source results in 85% and 90% DAF values that are actually lower, i.e. more conservative, than placement of the well directly at the edge of the waste source. This is a counter-intuitive result, but may be explained from the interaction between distance from the waste source and vertical extent of the contaminant plume below the water table. Close to the waste source, the contaminant concentrations within the plume are highest, but the plume may not have penetrated very deeply into the saturated zone (Figure 2).

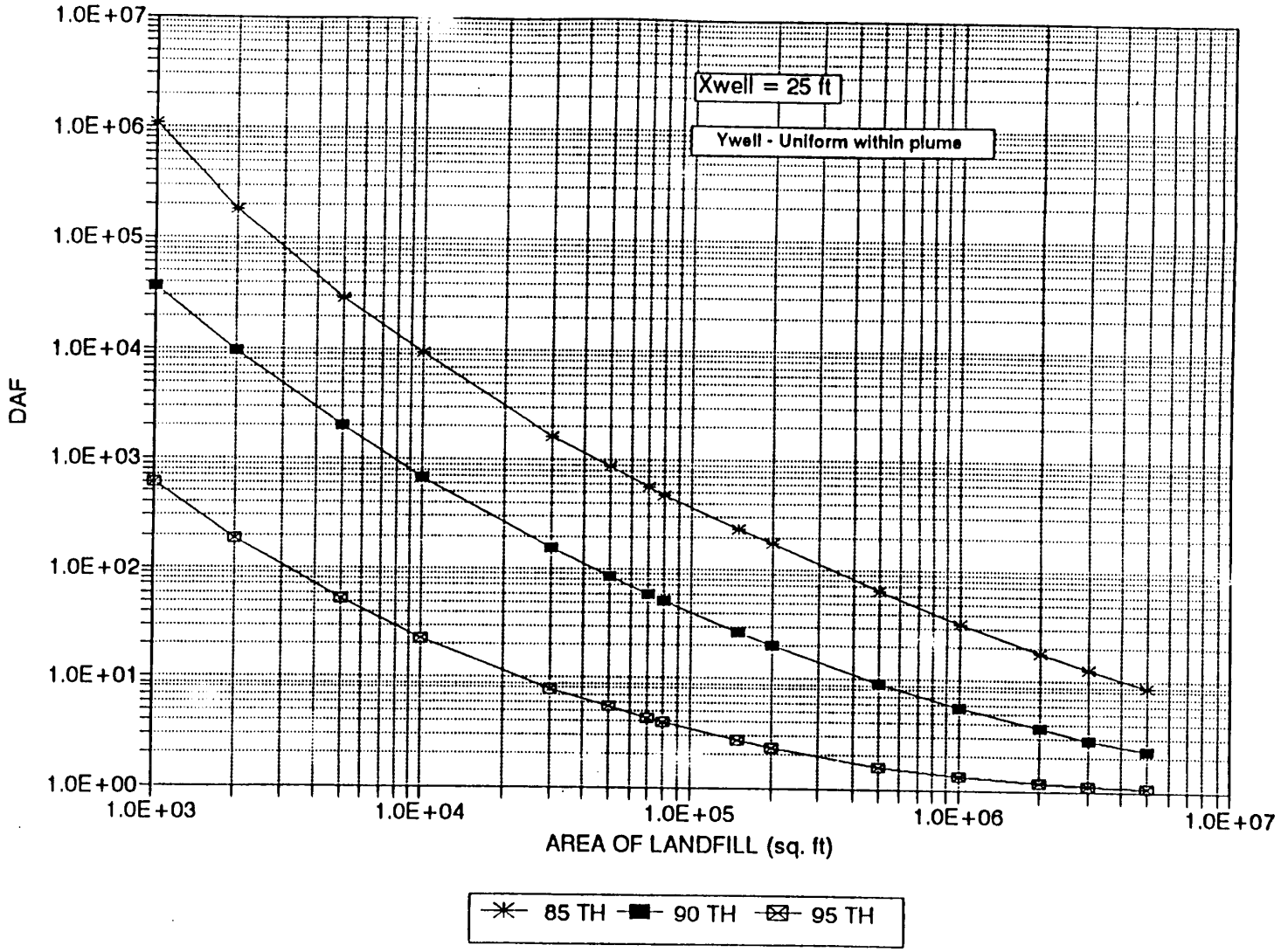


Figure 5
Variation Of DAF With Size Of Source For The Base Case Scenario
(x=25 ft, y=uniform in plume, z=nationwide distribution)

