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Industrial Waste Management Evaluation Model (IWEM) Version 3.1: Technical Background Document

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Office of Solid Waste and Emergency Response
Office of Resource Conservation and Recovery

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Acknowledgments

Numerous individuals have contributed to the development of the IWEM software and documentation since IWEM version 1. At EPA, Mr. Taetaye Shimeles served as Work Assignment Manager for the current version of the model, providing directions and technical assistance, and is also a contributing author. Dr. Zubair Saleem, Ms. Ann Johnson, and Mr. David Cozzie had filled this role for the past versions. A variety of other EPA staff have provided additional technical guidance and suggestions, including Dr. Peter Grevatt, Dr. Lee Hofmann, Dr. Colette Hodes, Mr. Richard Kinch, Mr. Jason Mills, Mr. John Sager, Mr. Timothy Taylor, Ms. Shen-Yi Yang, and Ms. Janvier Young. The EPA has been assisted in the development of IWEM by several contractors: RTI International, HydroGeoLogic, and Resource Management Concepts, Inc.

Software Development History

The Industrial Waste Management Evaluation Model (IWEM 3.1) is the latest version of a ground water fate and transport developed by the U.S. EPA's Office of Resource Conservation and Recovery (ORCR). IWEM, since its initial development in 2002, has undergone a number changes and revisions. Some of the changes were done to expand the scope of the model from modeling just waste management units, also to evaluate potential contaminant releases from recycled industrial materials used in beneficial use applications. Additional revisions were also made to increase the usability of the model, and to allow the user greater control over the input parameters. The changes and revisions made the model more flexible and user friendly, as well as usable by various stakeholders. Brief descriptions of the major changes made to model since its initial release are presented below.

The original IWEM 1.0 (U.S. EPA, 2002a, b) was developed as part of the *Guide for Industrial Waste Management* (U.S. EPA, 2002c) to conduct a tiered screening analysis (Tier 1 and Tier 2) to determine the most appropriate liner design for several types of waste management units in order to minimize or avoid adverse ground water impacts. In Tier 1, the analysis considered a national distribution of waste management units and site conditions that affect the fate and transport of constituents in subsurface media. On the other hand, site-specific parameters were required for key parameters in the Tier 2 probabilistic analysis. In addition, this version was based on Version 2.0 of the U.S. Environmental Protection Agency's (EPA's) Composite Model for Leachate Migration and Transformation Products (EPACMTP) code (U.S. EPA, 2003a, b), which included the vadose-zone and aquifer modules developed under the Multimedia, Multipathway, Multireceptor Exposure and Risk Assessment (3MRA) framework (U.S. EPA, 1999).[1]

In 2006, building on version 1, IWEM 2.0 was developed by adding a module to simulate fate and transport from a new source type—a roadway constructed using recycled industrial materials (i.e., byproducts). The new source type was restricted to Tier 2 analyses. In addition to the new roadway source, IWEM 2.0 used the latest version of EPACMTP, Version 2.2. EPACMTP Version 2.2 includes non-science related changes to the input and output streams of EPACMTP Version 2.1 (U.S. EPA 2003c, d).

IWEM 3.0 enhanced the functionality of its predecessor, by introducing a more rigorous treatment of leaching through the roadway cross section by including ditches, drainage, and surface runoff as optional elements. The graphical user interface was also modified to accommodate the improved source type. In addition, two significant revisions were made to the model, which included the following:

- Tier 1 analysis for waste management units was eliminated. The leachate concentration threshold values stored in the IWEM database and used for Tier 1 analyses were based on human health benchmarks (e.g., reference doses and slope factors) that were current as of

[1] IWEM 1.0 and EPACMTP 2.0 were developed and tested concurrently, whereas the supporting documentation for IWEM 1.0 was released prior to EPACMTP 2.0 documentation.

2002 when IWEM 1.0 was released. To avoid generating a "protective" liner recommendation based on an out-of-date benchmark, the Agency opted to remove the Tier 1 analysis option from Version 3.0.

- Built-in human health benchmarks, with the exception of maximum contaminant levels (MCLs), have been removed from the database.

This decision resulted in two significant changes to the model: (1) only Tier 2 analyses are now available in the software, so references to Tier 2 and the "tiered approach" were removed from the software and documentation; and (2) other than MCLs, the user is now required to provide human health benchmarks for the screening evaluation.

The current version, IWEM 3.1 replaces IWEM 3.0. IWEM 3.1 adds a new module to simulate leaching from a structural fill site constructed with industrial materials and related byproducts. Structural fills evaluated in IWEM 3.1 include, the use of industrial materials and related byproducts as substitutes for the earthen materials to provide structural support for parking lots, roads, airstrips, tanks/vaults, and buildings; construction of highway embankments and bridge abutments; filling of borrow pits, and other landscape irregularities; and changing of landscapes for development or reclamation projects.

Online Resources

EPA's Nonhazardous Industrial Waste Management tools web page (http://www.epa.gov/waste/nonhaz/industrial/tools/index.htm) provides links to the *Guide for Industrial Waste Management*, IWEM, and EPACMTP. The linked IWEM webpage also provides access to the model as well as its supporting Technical Background Document and the User's Guide.

Acronyms

3-D	Three-dimensional
Agency	U.S. Environmental Protection Agency
EPA	U.S. Environmental Protection Agency
EPACMTP	EPA's Composite Model for Leachate Migration with Transformation Products
Guide	The Guide for Industrial Waste Management
HBN	Health-based number
HELP	Hydrologic Evaluation of Landfill Performance
HGDB	Hydrogeologic Database for Ground-Water Modeling
IWEM	Industrial Waste Management Evaluation Model
Kd	Soil-water partition coefficient
Koc	Organic carbon partition coefficient
MCL	Maximum Contaminant Level
MINTEQA2	EPA's geochemical equilibrium speciation model for dilute aqueous systems
RGC	Reference ground-water concentration
WMU	Waste management unit

Units of Measure

This Technical Background Document uses the following abbreviations for standard units of measures; these may be found in combination. In some instances, general units (e.g., length per time) may be used and in others, specific units (e.g., m/sec). Superscripts indicate the unit is squared (e.g., m^2) or cubed (e.g., m^3).

Specific units:

µg	microgram
cm	centimeter
day	day
g	gram
hr	hour
kg	kilogram
km	kilometer
L	liter (if used with other specific units, as mg/L)
m	meter
mg	milligram
min	minutes
mL	milliliter
mm	millimeter
mo	month
sec	second
yr	year

General units:

L	General unit for length (if used with other general units, as M/L^3)
M	General unit for mass
M/L^3	General unit for mass concentration (mass per length cubed)
M/M	General unit for mass fraction (mass per mass)
T	General unit for time

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Executive Summary

ES.1 Objectives and Background

This technical background document provides the assumptions, methodologies, and data used by the U.S. Environmental Protection Agency (EPA) to develop a ground water impact evaluation tool for waste management units, structural fills, and roadways in the Industrial Waste Management Evaluation Model (IWEM).

IWEM was originally introduced as part of the Agency's *Guide for Industrial Waste Management* (U.S. EPA, 2002c; hereafter, the *Guide*) in 2002. This voluntary guide was developed by EPA and representatives from 12 state environmental agencies to recommend a baseline of protective design and operating practices for managing non-hazardous industrial waste nationwide. The guidance was intended for facility managers, regulatory agencies , and interested members of the public.

The *Guide* recommended best management practices and key factors to consider in all phases of the waste management unit lifecycle. Among the recommendations, the *Guide* called for risk-based approaches to designing waste management units, and determining waste application rates for the protection of ambient air quality and ground water resources. IWEM 1.0, was the ground water risk evaluation tool developed to support the *Guide*. Over the years, several newer versions of the model were developed expanding the scope and usability of the model.

IWEM 1.0 provided a tiered approach that consisted of a national screening-level analysis (Tier 1) and a location-specific probabilistic analysis (Tier 2) for waste management units (e.g., landfills, waste piles, surface impoundments, and land application unites). Both tiers of the model considered all aspects of the Agency's risk assessment paradigm (i.e., problem formulation, exposure assessment, toxicity assessment, and risk characterization) to generate results that vary from a national-level screening evaluation to a site-specific assessment.

Building on IWEM 1.0, IWEM 2.0 added a new evaluation tool to evaluate contaminant releases from roadways constructed with beneficially reused industrial materials or byproducts. This evaluation tool was limited to Tier 2 analysis.

IWEM 3.0 provided the same location-specific analysis tools for waste management units and roadways, as its predecessors. However, Tier 1 analysis was eliminated. In addition, it provided some refinements to the roadway source, the benchmarks, and the user interface.

The current version, IWEM 3.1, adds structural fills as source. A companion document, *IWEM v3.1 User's Guide* (U.S. EPA, 2015a; hereafter, the *User's Guide)*, describes how to use the software.

ES.2 Overview

IWEM is a screening level ground water model developed to evaluate ground water impacts from industrial waste management practices or the beneficial reuse of industrial materials. The software helps determine the most appropriate liner design for a waste management unit that is protective of human health as well as ground water resources. In addition, the model helps determine the appropriateness of reusing industrial materials in beneficial use applications such as structural fills or roadways. IWEM does this by considering several factors that determine the fate and transport of contaminant in ground water, which include: one or more types of liners (for waste management units) or the material properties and structure (of a structural fill or roadway), the expected leachate concentrations of the anticipated waste or reused industrial material constituents, and the hydrogeologic conditions of the site. The ultimate goal of the model is to minimize, or avoid adverse ground water impacts.

IWEM models four types of waste management units:

- Landfills,
- Waste piles,
- Surface impoundments, and
- Land application units.

For landfills, waste piles, and surface impoundments, IWEM evaluates three liner scenarios: no liner, single clay liner, and composite liner. For land application units, only the "no liner" scenario is evaluated, because liners are not typically used for this type of unit. The user specifies the dimensions and other properties of the waste management unit.

For structural fills, IWEM evaluates a single emplacement scenario where a permanent, unlined monofill containing a specified mixture of reused industrial materials and other native or non-native soils. The user specifies the dimensions and other properties of the structural fill.

For roadways, IWEM evaluates a variety of roadway components, including paved areas, medians, shoulders, ditches, embankments and drains. The design of the roadway (and the inclusion of various components) is user-specified.

For waste management units, structural fills, and roadways, IWEM uses leachate concentrations entered by the user to model the fate and transport of the specified constituents from the source (the waste management unit, structural fill or roadway) through subsurface soils and ground water to calculate a distribution of estimated ground water concentrations at a downgradient well.[1] For roadways, IWEM compiles the results for all roadway components. A representative value from the distribution of estimated ground water well concentrations is compared with the reference ground water concentrations (to user-specified constituent- and exposure-route-specific human health or regulatory benchmarks), to determine whether a modeled scenario is protective of human health (i.e., the representative ground water well concentration is less than or equal to the reference ground water concentration) or not.

Finally, IWEM compiles the results for all constituents expected in the leachate and then reports:

- For waste management units, the minimum liner scenario at which the resulting ground water well concentrations of all constituents are at or below their respective reference ground water concentrations. In the case of land application units, since IWEM only models the "no liner" scenario, the outcome of the analysis reflects whether resulting ground water well concentrations from land application are

[1] In IWEM, the term "well" is used to represent an actual or hypothetical ground water monitoring well or drinking-water well, located downgradient from a source.

above or below reference ground water concentrations;

- For structural fills, whether the reuse of industrial materials in the fill application generates ground water well concentrations above or below a user-specified reference ground water concentrations; or
- For roadways, whether the reuse of industrial materials in the specified roadway design is appropriate or not, given the reference ground water concentrations specified.

ES.3 Source Modeling

As noted in the Overview, IWEM models three types of sources: waste management units, structural fills, and roadways constructed of reused industrial materials.

ES.3.1 Waste Management Units

The four types of waste management unit represented in IWEM have the following key characteristics:

- ***Landfills.*** IWEM considers closed landfills with an earthen cover and either no liner; a single clay liner; or a composite, clay-geomembrane liner. The release of waste constituents into the soil and ground water underneath the landfill is caused by dissolution and leaching of the constituents due to precipitation that percolates through the landfill. The type of liner controls the amount of leachate that is released from the unit. Because the landfill is closed, the concentration of the waste constituents will diminish with time due to depletion of landfill wastes. The leachate concentration value, an IWEM input, is the expected initial leachate concentration, when the waste is "fresh."
- ***Waste Piles.*** Waste piles are typically used as temporary storage units for solid wastes. Due to their temporary nature, they are typically not covered. However, IWEM does allow use of liners similar to landfills. In IWEM, the user specifies the fixed operational life in years, after which the waste pile is removed. IWEM, therefore, models waste piles as a temporary source.
- ***Surface Impoundments.*** In IWEM, surface impoundments are modeled as flow-through units situated at or below ground level. Surface impoundments may have the same liner types as landfills and waste piles. Release of leachate is driven by the ponding of water in the impoundment, creating a hydraulic head gradient with the ground water underneath the unit.
- ***Land Application Units.*** Land application units (or land treatment units) are areas of land that receive regular applications of waste that can be either tilled into the soil or sprayed directly onto the soil and subsequently mixed with the soil. IWEM models the leaching of wastes after tilling with soil and does not account for the losses due to volatilization during or after waste application. Only the no-liner scenario is evaluated for land application units, because liners typically are not used for this type of unit.

Releases from waste management unit sources are modeled using EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP).

A small number of site-specific inputs are required parameters for waste management units:

- Area,
- Depth (landfill and surface impoundment),
- Geographic location (to select the appropriate climate parameters).

However, the user can also enter site-specific data for up to 20 of the most sensitive waste management unit and hydrogeologic characteristics to assess whether a particular liner design will be protective with respect to the user-specified reference ground water concentration. In addition, some default constituent fate parameters can be modified, including adding biodegradation.

ES.3.2 Structural Fills

IWEM considers structural fills to be any one of the following permanent constructions that include the use of industrial wastes and related byproducts as substitutes for earthen materials for the support of parking lots, roads, airstrips, tanks/vaults, and buildings; construction of highway embankments and bridge abutments; filling of borrow pits, and other landscape irregularities; and changing the landscape for development or reclamation projects. The release of waste constituents into the soil and ground water underneath the structural fill is caused by dissolution and leaching of the constituents due to precipitation that percolates through the structural fill.

Releases from structural fill sources are modeled in the same way as waste management units. However, the structural fill source term requires additional input parameters to calculate the amount of leachable mass in the fill; the time it takes to deplete the leachable mass; and to cap the rate of percolation if material properties limit the vertical flow of water. The additional parameters include:

- Material properties of the structural fill (bulk density and hydraulic conductivity), and
- The fractional volume of the structural fill occupied by leachable materials.

The user can also enter site-specific data for sensitive hydrogeologic characteristics to assess whether a particular use of industrial materials in a structural fill design will be protective with respect to a user-specified reference ground water concentration. In addition, some default constituent fate parameters can be modified, including adding biodegradation.

ES.3.3 Roadways

IWEM provides a flexible framework for defining a roadway cross-section consisting of one or more idealized columns to represent the various components of a roadway (e.g., a travel lane, median, shoulder, or embankment). Each column may be composed of one or more material layers, which are assumed to be uniform along the length of interest. Industrial materials containing leachable components used as structural elements in any of the layers are treated as individual finite sources where the leachate is released from the bottom of the column. Much like a landfill, the release of constituents from a layer containing industrial materials into the soil and ground water underneath the roadway column is caused by dissolution and leaching of the constituents due to precipitation which percolates through the column. IWEM will cap the rate of percolation if material properties limit the vertical flow of water. IWEM determines the time to deplete the leachable mass in each layer. Releases from a roadway source are modeled with a model developed specifically for IWEM.

Site-specific data to define the geometry and material properties for all columns and layers of a roadway are required inputs:

- Number of roadway strips,
- Roadway segment length,
- Roadway geometry parameters,
- Layer properties,
- Ditch properties (required if a ditch is included in the roadway scenario),
- Drain properties (required if a drain is included in the roadway scenario), and
- Location of nearest down-gradient well.

The user can also enter site-specific data for sensitive hydrogeologic characteristics to assess whether a particular use of industrial materials in a roadway design will be appropriate with respect to a user-specified reference ground water concentration. In addition, some default constituent fate parameters can be modified, including adding biodegradation.

ES.4 Unsaturated and Saturated Zone Modeling

IWEM uses EPACMTP to model the fate and transport of constituents in the subsurface (i.e., the unsaturated and saturated zones). **Figure ES-1** shows a conceptual, cross-sectional view of the subsurface system modeled by EPACMTP (and hence, IWEM).

EPACMTP simulates fate and transport in both the unsaturated zone and the saturated zone (ground water) using the advection-dispersion equation with terms to account for equilibrium sorption and first-order transformation. The source of constituents (i.e., the waste management unit, structural fill, or roadway) is assumed to be overlying an unconfined aquifer. The base of a waste management unit or structural fill can be below the actual ground surface, whereas the base of a roadway is always assumed to be built upon the actual ground surface. Waste constituents leach from the base of a source into the underlying soil. They migrate vertically downward until they reach the water table. As the leachate enters the ground water, it will mix with ambient ground water (which is assumed to be free of pollutants) and a ground water plume will

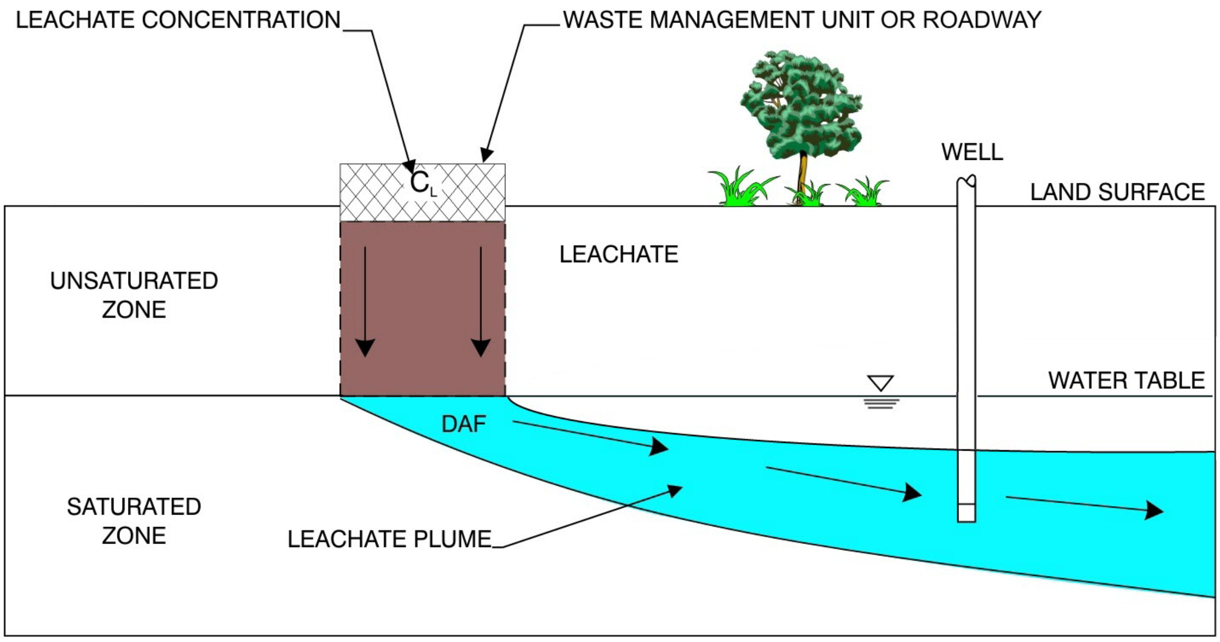

Figure ES-1 Conceptual cross-section view of the subsurface system simulated by EPACMTP.

develop that extends in the direction of downgradient ground water flow. EPACMTP accounts for the spreading of the plume in all three dimensions.

Leachate generation is driven by the infiltration of precipitation that has percolated through the source, from the base of either the waste management unit, structural fill, or roadway, into the soil. Different waste management unit liner designs control the rate of infiltration that can occur. Similarly, the properties of structural fill and roadway materials will govern the rate of infiltration through those sources. EPACMTP models flow in the unsaturated zone and in the saturated zone as steady-state processes (that is, representing long-term average conditions).

In addition to dilution of the constituent concentration caused by the mixing of the leachate with ground water, EPACMTP accounts for attenuation due to sorption of waste constituents in the leachate onto soil and aquifer solids, and for bio-chemical transformation (degradation) processes in the unsaturated and saturated zone. By default, IWEM instructs EPACMTP to account for chemical transformations caused only by hydrolysis reactions. However, the user can enter site-specific degradation rates that include other degradation processes. EPACMTP simulates all transformation processes as first-order reactions (i.e., processes that can be characterized with a half-life).

For organic constituents, EPACMTP models sorption between the constituents and the organic matter in the soil or aquifer, based on constituent-specific organic carbon partition coefficients, and a site-specific organic carbon fraction in the soil and aquifer. For metals, EPACMTP accounts for more complex geochemical reactions by using effective sorption isotherms for a range of aquifer geochemical conditions. These isotherms were generated using MINTEQA2, EPA's geochemical equilibrium speciation model for dilute aqueous systems.

EPACMTP outputs the predicted maximum ground water exposure concentration, measured at a well situated down-gradient from a waste management unit, structural fill, or roadway. In IWEM, the well is restricted to be on the plume centerline for a waste management unit or structural fill, but the distance (up to one mile) can be entered as a site-specific value. For roadways, IWEM permits more flexibility when specifying the well location, as well as the orientation of the roadway to the direction of ground water flow.