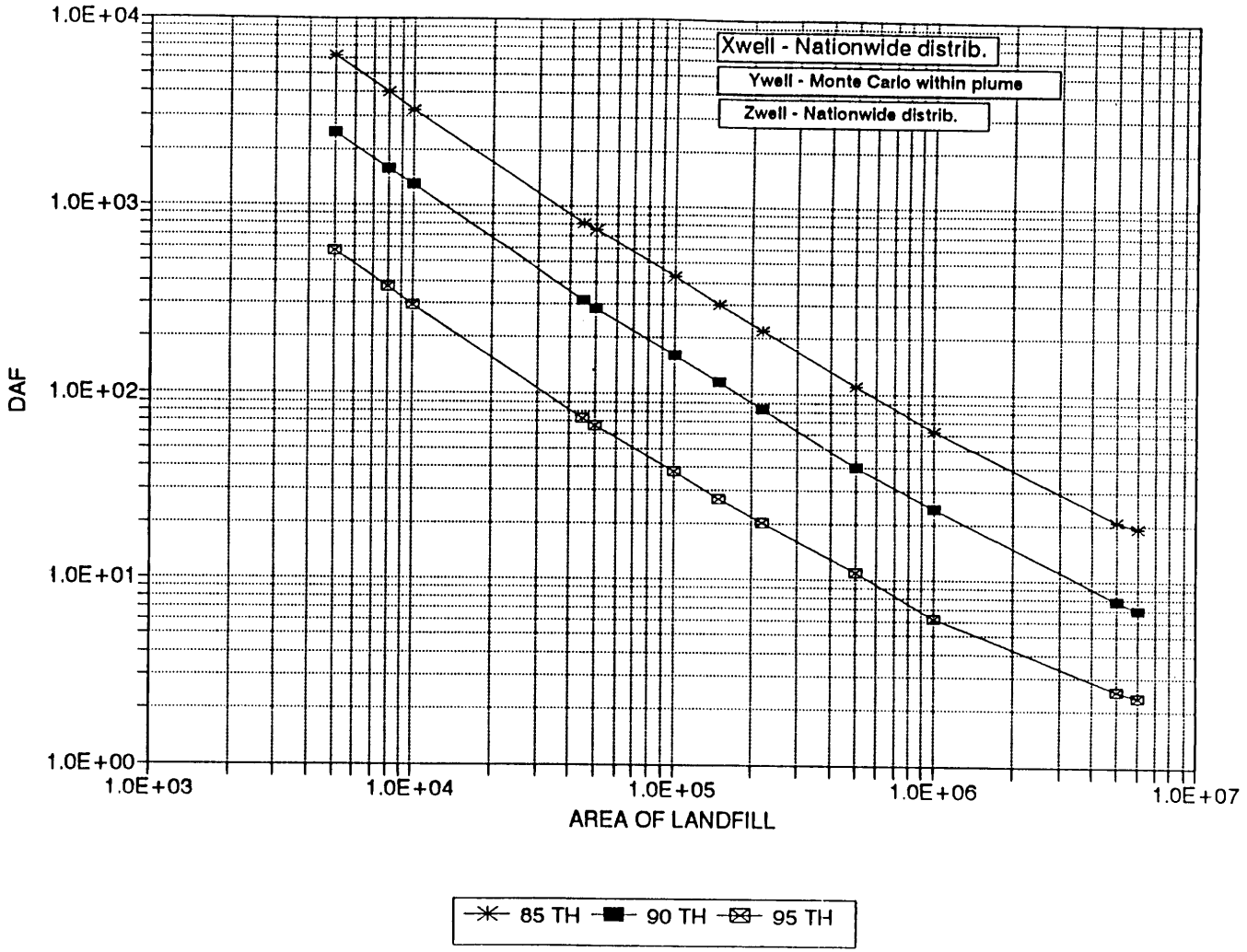


Figure 6
Variation Of DAF With Size Of Source Area For The Default Nationwided Scenario (Scenario 2: x=nationwide distribution, y=uniform in plume, z=nationwide distribution)

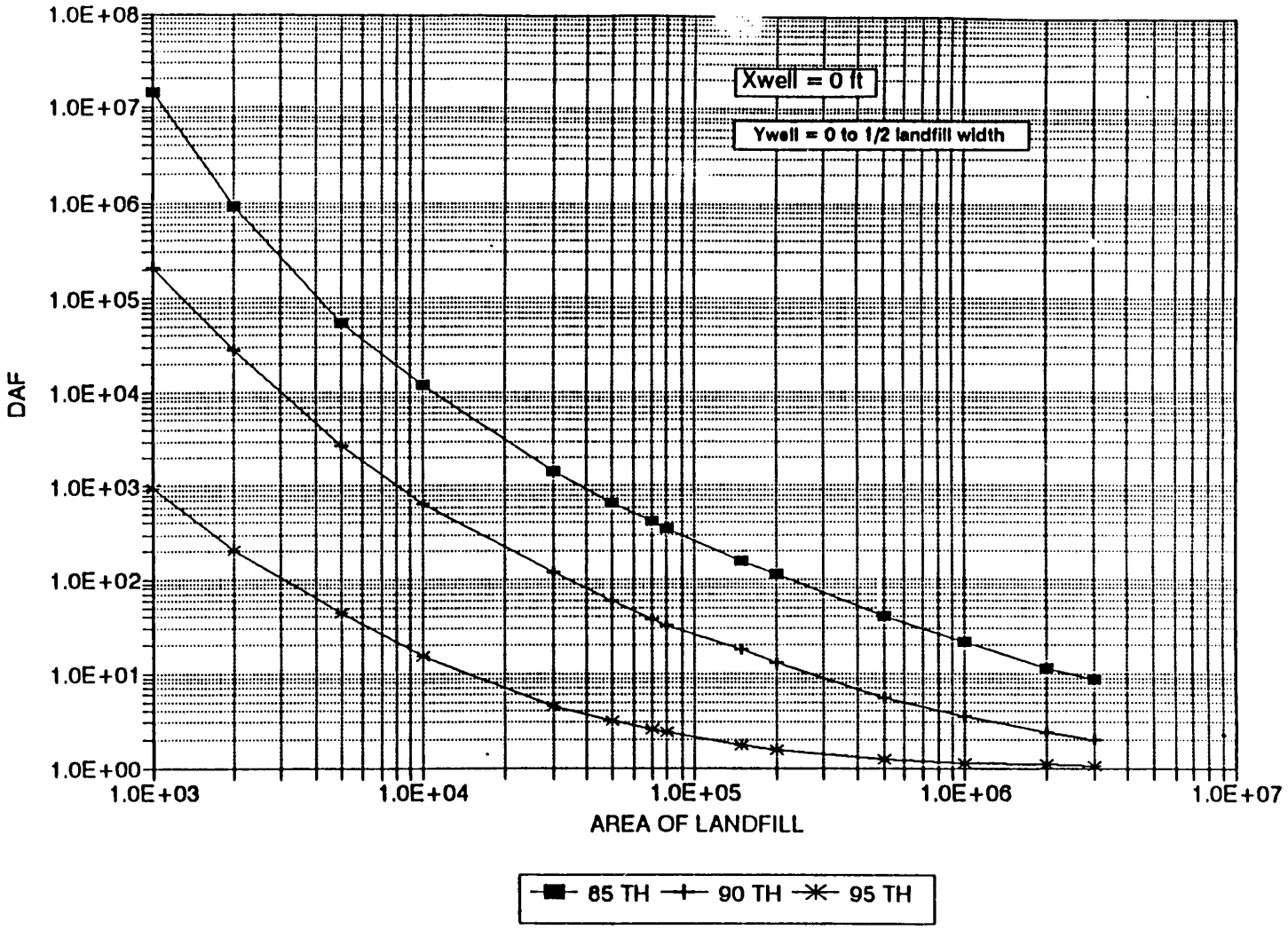


Figure 7
Variation Of DAF With Size Of Source Area For Scenario 3
(x=0, y=uniform within half-width of source area, z=nationwide distribution