ES.5 Monte Carlo Implementation

IWEM uses Monte Carlo simulation to determine the probability distribution of predicted ground water concentrations as a function of the variability of modeling input parameters. The Monte Carlo technique is based on the repeated random sampling of input parameters from their respective frequency distributions, and executing the EPACMTP fate and transport model for each combination of input parameter values. At the conclusion of the Monte Carlo analysis, it is then possible to construct a probability distribution of ground water concentration values and associated ground water dilution and attenuation factors. IWEM suggests that results are based on Monte Carlo analyses of 10,000 realizations; however, the number of iterations can be changed.

IWEM selects the 90th percentile of the predicted distribution of ground water concentration values for comparison to user-entered reference ground water concentrations to determine if a waste management unit liner scenario, structural fill design, or roadway design is protective or not. The resulting location-specific estimated ground water concentrations, therefore, represent a 90th percentile protection level for the specified site conditions.

ES.6 Inputs

An IWEM evaluation uses site-specific data for key, sensitive parameters related to waste management units, structural fills, or roadways, supplemented by nationwide parameter distributions for less sensitive parameters. The user must enter site-specific values for some parameters, and may for additional parameters if site-specific data are available. If site-specific data are not entered, values are selected probabilistically from nationwide distributions for each model iteration. The underlying assumption is that the uncertainty in the value of the parameter is captured by the nationwide range in values of that parameter. However, the use of site-specific data, when available, may help to avoid unnecessarily costly waste management unit designs or allow a larger fraction of industrial materials to be incorporated into a structural fill or roadway structure if appropriate for certain kinds of site conditions (e.g., an arid climate where little infiltration and leaching will occur). Site-specific data may also provide an additional level of certainty that liner designs are protective of sites in vulnerable settings, such as sites with high rainfall and shallow ground water.

ES.7 Reference Ground Water Concentrations

Reference ground water concentrations are maximum allowable concentrations of constituents in ground water, based on a specified exposure pathway (e.g., consumption of drinking water) and exposure route (i.e., oral, inhalation, dermal). IWEM evaluations incorporate three types of reference ground water concentrations:

- ***Maximum Contaminant Levels (MCLs)***. MCLs are available in IWEM for some IWEM constituents. MCLs are maximum permissible constituent concentrations allowed in public drinking water and are established under the Safe Drinking Water Act. In developing MCLs, EPA considers not only a constituent's health effects via consumption of drinking water, but also additional factors, including the cost of treatment.
- ***Health-based numbers***. IWEM allows health-based numbers for residential exposures to ground water to be entered for three pathways/routes of exposure: ingestion (of drinking water), inhalation (of constituents that volatilize from drinking water during household water use), and dermal (exposure to ground water during bathing or showering). Health-based numbers are the maximum constituent concentrations in ground water that are not expected to cause adverse noncancer health effects in the general population (including sensitive subgroups), or that will not result in an additional incidence of cancer in more than approximately one person out of a specified number of individuals exposed to the constituent (usually 100,000 or 1 million). Although MCLs are provided in IWEM, health-based numbers must be supplied by the user. One example of a health-based numbers is the "Regional Screening Levels for Chemical Contaminants at Superfund Sites" (http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/index.htm).
- ***Other Drinking Water Standards***. These are comparable to MCLs, but state standards may be more stringent than federal MCLs. These must be entered by the user.

IWEM evaluations do not consider combined exposure from ground water ingestion (from drinking water), ground water inhalation (from showering or other household uses), or dermal exposure to ground water (while showering or bathing), nor do they consider the potential synergistic effect of exposure to multiple constituents.

ES.8 IWEM Recommendations

The IWEM tool provides recommendations for waste management units and beneficial reuse of industrial materials in structural fills and roadways in terms of how the estimated 90th percentile ground water concentration compares to reference ground water concentrations. IWEM uses ground water modeling to predict expected waste- and site-specific ground water exposure concentrations for all waste constituents evaluated. IWEM then compares the estimated exposure concentrations to reference ground water concentrations to determine whether or not a liner is protective for waste management units, or the reuse of industrial materials for structural fill or roadway design is appropriate for each constituent evaluated. For waste management units that can have liners, the final IWEM liner recommendations are based on the minimum liner design that is protective for all constituents.

1.0 Introduction

This document provides technical information on the Industrial Waste Management Evaluation Model version 3.1 (IWEM 3.1). A companion document, *Industrial Waste Management Evaluation Model* (*IWEM) v3.1: User's Guide* (hereafter, *IWEM 3.1 User's Guide*; U.S. EPA, 2015a) provides detailed information on installation and use of the IWEM software.

Section 1.1 describes how IWEM was developed. **Section 1.2** provides an overview of IWEM's design (i.e., what IWEM does and key components of IWEM). **Section 1.3** provides a guide to the organization of the rest of this document. **Appendix A** is a glossary that defines many of the technical terms used in this document.

1.1 The Guide for Industrial Waste Management and IWEM

The U.S. Environmental Protection Agency (EPA or the Agency) and representatives from 12 state environmental agencies developed a voluntary *Guide for Industrial Waste Management* (hereafter, the *Guid*e) to recommend a baseline of protective design and operating practices to manage non-hazardous industrial waste throughout the country. The guidance was designed for facility managers, regulatory agency staff, and the public, and it reflects four underlying objectives:

- **Adopt a multimedia approach** to protect human health and the environment;
- **Tailor management practices** to risk using the innovative, user-friendly modeling tools provided in the *Guide;*
- **Affirm state and tribal leadership** in ensuring protective industrial waste management, and use the *Guide* to complement state and tribal programs; and
- **Foster partnerships** among facility managers, the public, and regulatory agencies.

The *Guide* recommended best management practices and key factors to consider in all phases of the lifecycle of a waste management unit (WMU):

- Protecting ground water, surface water, and ambient air quality during the design, siting, and operation of WMUs;
- Monitoring the impact of WMUs on the environment;
- Determining necessary corrective action;
- Closing WMUs; and
- Providing post-closure care.

In particular, the *Guide* recommended risk-based approaches to designing liner systems, determining waste application rates for ground water protection, and evaluating the need for air controls. The original version of the *Guide* included user-friendly air and ground water models to conduct these risk evaluations. The IWEM software distributed with the *Guide* (on a CD), IWEM 1.0, was the ground water tool developed to support the *Guide*. IWEM 1.0 provided a tiered approach that consisted of a national screening-level analysis (Tier 1) and a location-adjusted probabilistic analysis (Tier 2).

Over the years, the Agency made progress in regulating the proper management of industrial wastes under the Resource Conservation and Recovery Act. The current challenge for EPA is to find ways to repurpose manufacturing and power generation byproducts, historically viewed as "wastes," in beneficial ways while minimizing human and environmental impacts. To address this need, the IWEM software has been expanded and enhanced to provide a risk-based approach for evaluating the use of materials generated from industrial processes in structural fills and roadways. The current version of the IWEM software, IWEM 3.1, is described in this *Technical Background Document* and provides the same location-adjusted analysis tools as previous versions for WMUs, and structural fills and roadways containing beneficially reused industrial byproducts. However, the national screening-level analysis is not available in this version. A complete history of the software development from version 1.0 to the current version 3.1 is provided at the beginning of this document under the heading Software Development History.

IWEM helps determine the most appropriate design for a WMU or evaluates the design of a structural fill or roadway built with reused industrial materials to minimize or avoid adverse ground water impacts by evaluating

- One or more liner scenarios for WMUs or the material properties and structure of a structural fill or roadway;
- The hydrogeologic conditions of the site; and
- The expected leachate concentrations of the anticipated waste or reused industrial material constituents.

The evaluation is completed by comparing the estimated ground water concentrations to user-specified constituent- and exposure-route-specific human health benchmarks, called reference ground water concentrations (RGCs) in IWEM.

The anticipated users of the original IWEM software were managers of proposed or existing units, state regulators, interested private citizens, and community groups. For example:

- **Managers of a proposed unit** may use the software to determine what type of liner would be appropriate for the particular type of waste that is expected at the WMU and the particular hydrogeologic characteristics of the site.
- **Managers of an existing unit** may use the software to determine whether to accept a particular waste at that WMU by evaluating the performance of the existing liner design.
- **State regulators** may use the software to develop permit conditions for a WMU.
- **Interested members of the public or community groups** may use the software to evaluate a particular WMU and to participate during the permitting process.

In addition, the incorporation of the structural fill and roadway modules provide state and local regulators, engineers, and other stakeholders (e.g., generators, beneficial users, and the public) a tool that can be used to determine if the reuse of industrial materials is environmentally sound.

The unique aspect of the IWEM software is that it allows the user to perform location-adjusted analyses and obtain either liner recommendations or beneficial reuse evaluations in structural fills or roadways with minimal data requirements. Users interested in a comprehensive and detailed site assessment are directed to the *Guide* for information regarding the selection of an appropriate site-specific ground water fate and transport model.

1.2 IWEM Design

1.2.1 What Does the Software Do?

IWEM uses a probabilistic (Monte Carlo) approach and a ground water fate and transport model to calculate a distribution of estimated ground water concentrations at a well resulting from the release of leachate containing dissolved constituents at concentrations entered by the user. IWEM then compares the 90th percentile of the distribution of estimated ground water concentrations to RGCs (constituent- and pathway-specific human health benchmarks provided by the user) to determine if the modeled liner scenario is protective, or whether the beneficial use of industrial material is appropriate (i.e., the representative ground water well concentration is less than or equal to the RGC).

In the case of WMUs, IWEM helps the user determine a recommended liner design that will minimize the potential for adverse ground water impacts caused by the leaching of waste constituents. The IWEM tool compares the estimated exposure concentration calculated by a ground water fate and transport model for three standard liner types. The IWEM software compiles the results for all constituents expected in the leachate and then reports the minimum liner scenario that is protective for all constituents. **Table 1-1** shows the WMU types and liner types that are evaluated in IWEM. For land application units only the "No Liner" scenario is evaluated, because liners are not typically used at this type of facility.

Table 1-1. IWEM WMU and Liner Combinations

WMU Type	Liner Type		
	No Liner (in-situ soil)	Single Clay Liner	Composite Liner
Landfill	✓	✓	✓
Waste Pile	✓	✓	✓
Surface Impoundment	✓	✓	✓
Land Application Unit	✓	×	×

✓= applies to WMU × = does not apply to WMU

For structural fills, similar to waste management units, the IWEM software calculates distributions of estimated ground water well concentrations for all leachable constituents present in the reused industrial materials included in the structural fill.

For roadways, which can include multiple structural components (strips and layers), the IWEM software calculates distributions of estimated ground water well concentrations for all leachable constituents present in the reused industrial materials for each roadway component containing leachable constituent mass. For each constituent, IWEM then sums the 90th percentiles of these distributions across all strips leaching that constituent to obtain the aggregate 90th percentile ground water estimated exposure concentration for comparison to the RGC(s) for that constituent.

1.2.2 IWEM Components

The IWEM software consists of four main components:

- **Graphical User Interface:** The IWEM user interface consists of a series of user-friendly data input and display screens guide the user through defining all aspects of an IWEM evaluation. The user interface provides a tailored front-end to the EPACMTP computational engine and built-in databases that support IWEM. The user interface module is described in detail in the companion to this Technical Documentation, the *IWEM v3 User's Guide* (U.S. EPA, 2015a).
- **Source Term Modules:** Source term modules represent the key characteristics and processes that simulate the release of dissolved constituents in leachate from a source (the WMU, structural fill, or roadway) to the subsurface. For WMUs and structural fills, IWEM uses EPACMTP to model the source, by passing information to EPACMTP to represent the source. For roadways, a special module determines constituent concentrations in leachate over time and prepares an additional input file for EPACMTP containing the release information for fate and transport modeling.
- **Fate and Transport Model:** IWEM uses EPACMTP to simulate the migration of chemical waste constituents in leachate through the subsurface (i.e., soil and ground water). In an IWEM evaluation, the fate and transport simulation is performed directly inside the IWEM tool. EPACMTP is described in detail in the *EPACMTP Technical Background Document* and its Draft Addendum (U.S. EPA, 2003a, c). This IWEM technical documentation discusses the application of EPACMTP as part of IWEM.
- **Databases:** IWEM contains an integrated set of databases that include waste constituent properties and default ground water modeling parameters for IWEM evaluations.
  - The *waste constituent database* includes 206 organic chemicals and 25 metals. The constituent databases include physical and chemical data needed for ground water transport modeling, as well as maximum constituent levels (MCLs) (which can be selected by the user as RGCs). **Appendix B** provides a complete list of all constituents and constituent property data.
  - The *ground water modeling parameters database* includes infiltration rates for different WMU types and liner designs and roadway materials for a range of locations and climatic conditions throughout the United States, and soil and hydrogeological data for different soil types and aquifer conditions.

  Details of the databases are provided in this background document, and in the *EPACMTP Parameters/Data Background Document* and its Draft Addendum (U.S. EPA, 2003b, d).

1.3 About This Document

The remainder of this document is organized as follows:

- **Section 2.0** *(Overview of the Approach)* presents the purpose and methodology of the IWEM analysis tools;
- **Section 3.0** *(Source Modeling)* describes how IWEM represents the releases of constituents in leachate to the subsurface fate and transport model;
- **Section 4.0** *(Unsaturated and Saturated Zone Modeling Using EPACMTP)* provides an overview of the EPACMTP ground water simulation model;
- **Section 5.0** *(Conducting Probabilistic Analyses Using EPACMTP)* shows how the Monte Carlo module in EPACMTP generates distributions of estimated ground water exposure concentrations;
- **Section 6.0** *(How EPA Developed the IWEM Evaluation)* describes the application of EPACMTP for the development of the IWEM tools, highlighting the input parameters used for WMU, structural fill, and roadway analyses;
- **Section 7.0** *(Reference Ground Water Concentrations)* describes the types of RGCs IWEM can use, and lists the MCLs included in IWEM;
- **Section 8 .0** *(How IWEM Makes Recommendations)* describes how IWEM uses the results of EPACMTP and user-supplied RGCs to provide protective liner recommendations for a WMU, or determine the appropriateness of using industrial materials in a structural fill or roadway application;
- **Section 9.0** *(References)* lists literature references that are cited in the document;
- **Appendix A** *(Glossary)* presents descriptions of the technical terms used in this document;
- **Appendix B** *(List of IWEM Waste Constituents and Default Physical and Chemical Property Data)* presents the list of chemicals included in IWEM and the default values for the chemical-specific inputs;
- **Appendix C** ***(****Formulation of the Roadway Module****)*** presents the technical details on the development of the roadway source term module;
- **Appendix D** *(Infiltration Rate Data for WMUs and Structural Fills)* presents infiltration rate data for WMUs and structural fills;
- **Appendix E** *(Infiltration Rates Through Pavements)* presents the development of infiltration rate data for roadway materials available in IWEM;
- **Appendix F** *(Formulation of Non-Orthogonality between the Highway Axis and the Regional Ground Water Flow Direction)* presents the methodology used in IWEM to represent roadways overlying ground water flow systems that are not perpendicular to the travel direction; and
- **Appendix G** *(Verification of the Roadway Module in IWEM)* describes the verification of the roadway module.

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2.0 Overview of the Approach

This section provides an overview of the methodology used to develop IWEM. **Section 2.1** discusses the purpose of the tools included in IWEM: WMUs, structural fills, and roadways. **Section 2.2** describes the approach used to develop IWEM and the input parameters required to run the model for all three cases.

2.1 Purpose of the Tool

IWEM analyzes the potential ground water impacts of managing a waste in four types of WMU (landfills, surface impoundments, waste piles, and land application units); three WMU liner scenarios (no liner, single clay liner, and composite liner); and a structural fill or roadway containing beneficially reused industrial materials. The purpose of an IWEM evaluation for WMUs is to determine the minimum recommended liner design generates an estimated 90th percentile ground water concentration that is equal to or less than a user-specified RGC for all constituents in the waste of concern. For structural fills and roadways, an IWEM evaluation determines if a specific fill or roadway design containing beneficial used industrial materials, generate an estimated 90th percentile ground water concentration equal to or less than a user-specified RGC for all constituents of concern in the materials.

IWEM chooses a high-end (i.e., 90th percentile) point estimate from a distribution of potential ground water exposure concentrations, because the use of conservative data and assumptions allows protective decisions to be made quickly and with greater confidence. This is a common approach used by EPA for screening-level analyses.

2.1.1 WMU Evaluation

The most effective approach to managing the release of waste constituents from a WMU to the subsurface is to install a low permeability liner at the base of the WMU. A liner generally consists of a layer of clay or other materials (e.g., geomembrane and geotextiles) with a low hydraulic conductivity that is used to prevent or mitigate the flow of liquids from a WMU. The amount of liquid that migrates into the subsurface from a WMU has been shown to be a highly sensitive parameter in predicting the release of constituents to ground water (and hence, human health risks). However, the type of liner necessary to protect human health for a specific WMU depends heavily on location-specific conditions such as climate and hydrogeology. Therefore, one of the main objectives of the IWEM modeling approach for WMUs is to evaluate the appropriateness of a proposed liner design in the context of other location-specific parameters such as the long-term recharge rate of water influenced by local precipitation and evaporation, and the hydrogeologic characteristics of the soil and aquifer beneath a facility.

EPA chose to evaluate three liner scenarios, which are shown in **Figure 2-1**: no-liner, single-liner, and composite-liner. The no-liner design (Figure 2-1a) represents a WMU that relies on location-specific conditions such as low permeability native soils beneath the unit or low annual precipitation rates to mitigate the release of constituents to ground water. The single-liner design (Figure 2-1b) represents a 3-foot-thick (0.91 m) clay liner with a low hydraulic conductivity (1×10^{-7} cm/sec). The composite liner design (Figure 2-1c) consists of a 1.5 mm high-density polyethylene layer underlain by either a geosynthetic clay liner with a maximum hydraulic conductivity of 5×10^{-9} cm/sec or a three-foot (0.91 m) compacted clay liner with a maximum hydraulic conductivity of 1×10^{-7} cm/sec.

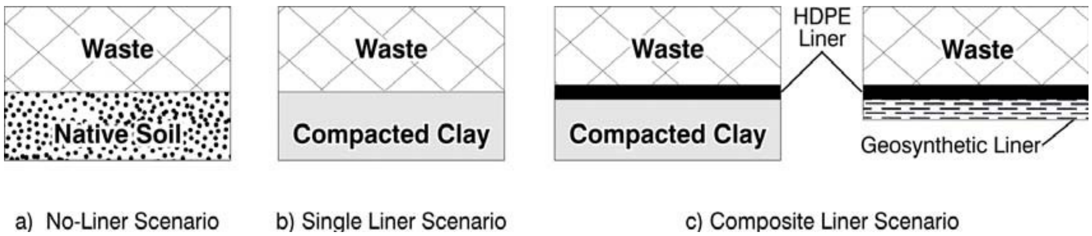


Figure 2-1. Three liner scenarios considered in IWEM.

For a given waste management scenario and waste leachate concentration, IWEM uses ground water modeling to estimate the ground water concentration at a well located downgradient from the WMU. IWEM then compares the 90th percentile estimated ground water concentration to established regulatory RGCs (i.e., an MCL) or to user-supplied, RGCs (see **Section 7** for a discussion of the types of RGCs that can be entered in IWEM). The recommended liner design is the minimum liner for which the estimated ground water concentration of all constituents is less than their selected RGC. For land application, the model evaluates whether waste can be applied on land without adverse impacts to ground water; only the “no liner” scenario is considered, because land application units do not typically have liners.

2.1.2 Structural Fill Evaluation

Structural fills evaluated in IWEM include the use of industrial materials and related byproducts as substitutes for earthen materials for support of parking lots, roads, airstrips, tanks/vaults, and buildings; construction of highway embankments and bridge abutments; filling of borrow pits, and other landscape irregularities; and changing the landscape for development or reclamation projects. IWEM can evaluate structural fills using both flowable fill and compacted installation methods. The general conceptual model for a structural fill is very similar to that of the unlined landfill scenario, graphically depicted by Figure 2-1a with two fundamental exceptions. First, the *waste* region shown in Figure 2-1a is assumed to consist of either all reused industrial materials or a mixture of reused materials and other inert earthen materials. Second, the duration of leaching for structural fills is calculated and completely dependent upon user-supplied information about material properties and concentrations of constituents in the materials.

For a given structural fill geometry and material and leachate concentrations, IWEM uses ground water modeling to predict the groundwater concentration at a well located down gradient from the source. IWEM compares the 90th percentile predicted exposure concentration to established regulatory RGCs (e.g., the MCL) or to user-supplied benchmark RGCs. If the estimated 90th percentile ground water concentrations of all constituents are at or below their respective benchmarks, then the structural fill application is deemed appropriate. The user should consider the conclusions in the context of the underlying assumptions of the model and the input data.

2.1.3 Roadway Evaluation

IWEM provides a flexible framework for defining a roadway cross-section consisting of one or more idealized columns to represent the various components of a roadway (e.g., lanes, median, shoulder, or embankment). **Figure 2-2** shows an example of a roadway cross section comprising three roadway-source strips representing, respectively, a median, a lane, and a ditch. Note that a more typical roadway may consist of up to 15 roadway-source strips: for example, left shoulder, left-lane, median, right-lane, and right shoulder. More strips are possible to account for drainage ditches, berms, and different configurations of layers; the IWEM roadway module limits the total number of roadway-source strips to 15. An example of only three roadway source strips is used here as a basis for further discussion.

Each roadway source strip may consist of several layers, depending on how a given roadway was constructed. A traffic lane strip may be composed of a pavement layer (such as portland cement concrete or asphalt concrete), a base-course layer, a subbase layer, and a subgrade layer. A median may comprise a base layer, a subbase layer, and a subgrade layer. An unpaved road shoulder may have only one layer—a subgrade layer. Industrial materials containing leachable components used as structural elements in any of the layers are treated as individual finite sources where the leachate is released from the bottom of the column. Much like a landfill, the release of constituents from a layer containing industrial materials into the soil and ground water underneath the roadway column is caused by dissolution and leaching of the constituents due to precipitation that percolates through the column, a key sensitive input. IWEM will cap the rate of percolation if material properties limit the vertical flow of water. IWEM determines the time to deplete the leachable mass in each layer.