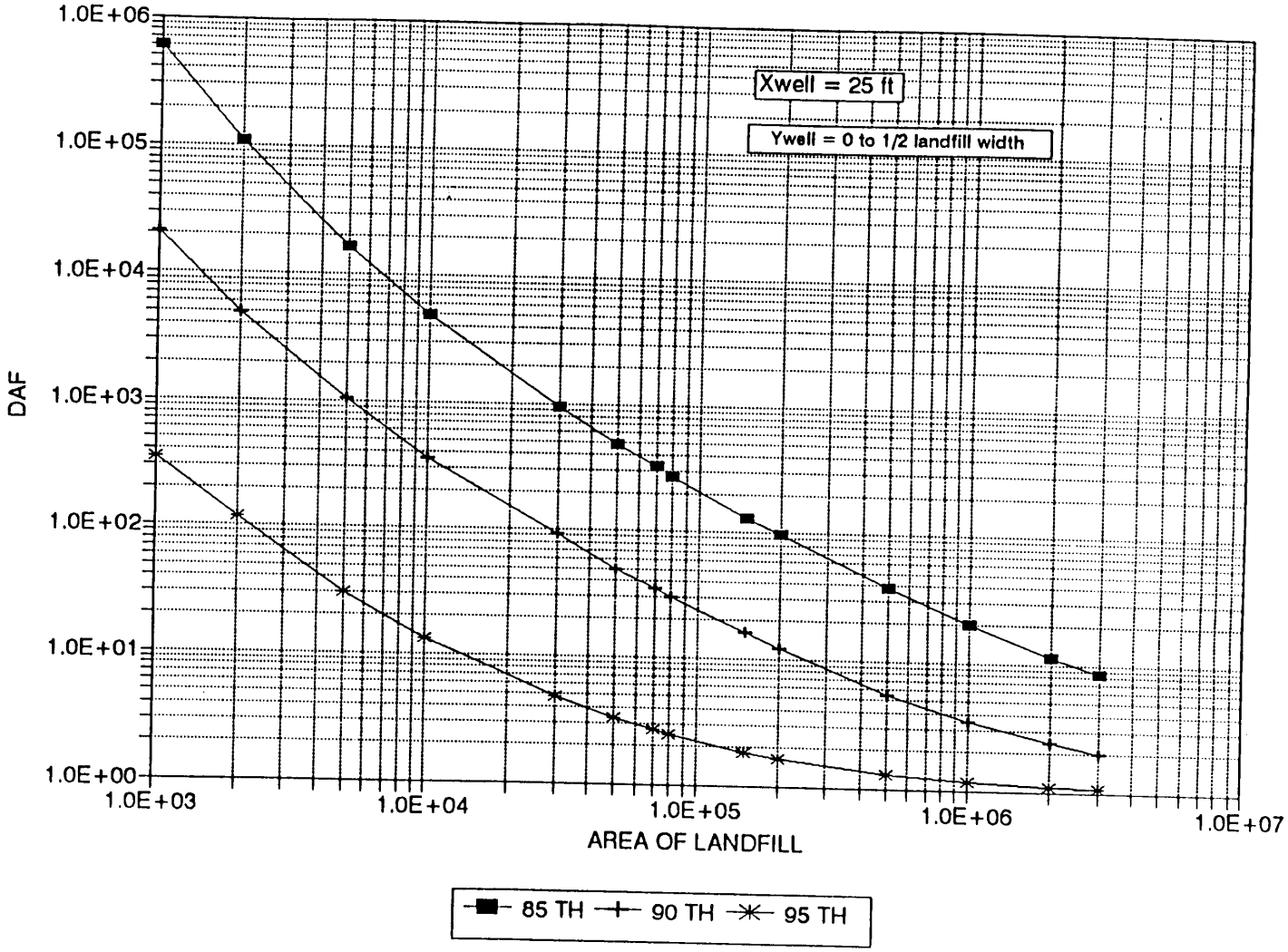


Figure 8
Variation Of DAF With Size Of Source Area For Scenario 4
(x=25 fy, y=uniform within half-width of source area, z=nationwide distribution)

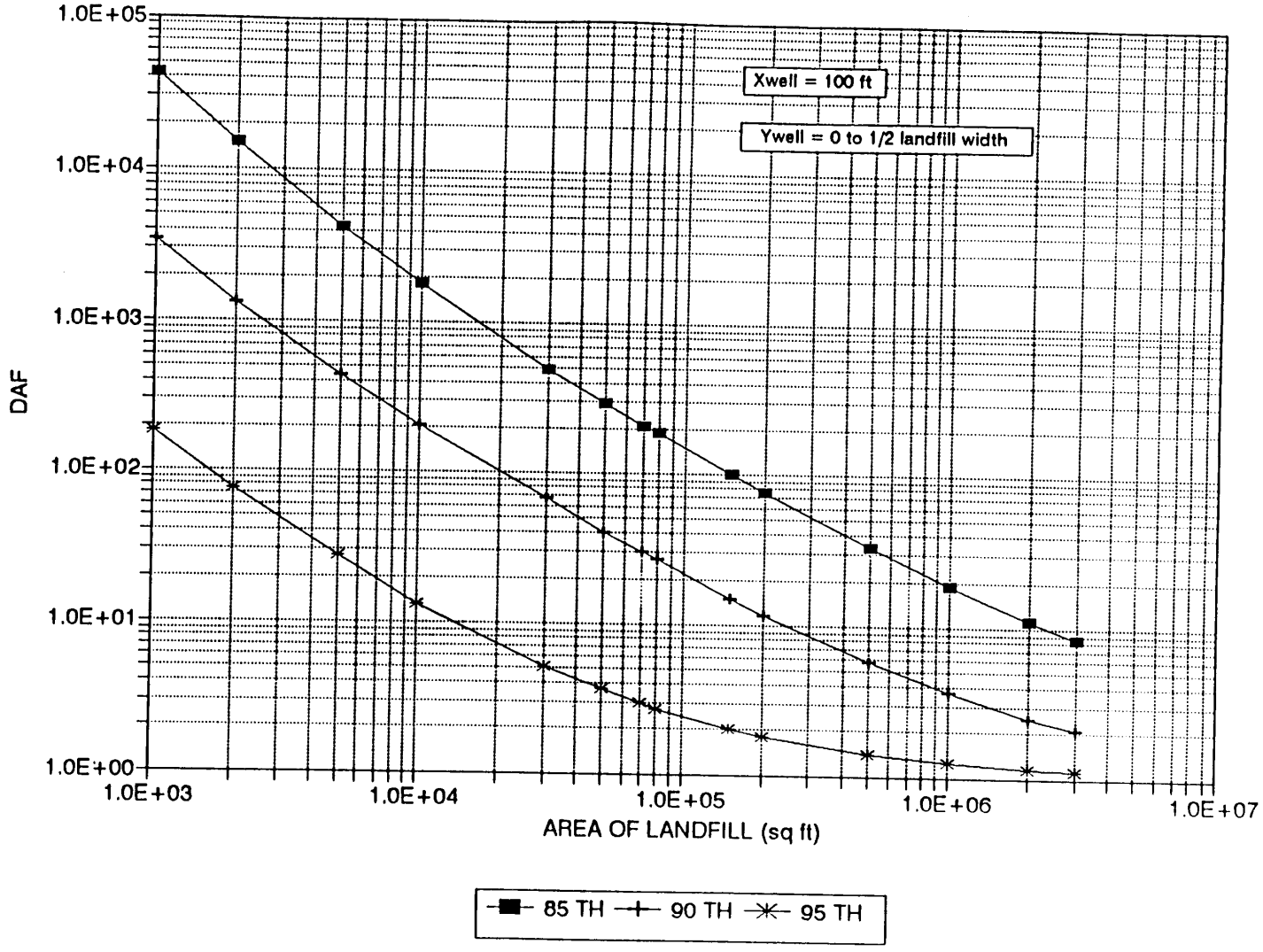


Figure 9
Variation Of DAF With Size Of Source Area For Scenario 5
(x=100 ft, y=uniform within half-width of source area, z=nationwide distribution)