For a given roadway scenario and material and leachate concentrations, IWEM uses ground water modeling to develop a probability distribution of the groundwater concentration at a well located downgradient from the roadway for each of the column strips containing leachable constituent materials. If only one strip is modeled, IWEM compares the 90th percentile predicted exposure concentration to established regulatory RGCs (e.g., the MCL) or to user-supplied benchmark RGCs. If all of the estimated 90th percentile ground water concentrations of all constituents are at or below their respective benchmarks, then the roadway design is deemed appropriate based on user-supplied information and assumptions. For roadways with multiple strips with leachable content, IWEM develops a distribution of exposure concentrations for each constituent for each roadway strip containing leachable constituent mass. IWEM then sums the 90th percentiles of these distributions across all strips leaching that constituent to obtain the aggregate 90th percentile ground water exposure concentration for comparison to the RGC(s) for that constituent. Aggregated ground water concentrations for any constituent are not allowed to exceed the maximum expected leachate concentration for that constituent.

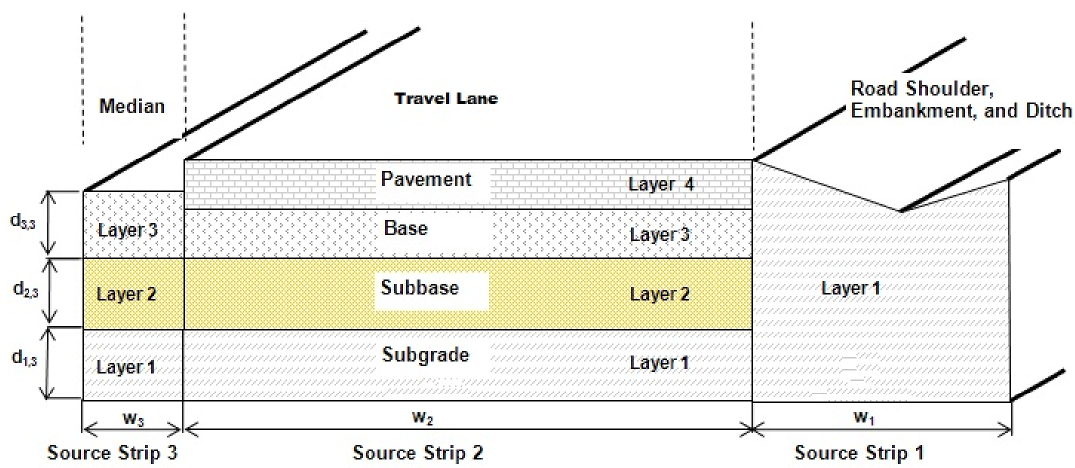


Figure 2-2. Generalized roadway scenario considered in IWEM

2.2 Approach Used to Develop the Tool

IWEM uses EPACMTP to model the WMU and structural fill sources, and an external roadway source module to model the roadway source (see **Section 3**). IWEM also relies on EPACMTP to model subsurface fate and transport of contaminants leaching from WMU, structural fill, or roadway sources (see **Section 4**). In addition, IWEM utilizes EPACMTP's Monte Carlo capabilities (see **Section 5**) to account for variability that occur in climate conditions, soil types, and subsurface characteristics.

EPACMTP consists of four major components:

- A **source module** that simulates the rate and concentration of leachate exiting from beneath a WMU, structural fill, or accepts pre-simulated releases for a roadway and entering the unsaturated zone. The source model aspects of EPACMTP are described in **Section 3.**
- An **unsaturated zone module** which simulates 1-D vertical flow of water and dissolved constituent transport in the unsaturated zone. The unsaturated zone aspects of EPACMTP are described in **Section 4**.
- A **saturated zone module** which simulates ground water flow and dissolved constituent transport in the saturated zone. The saturated zone aspects of EPACMTP are described in **Section 4**.
- A **Monte Carlo module** for randomly selecting input values to account for the effect of variations in model parameters on estimated ground water well concentrations, and determining the probability distribution of estimated ground water concentrations. The Monte Carlo aspects of EPACMTP are described in **Section 5**.

IWEM links EPACMTP and the roadway source module to a series of databases behind a user-friendly interface. The databases describe source characteristics, hydrogeological characteristics, and constituent fate and transport data (see **Section 6**).

An IWEM evaluation for a WMU, structural fill, or roadway consists of a comparison of an estimated ground water well concentration to a health-based number (user-specified benchmark) or an MCL (provided in IWEM). The representative ground water concentration is derived from a probabilistic ground water fate and transport simulation using EPACMTP. Based on the comparisons, IWEM recommends the minimum protective liner design for WMUs, or determines the appropriateness of reusing of industrial waste materials in structural fills or roadways.

Figure 2-3 depicts a cross-sectional view of the subsurface system simulated by EPACMTP. For the purposes of simplicity, the WMU, structural fill, and roadway are considered as just a "source." EPACMTP treats the subsurface aquifer system as a composite domain, consisting of an unsaturated (vadose) zone and an underlying saturated zone. The two zones are separated by the water table.

IWEM uses EPACMTP in a probabilistic (Monte Carlo) mode to generate a probability distribution of well concentrations that reflects the variability in the various modeling parameters, for instance the variation of rainfall rate across the United States. IWEM uses the 90th percentile exposure concentration to represent the estimated constituent concentration at a well for a given leachate concentration. The 90th percentile exposure concentration is determined by running EPACMTP in a Monte Carlo mode for 10,000 realizations (the user also has the option of adjusting the number of simulations). For each realization, EPACMTP calculates a peak and one or more maximum time-averaged concentrations at a well, depending on the exposure duration of the RGC of interest. For example, if a 30-year exposure duration for carcinogens is specified, the maximum time-averaged concentration is the highest 30-year average across the modeling horizon. To enable the IWEM software to perform the Monte Carlo analyses required for an evaluation on common desktop computer systems, the implementation of EPACMTP in IWEM uses a computationally efficient pseudo-3-D approximation for modeling saturated zone plume transport (see **Section 4.2**).

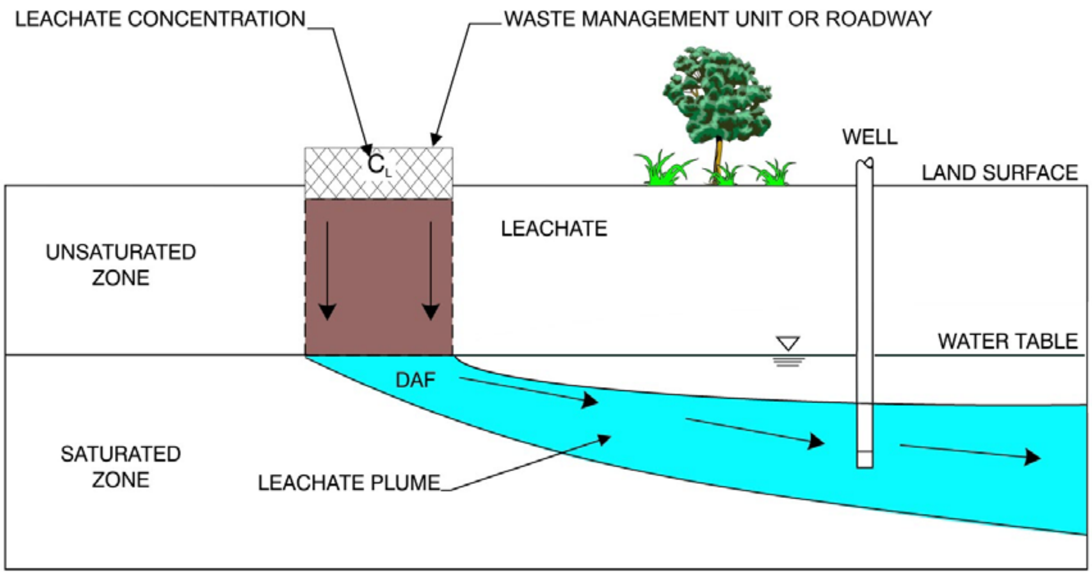


Figure 2-3. Conceptual cross-section view of the subsurface system simulated by EPACMTP.

After calculating the maximum time-averaged concentration for each of the 10,000 realizations, the concentrations are arrayed from lowest to highest and the 90th percentile of this distribution is selected as the constituent exposure concentration. IWEM then directly compares the estimated 90th percentile ground water concentrations generated by EPACMTP to the respective RGCs for those constituents to determine whether a particular liner scenario is protective or not; similarly, following the structural fill and roadway evaluation, IWEM makes a determination on the appropriateness of using industrial materials for these beneficial use applications. If the estimated ground water concentration is less than the RGC for every constituent, then the modeled source scenario being evaluated is deemed protective (for WMUs) or appropriate (for beneficial use). If the estimated exposure ground water concentration of any waste constituent exceeds its RGC, then the scenario is not protective.

For WMU analyses, up to 20 of the most sensitive site-specific, waste-specific and hydrogeologic characteristics can be entered to assess whether a particular design will be protective with respect to a user-specified benchmark. In addition, some default constituent fate parameters can be modified, including adding biodegradation.

A small number of site-specific parameters are required inputs for WMUs:

- WMU area
- WMU depth (landfill and surface impoundment)
- WMU geographic location (to select the appropriate climate parameters).

Structural fills are treated very similarly to the unlined landfill type WMU with the addition of three new required parameters for the reused industrial materials or the material mixture that includes the industrial byproduct:

- Hydraulic conductivity

- Dry bulk density
- The ratio of the volume of industrial materials to the volume of the structural fill.

However, the user can also enter site-specific data for up to 20 of the most sensitive source (WMU or structural fill) and hydrogeologic characteristics to assess whether a particular liner design or beneficial reuse will be protective or appropriate (for structural fills) with respect to the user-specified RGC. In addition, some default constituent fate parameters can be modified, including adding biodegradation. See **Section 6** for more details on specific inputs.

For roadway analyses, site-specific data to define the geometry and material properties for all columns and layers are required inputs:

- Number of roadway strips
- Roadway segment length
- Roadway geometry parameters:
  - Strip type
  - Width
  - Number of layers
- Layer properties:
  - Layer type
  - Thickness
  - Hydraulic conductivity of layer material
  - Dry bulk density of layer material
- Ditch properties (required if a ditch is included in the scenario):
  - Manning’s n coefficient
  - Slope of the ditch
  - Maximum water depth in the ditch
  - Location of gutter(s)
- Drain properties (required if a drain is included in the scenario):
  - Thickness
  - Hydraulic conductivity
  - Bulk density of layer material
- Location to the nearest down-gradient well
  - Distance along roadway edge from midpoint to location of previous measurement
  - The angle between the ground water flow direction and the edge of the roadway
  - The location setting of the receptor well with respect to the roadway and the ground water flow direction

However, the user can also enter site-specific data for sensitive hydrogeologic characteristics to assess whether a particular use of industrial materials in a roadway design will be appropriate with respect to a user-specified RGC. In addition, some default constituent fate parameters can be modified, including adding biodegradation. See **Section 6** for more details on specific IWEM inputs.

3.0 Source Modeling

> **IWEM's Source Term Modules**
> - Integrated into EPACMTP:
>   - Landfill
>   - Waste Pile
>   - Surface Impoundment
>   - Land Application Unit
>   - Structural Fill (modeled like WMUs)
> - External:
>   - Roadway (executes prior to EPACMTP and passes magnitude and duration of leaching to EPACMTP)

IWEM uses EPACMTP's built-in source term modules to simulate the leachate flux from WMUs (landfill, waste pile, surface impoundment, and land application unit) to the underlying unsaturated zone. Although the structural fill source term is not directly integrated into EPACMTP, IWEM utilizes the WMUs source term module in EPACTMP to estimate the leachate flux from structural fills. Improvements to EPAMCTP have made it possible to couple external source term modules to EPACMTP to expand the applicability of the ground water model. The roadway source term is an external module developed specifically for IWEM to address the beneficial reuse of industrial materials as structural components of a roadway design.

The purpose of these sources is to provide EPACMTP with a leachate concentration and a long-term infiltration rate for a period of time to simulate the vertical migration of the leached constituents and water through the unsaturated zone to the water table and into the saturated zone. The period of time that constituents leach from the source may be predetermined (e.g., the operating life of the WMU equals the leaching duration); nearly infinite, as is the case for landfills; or derived from user inputs (e.g., structural fills and roadways). The leachate concentration value might change over time, as well.

This section will review the internal and external source modules available in IWEM: **Section 3.1** describes the WMU source modules built into EPACMTP; **Section 3.2** describes the structural fill source module; and **Section 3.3** describes the external roadway source module briefly. Additional details on the roadway source-term module are presented in **Appendix C**. For some modeling scenarios, either the structural fill or roadway module may be used; **Section 3.4** provides guidance on deciding which is more appropriate for a particular scenario.

3.1 WMU Source Modules

This section describes how EPACMTP models the release of constituents from a WMU: **Section 3.1.1** provides a general overview of the EPACMTP source module; **Section 3.1.2** presents a discussion of how EPACMTP handles infiltration from surface impoundment units; and **Section 3.1.3** identifies the assumptions and limitations of the WMU source terms.

3.1.1 Releases From a WMU Source

The purpose of the WMU source module in EPACMTP is to provide a leachate flux and concentration to the unsaturated zone. The source module relies on the design and operational characteristics of the WMU and the waste stream characteristics (quantity and concentrations); specifically, it uses four primary parameters provided by IWEM user:

- Area of the waste unit;
- Leachate flux rate emanating from the waste unit (infiltration rate);
- Constituent-specific leachate concentration; and

- Leaching duration.

Based on these parameters, EPACMTP generates a rate of leaching and the constituent concentration in the leachate as a function of time from the bottom of the WMU.

Mathematically, EPACMTP regards the source as a rectangular planar area located between the bottom of the WMU and the top of the unsaturated zone column, through which leachate passes. The WMU source module estimate the magnitude of the rate of water infiltration and constituent concentration crossing this plane. The model does not attempt to account explicitly for the multitude of physical and biochemical processes inside the waste unit that may control the release of waste constituents to the subsurface. Instead, the net results of these processes are used as inputs to the model. For instance, for landfills, waste piles, and land application units, the Hydrologic Evaluation of Landfill Performance (HELP) model (Schroeder et al, 1994) was used to estimate infiltration rates for unlined and single clay lined units outside of EPACMTP, and those infiltration rates are then supplied as inputs to EPACMTP (see **Appendix D** for the infiltration rates and supporting data). Likewise, the model does not explicitly account for the complex physical, biological, and geochemical processes that may influence leachate concentration. These processes are typically estimated outside the EPACMTP model using geochemical modeling software, equilibrium partitioning models, or analytical procedures such as the Toxicity Characteristic Leaching Procedure or Synthetic Precipitation Leaching Procedure test; the resulting leachate concentration is then used as an EPACMTP input.

EPACMTP can model sources as continuous or finite. Continuous sources are characterized by a fixed leachate concentration for an infinite time. Under these conditions, the ground water concentration at the modeled receptor well location will eventually reach a constant value. For finite source conditions, the leachate concentration is a function of time, and the constituent presents in the leachate for a finite time. EPACMTP models the duration of finite source leachate concentration releases in one of two ways:

- **Depleting source:** the WMU is considered permanent, and leaching continues (at a concentration that varies over time) until all waste that was originally present has been depleted; or
- **Pulse source:** the WMU is considered temporary, and leaching occurs at a constant leachate concentration for a specified fixed time, after which clean closure occurs and leaching stops.[1] Usually the leaching period represents the operational life of the unit.

In IWEM, waste piles, surface impoundments, and LAUs are modeled as pulse (finite) sources. Landfills are modeled as depleting finite sources; however, in practice, the duration of leaching is long enough for landfills that the landfill source behaves like a continuous source.

Figure 3-1 graphically presents the leachate concentration under the depleting source (dashed line) and pulse source (solid line) scenarios. In the depleting source scenario, the leachate concentration gradually decreases over time. The user must provide a value for the initial leachate concentration (for example, a measured value from a leaching test), and EPACMTP will calculate the rate of depletion as a function of the infiltration rate through the unit. The *EPACMTP Technical Background Document* (U.S. EPA, 2003a) provides a detailed discussion of the depleting source scenario. In the pulse source scenario, the user must provide the value of

[1] If the leaching period is set to a very large value, EPACMTP will simulate continuous source conditions.

the leachate concentration (for example, a measured value from a leaching test) and the duration of the leaching period. Based on these values, EPACMTP will calculate the leachate pulse.

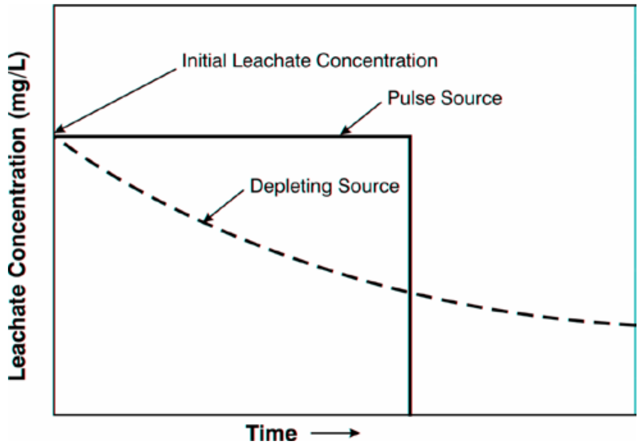


Figure 3-1. Leachate concentration vs. time for pulse and depleting source scenarios.

3.1.2 Infiltration Rate for Surface Impoundments

Because the infiltration rate from surface impoundments is controlled primarily by the unit's engineering and operational characteristics rather than external climate factors, the EPACMTP source module includes the capability to calculate surface impoundment infiltration rates as a function of impoundment depth and other surface impoundment parameters. In particular, the surface impoundment module calculates the infiltration rate through a zone of reduced permeability materials (which may or may not include engineered liners) at the base of the impoundment. The various reduced permeability layers represented in the surface impoundment infiltration module are depicted graphically in **Figure 3-2.**

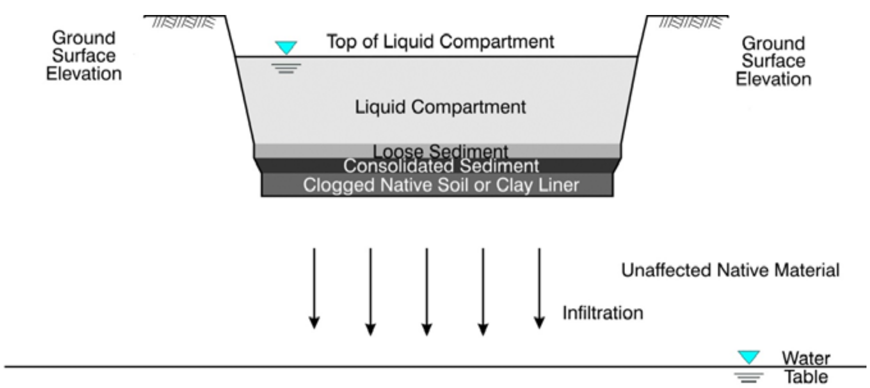


Figure 3-2. Surface impoundment infiltration module.

EPACMTP assumes that while the impoundment is in operation, a layer of fine-grained sediment ("sludge") naturally accumulates at the bottom of the impoundment as the result of the settling of suspended solids in the waste liquid. The upper half of this layer consists of unconsolidated material; the lower half is consolidated (compacted) due to the weight of the sediment and wastewater above it. EPACMTP calculates the effective hydraulic conductivity of the consolidated sediment layer as a function of its porosity, using an empirical relationship based on work of Lambe and Whitman (1969), which results in a calculated hydraulic conductivity on the order of 1×10^{-7} to 6×10^{-7} cm/s. The module also takes into account the hydraulic properties of a clay liner (if present), as well as the properties of the native soil underlying the impoundment. If no liner is present, EPACMTP assumes that over time, the upper soil layer becomes clogged due to deposition of solids from the impoundment. The thickness of this clogged layer is always assigned a value of 0.5 m, and the hydraulic conductivity of this clogged layer is assigned a value that is 10% of the hydraulic conductivity of the native soil material.

If a clay liner is present, the liner replaces the clogged native material layer that is depicted in **Figure 3-3**. If EPACMTP is used to model a lined surface impoundment, the thickness and hydraulic conductivity of the clay liner are model inputs.

The EPACMTP surface impoundment module calculates the steady state infiltration rate through the multi-layer system of sediment-clogged native soil/clay liner-native soil by applying the one-dimensional Richards equation (Jury et al., 1991) with a constant head boundary condition that is given by the ponding depth of the impoundment. EPACMTP uses the Richards equation to accommodate partially saturated conditions that may exist in the multi-layer system. For a detailed description of the solution of the Richards equation for the system, see the *EPACMTP Technical Background Document* (U.S. EPA, 2003a).

3.1.3 Assumptions and Limitations for WMU Source Modeling

EPA designed the EPACMTP fate and transport model to be used for regulatory assessments in a probabilistic framework. The simulation algorithms that are incorporated into the model are intended to meet the following requirements:

- Account for the primary physical and chemical processes that affect constituent fate and transport in the unsaturated and saturated zone;
- Run (and produce useful results) with relatively little site input data; and
- Be computationally efficient for Monte Carlo analyses.

This section discusses the primary assumptions that EPA made in developing the EPACMTP WMU source module to balance these competing requirements, and the resulting limitations. **EPACMTP may not be suitable for all sites, and the user should understand the capabilities and limitations of the model to ensure that it is used appropriately.**

The EPACMTP source module provides a relatively simple representation of different types of WMUs. WMUs are represented in terms of a source area and a defined rate and duration of leaching. EPACMTP only accounts for the release of leachate through the base of the WMU and assumes that the only mechanism of constituent release is through dissolution of waste constituents in the water that percolates through the WMU. In the case of surface impoundments, EPACMTP assumes that the leachate concentration is the same as the constituent concentration in the wastewater in the surface impoundment. EPACMTP does not account for the presence of non-aqueous free-phase liquids, such as an oily phase that might provide an additional release mechanism into the subsurface. EPACMTP does not account for releases from the WMU via other environmental pathways, such volatilization or surface run-off. EPACMTP assumes that the rate of infiltration through the WMU is constant, representing long-term average conditions. EPACMTP does not account for fluctuations in rainfall rate or degradation of liner systems that may cause the rate of infiltration to vary over time. It is important to note that while the concentration of constituents dissolved in infiltrating water may change over time, the rate at which water infiltrates to the subsurface must remain constant to satisfy steady state flow assumptions. **EPACMTP cannot simulate stored solid wastes managed in landfills, waste piles, or land application units that are in direct contact with the water table**.

Three of the four WMUs in IWEM and EPACMTP (surface impoundment, waste pile, and land application unit) are considered finite sources, and their leaching durations are determined by the user-supplied value for operational life. Although these WMUs might be described as temporary, default values for their operational lives range from 20 to 50 years. EPACMTP was designed to estimate peak and average ground water concentrations at a well assuming that leaching durations would be long enough to capture the changing ground water concentrations in terms of years rather than days. As a result, **EPACMTP may not adequately represent well concentrations for extremely short leaching durations of 1 year or less**.

A detailed discussion of assumptions and limitations and the numerical formulation for EPACMTP can be found in Section 2 of the *EPACMTP Technical Background Document* (U.S. EPA, 2003a).

3.2 Structural Fill Module

This section describes how EPACMTP models the release of constituents from a structural fill. **Section 3.2.1** provides a general overview of the EPACMTP structural fill source module; and **Section 3.2.2** identifies the assumptions and limitations of the structural fill source terms.

3.2.1 Releases From a Structural Fill

The purpose of the structural fill source module is the same as the WMU source modules: to provide a leachate flux and concentration to the unsaturated zone. The module relies on the design characteristics of the structural fill and the waste stream characteristics (material properties, quantity, and concentrations). The release of constituent mass from the structural fill is modeled as a finite pulse source (see Figure 3-1 above). The main difference between a structural fill and a WMU is in how the duration of leaching is controlled. As mentioned above, WMUs other than the landfill have a specified operational life, which determines how long leachate is released from the unit. The duration of leaching from a structural fill is controlled by a combination of the leachate flux rate and the amount of available constituent mass to be leached; the pulse will persist until all available mass is depleted. To define this behavior, the structural fill source module uses the following equation to calculate the length of the pulse, t_p, in years (units conversion factors are omitted):

$$t_p = \frac{C^0_{Total} \times d \times \rho_b \times f}{C^0_L \times I} \qquad (3\text{-}1)$$

where

t_p	=	length of pulse (years)
C^0_{Total}	=	constituent-specific total leachable materials concentration (mg/kg)
d	=	depth of the structural fill (m)
ρ_B	=	bulk density of the structural fill material (g/cm^3)

f = fractional volume of the structural fill occupied by materials with leachable components of interest (unitless)

C_L^0 = constituent-specific leachate concentration (mg/L)

I = leachate flux rate emanating from the structural fill (m/yr).

Mathematically, EPACMTP treats the structural fill the same way as it treats WMUs. A rectangular footprint is assumed between the bottom of the structural fill and the top of the unsaturated zone column, through which leachate passes. The structural fill source module estimates the magnitude of the rate of water infiltration and constituent concentration crossing this plane. Input leachate and total leachable material concentrations are assumed to represent the net result of internal chemical and physical processes within the modeled unit.

Typically, structural fills are unlined and when not covered by an impermeable or nearly impermeable surface (e.g., pavement or a building), they are often designed to have the same or greater permeability as the surrounding soils (NRMCA, nd). Therefore, IWEM provides the regional infiltration rates developed with the HELP model (Schroeder et al, 1994) as available default values based on the geographic location. IWEM requires the user to provide a value of the effective hydraulic conductivity of the structural fill material as a potential physical limiter on the HELP-derived infiltration rates or user-specified infiltration rate.

3.2.2 Assumptions and Limitations for Structural Fill Source Modeling

As mentioned in **Section 3.1.3**, EPA designed the EPACMTP fate and transport model to be used for regulatory assessments in a probabilistic framework. The simulation algorithms that are incorporated into the model are intended to meet the following requirements:

- Account for the primary physical and chemical processes that affect constituent fate and transport in the unsaturated and saturated zone;
- Run (and produce useful results) with relatively little site input data; and
- Be computationally efficient for Monte Carlo analyses.

As also mentioned in **Section 3.1.3**, the same assumptions and caveats that were applicable to the WMU source term apply to the structural fill source term.

The EPACMTP source module provides a relatively simple representation of the structural fill: structural fills are represented in terms of a source area and a defined rate and duration of leaching. EPACMTP only accounts for the release of leachate through the base of the fill and assumes that the only mechanism of constituent release is through dissolution of waste constituents in the water that percolates through the fill. EPACMTP does not account for releases from the structural fill via other environmental pathways, such volatilization or surface run-off. EPACMTP assumes that the rate of infiltration through the structural fill is constant, representing long-term average conditions. EPACMTP does not account for fluctuations in rainfall rate that may cause the rate of infiltration and release of leachate to vary over time. Like landfills, waste piles, and land application units, **EPACMTP cannot simulate a structural fill that is in direct contact with the water table**.

Structural fills are considered permanent constructions, and thus, the leaching duration is calculated using the site-specific, user-supplied inputs that define the geometry, material and constituent composition, and infiltration rate. EPACMTP was designed to determine peak and average ground water concentrations at a well assuming that leaching durations would be long enough to capture the changing ground water concentrations in terms of years rather than days. As a result, **EPACMTP does not adequately represent well concentrations for extremely short leaching durations of 1 year or less**.

3.3 Roadway Source Module

Unlike the WMU source modules, the roadway source-term module is outside of EPACMTP, but incorporated in IWEM. Therefore, prior to the execution of EPACMTP subsurface modeling, the external roadways source module provides the magnitude and duration of leaching to EPACMTP. This section describes how IWEM determines the release of constituents from a roadway constructed with industrial materials. **Section 3.3.1** provides a general overview of the roadway source module; **Section 3.3.2** presents a discussion of how the roadway source module was integrated into IWEM; and **Section 3.3.3** identifies the assumptions and limitations of the roadway source module. The details of the roadway source-module design and implementation are provided in **Appendix C**. **Appendix E** addresses the derivation of infiltration rates through pavements and other roadway design elements available in IWEM. **Appendix F** describes the mathematical approach of accommodating modeling scenarios where the direction of ground water flow is not perpendicular to the axis of travel on the roadway. **Appendix G** describes the verification of the roadway module.

3.3.1 General Conceptualization

The purpose of the roadway source module is to provide a leachate fluxes and concentrations to the unsaturated zone. Whereas the WMU source modules provide a uniform, finite source leachate concentration over the entire footprint of the WMU, the structure of a roadway cross-section and the source module make it possible to have different leachate concentrations and infiltration rates across the roadway cross-section. Leachate releases from the roadway source module are a function of the design of the roadway, the material properties of the unique structural elements in the roadway, and the characteristics (quantity and concentrations) of reused materials having leachable components incorporated in the structural elements.

Figure 3-3 depicts a typical roadway with a segment constructed with industrial materials. For the purposes of model simplicity, that segment is assumed to be nearly linear and thus can be approximated by the straight line segment. If the segment to be modeled is long and meandering, it must be subdivided into several nearly linear segments that can each be represented by a straight line, each segment requiring a separate evaluation (see Example Problem 4 in Appendix C of the *IWEM v. 3.1 User's Guide* for an example of how to evaluate a multi-segment roadway).

Figure 3-4 shows a typical cross section of a roadway, which may comprise several components (e.g., lanes, shoulder, and ditch). For the roadway module, each component was idealized as a column, referred to henceforth as the roadway-source column. In the vertical direction, as shown in **Figure 3-5**, each roadway-source column includes materials starting vertically upward from a reference datum (which could be the top of subgrade), to the surface of a pavement or a road shoulder or an embankment or a ditch. As shown in Figure 3-5, each roadway-source column is underlain by a corresponding vadose-zone column.

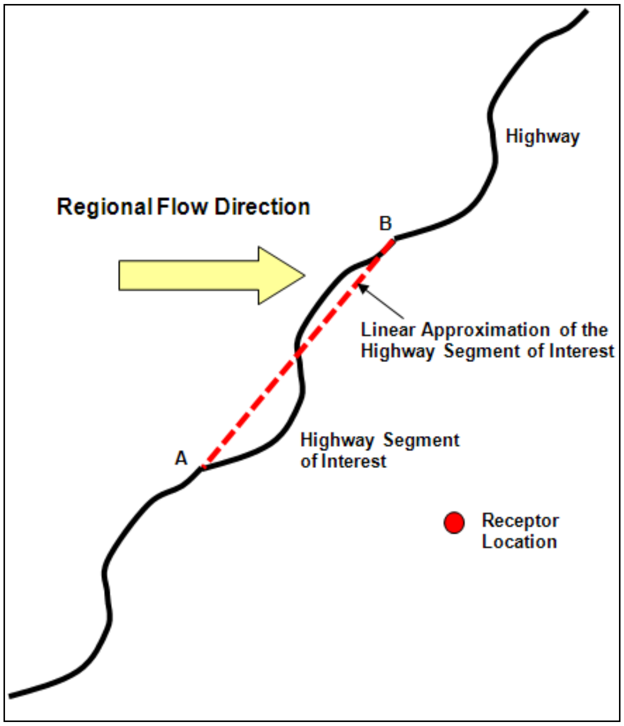


Figure 3-3. A typical roadway with a recycled-material segment.

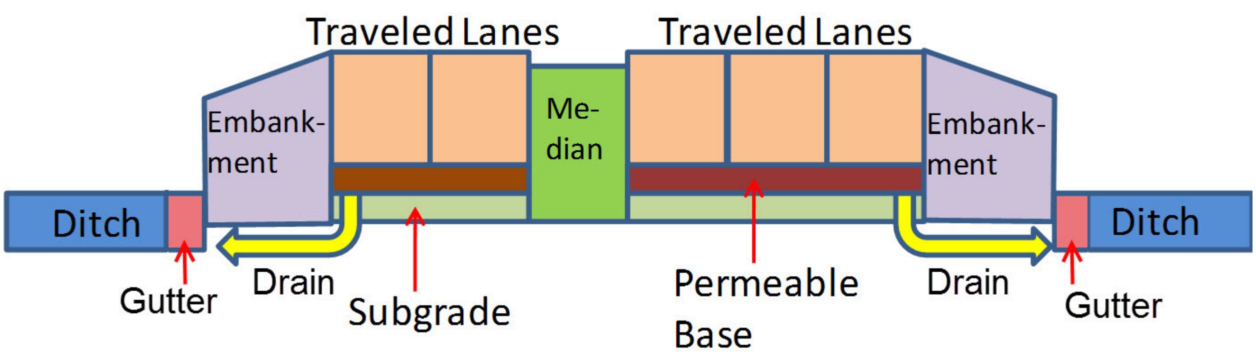


Figure 3-4. A typical cross section of a roadway.

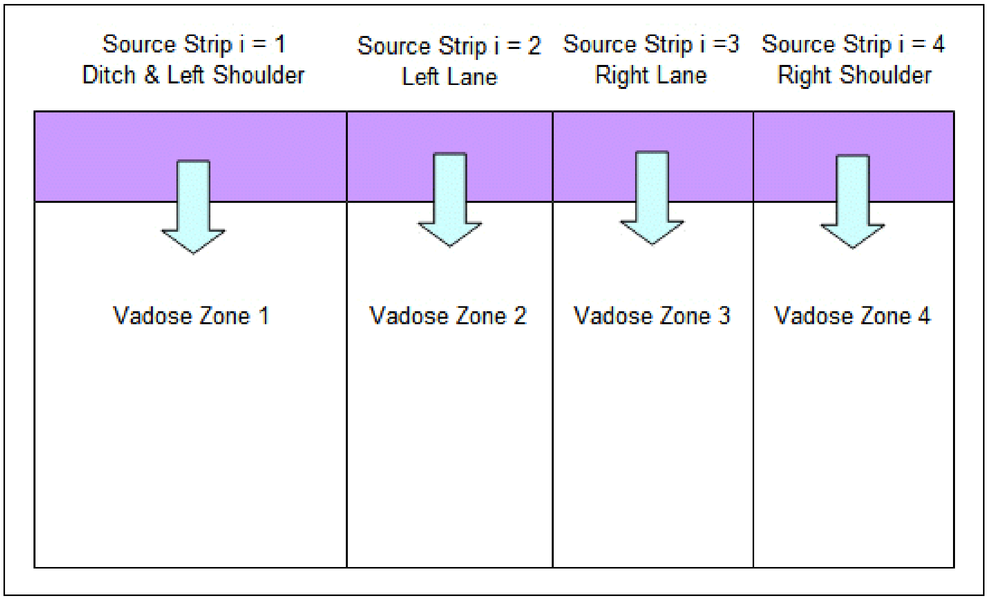


Figure 3-5. Modules of IWEM corresponding to multiple roadway-source strips.

A roadway-source column was assumed to be uniform in terms of parameters and properties along the length of interest (i.e., the modeled segment shown in Figure 3-4). Therefore, a roadway-source column becomes a roadway-source strip in three dimensions. **Figure 3-6** shows an example of a roadway cross section comprising three roadway-source strips representing, respectively, a median, a lane, and a ditch. Note that a more typical roadway may consist of up to 15 roadway-source strips: for example, left shoulder, left lane, median, right lane, and right shoulder. More strips are possible to account for drainage ditches and berms and different configurations of layers; the IWEM roadway module limits the total number of roadway-source strips to 15.

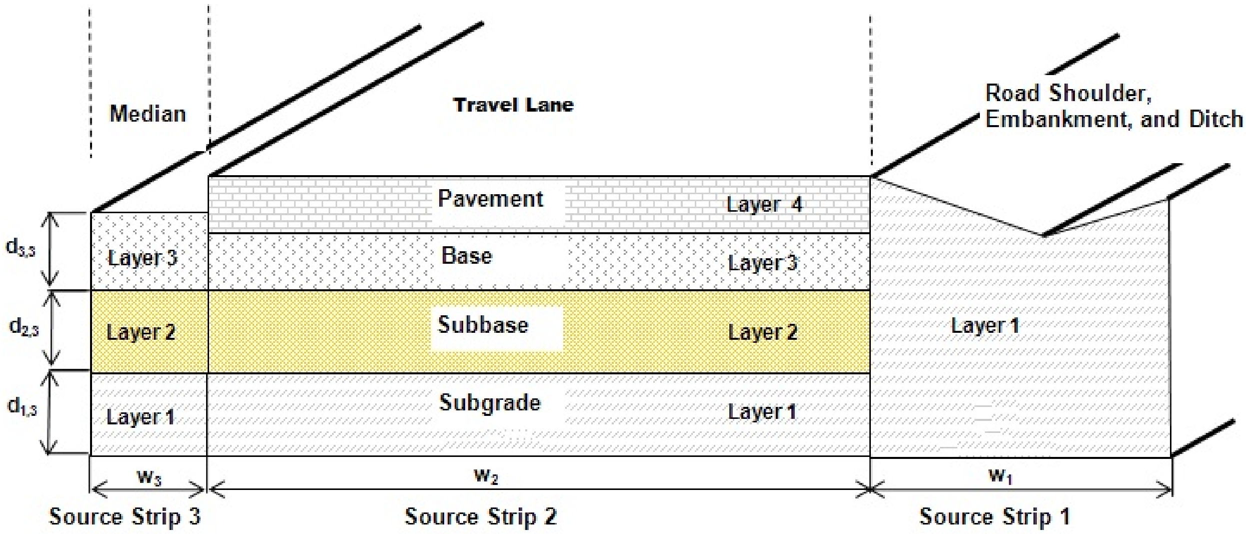


Figure 3-6. An example of layering in roadway-source strips.

An example of only three roadway-source strips is used here as a basis for further discussion. Each roadway-source strip may consist of several layers, depending on how a given roadway was constructed. A lane strip may be composed of a pavement layer (Portland cement concrete or asphalt concrete), a base-course layer, a subbase layer, and a subgrade layer. A median may comprise a base layer, a subbase layer, and a subgrade layer. An unpaved road shoulder may have only one layer—a subgrade layer. With this type of conceptualization, one can easily see that each roadway-source strip is nearly equivalent to the existing landfill source module that is available within EPACMTP. However, the EPACMTP landfill module integrated into IWEM can accommodate only sources with a square footprint and one layer.

As illustrated in Figure 3-4, the ground water flow direction may not be perpendicular to the segment of interest. The roadway module can accommodate a scenario where the ground water flow direction is not perpendicular to the model. In addition, the location of the ground water well is not restricted. These two features are unique to the roadway module (and are discussed in more detail in **Appendix F**).

As mentioned above, the roadway source module is based on the design, material properties, and constituent characteristics in the materials; specifically, it uses six primary parameters:

- Area of each roadway source strip (specified as a width for each strip and the length of the segment being modeled);
- The thickness of each layer in each strip;
- The material properties of each layer (bulk density, hydraulic conductivity)
- Leachate flux rate emanating from the strip (infiltration rate subject hydraulic conductivity);
- Constituent-specific leachate and total leachable material concentrations in layers containing reused materials; and
- Leaching duration (derived from material properties and dimensions, leachate flux rate and constituent concentrations).

Based on these parameters, the roadway source module generates a rate of leaching and the constituent concentration in the leachate as a function of time from the bottom of each strip containing leachable constituent mass.

3.3.2 Approach to Integration into IWEM

Based on the general conceptualization described above, a number of modifications were made to the IWEM interface to simulate a roadway, including changes to

- Accommodate multiple layers;
- Handle rectangular sources;
- Account for multiple roadway-source strips, drainage systems and ditches and their material properties and flow characteristics;
- Account for a general regional flow field that may not be perpendicular to the roadway axis; and
- Include default pavement infiltration rates (**Appendix E** addresses the derivation of infiltration rates through pavements and other roadway design elements available in IWEM).

Additional parameters were added to IWEM to describe the pavement geometry, receptor location, material properties, and the concentrations of constituents present in the industrial materials. Also, the IWEM database was updated to store these new parameters associated with the roadway, as well as intermediate values calculated for the module.

The roadway module was verified to ensure that these modifications were correctly implemented and to ascertain the degree of accuracy of the transformation of the transport equation for non-perpendicular regional flow. **Appendix G** details the verification process.

3.3.3 Assumptions and Limitations of Roadway Source Module

The following assumptions are used in the formulation of the roadway source term:

- In the region of interest, the general regional ground water flow pattern is assumed not to be affected by the presence of a traversing roadway. It follows from this assumption that infiltration from the traversing roadway is on the same order of magnitude as regional recharge. Furthermore, the areal coverage of the roadway contributing infiltration is assumed to be very small compared to the total regional area contributing recharge, so that any difference between the infiltration and recharge rates does not significantly influence the regional flow field.
- Lateral communication between roadway-source strips is assumed to be insignificant.
- A single, long-term average infiltration rate is assumed to represent percolation through each roadway-source strip.
- Leaching begins at the end of pavement construction and is modeled as a depleting finite source.
- Material properties of each roadway-source strip do not vary in time.

3.4 Structural Fill or Roadway?

Structural fills evaluated in IWEM include the use of industrial materials and related byproducts as substitutes for the earthen materials for supporting parking lots, roads, airstrips, tanks/vaults, and buildings; construction of highway embankments and bridge abutments; filling of borrow pits, and other landscape irregularities; and changing the landscape for development or reclamation projects. IWEM can evaluate structural fills using both flowable fill and compacted installation methods. Applications that include reused materials can range from the conceptually simple (e.g., filling a borrow pit) to the very complex (e.g., support for a multi-lane roadway and component layers in an adjoining embankment). The complexity of the specific application will govern the choice between a structural fill and a roadway source term.

If the application to be modeled can be conceptualized as containing a single layer of reused material having the same material (i.e., hydraulic conductivity and bulk density) and constituent (i.e., leachate and total leachable material concentrations) characteristics, then the structural fill source term would be most applicable. Even in the case of a multi-layer structure where the same reused material is employed, these layers can be collapsed into a single layer – the time it takes for leachate to travel through "clean" layers between layers containing reused materials is not modeled in either the structural fill module or in the roadway module; only the net leaching profile is released to the soil column beneath the source area (See **Appendix C**, Section C.2.2.1 for more details).

The structural fill source-term would be applicable to a parking lot or a simple roadway presuming that (1) the one or more layers of the structure with reused materials have same material and constituent properties; (2) the layering configuration is the same everywhere in the structure; and (3) an infiltration rate that represents the flux of water through the paved surface is available. If, on the other hand, there are multiple layers and the layering structure within the source varies from one end to the other, the roadway source term would be more appropriate.

4.0 Unsaturated and Saturated Zone Modeling Using EPACMTP

This section describes the EPACMTP's subsurface modeling modules used in IWEM to simulate the migration of waste constituents through the ground water pathway from land-based sources to wells. The section provides information about EPACMTP that is relevant to IWEM, including important fate and transport equations and some of the key assumptions and limitations of the model. However, the section does not attempt to provide detailed derivations of the fate and transport equations. For complete documentation on the EPACMTP model, the reader should refer to *EPACMTP Technical Background Document* (U.S. EPA, 2003a).