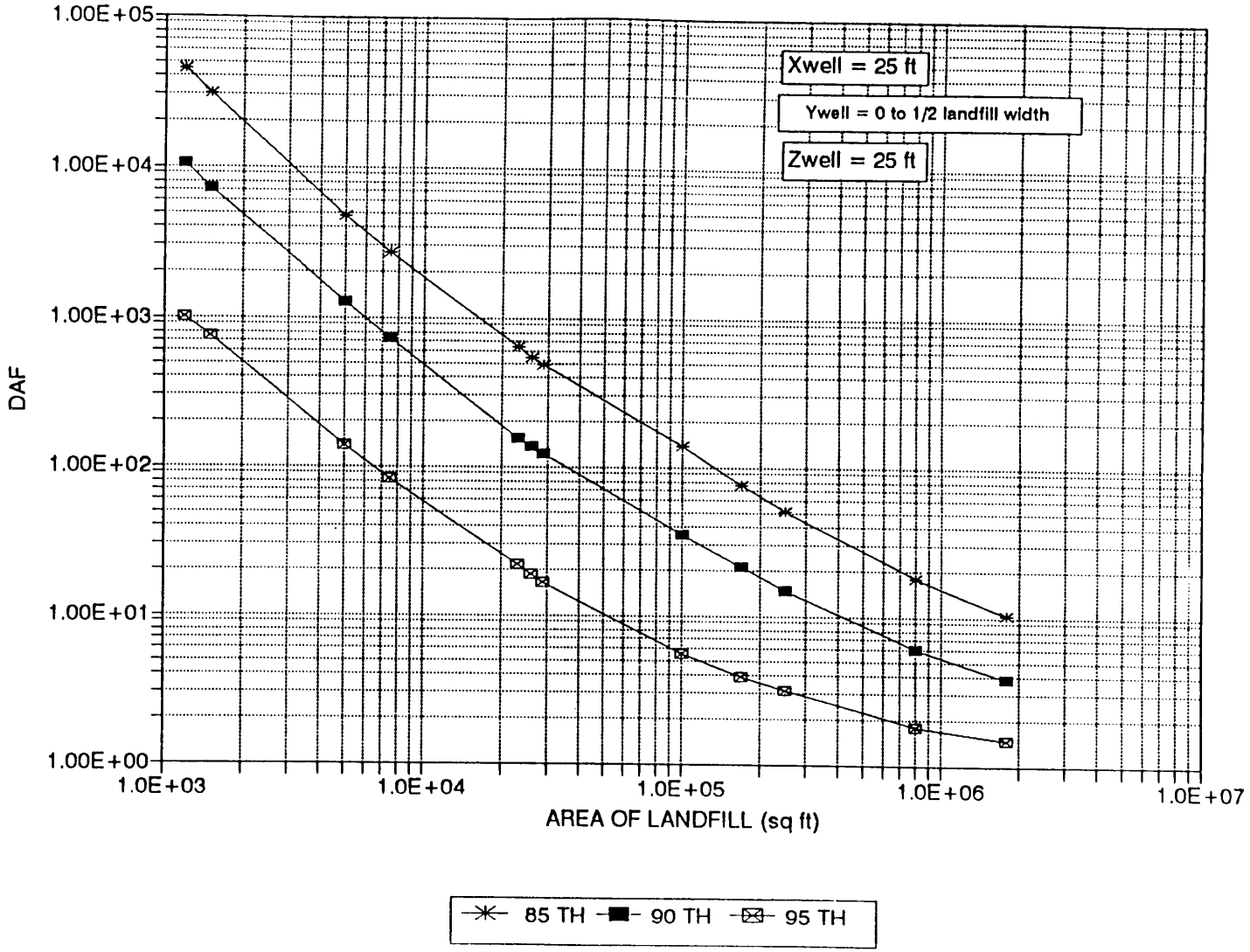


Figure 10
Variation Of DAF With Size Of Source Area For Scenario 6
(x=25 ft, y=width of source area + 25 ft, z=25 ft)

Table 8
DAF values for waste site area of 150,000 ft^2.

Model Scenario	DAF Percentile 85	90	95
1 (base case)	237.5	26.4	2.8
2	300.1	114.7	26.8
3	158.8	17.9	1.7
4	132.1	16.6	1.8
5	98.8	15.1	2.0
6	94.7	25.3	4.4

Because the vertical position of the well was taken as a random variable, with a maximum value of up to 300 feet, the probability that a receptor well samples pristine groundwater underneath the contaminant plume is higher at close distances from the waste area. Conversely, as the distance from the source increases, the plume becomes more dilute but also extends deeper below the water table. The final result is that the overall DAF may actually decrease with distance from the source. The table also shows that at the 95% level, the lowest DAF is obtained in the case where the well is located at the edge of the waste source. This reflects that the highest concentration values will be obtained only very close to the waste source.

The results for the last scenario, in which the x, y, and z locations of the receptor well were all fixed, show that fixing the well depth at 25 feet ensures that the well is placed shallow enough that it will be located inside the plume in nearly all cases, resulting in low DAF values at the 85th and 90th