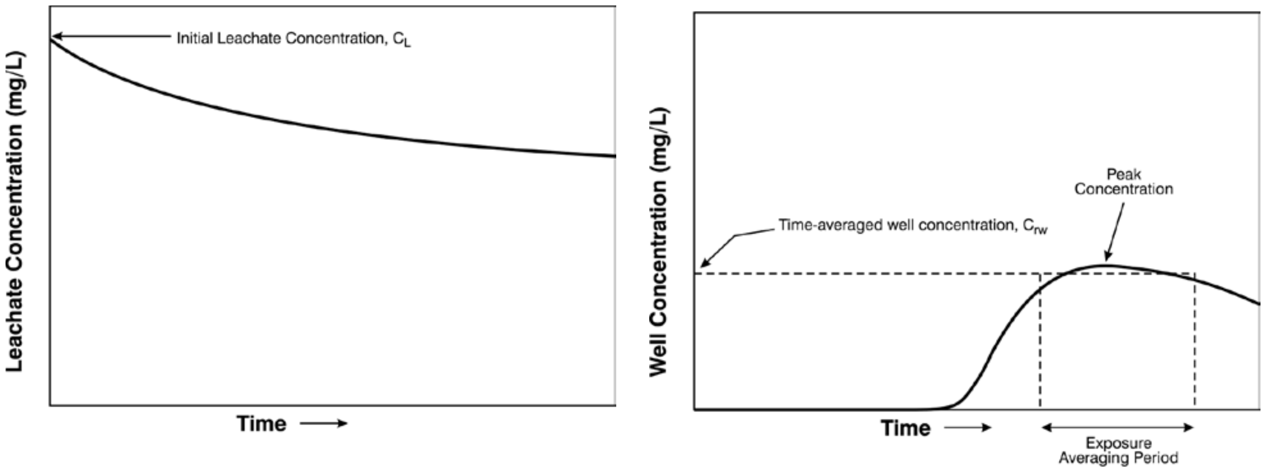
EPACTMP contains two modular components to model the subsurface migration of constituents: the unsaturated and saturated zone modules. The unsaturated zone module simulates one-dimensional, vertically downward flow and transport of constituents in the vadose zone underneath a source. On the other hand, the saturated zone module simulates the ground water flow and three-dimensional constituent transport within the saturated zone. These modules are computationally linked through continuity of flow and constituent concentration across the water table directly underneath the source. The modules account for several processes affecting constituent fate and transport including: advection, hydrodynamic dispersion and molecular diffusion; linear or nonlinear equilibrium sorption; first-order decay and zero-order production reactions (to account for transformation breakdown products); and dilution from recharge in the saturated zone.

The main inputs to the subsurface component of EPACMTP are the rate of constituent release (leaching) from a source, source design, and site hydrogeological characteristics. The output from EPACMTP, as it is employed in IWEM, is a time-dependent estimation of the constituent concentrations arriving at a down gradient well. The timing and magnitude of the prediction can vary, depending on a number of factors not limited to the nature of the source,[1] the distance between the source and the receptor well, constituent fate and transport properties, and the exposure period. EPACMTP can calculate the peak concentration arriving at the well or a time-averaged concentration corresponding to a specified exposure duration (for example, a 30-year average exposure time).

The relationship between the constituent concentration leaching from a source and the resulting ground water exposure at a well located down-gradient from the source is depicted in **Figure 4-1**. Figure 4-1a shows how the leachate concentration emanating from the source gradually diminishes over time as a result of depletion of the contaminant mass remaining in the unit. As seen in Figure 4-1b, the constituent does not arrive at the well until sometime after the leaching begins. Eventually the ground water concentration will reach a peak value and then begin to diminish because the leaching from the source occurs only over a finite period of time. This curve is also called the breakthrough curve. The maximum constituent concentration at the well will generally be lower than the original leachate concentration as a result of various dilution and attenuation processes, which occur during the transport through the unsaturated and saturated zones. EPACMTP has the capability to calculate the maximum average ground water

[1] See the discussion of source scenarios in **Section 3.1.1**; the IWEM sources are all modeled as finite sources, although landfills behave more like continuous sources due to the long time to deplete.

concentration over a specified exposure period, as depicted by the horizontal dashed line in Figure 4-1b.



(a) Leachate concentration vs time **(b) Ground water well concentration vs time**

Figure 4-1. Relationship between leachate concentration and well concentration.

The following sections provide more detailed discussions of the unsaturated and saturated zone modules of EPACMTP and the role of each in simulating constituent fate and transport. **Section 4.1** describes the unsaturated zone module and the mathematical equations used to model constituent fate and transport; **Section 4.2** describes the saturated zone module and mathematical equations related to this environment; and, **Section 4.3** describes the important modeling assumptions and limitation considered in developing the modules.

4.1 Unsaturated Zone Module

IWEM uses the unsaturated zone module in EPACMTP to model water flow and solute transport in the unsaturated zone – between the base of the source and the water table. EPACMTP assumes that constituent migration through this media is entirely one-dimensional (vertically downward). EPACMTP also assumes the flow rate is steady state, that is, it does not change in time. The soil underneath the source is assumed to be uniform with hydraulic properties described by the Mualem–Van Genuchten model (Jury et al., 1991). The flow rate is determined by the long-term average infiltration rate through the source. Inputs to the unsaturated zone module are the rate of water and constituent leaching from the source, as well as soil hydraulic properties. EPACMTP solves the governing one-dimensional steady-state Richards flow equation (Jury et al., 1991) using a semi-numerical technique described in the *EPACMTP Technical Background Document* (U.S. EPA, 2003a).

Constituent transport in the unsaturated zone is assumed to occur by advection and dispersion.[2] It is also assumed that the unsaturated zone is initially constituent-free and that constituents migrate vertically downward from the source. EPACMTP can simulate both steady state and transient

[2] In the case of metals, which are subject to nonlinear sorption, EPACMTP uses a method-of-characteristics solution method that does not include dispersion. In this case, transport is dominated by the nonlinear sorption behavior, and dispersion effects are minor.

transport in the unsaturated zone, with single-species or multiple-species chain decay reactions. The transport module can also simulate the effects of both linear and nonlinear sorption reactions. When decay reactions involve the formation of daughter products, EPACMTP has the capability to perform a multi-species transport simulation of a decay chain consisting of up to seven members.

Mathematically, the transport process is represented by the advection-dispersion equation:

$$\frac{\partial}{\partial z}\left(D\frac{\partial c}{\partial z}\right) - V\frac{\partial c}{\partial z} - \theta B\lambda c = \theta R\frac{\partial c}{\partial t} + Q \qquad (4\text{-}1)$$

where (using general units for L[ength], M[ass], and T[ime])

z	=	Soil depth coordinate (L)
c	=	Constituent concentration (M/L^3)
t	=	Time (T)
D	=	Dispersion coefficient, (L^2/T)
V	=	Darcy velocity (L/T)
θ	=	Volumetric water content (dimensionless)
B	=	Phase distribution coefficient (dimensionless)
λ	=	Lumped first-order decay constant (1/T)
R	=	Retardation factor (dimensionless)
Q	=	Zero-order production term to account for transformation of parent constituents ($M/L^3 \cdot T$)

EPACMTP uses units of meters for L(ength), years for T(ime), and kilograms for M(ass). Consistent with common practice, EPACMTP uses units of mg/L for constituent concentration. Numerically, this is the same as kg/m^3.

The dispersion coefficient, *D*, in the above transport equation accounts for the effects of hydrodynamic dispersion and molecular diffusion in the vertical direction and is defined as

$$D = \alpha V + D_m \qquad (4\text{-}2)$$

where

D	=	Dispersion coefficient (m^2/yr)
α	=	Dispersivity (m)
V	=	Darcy velocity (m/yr)
D_m	=	Molecular diffusion coefficient (m^2/yr)

Accounting for dispersion only in the vertical direction (downward only) is consistent with the one-dimensional unsaturated flow formulation, and also provides some additional, but relatively small, conservatism for a screening model. The effective molecular diffusion coefficient, D_m, is calculated using the Millington-Quirk relationship (Jury et al., 1991) as

$$D_m = D_w\ \theta^{10/3} / \theta^2 \qquad (4\text{-}3)$$

where

D_m = Effective molecular diffusion coefficient (m^2/yr)
D_w = Free-water diffusion coefficient (m^2/yr)
θ = Volumetric water content (dimensionless)

The retardation factor, *R*, in the transport equation (Equation 4-1) accounts for the effects of equilibrium sorption of dissolved constituents onto the solid phase and is calculated as

$$R = 1 + (\rho_b\ k_d)/\theta \qquad (4\text{-}4)$$

where

R = Retardation factor (dimensionless)
ρ_b = Bulk density (kg/L)
k_d = Constituent-specific soil-water partition coefficient (L/kg)
θ = Volumetric water content (dimensionless)

EPACMTP's unsaturated zone module includes options for both linear and nonlinear sorption isotherms. In the first case, the partition coefficient, k_d, is independent of the constituent concentration. In the second case, the value of the partition coefficient is a function of concentration. For linear sorption isotherms, the partition coefficient can be entered as a single EPACMTP parameter, or the model can calculate its value from the fraction organic carbon in the soil and a constituent-specific organic carbon partition coefficient as

$$k_d = f_{oc} \times K_{oc} \qquad (4\text{-}5)$$

where

k_d = Partition coefficient (L/kg)
f_{oc} = Fraction organic carbon in the soil (dimensionless)
K_{oc} = Constituent-specific organic carbon partition coefficient (L/kg)

The phase distribution coefficient, *B*, is identical to the retardation factor and accounts for degradation in both the dissolved and sorbed phases when multiplied by the lumped degradation coefficient, λ. *B* is calculated as

$$B = 1 + (\rho_b\ k_d)/\theta \qquad (4\text{-}6)$$

where

B = Phase distribution coefficient (dimensionless)
ρ_b = Bulk density (kg/L)
k_d = Constituent-specific soil-water partition coefficient (L/kg)
θ = Volumetric water content (dimensionless)

When modeling constituents with non-linear sorption isotherms, the partition coefficient data are read in by EPACMTP as a table of paired concentration-k_d values. In principle, the user can employ a variety of methods for generating the concentration-k_d values, including using measured data. In practice, EPACMTP applications typically use data generated using the MINTEQA2 geochemical speciation model (see **Section 6.5.2**).

The parameter λ in the transport equation (Equation 4-1) accounts for first-order transformation processes. Finally, the term Q in the transport equation is a source term that represents the production of a constituent species due to the transformation of parent constituents. This term is zero for parent constituents that are at the beginning of a decay chain, but non-zero for any transformation daughter products.

The output from the unsaturated zone transport solution is a time history (breakthrough curve) of the constituent concentration arriving at the water table, which provides the input for the saturated zone transport simulation.

4.2 Saturated Zone Module

The saturated zone module of EPACMTP used in IWEM is designed to simulate flow and transport in an unconfined aquifer with constant saturated thickness. The model simulates regional flow in a horizontal direction with recharge and infiltration from the overlying unsaturated zone and source entering at the water table. Localized water table mound effects are possible when infiltration through the source area is greater than the regional recharge. The lower boundary of the aquifer is assumed to be impermeable.

EPACMTP assumes that flow in the saturated zone is steady state. In other words, EPACMTP models long-term average flow conditions. The steady-state ground water flow solution provided in EPACMTP accounts for different recharge rates beneath and outside the source area. Ground water mounding beneath the source is represented in the flow system by increased head values at the top of the aquifer. It is important to realize that while EPACMTP calculates the degree of ground water mounding that may occur underneath a source due to high infiltration rates, the actual saturated flow and transport modules in EPACMTP are based on the assumption of a constant saturated thickness. The only direct effect of ground water mounding in EPACMTP is to increase localized, simulated ground water velocities where the water table has been elevated.

EPACMTP incorporates a number of different mathematical solutions for saturated zone flow and transport. The *EPACMTP Technical Background Document* (U.S. EPA, 2003a) discusses these in detail. Because of the high premium on computational efficiency in the IWEM Monte Carlo tool, a pseudo-3-dimensional modeling approach was used in IWEM. The pseudo-3-dimensional module simulates ground water flow using a one-dimensional steady-state solution for predicting hydraulic head and Darcy velocities. The flow solution is formulated based on the Dupuit-Forchheimer's assumption of hydrostatic pressure distribution (de Marsily, 1986). The hydraulic head is also horizontally averaged in the cross-gradient direction.

EPACMTP models transport of dissolved constituents in the saturated zone using the advection-dispersion equation. The aquifer is assumed to be initially constituent-free, and constituents enter the saturated zone only from the unsaturated zone directly beneath the source. In the pseudo-3-dimensional option of EPACMTP used for IWEM, it is assumed that advection is predominantly along the longitudinal direction (direction along the ambient ground water gradient), while dispersion occurs in three dimensions.

The pseudo-3-dimensional transport option is based on the concept that when ground water flow is predominantly in one direction, the movement of a dissolved constituent plume can be approximated as the product of three terms: the first term describes the movement by advection and dispersion along the direction of ground water flow (the x-direction); and the second and third terms account for the effect of dispersion in the horizontal transverse (y-) direction, and the vertical (z-) direction, respectively. The effects of constituent sorption and transformation are incorporated into the first term of the mathematical solution. The second (y-direction) and third (z-direction) terms in the solution can be regarded as adjustment factors that account for the reduction in concentration along the x-direction, due to dispersion into the y- and z-directions. The y- and z- solution terms are given by straight-forward error-functions that can be computed very quickly. From a computational point, the pseudo-3-dimensional solution option therefore requires about the same effort as a one-dimensional solution. The treatment of boundary conditions for the pseudo-3-dimensional transport solution option, especially the transfer of mass at the water table, is discussed in much greater detail in the *EPACMTP Technical Background Document* (U.S. EPA, 2003a).

The governing equation for transport in the saturated zone can be written as:

$$\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial c}{\partial x_j}\right) - V_x\frac{\partial c}{\partial x} - \varphi B\lambda c = \varphi R\frac{\partial c}{\partial t} + Q \qquad (4\text{-}7)$$

where (using general units for L[ength], M[ass], and T[ime])

i,j	=	Indices to represent different spatial directions; i,j = 1, 2, or 3
x_i	=	Spatial coordinate (L)
c	=	Constituent concentration (M/L^3)
t	=	Time (T)
D_{ij}	=	Dispersion coefficient (L^2/T),
V_x	=	Ground water flow rate in the x-direction (L/T)
φ	=	Porosity (dimensionless)
B	=	Phase distribution coefficient (dimensionless)
λ	=	First-order transformation coefficient (1/T)
R	=	Retardation coefficient (dimensionless)
Q	=	Zero-order production term to account for transformation of parent constituents ($M/L^3 \cdot T$)

EPACMTP uses units of meters for L(ength), years for T(ime), and kilograms for M(ass). Consistent with common practice, EPACMTP uses units of mg/L for constituent concentration, which numerically is the same as kg/m^3.

The transport processes modeled in the saturated zone module of EPACMTP are analogous to those in the unsaturated zone, but they are extended to three dimensions instead of just one. The spatial coordinate, x_i, in Equation 4-7 represents the three dimensions. The coordinate x_1 (or just x), represents the horizontal coordinate along the direction of ground water flow. The coordinate x_2 (or y) represents the horizontal coordinate perpendicular to the flow direction; and the coordinate x_3 (or z) represents the vertical direction. The dispersion coefficient D_{ij} (where i and j can be 1, 2, or 3) is subscripted to indicate that this coefficient has components in all three directions. Conversely, the ground water flow term, V_x, has only a single subscript to indicate the assumption in the pseudo-3-dimensional option of EPACMTP, that ground water flow is a one-dimensional process. The other terms in Equation 4-7 are defined in the same way as in Equation

4-1, except that the porosity, φ, replaces the volumetric water content, θ. By definition, under fully saturated conditions, the water content of a porous medium is equal to its porosity; therefore, using φ instead of θ in Equation 4-7 is just another way of stating that the system is water-saturated.

In many aquifers, only a portion of the total pore space is active in the transport process, so that the effective porosity (φ_e) is less than the total porosity (φ). EPACMTP uses the effective porosity in the calculation of ground water seepage velocity, i.e.:

$$v_x = \frac{V_x}{\varphi_e} \tag{4-8}$$

where

v_x = Average pore water (seepage) velocity (m/yr)
V_x = Ground water flow rate (Darcy velocity; m/yr)
φ_e = Effective porosity (dimensionless)

The retardation coefficient, R is expressed as:

$$R = 1 + \frac{\rho_b k_d}{\varphi_e} \tag{4-9}$$

where

R = Retardation coefficient (dimensionless)
ρ_b = Saturated zone bulk density (kg/L)
k_d = Constituent-specific partition coefficient (L/kg)
φ_e = Effective porosity (dimensionless)

The phase distribution coefficient, B, is expressed as:

$$B = 1 + \frac{\rho_b k_d}{\varphi_e} \tag{4-10}$$

where

B = Phase distribution coefficient (dimensionless)
ρ_b = Saturated zone bulk density (kg/L)
k_d = Constituent-specific partition coefficient (L/kg).
φ_e = Effective porosity (dimensionless)

In order to determine the value of φ_e, EPACMTP uses a statistical distribution of the ratio φ_e/φ, which is presented in **Section 6.4.3**.

The dispersion coefficient (D_{ij}) in Equation 4-7 accounts for hydrodynamic dispersion and molecular diffusion and uses separate longitudinal, horizontal transverse and vertical dispersivities as described by Burnett and Frind (1987). The effect of molecular diffusion is incorporated using the Millington-Quirk equation, as described in the preceding section.

Likewise, the retardation and transformation terms are modeled in the same way in the saturated zone module of EPACMTP as they are in the unsaturated zone module.

A key distinction between the way the saturated zone module handles constituent fate and transport, as compared to the unsaturated zone module, is the approach for constituents with nonlinear sorption isotherms. The saturated zone module only simulates linearized isotherms. For constituents with nonlinear sorption isotherms, the unsaturated zone module simulates partitioning by using concentration-dependent partitioning coefficient; the saturated zone module uses a linearized isotherm, based upon the maximum constituent concentration at the water table (see *EPACMTP Technical Background Document*; U.S. EPA, 2003a). The reason is that upon dilution of the leachate in the ambient ground water as the leachate enters the saturated zone, concentrations will be reduced to a range in which constituent isotherms generally are linear.

4.3 Assumptions and Limitations for Unsaturated and Saturated Zone Modeling

EPA designed the EPACMTP fate and transport model to be used for regulatory assessments in a probabilistic framework. The simulation algorithms that are incorporated into the model are intended to meet the following requirements:

- Account for the primary physical and chemical processes that affect constituent fate and transport in the unsaturated and saturated zone;
- Be able to be used with relatively little site input data; and
- Be computationally efficient for Monte Carlo analyses.

This section discusses the primary assumptions that EPA made in developing the model to balance these competing requirements, and the resulting limitations. **EPACMTP may not be suitable for all sites conditions**. As such, the IWEM user should understand the capabilities and limitations of EPACMTP to ensure the use of IWEM is appropriate.

4.3.1 Uniform Soil and Aquifer Assumption

EPACMTP simulates the unsaturated zone and saturated zone as separate domains that are connected at the water table. Both zones are assumed to be uniform porous media. EPACMTP does not explicitly account for the presence of macro-pores, fractures, solution features, faults or other heterogeneities in the soil or aquifer that may provide pathways for rapid movement of constituents. A certain amount of heterogeneity always exists at actual sites and it is not uncommon in ground water modeling to use average parameter values. This means that parameters such as hydraulic conductivity and dispersivity represent effective site-wide average values. However, **EPACMTP may not be appropriate for sites overlying fractured or very heterogeneous aquifers**.

4.3.2 Steady-State Flow Assumption

Flow in the unsaturated zone and saturated zone is assumed to be driven by long-term average infiltration and recharge; EPACMTP treats flow in the unsaturated zone as steady state and does not account for fluctuations in the infiltration or recharge rate, either over time or over area. **The use of EPACMTP may not be appropriate at sites with large seasonal fluctuations in rainfall conditions or at sites where the recharge rate varies locally**. Examples of the latter include the presence of surface water bodies such as rivers, lakes, ponds, or man-made recharge sources near the source.

EPACMTP models ground water flow based on the assumption that the contribution of recharge and infiltration from the unsaturated zone are small relative to the regional ground water flow, and that the saturated aquifer thickness is large relative to the head difference that establishes the regional gradient. While horizontal flow conditions and recharge represent regional flow conditions, infiltration through the source area can result in localized mounding of the water table when infiltration is larger than recharge. The implication is that the saturated zone can be modeled as having a uniform thickness, with mounding underneath the source represented by an increased head distribution along the water table. The mathematical ground water flow solutions incorporated in EPACMTP are based on confined aquifer conditions. While EPACMTP accounts for ground water mounding underneath a source, the saturated zone module of EPACMTP only accounts for the effect of mounding on ground water flow velocities; it does not simulate the actual physical increase in the thickness of the saturated zone. The assumption of constant and uniform saturated zone thickness means that EPACMTP may not be suitable at sites with a non-uniform thickness of the water-bearing zone, or sites with significant seasonal variations in water table elevation. EPACMTP is designed for relatively simple ground water flow systems in which flow is dominated by a regional gradient. EPACMTP does not account for the presence of ground water sources or sinks such as pumping or injection wells. The presence of such man-made or natural features may cause a more complicated flow field than EPACMTP can handle. EPACMTP does not account for free-phase flow conditions of an oily or non-aqueous phase liquid.

4.3.3 Constituent Fate and Transport Assumptions

The unsaturated zone and saturated zone modules of EPACMTP account for constituent fate and transport by advection, hydrodynamic dispersion, molecular diffusion, sorption and first-order transformation. Advection refers to transport along with ground water flow. Hydrodynamic dispersion and molecular diffusion both act as mixing processes. Hydrodynamic dispersion is caused by local variations in ground water flow rate and is usually a significant plume-spreading mechanism. Molecular diffusion, on the other hand, is usually a minor mechanism, except when ground water flow rates are very low. EPACMTP does not account for matrix-diffusion processes, which may occur when the aquifer formation is comprised of zones with widely varying permeabilities. In these situations, transport occurs primarily in the more permeable zones, but constituents can move into and out of the low permeability zones by diffusion.

Leachate constituents can be subject to complex geochemical interactions in soil and ground water. EPACMTP treats these interactions as equilibrium sorption processes. The equilibrium assumption means that the sorption process occurs instantaneously or at least very quickly relative to the time-scale of constituent transport. Although sorption, or the attachment of leachate constituents to solid soil or aquifer particles, may result from multiple chemical processes, EPACMTP lumps these processes together into an effective soil-water partition coefficient.

For organic constituents, EPACMTP assumes that the partition coefficient is constant and equal to the product of the mass fraction of organic carbon in the soil or aquifer and a constituent-specific organic carbon partition coefficient (see Equation 4-5). In the case of metals, EPACMTP allows the partition coefficient to vary as a function of a number of primary geochemical parameters, including pH, leachate organic matter, soil organic matter, and the fraction of iron-oxide in the subsurface.

For metals, EPACMTP uses a set of effective sorption isotherms, which were developed by EPA by running the MINTEQA2 geochemical speciation model (U.S. EPA, 1991) for each metal and each combination of geochemical parameters. In modeling metals transport in the unsaturated zone, EPACMTP uses the complete, nonlinear sorption isotherms. In modeling metals transport in the saturated zone, EPACMTP uses linearized MINTEQA2 isotherms, based on the assumption that after dilution of the leachate plume in ground water, concentration values of metals will typically be in a range where the isotherm is approximately linear. This assumption may not be valid when the metal concentrations in the leachate are high. Although EPACMTP is able to account for the effect of the geochemical environment at a site on the mobility of metals, the model assumes that the geochemical environment at a site is constant and not affected by the presence of the leachate plume. In reality, the presence of a leachate plume may alter the ambient geochemical environment.

EPACMTP does not account for colloidal transport or other forms of facilitated transport. For metals and other constituents that tend to strongly sorb to soil particles, and which EPACMTP will simulate as relatively immobile, movement as colloidal particles can be a significant transport mechanism. It is possible to approximate the effect of these transport processes by using a lower value of the partition coefficient as a user-input. In the IWEM application of EPACMTP, the model uses the same partition coefficient for the unsaturated and saturated zone if this parameter is provided as a user-input.

EPACMTP accounts for biological and chemical transformation processes as first-order degradation reactions. That is, it assumes that the transformation process can be described in terms of a constituent-specific half-life. EPACMTP allows the degradation rate to have different values in the unsaturated zone and the saturated zone, but the model assumes that the value is uniform throughout the unsaturated zone and uniform throughout the saturated zone for each constituent. EPA’s ground water modeling database includes constituent-specific hydrolysis rate coefficients for constituents that are subject to hydrolysis transformation reactions; for these constituents, EPACMTP simulates transformation reactions subject to site-specific values of pH and soil and ground water temperature, but other types of transformation processes are not explicitly simulated in EPACMTP.

For many organic constituents, biodegradation can be an important fate mechanism, but EPACMTP has only limited ability to account for this process. The user must provide an appropriate value for the effective first-order degradation rate. In the IWEM application of EPACMTP, the model uses the same degradation rate coefficient for the unsaturated and saturated zone if this parameter is provided as a user-input. In an actual leachate plume, biodegradation rates may be different in different regions in the plume; for instance in portions of the plume that are anaerobic some constituents may biodegrade more readily, while other constituents will biodegrade only in the aerobic fringe of the plume. EPACMTP does not account for these or other processes that may cause a constituent’s rate of transformation to vary in space and time.

5.0 Conducting Probabilistic Analyses

The final component of EPACMTP is the Monte Carlo module, and the integration of EPACMTP in IWEM, provides IWEM the capability to simulate constituent fate and transport probabilistically. Monte Carlo simulation is a statistical technique by which a quantity is calculated repeatedly, using randomly selected parameter values for each calculation. The results approximate the full range of possible outcomes and the likelihood of each. The Monte Carlo module in EPACMTP makes it possible to incorporate variability into the subsurface pathway modeling analysis, and to quantify the impact of parameter variability on ground water concentrations. In particular, Monte Carlo simulation is used to determine the likelihood, or probability, that the ground water concentration of a constituent at a well, and hence exposure and risk, will be either above or below a certain regulatory or health-based value.

In a Monte Carlo simulation, the values of the various source-specific, chemical-specific, unsaturated zone-specific, and saturated zone-specific model parameters are represented as probability distributions. Precisely, Monte Carlo analysis can account only parameter variability, not uncertainty. ***Variability*** describes parameters whose values are not constant, but which can be measured and characterized with relative precision in terms of a frequency distribution. An example is annual rainfall in different parts of the country. ***Uncertainty***, on the other hand, pertains to parameters whose values are known only approximately, such as the hydraulic conductivity of an aquifer. In practice, probability distributions are used to describe both variability and uncertainty, and for the purpose of the EPACMTP Monte Carlo module, are treated as more or less equivalent. Thus, the probability distributions used in IWEM reflect both the range of variation that may be encountered at different waste sites, as well as uncertainty about the specific conditions at each site.

5.1 EPACMTP Monte Carlo Module

The Monte Carlo module in EPACMTP is described in detail in the *EPACMTP Technical Background Document (U.S. EPA, 2003a),* and the *EPACMTP Parameters/ Data Background Document (U.S. EPA, 2003b)*. A general overview of the methodology is presented in the following paragraphs.

Figure 5-1 presents a graphical illustration of the Monte Carlo simulation process. The Monte Carlo method requires that for each input parameter, except constant parameters, a probability distribution be provided (Figure 5-1a). The method involves the repeated generation of random values of the input variables (drawn from the known distribution and within the range of any imposed bounds). The EPACMTP model is executed (Figure 5-1b) for each set of randomly generated model parameters and the corresponding ground water well exposure concentration is calculated and stored. Each set of input values and corresponding well concentration is termed a ***realization***.

At the conclusion of the Monte Carlo simulation, the realizations are statistically analyzed to yield a cumulative probability density function of the ground water exposure concentration (Figure 5-1c). The construction of the cumulative probability density function simply involves sorting the ground water well concentrations calculated in each of the individual Monte Carlo realizations from low to high. In the example used to construct Figure 5-1, an EPACMTP input leachate concentration value of 10 mg/L was assumed and a Monte Carlo simulation of 10,000 iterations was performed. The well concentration values simulated in the EPACMTP Monte Carlo process range from very low values to values that approach the leachate concentration. By examining how many of the 10,000 Monte Carlo realizations resulted in a high value of the estimated ground water concentration, it is possible to assign a probability to these high-end events, or conversely determine what is the estimated ground water concentration corresponding to a specific probability of occurrence.

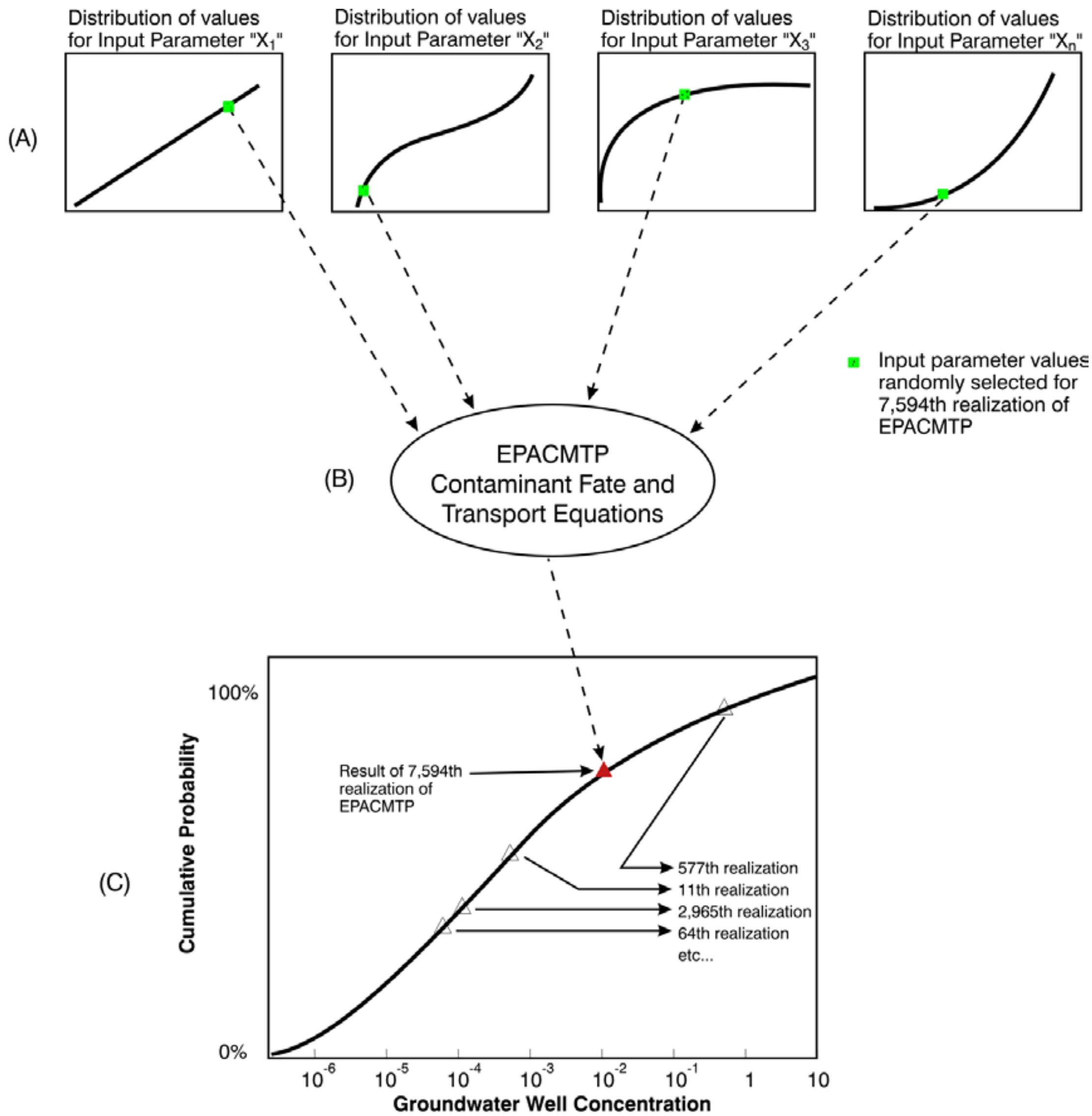


Figure 5-1. Graphical representation of the EPACMTP Monte Carlo process.

5.2 Implementation of Monte Carlo Analysis in IWEM

To conduct the Monte Carlo analysis in IWEM, the user is required to input a small set of site-specific source parameters; the user may also set values for additional parameters if site-specific data are available. For optional inputs for which site-specific data that are not available, and for additional input parameters that cannot be modified by the user, EPACMTP draws values randomly from national or regional distributions stored in the databases. The underlying assumption is that if a site-specific parameter value is not available, the uncertainty in the value of the parameter is captured by the nationwide range in values of that parameter.

IWEM can reduce the uncertainty associated with some of the modeling parameters even if the actual value of a parameter is not known, by using supporting site characterization data. For instance, if the actual value of hydraulic conductivity in the saturated zone is unknown, but information is available about the type of subsurface environment at the site (for example, alluvial versus sedimentary rock), IWEM will use this information to reduce the uncertainty in the hydraulic conductivity by selecting only hydraulic conductivity values in the Monte Carlo process that are representative of alluvial aquifers. This methodology is discussed in detail in **Section 6.4.1**.

In using a Monte Carlo modeling approach, more iterations usually leads to a more stable and more accurate result. However, it is generally not possible to determine beforehand how many iterations are needed to achieve a specified degree of convergence (that is, stability), because the value can be highly dependent on parameter distributions. EPA has used an empirical technique called bootstrap analysis to determine that an appropriate number of iterations for EPACMTP Monte Carlo analyses is about 10,000 (see side bar box). Consequently, IWEM defaults to 10,000 iterations. The user can change this value, but the Agency cautions that significantly fewer iterations will affect the repeatability of the results.

EPACMTP Monte Carlo Bootstrap Analysis

In a Monte Carlo analysis, the output percentile values depend on the number of iterations. For instance, if a Monte Carlo analysis consisting of 10 iterations of randomly selected model input values is performed, the 90th percentile of the model output can be determined by ordering the output values from low to high and then picking the ninth highest value. This 90th percentile value is likely to be different if another Monte Carlo simulation of 10 iterations with randomly selected inputs is performed, and different still if 1,000 iterations are simulated to calculate the 90th percentile output value.

Bootstrap analysis is a technique of replicated resampling of a large data set for estimating standard errors, biases, confidence intervals, or other measures of statistical accuracy. It can produce accuracy estimates in almost any situation without requiring subjective statistical assumptions about the original distribution.

As part of the background for EPA's proposed 1995 Hazardous Waste Identification Rule (HWIR), a bootstrap analysis was conducted for the EPACMTP model to evaluate how Monte Carlo convergence improves with increasing numbers of realizations. The analysis was based on a continuous source, LF disposal scenario in which the 90th percentile dilution and attenuation factor (DAF) was 10. The bootstrap analysis results suggested that, with 10,000 iterations, the expected value of the 90th percentile DAF was 10 with a 95 percent confidence interval of 10 ± 0.7. Decreasing the number of iterations to 5,000 increased the confidence interval to 10 ± 1.0.

5.3 Assumptions and Limitations for Monte Carlo Module

The Monte Carlo module used in IWEM allows to account for the effect of parameter variability on estimated ground water concentrations. The resulting probability distribution of outcomes is valid only to the extent that EPACMTP can accurately simulate actual constituent fate and transport processes; it does not account for the uncertainty arising from the omission of some processes from EPACMTP, or the simplification of other processes that are modeled in EPACMTP. For instance, the Monte Carlo modeling process can account for the site-to-site variability in the average hydraulic conductivity in the aquifer, but it cannot account for the uncertainty associated with treating each site as uniform and ignoring aquifer heterogeneity. Thus, the IWEM user should interpret the results of the Monte Carlo outputs in the context of the capabilities and limitations of EPACMTP.

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6.0 IWEM Inputs

This section describes the various parameters used in IWEM, including data sources, methodologies, and values. **Sections 6.1**, **6.2**, and **6.3** describe WMU, structural fill, and roadway parameters, respectively. **Section 6.4** describes the infiltration and recharge parameters. **Section 6.5** describes the unsaturated zone and saturated zone parameters. **Section 6.6** describes constituent-specific chemical fate parameters. Finally, **Section 6.7** describes the screening procedures implemented in the Monte Carlo analysis to eliminate physically unrealistic parameter combinations.

6.1 WMU Parameters

This section provides details about the four types of WMUs and the specific parameters in IWEM used to define intrinsic and operational WMU characteristics.

6.1.1 WMU Types

IWEM simulates four different types of WMUs. Each of the four IWEM units reflects waste management practices that are likely to occur at industrial Subtitle D facilities. The WMU can be a landfill, a waste pile, a surface impoundment, or a land application unit. The four WMU types are represented graphically in **Figure 6-1**. All units are assumed to contain only one type of waste, so that the entire capacity of the WMU is devoted to a single waste.

Landfills. IWEM only considers closed landfills. A closed landfill is assumed to have a 2-ft (0.6 m) soil cover and one of three liner types: no liner; a single clay liner; or a composite liner. The landfill is filled with waste during the unit's operational life. Upon closure of the landfill, the waste is left in place, and a final soil cover is installed. The starting point for the simulation is when the landfill is closed, i.e., the unit is at maximum capacity. The release of waste constituents into the soil and ground water underneath the landfill is caused by dissolution and leaching of the constituents due to precipitation that percolates through the unit. The type of liner that is present controls, to a large extent, the amount of leachate that

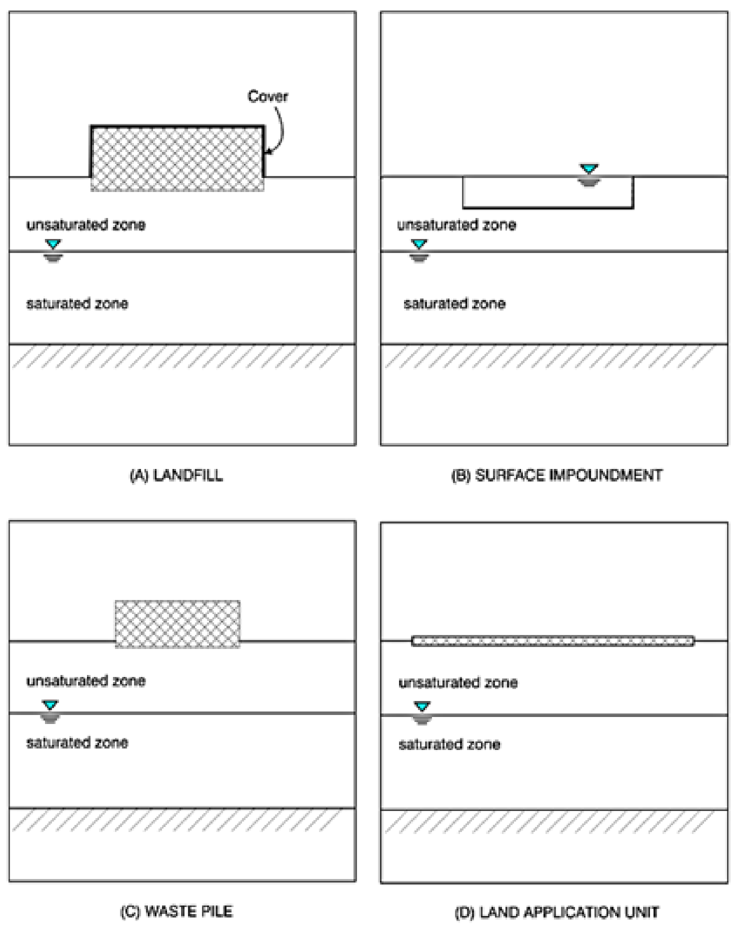


Figure 6-1. WMU types modeled in IWEM.

is released from the unit. Landfills are modeled as a permanent WMU, with a rectangular footprint and a uniform depth. IWEM does not simulate any loss processes that may occur during the unit's active life (for example, due to leaching, volatilization, runoff or erosion, or biochemical degradation). Landfills are modeled as a depleting source: the WMU is considered permanent and leaching continues until all leachable mass present has been depleted. In IWEM, the magnitude of the initial leachate concentration, when the waste is "fresh," is a model input; the rate of depletion is calculated internally by EPACMTP (*see EPACMTP Technical Background Document*, U.S. EPA, 2003a*).*[1]

Waste Piles. IWEM models waste piles as temporary sources used for storage of solid wastes. Due to their temporary nature, they typically will not be covered. IWEM allows liners to be present, similar to landfills. In IWEM, waste piles are modeled as a pulse-type source, with pulse duration equal to the unit's operating life.

Surface Impoundments. In IWEM, surface impoundments are ground level or below-ground level, flow-through units, which may be unlined, have a single clay liner, or have a composite clay-geomembrane liner. Release of leachate is driven by the ponding of water in the impoundment, which creates a hydraulic head gradient with the ground water underneath the unit. At the end of the unit's operational life, IWEM assumes there is no further release of waste constituents to the ground water (i.e., clean closure assumed). Surface impoundments are modeled as pulse-type sources; leaching occurs at a constant leachate concentration over a fixed time equal to the unit's operating life. IWEM also assumes a constant ponding depth (depth of wastewater in surface impoundment) during the operational life.

Land Application Units. Land application units (or land treatment units) are areas of land that receive regular applications of waste that can be either tilled or sprayed directly onto the soil and subsequently mixed with the soil. IWEM models the leaching of wastes after tilling with soil. IWEM does not account for the losses due to volatilization during or after waste application. Land application units are modeled in IWEM as a constant pulse-type leachate source, with a leaching duration equal to the unit's operational life. Only the no-liner scenario is evaluated for land application units, because liners are not typically used at this type of unit.

6.1.2 WMU Parameters

Table 6-1 summarizes the modeling options and parameters used to develop WMU analyses in IWEM. The required site-specific parameters are shown in ***bold italics*** in Table 6-1. Also, the last column in Table 6-1 provides the user section references for detailed discussions of each parameter. The user may refer to the *IWEM v3.1 User's Guide* (U.S. EPA, 2015a) for additional guidance in selecting site-specific values for these parameters.

[1] In EPACMTP's finite source module for landfills, the rate of depletion is a function of the ratio between the waste concentration (C_W) and the leachate concentration (C_L). In IWEM, this ratio is set to a constant, protective value of C_w/C_L = 10,000.