percentile values. On the other hand, the well in this case is never placed immediately at the plume centerline, so that the highest concentrations sampled in this scenario are always lower than in the other scenarios. This is reflected in the higher DAF value at the 95th percentile level.

One of the key objectives of the present analyses was to determine the appropriate groundwater DAF value for a waste area of given size. For the base case scenario, the 90th percentile DAF value is on the order of 100 or higher for a waste area size of 1 acre (43,560 ft^2) and less. For waste areas of 10 acres and greater, the 90th percentile DAF is 10 or less.

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APPENDIX A

Table A1 DAF values as a function of source area for base case scenario (x=25 ft., y=uniform in plume, z-nationwide distribution).

	DAF		
Area (sq. ft.)	85th	90th	95th
1000	1.09E+06	3.76E+04	609.01
2000	1.86E+05	9.63E+03	187.69
5000	2.91 E+04	2.00E+03	53.02
10000	9.31 E+03	680.27	22.57
30000	1647.18	155.21	7.82
50000	869.57	84.25	5.41
70000	569.80	59.28	4.34
80000	477.33	50.56	3.97
150000	237.47	26.36	2.77
200000	174.86	20.19	2.37
500000	64.52	9.12	1.61
1000000	32.27	5.61	1.32
2000000	17.83	3.68	1.16
3000000	12.94	2.94	1.11
5000000	8.91	2.33	1.06

Table A2 DAF values as a function of source area for Scenario 2 (x=nationwide distribution, y=uniform in plume, z=nationwide distribution).