Table 6-1. Summary of IWEM Options and Parameters for WMUs

Modeling Element	Description or Value	Required or Default Value	Section Reference
WMU Parameters			
WMU Area (m²)	Required site-specific user input	Required	6.1.2
Depth of Waste in WMU (m)	Required site-specific user input for LF and SI (equivalent to ponding depth for SIs) Not applicable in case of WP or LAU.	Required	6.1.2
WMU Location (Nearest Climate Station)	Required site-specific user input	Required	6.1.2
Waste leachate concentration (mg/L)	Required constituent-specific user input	Required	6.1.2
Operational Life/Leaching Duration (yrs)	LF: leaching duration calculated inside EPACMTP; continues until all waste depleted. SI, WP & LAU: Operational life is an optional user input with defaults as shown; leaching duration is set equal to operational life	WP = 20 yrs LAU = 40 yrs SI = 50 yrs	6.1.2
WMU Base Elevation below Ground Surface (m)	Optional user input	0 m	6.1.2
Distance to Nearest Surface Water Body (m)	Used to evaluate water table mounding for SI units	360 m	6.1.2
SI sediment layer thickness (m)	Thickness of accumulated sediment (sludge) layer in SI. Optional user input	0.2 m	6.1.2
Waste type permeability (cm/sec)	Used for WPs only; not applicable to other WMUs. Optional user input	low, medium, high selected with equal probability	6.1.2
Well Location Parameters			
Downgradient Distance from WMU (m)	Optional user input (maximum of 1,600 m)	150 m	6.1.3
Transverse Distance from Plume Centerline (m)	Well always on centerline of plume (user cannot change)	0 m	6.1.3
Vertical distance below the water table (m)	Depth of the well intake below water table (user cannot change)	Uniform distribution from 0 – 10 m	6.1.3

LAU = land application unit LF = landfill SI = surface impoundment WP = waste pile

6.1.2.1 Required User Inputs

WMU Area (m^2). This parameter reflects the footprint area of the WMU (i.e., length by width). This parameter represents the total surface area over which infiltration and leachate enter the subsurface.

WMU Waste Depth (m). The WMU waste depth is used for landfill and surface impoundment simulations only. For landfills, this parameter represents the average waste thickness in the landfill at closure. EPACMTP uses the waste depth as one of the parameters to calculate the landfill source depletion rate (see *EPACMTP Technical Background Document*; U.S. EPA, 2003a). For surface impoundments, the waste depth is equal to the ponding depth, or average depth of free liquid in the impoundment. The surface impoundment ponding depth represents the hydraulic head that drives leakage of water from the surface impoundment; EPACMTP uses this parameter to calculate surface impoundment infiltration rates (see **Section 3.1.2**).

WMU Location. Location is needed by IWEM to assign the appropriate climate-related parameter values and is represented by selecting one of the 102 climate stations for which the HELP model database provides climatological data. Location-specific climate data from these climate stations were used to develop infiltration and recharge rates using the HELP model for unlined and single-lined WMUs (see **Section 6.4.2** and **6.4.3**), and to determine soil and aquifer temperature in order to calculate hydrolysis transformation rates (see **Section 6.5.2**).

Waste Leachate Concentration (mg/L). Values of leachate concentration for all constituents of concern are required input parameters. This parameter can be an actual measured value or an expected or estimated value. The user-provided leachate concentration values are the basis for IWEM's estimation of a well concentration and recommendation of the minimum protective liner design. IWEM compares the entered leachate concentration values against each constituent's aqueous solubility from the IWEM database. If the entered value exceeds the solubility, IWEM will display a warning message. A leachate concentration value above the aqueous solubility value may indicate a measurement error, in which case, the value should be corrected. It may also reflect a modeling scenario that is outside the range of validity of the EPACMTP fate and transport model. EPACMTP is designed to simulate transport of dissolved aqueous phase constituents, and therefore, the solubility is the theoretical maximum concentration value for which EPACMTP is valid. Despite this, IWEM will not reject user-entered leachate concentration values that exceed the solubility; however, such scenarios are inappropriate for modeling with IWEM and may indicate that more detailed site-specific evaluation is needed.

6.1.2.2 Optional Parameters

Operational Life (Duration of Leaching Period) (yr). For waste piles, surface impoundments, and land application units, operational life is used to establish the duration of leach in the finite pulse source modeling. Default values for this parameter are as follows:

- Waste pile = 20 years
- Surface impoundment = 50 years
- Land application unit = 40 years

For landfills, which are modeled as a finite depleting source, IWEM does not use an operational life, but estimates the duration of the leaching period internally, as a function of the amount of waste in the unit at closure and IWEM.

WMU Base Elevation Below Ground Surface (m). This parameter represents the depth of the base of the unit below the ground surface, as schematically depicted in **Figure 6-2**. Constituents leaching from a unit with a base located below the ground surface will experience reduced travel distances through the unsaturated zone before reaching the ground water. This parameter is an optional site-specific user input parameter, with a default value of zero. If a non-zero value is entered, IWEM will verify that the entered value, in combination with the depth to the water table and magnitude of the unit's infiltration rate, does not lead to a physically infeasible condition (e.g., water table mound height above the ground surface or above the level of the waste liquid in an impoundment), in accordance with the infiltration screening methodology presented in **Section 6.7**.

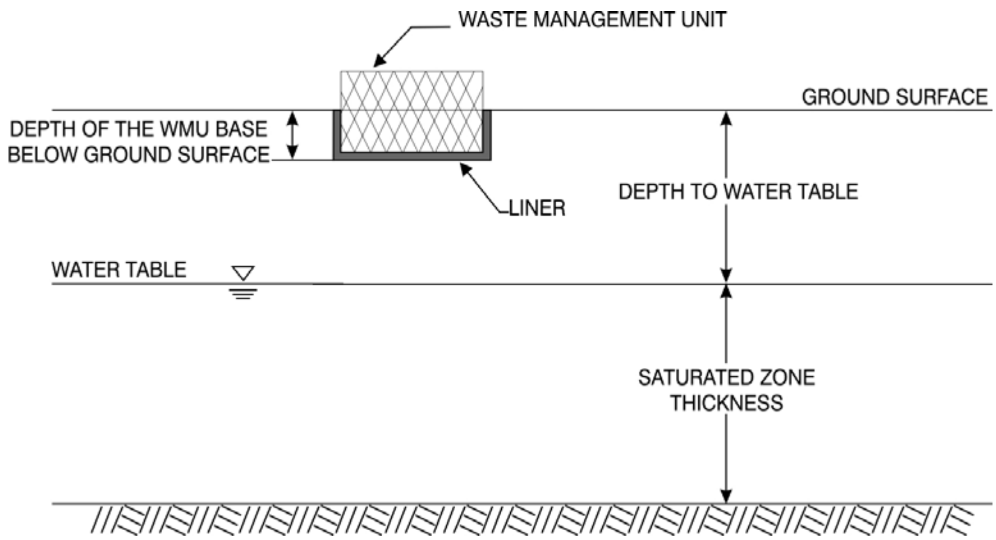


Figure 6-2. WMU with base elevation below ground surface.

Distance to Nearest Surface Water Body (m). For surface impoundments only, IWEM uses information on the distance to the nearest permanent surface water (that is, a river, pond or lake) in the infiltration screening procedure presented in **Section 6.7.** This parameter is an optional site-specific user input. Because the exact distance may not be known in many cases, the input is framed in terms of whether or not there is surface water body within 2,000 m of the unit. If a surface water body is present within 2,000 m, IWEM uses the median value of 360 m as a default. If there is no water body within 2,000 m, IWEM will use a value of 5,000 m in its calculations.

Surface impoundment Sediment Layer Thickness (m). This parameter is applicable to surface impoundments only and represents the average thickness of accumulated sediment (sludge) deposits on the bottom of the impoundment. This layer of accumulated sediment is different from an engineered liner underneath the impoundment, but its presence will serve to retard the leakage of water from an impoundment, especially in unlined units. EPACMTP uses this parameter to calculate the rate of infiltration from unlined and single lined surface impoundments. The EPACMTP surface impoundment infiltration module is described in **Section 3.1.2**, with a detailed description in the *EPACMTP Technical Background Document* (U.S. EPA, 2003a). The accumulated sediment is divided into two equally thick layers, an upper unconsolidated layer and a lower consolidated layer that has been compacted due to the weight of the sediment above it, and therefore has a reduced porosity and permeability. This is an optional site-specific user input parameter, with a default value of 0.2 m (for total thickness; 0.1 m unconsolidated and 0.1 m consolidated).

Waste Permeability. This parameter is used only for waste piles. Waste piles are not typically covered and the permeability of the waste itself is a factor in determining the rate of leachate released due to water percolating through the WMU. For waste piles, IWEM recognizes three categories of waste permeability and their associated infiltration rate: high permeability (0.041 cm/sec); moderate permeability (0.0041 cm/sec); and low permeability (0.00005 cm/sec). The waste permeability is correlated with the grain size of the waste material, ranging from coarse to five-grained materials. If a waste type is not specified for waste piles, IWEM will default to randomly selecting between the infiltration rates for each of the three waste types in the Monte Carlo process, with each type having equal probability. That is, IWEM will use a uniform probability distribution.

6.1.3 Well Location Parameters

In IWEM, the ground water exposure location is modeled as the intake point of a ground water well located down gradient from the source. The location of the well in IWEM is described by three parameters depicted schematically in **Figure 6-3,** which shows the location of the well relative to the WMU in plan view (top) and cross-section view (bottom).

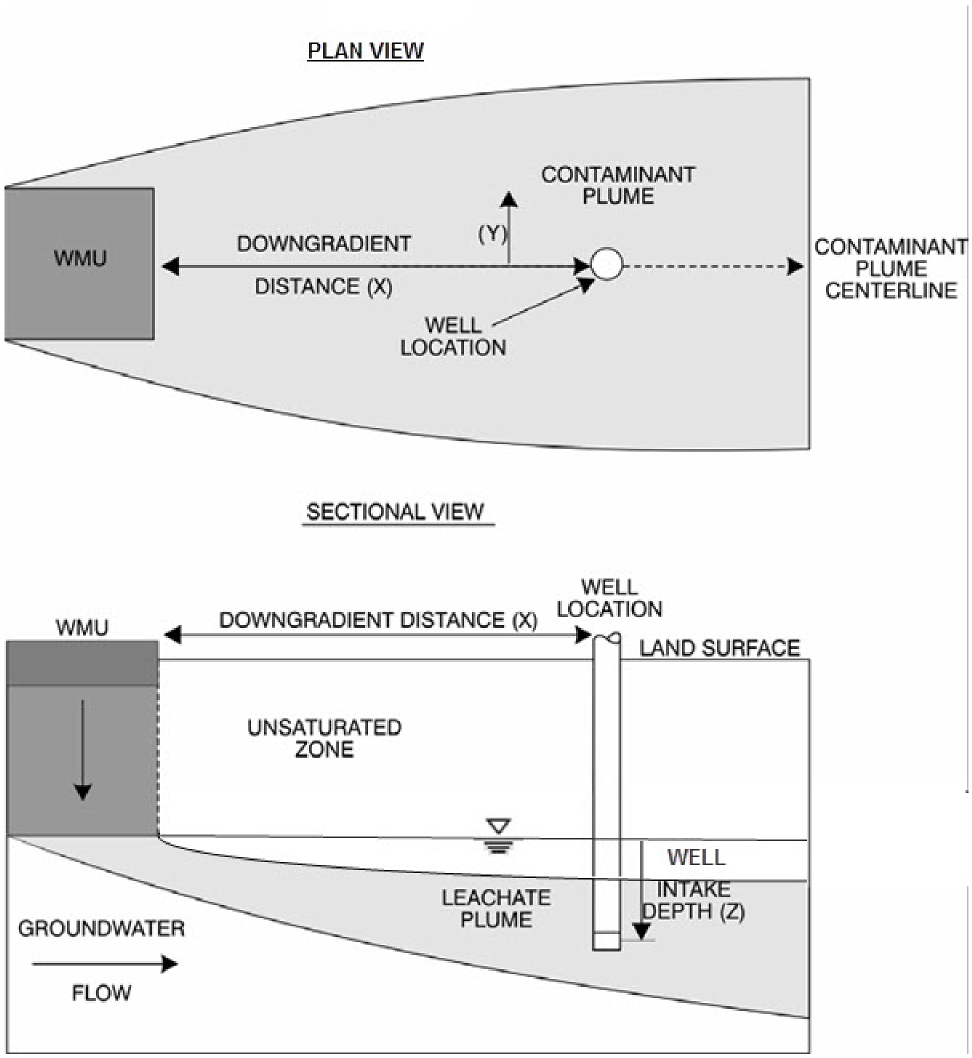


Figure 6-3. Position of the modeled ground water well relative to the WMU.

Downgradient Distance from WMU, x (m). This parameter represents the distance between the downgradient edge of the WMU and the position of the well, measured along the direction of ground water flow. This direction represents the x-coordinate as depicted in Figure 6-3. In IWEM, this parameter is an optional site-specific user input value, with a maximum allowed value of 1,600 m (1 mile). The default value is 150 m.

A cautionary warning is necessary when specifying a down gradient distance of a ground water well that is very close to the WMU (for example 5 m or less). The random nature of the well intake depth (described below) for a well that is close to the WMU can produce unreliable estimates. As shown in Figure 6-3, the penetration depth of the leachate plume increases with increasing distance from the WMU. If the well is placed very close to the WMU, there is an increased likelihood that the well intake point will be below the penetration depth of the plume. These types of configurations will likely lead to underestimating the 90th percentile ground water concentration. For such type of configurations, IWEM is not recommended.

If the objective is to determine the maximum possible ground water impact, a recommended approach would be to experiment with the distance from the WMU, gradually increasing the distance from 1 meter until the 90th percentile concentration reaches a definitive maximum value. The distance that generates the maximum value will be sensitive to the initial penetration depth of the leachate plume at the down-gradient edge of the WMU. Higher values of infiltration and source area will result in deeper penetration depths.

Well Transverse Distance from the Plume Centerline, y (m). This parameter represents the horizontal distance between the well and the modeled centerline of the plume, or they y coordinate depicted in Figure 6-3. This parameter is always set to zero for IWEM (i.e., the ground water well is always located on the centerline of the plume) and cannot be changed by the user. This is a conservative assumption because the ground water concentrations predicted by the model will be highest along the centerline of the plume, and decrease with distance away from the centerline.

Well Intake Depth Below the Water Table, z (m). This parameter represents the vertical distance of the well intake point below the water table. In calculating the position of the well intake, the model uses the water table elevation before any mounding effects are taken into consideration. In IWEM, the well depth parameter has a uniform probability distribution with a range of 0 to 10 m. This means that all depth values are between 0 to 10 m below the water table are equally likely. For each Monte Carlo simulation in which the modeled saturated zone thickness is less than 10 m, the maximum well depth of 10 m is replaced with the actual saturated zone thickness used in the iteration. This parameter cannot be changed by the user.

6.2 Structural Fill Parameters

This section provides details about the structural fill source term and the specific parameters in IWEM used to define intrinsic and operational structural fill characteristics.

6.2.1 The Structural Fill

The structural fill is conceptualized in much the same way as the landfill WMU type, as represented graphically in **Figure 6-4**. A structural fill is assumed to contain only one type of reused material, but the entire volume of the structural fill is not required to consist of only that material—other non-reused industrial materials may be included. As a result, IWEM requires that the user provide the ratio of the volume of reused materials to the volume of the structural fill, as a fraction. IWEM assumes that the construction of the structural fill is complete and that the fill will have a cover material of some type (e.g., soil, pavement), which may or may not limit the infiltration of water. The selection of an infiltration rate implies what type of cover material is present. For example, if the regional infiltration rates developed with the HELP model are used, then that implies that regional soils (or the equivalent) are used to cover the structural fill.

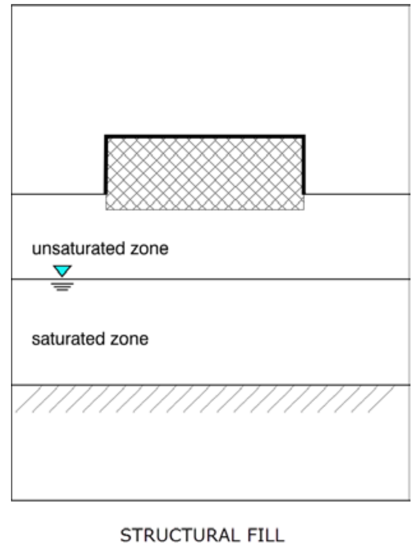


Figure 6-4. Structural fill modeled in IWEM.

The starting point for the simulation is when construction of the structural fill is completed. The release of waste constituents into the soil and ground water underneath the structural fill is caused by dissolution and leaching of the constituents due to precipitation that percolates through the unit. The cover material or the hydraulic conductivity of the reused materials in the structural fill controls, to a large extent, the amount of leachate that is released from the structural fill. Structural fills are modeled as a permanent construction with a rectangular footprint and a uniform depth. IWEM does not simulate any loss processes that may occur during construction (for example, due to leaching, volatilization, runoff or erosion, or biochemical degradation). Structural fills are modeled as a pulse-type source: leaching occurs at a constant leachate concentration until the mass in the structural fill is depleted. EPACMTP determines the pulse duration from required and optional inputs described in **Section 3.2.1** and below, in **Section 6.6.2**.

6.2.2 Structural Fill Parameters

Table 6-2 summarizes the modeling options and parameters used to develop structural fill analyses in IWEM. The required site-specific parameters are shown in ***bold italics*** in Table 6-2. The last column in Table 6-2 provides the user section references for detailed discussions of each parameter. The *IWEM v3.1 User's Guide* (U.S. EPA, 2015a) provides additional guidance in selecting site-specific values for these parameters.

Table 6-2. Summary of IWEM Options and Parameters for Structural Fills

Modeling Element	Description or Value	Required or Default Value	Section Reference
Structural Fills Parameters			
Structural Fill Area (m^2)	Required site-specific user input	Required	6.2.2
Depth of Structural Fill (m)	Required site-specific user input	Required	6.2.2
Effective Bulk Density (g/cm^3)	Required site-specific user input	Required	6.2.2
Effective Hydraulic Conductivity (m/yr)	Required site-specific user input	Required	6.2.2
Volume Fraction Occupied by Leachable Material	Required site-specific user input	Required	6.2.2
Structural Fill Location (Nearest Climate Station)	Required site-specific user input	Required	6.2.2
Waste Leachate Concentration (mg/L)	Required constituent-specific user input	Required	6.2.2
Total Waste Concentration (mg/kg)	Required constituent-specific user input	Required	6.2.2
Structural Fill Base Elevation below Ground Surface (m)	Optional user input	0 m	6.2.2
Well Location Parameters			
Downgradient Distance from SF (m)	Optional user input (maximum of 1,600 m)	150 m	6.1.3
Transverse Distance from Plume Centerline (m)	Well always on centerline of plume (user cannot change)	0 m	6.1.3
Vertical distance below the water table (m)	Depth of the well intake below water table (user cannot change)	Uniform distribution from 0 – 10 m	6.1.3

6.2.2.1 Required User Inputs

Structural Fill Area (m^2). This parameter reflects the footprint area of the structural fill (that is, length by width). This parameter represents the total surface area over which infiltration and leachate enter the subsurface.

Structural Fill Depth (m). The structural fill depth represents the average thickness of all materials in structural fill when construction is complete. EPACMTP uses the depth as one of the parameters to calculate the mass of leachable constituent in the source and the time it takes to deplete that mass (see *EPACMTP Technical Background Document*; U.S. EPA, 2003a).

Structural Fill Location. Location is needed by IWEM to assign the appropriate climate-related parameter values and is represented by selecting one of the 102 climate stations for which the HELP model database provides climatological data. Location-specific climate data from these climate stations were used to develop recharge rates using the HELP model, and to determine soil and aquifer temperature in order to calculate hydrolysis transformation rates (see **Section 6.5.2**).

Effective Bulk Density (g/cm^3). The dry bulk density is one of the parameters used to calculate the mass of leachable constituent present in structural fill. Once the mass of leachable constituent is known, the duration of leaching from the structural fill is calculated in EPACMTP.

Effective Hydraulic Conductivity (m/yr). The material hydraulic conductivity is a required parameter for determining the limiting value of infiltration through the structural fill.

Volume Fraction Occupied by Leachable Material (unitless). IWEM does not assume that the entire structural fill is comprised of reused industrial materials. In practice, reused materials are only one of several components or layers in the structure. Therefore, IWEM requires the user to provide a number greater than 0 and less than or equal to 1 to represent the fractional volume of the structural fill occupied by reused materials with leachable components. A value less than 1 would indicate that only part of the structural fill contains leachable materials; for example, a value of 0.5 would reflect that half of the structural fill by volume contains reused materials.

Waste Leachate Concentration (mg/L). Values of leachate concentration for all constituents of concern are required input parameters. This parameter can be an actual measured value or an expected or estimated value. Input values for reused industrial materials can be obtained from empirical testing data or field data. In practice, the producer of an industrial material would be the most likely resource for obtaining this data through engineering and environmental testing, both in the laboratory and in the field. The user-provided leachate concentration values are the basis for IWEM's determination of whether the predicted ground water exposure concentration is below or exceeds user-specified benchmarks. IWEM screens structural fill leachate concentrations against aqueous solubility data in the same manner as for WMUs. The leachate concentration is also used to determine the time it takes to deplete leachable mass from the structural fill (e.g., pulse duration).

Total Leachable Waste Concentration (mg/kg). Values of total leachable concentration in reused material for all constituents of concern are required input parameters. This parameter can be an actual measured value or an expected or estimated value. Input values for reused industrial materials can be obtained from empirical testing data or field data. In practice, the producer of an industrial material would be the most likely resource for obtaining this data through engineering and environmental testing, both in the laboratory and in the field. User-provided total concentration is the basis for computing the time it takes to deplete the leachable mass from the structural fill.

6.2.2.2 Optional Parameters

Structural Base Elevation Below Ground Surface (m). This parameter represents the depth of the base of the fill below the ground surface, as schematically depicted in Figure 6-2 for WMUs (the principle is the same for structural fills). Constituents leaching from a unit with a base located below the ground surface will experience reduced travel distance through the unsaturated zone before reaching the ground water. This parameter is an optional site-specific user input parameter, with a default value of zero. If a non-zero value is entered, IWEM will verify that the entered value, in combination with the depth to the water table and magnitude of the unit's infiltration rate, does not lead to a physically infeasible condition (e.g., water table mound height above the ground surface or above the level of the waste liquid in an impoundment), in accordance with the infiltration screening methodology presented in **Section 6.7**.