Area (sq. ft.)	DAF		
	85th	90th	95th
5000	6222.78	2425.42	565.61
8000	3977.72	1573.32	371.06
10000	3215.43	1286.01	298.78
45000	817.66	315.06	73.48
50000	745.16	288.27	67.20
100000	424.81	160.82	38.11
150000	300.12	114.71	26.82
220000	218.87	82.30	20.00
500000	110.35	40.10	10.92
1000000	63.45	23.75	6.22
5000000	21.03	7.85	2.55
6000000	19.06	7.01	2.39

Table A3 DAF values as a function of source area for Scenario 3 (x=0 ft, y=uniform within half-width of source area, z=nationwide distribution).

Area (sq. ft.)	DAF		
	85th	90th	95th
1000	1.42E+07	2.09E+05	946.07
2000	9.19E+05	2.83E+04	211.15
5000	5.54E+04	2.74E+ 03	44.23
10000	1.16E+04	644.33	15.29
30000	1.43E+03	120.42	4.48
50000	668.45	60.02	3.10
70000	417.19	37.97	2.53
80000	350.39	33.16	2.34
150000	158.76	17.87	1.74
200000	114.63	12.96	1.56
500000	40.55	5.54	1.23
1000000	21.13	3.50	1.15
2000000	11.58	2.38	1.08
3000000	8.66	1.98	1.06

Table A4 DAF values as a function of source area for Scenario 4 (x=25 ft, y=uniform within half-width of source area, z=nationwide distribution).

Area (sq. ft.)	DAF		
	85th	90th	95th
1000	5.93E + 05	2.07E + 04	348.31
2000	1.09E+05	4.92E+03	118.11
5000	1.64E + 04	1.03E + 03	29.86
10000	4.89E+03	352.49	13.14
30000	928.51	93.98	4.73
50000	490.20	49.78	3.28
70000	323.42	34.79	2.69
80000	272.85	29.82	2.47
150000	132.05	16.55	1.82
200000	97.94	12.29	1.61
500000	37.99	5.50	1.29
1000000	20.08	3.50	1.17
2000000	11.35	2.40	1.10
3000000	8.49	2.00	1.07

Table A5 DAF values as a function of source area for Scenario 5 (x=100 ft, y=uniform within half-width of source, z=nationwide distribution).

	DAF		
Area (sq. ft.)	85th	90th	95th
1000	4.24E+04	3.43E+03	181.88
2000	1.52E + 04	1.33E + 03	74.79
5000	4.24E+ 03	437.25	27.23
10000	1.81 E+03	204.29	13.09
30000	497.27	68.21	5.10
50000	293.34	40.72	3.71
70000	207.77	29.89	2.96
80000	184.57	26.86	2.73
150000	98.81	15.05	2.03
200000	74.63	11.55	1.82
500000	32.99	5.83	1.40
1000000	18.66	3.71	1.26
2000000	11.14	2.53	1.16
3000000	8.33	2.09	1.13

Table A6 DAF values as a function of source area for Scenario 6 (x=25 ft, y=source width + 25 ft, z=25 ft).

	DAF		
Area (sq. ft.)	85th	90th	95th
1200	44247.79	10479.98	1004.72
1500	30759.77	7215.01	744.05
5000	4789.27	1273.40	140.81
7500	2698.33	725.69	82.51
23000	637.76	155.16	21.82
26000	544.66	135.91	18.84
29000	482.63	121.43	16.52
100000	139.66	35.55	5.56
170000	76.69	21.24	3.94
250000	50.40	15.04	3.19
800000	18.10	6.04	1.81
1800000	10.26	3.87	1.48