6.2.3 Well Location Parameters

IWEM treats the ground water exposure location due to leaching from structural fills in the same way as for WMUs, as described in **Section 6.1.3**.

6.3 Roadway Parameters

Few of the parameters for the IWEM roadway source module correspond to those of the existing EPACMTP parameters. For roadway analyses, site-specific data are required to define the geometry and material properties for all strips and layers.

Table 6-3 summarizes the modeling options and parameters used to develop roadway analyses in IWEM. IWEM parameters for roadways module can be grouped into seven categories: well location, general parameters, roadway geometry, layer properties, ditch properties, drain properties, and flow characteristics. The required site-specific parameters are shown in ***bold italics*** in Table 6-3. The last column in Table 6-3 indicates where the user can find a detailed discussion of each parameter in this document. The *IWEM v3.1 User's Guide* (U.S. EPA, 2015a) provides additional guidance in selecting site-specific values for these parameters.

Table 6-3. Summary of IWEM Options and Parameters for Roadways

Modeling Element	Description	Required or Default Value	Section Reference
Well Location Parameters			
Angle between roadway and ground water flow (degrees)	Required site-specific user input	Required	6.3.1
Location of receptor well relative to 90° line from roadway edge	Required site-specific user input	Required	6.3.1
Distance from edge of roadway (m)	Shortest distance between roadway edge and monitoring well. Required site-specific user input	Required	6.3.1
Distance from middle of roadway (m)	Distance along roadway from point at which distance measurement was made to midpoint of roadway segment. Required site-specific user input	Required	6.3.1
General Parameters			
Number of roadway strips (including ditches)	Required site-specific user input	Required	6.3.2
Roadway segment length (m)	Required site-specific user input	Required	6.3.2
Number of drains	Optional user input if ditches are defined as a strip type; maximum = 2	0	6.3.2
Geometry Parameters			
Roadway Geometry Parameters			
Strip type	Required site-specific user input	Required	6.3.3
Strip width (m)	Required site-specific user input	Required	6.3.3
Number of layer in a strip	Required site-specific user input	Required	6.3.3

(continued)

Table 6-3. Summary of IWEM Options and Parameters for Roadways

Modeling Element	Description	Required or Default Value	Section Reference
Geometry Parameters (continued)			
Drain Geometry – Configuration			
Drained strip(s) (can specify more than one)	Required user input IF ditches are defined AND number of drains > 0. Identifies which strips contain a particular drain		6.3.4
Ditch strip that the drain discharges into	Required user input IF ditches are defined AND number of drains > 0. Connects a drain to a ditch		6.3.4
Layer that the drain lies over	Required user input IF ditches are defined AND number of drains > 0. Specifies where the drain is located in the strip layer structure		6.3.4
Layer Properties			
Layer type	Required site-specific user input		6.3.5
Layer thickness (m)	Required site-specific user input		6.3.5
Layer hydraulic conductivity (m/yr)	Required site-specific user input		6.3.5
Layer dry bulk density (g/cm^3)	Required site-specific user input		6.3.5
Ditch Properties			
Manning's n coefficient	Required site-specific user input if a ditch is defined	Required	6.3.6
Slope of the ditch (m/m)	Required site-specific user input if a ditch is defined	Required	6.3.6
Maximum water depth in the ditch	Required site-specific user input if a ditch is defined	Required	6.3.6
Is there a gutter?	Optional user input (default is no gutter)		6.3.6
Location of gutter(s) (between what strips)	Required user input IF a gutter is present		6.3.6
Drain Properties			
Layer thickness (m)	Required site-specific user input if a drain is defined	Required	6.3.7
Layer hydraulic conductivity (m/yr)	Required site-specific user input if a drain is defined	Required	6.3.7
Layer dry bulk density (g/cm^3)	Required site-specific user input if a drain is defined	Required	6.3.7
Flow Characteristics			
Percent of Runoff or Flow That Reaches Ditch Strips (for relevant strips and drains)			
Percent of roadway runoff that reaches ditch	Required user input if a ditch is defined	Required	6.3.8
Percent of flow in drain that reaches ditch	Required user input if a drain is defined	Required	6.3.8
Flow Paths to Ditches			
Ditch strip(s) receiving overland flows	Required user input if a ditch is defined	Required	6.3.8

6.3.1 Well Location

EPACMTP can only simulate a receptor well that is down-gradient of the leachate source where ground water flow is perpendicular to the source of leachate (as shown in the top of Figure 6-3). In order to accommodate non-perpendicular ground water flow directions, IWEM applies a geometric transformation to the conceptual model that allows IWEM and EPACMTP to represent non-perpendicular flow as perpendicular. The details of the transformation are presented in **Appendix F**.

IWEM uses the angle between the roadway edge, the ground water flow direction away from the roadway, and the general location of the well to help determine the exact location of the well, first in general terms and then in more refined terms. **Figure 6-5** helps illustrate the inputs described below.

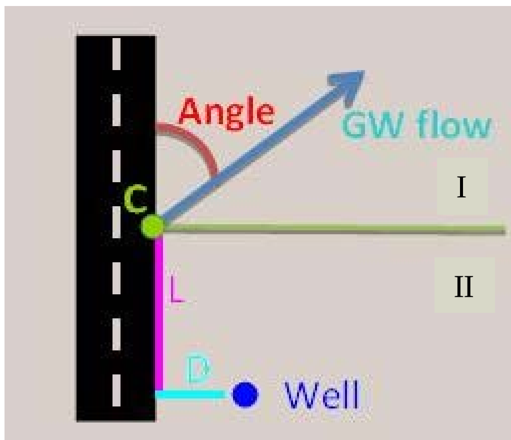


Figure 6-5. Diagram used by IWEM to specify roadway geometry.

The angle between roadway and ground water flow (degrees). This is labeled “Angle” in red in Figure 6-5 and is specified first as a range (0 – 90° or 90 – 180°) and then as the actual angle between the ground water flow and roadway. In Figure 6-5, the angle is 45°.

Location of receptor well relative to 90° line from roadway edge. The well can be in either Region I (above the 90° line from the center point of the roadway segment length, shown in green in Figure 6-5) or Region II (below the 90° line). In the example in Figure 6-5, the well is in Region II.

Shortest distance between roadway edge and monitoring well (m). This is the distance from the well to the roadway along a line perpendicular to the roadway length. It is labeled D in Figure 6-5.

Distance along roadway from point at which distance measurement was made to midpoint of roadway segment (m). This is the distance from the midpoint of the roadway segment length to the location where the distance between the roadway edge and well was measured. It is labeled L in Figure 6-5.

As mentioned above in **Section 6.1.3**, IWEM may not generate reliable results for a well that is very close (less than 5 m) to the source. The maximum ground water exposure concentration will likely be found at a distance of 5 m or greater due to the combination of a random well intake depth and the penetration depth of the leachate plume. See **Section 6.1.3** for additional discussion.

6.3.2 General Roadway Description

Number of Strips. The number of roadways strips represents the number of major designs element in a roadway cross-section such as paved or unpaved driving surfaces, embankments, shoulders, medians, or ditches. The number of strips is generally equal to the number of surface material types encountered as one traverses the roadway cross-section. If there are changes in material types within a layer below a single surface material, the user may want to consider dividing that strip into as many different materials that comprise that subsurface layer. The number of roadway strips is a required input parameter used to define the problem size. IWEM allows for a roadway to be composed of a maximum of 15 strips, 5 layers per strip, 2 drains, 2 ditches, and 2 gutters.

Number of Drains. A drain moves water from underneath the roadway to a ditch. Thus, the user **must** define at least one strip as a ditch before n adding the number of drains. A maximum of two drains is allowed.

Roadway Length (m). The length of the modeled roadway section is measured in meters (m) and this parameter represents the idealized, straight line length of the roadway, as depicted in Figure 3-3. Roadway length is a required input parameter used to determine the areal extent of any potential leaching through components of the modeled roadway.

6.3.3 Roadway Geometry

Strip Type. Roadways strips represent the major designs elements of a roadway cross-section used in IWEM. IWEM provides the following five strip types:

- **Paved Areas** are typically used for the traveled surface;
- **Median** is usually an unpaved or vegetated region between traveled surfaces;
- **Shoulders** are found on the sides of traveled surfaces;
- **Embankments** are raised structures (as of earth or gravel) used especially to carry a roadway or provide separation between a roadway and the surrounding area; and,
- **Ditches** are used to receive runoff from the roadway and diverted flows from drainage layers.

Strip Width (m). The width of a roadway strip is measured in meters. The strip width is a required input parameter used to determine the areal extent of any potential leaching through components of the modeled roadway. If ditches are defined in the roadway cross-section, the width is also used to determine the volume of runoff water that may flow to the ditch.

Number of Layers in a Strip. The number of roadway layers in a strip represents the number of distinct material layers in the cross section of a roadway strip. The number of layers in a strip is a required parameter used to define the problem size. Examples of layers are pavement, base, sub-base, and sub-grade. At least one layer of at least one roadway strip is required to contain a material with leachable constituents to perform the analysis.

6.3.4 Drain Geometry

Drained strip(s). A drain can drain more than one strip, but the user must specify which strips are drained by each drain. The strips drained by a drain must be located above the drain.

Ditch strip that the drain discharges into. This is the strip number of the ditch that the drain discharges into. It does not have to be on the same side of the roadway as the drain.

Layer that the drain lies over. This is the layer number for the layer below the drain.

6.3.5 Roadway Layer Properties

Layer Type. Layer types are provided as descriptive labels for the convenience of the user and are as follows

- Base
- Sub-base
- Grade
- Sub-grade
- Fill
- Pavement

Layer Thickness (m). Layer thickness is a required input for strip layers. The thickness is used along with bulk density of the layer material to calculate the mass of leachable constituent present in a layer. The mass of leachable constituent is used in conjunction with the infiltration rate through a layer to calculate the time required to exhaust the mass from that layer given a leachate concentration.

Layer Hydraulic Conductivity (m/yr). The material hydraulic conductivity is a required parameter for determining the limiting value of infiltration through strip layers.

Bulk Density (g/cm^3). The dry bulk density is a required input for strip layers. As mentioned above, the bulk density and layer thickness are used to calculate the mass of leachable constituent present in a layer. Once the mass of leachable constituent is known, IWEM uses the constituent mass, infiltration rate, and leachate concentration to determine the time required to deplete all of the constituent mass from a material layer.

6.3.6 Roadway Ditch Properties

Manning's Roughness Coefficient, n. If ditches are defined in the roadway cross-section, the user is required to provide a value for Manning's roughness coefficient, *n*, for each ditch. An estimate of the average water velocity in a ditch is estimated using Manning's equation which requires a non-dimensional coefficient, *n*, that reflects the hydraulic resistance induced from the roughness of the channel surface. A smooth channel generally has less hydraulic resistance and is represented by a lower coefficient value, resulting in higher velocity estimates. A rough channel is generally more hydraulically resistant and has correspondingly higher coefficient values. The best source for this parameter would be engineering design drawings or a design report.

Appendix C (Section C.2.2.5), describes how IWEM treats flow in roadside drainage areas, ditches, or streams. An estimate of the average water velocity in an open-channel cross-section in a water-filled or wet ditch is determined using Equation C-31. The average velocity is estimated using Manning's equation (Equation C-29), which requires a non-dimensional coefficient, *n*, that reflects the hydraulic resistance induced from the roughness of the channel surface. A smooth channel generally has less hydraulic resistance and is represented by a lower coefficient value, resulting in higher velocity estimates. A rough channel is generally more hydraulically resistant and has correspondingly higher coefficient values. Chow (1959) compiled many values for Manning's *n* for a wide range of channel conditions. **Table 6-4** presents values for *n* corresponding to typical roadside drainage conditions.

Table 6-4. Manning's *n* for Typical Roadside Channels (Chow, 1959)

Type of Channel and Description	Minimum	Normal	Maximum
Excavated or Dredged Channels			
Earth, Straight and Uniform			
Clean, recently completed	0.016	0.018	0.02
Clean, after weathering	0.018	0.022	0.025
Gravel, uniform section, clean	0.022	0.025	0.03
With short grass, few weeds	0.022	0.027	0.033
Earth Winding and Sluggish			
No vegetation	0.023	0.025	0.03
Grass, some weeds	0.025	0.03	0.033
Dense weeds or aquatic plants in deep channels	0.03	0.035	0.04
Earth bottom and rubble sides	0.028	0.03	0.035
Stony bottom and weedy banks	0.025	0.035	0.04
Cobble bottom and clean sides	0.03	0.04	0.05
Dragline-Excavated or Dredged			
No vegetation	0.025	0.028	0.033
Light brush on banks	0.035	0.05	0.06
Rock Cuts			
Smooth and uniform	0.025	0.035	0.04
Jagged and irregular	0.035	0.04	0.05
Channels Not Maintained, Weeds and Brush Uncut			
Dense weeds, high as flow depth	0.05	0.08	0.12
Clean bottom, brush on sides	0.04	0.05	0.08
Same as above, highest stage of flow	0.045	0.07	0.11
Dense brush, high stage	0.08	0.1	0.14
Constructed Channel with Vegetal Lining			
Constructed channel with vegetal lining	0.03		0.5

Slope (m/m). For each ditch, slope of the ditch bed must be provided. The slope can be calculated as the change in elevation of the ditch bed over its length divided by the length of the ditch. The slope should be set to zero if there is stagnant water in the ditch (no flow).

Maximum Depth (m). To safeguard against possible unrealistic values of water depth in a ditch, the estimated water depth is limited to this maximum water depth. The maximum water depth corresponds to the height from the ditch bed to the lowest cresting side.

Gutter. IWEM allows the user to define a gutter between two adjacent roadway strips for each ditch in the roadway cross-section (however, a gutter is not required, and the default if the user does not specify a gutter is not to include a gutter). A gutter is a structure on the surface of the roadway that can intercept and divert runoff from roadway strips *uphill* of a gutter. The user can define the percentage of runoff **not** diverted by a gutter. Runoff diverted by a ditch is assumed to leave the modeled system. All runoff from roadway strips *downhill* of the gutter will flow to their assigned ditch.

6.3.7 Roadway Drains Properties

Drains are an optional design element that can be used in the roadway cross-section. The purpose of the drain is to divert a portion of vertically infiltrating water, and any dissolved constituent in that water, to a ditch and prevent the constituents from leaching into the environment. IWEM allows the used to add up to two drains, as long as there is at least one ditch in the cross-section.

A drain consists of a highly permeable material layer placed between layers of a single strip or between the same layers of multiple contiguous strips. To define a drain, the user must provide the following properties:

Thickness (m). Drain thickness is a required input for drains.

Hydraulic Conductivity (m/yr). The hydraulic conductivity is a required parameter for determining the limiting value of infiltration through strip layers and for drains.

Bulk Density (g/cm^3). The dry bulk density is a required input for strip layers and for drains. The thickness and bulk density are used to calculate the mass of leachable constituent present in a layer. Once the mass of leachable constituent is known, the duration of leaching from a material layer is calculated.

6.3.8 Roadway Flow Characteristics

Percent of roadway runoff that reaches ditch beyond gutter (%). A gutter is used to divert some or all of the runoff water from strips *above* or *uphill* of the gutter, away from the associated ditch and out of the modeled system. Including a gutter is optional. When a gutter has been defined for a ditch, the user is required to provide a value for the percentage of runoff from those strips that flows to the ditch. In other words, the percentage of runoff **NOT** diverted by the gutter. If a gutter is not present, then 100% of the runoff should reach the ditch. If a gutter is present, the percentage should be equal to the ratio of the width of all strips between the gutter and the ditch to the width of all strips that are associated with the ditch (See Section 3.4.2.3 in the *IWEM User's Guide* under *Roadway Source Parameters*, Ditch Properties and Flow Characteristics and the section below, *Ditch strip(s) receiving overland flows*).

Percent of flow in drain that reaches ditch (%). This parameter accounts for the possibility that not all infiltrating water, and the constituents dissolved in that water, is diverted by the permeable layer or drain to its associated ditch. A value must be provided for each defined drain, a percentage ranging from 0 to 100%, to indicate how much of the infiltrate entering the drain is diverted to the ditch. A value of 0 indicates that no drainage flow will reach the ditch. A value of 100% indicates that all infiltrate entering the drain will be diverted to the ditch. Selecting a value for a drain will depend on the continuity of the drain in the direction of travel. If the drain is represented as a continuous layer of highly permeable material, then the value would tend to be low. If, however, drainage pipe is used at intervals, then the value could be estimated as a ratio of the area drained by the drainage pipe to the entire area of the roadway underlain by the drain.

Ditch strip(s) receiving overland flows. When a ditch has been defined for a roadway cross-section, the user is required to associate every non-ditch strip with a ditch. The association directs the model to apply any runoff from that strip to the specified ditch. For roadway cross-sections where two ditches are defined, the association of strip runoff to ditches cannot create a scenario where runoff flows cross each other – IWEM will prevent that scenario.

6.3.9 Leachate Concentrations

Input values for source constituent parameters (i.e., initial leachate concentration, initial total leachable mass concentration) can be obtained from empirical testing data or field data. In practice, the producer of an industrial material would be the most likely resource for obtaining this data through engineering and environmental testing, both in the laboratory and in the field. The Recycled Materials Resource Center (RMRC; http://rmrc.wisc.edu/), a federal university–partnered research and outreach facility for the highway community, has developed the *User Guidelines for Byproducts and Secondary Use Materials in Pavement Construction*, available online[2]. The online guidance document provides detailed information on many industrial materials commonly used in roadway construction.

Recently, new leaching test methods, EPA SW-846 Methods 1313, 1314, 1315, and 1316[3], were developed to support the evaluation of coal combustion residual materials. These methods were developed by a collaborative research effort between the U.S. EPA, Vanderbilt University, and Dutch and Danish partners (Kosson et al, 2002; U.S. EPA, 2010; Garrabrants et al., 2013; Kosson et al., 2013). Leaching test results acquired from these new methods were recently used in probabilistic fate and transport modeling of managed coal combustion wastes (U.S. EPA, 2014a). In addition, data acquired from these methods were also used by EPA to evaluate the beneficial use of coal combustion residuals in concrete (U.S. EPA, 2014b).

6.4 Infiltration and Recharge Rates

IWEM requires the input of the rate of downward percolation of water and leachate through the unsaturated zone to the water table. The model distinguishes between two types of percolation, which differ in where they occur relative to the source:

- **Infiltration** is defined as water percolating through the *source* (i.e., WMU, structural fill, or roadway) to the underlying soil.
- **Recharge** is water percolating through the soil *outside the footprint of the source* to the aquifer.

Infiltration is one of the key parameters affecting the leaching of waste constituents into the subsurface. For a given leachate concentration, the mass of constituents leached is directly proportional to the infiltration rate. For WMUs, the different liner types correlate directly to changing the infiltration rate; more protective liner designs reduce leaching by decreasing the rate of infiltration. The user can select either a liner type, or an infiltration rate (which will be evaluated as a user-specified liner, in place of the three predefined liner types). For structural fills and roadways, the type of reused materials, the nature of compaction, and the sized, number and orientation of cracks present on the road surface can influence the amount of water infiltration.

[2] http://rmrc.wisc.edu/user-guidelines-2/

[3] http://www.epa.gov/epawaste/hazard/testmethods/sw846/new_meth.htm

In contrast, recharge introduces pristine water into the aquifer, from the area outside the source. Increasing recharge therefore tends to result in a greater degree of plume dilution and lower constituent concentrations. High recharge rates may also affect the extent of ground water mounding and ground water velocity. The recharge rate is independent of the type and design of the source; rather it is a function of the climatic and hydrogeological conditions at the source location, such as precipitation, evapotranspiration, surface run-off, and regional soil type.

Table 6-5 summarizes the parameters used to characterize infiltration and recharge. The required site-specific parameters are shown in ***bold italics***. The last column guides the user where to find a detailed discussion of each parameter in this document. The *IWEM v3.1 User's Guide* (U.S. EPA, 2015a) provides additional guidance in selecting values for these parameters.

Table 6-5. Summary of IWEM Infiltration and Recharge Parameters

Modeling Element	Description or Value	Section Reference
	Infiltration Rates	
WMUs		
Unlined Infiltration (m/yr)	LF, WP, LAU: Optional user input; default generated using HELP model based on site location SI: Optional user input; default calculated by EPACMTP based on site-specific ponding depth	6.4.1.2
Single Liner Infiltration (m/yr)	LF, WP: Optional user input; default generated using HELP model based on site location and 3-ft (0.9-m) clay liner SI: Optional user input; default calculated by EPACMTP based on site-specific ponding depth and 3-ft (0.9-m) clay liner LAU: Not Applicable	6.4.1.3
Composite Liner Infiltration (m/yr)	LF, WP: Optional user input; nationwide distribution of reported leak detection system flow rates for composite lined units SI: Optional user input; calculated using Bonaparte (1989) equation for geomembrane liner using nationwide distribution of leak densities and unit-specific ponding depths LAU: Not Applicable	6.4.1.4
Structural Fills		
Infiltration rate (m/yr)	Optional user input; default values are assumed to be the same as no liner infiltration rates for LFs, based on climate center and cover soil type; user-specified value can also be provided	6.4.2
Roadways		
Infiltration rate through a strip (m/yr)	Required site-specific user input for each strip; default values are based on climate center and surface material type; user-specified value can also be provided	6.4.3
Runoff rate (m/yr)	Required user input if a ditch is defined; default=0	6.4.3
Precipitation rate (m/yr)	Required user input if a ditch is defined; default=0	6.4.3
Evaporation rate (m/yr)	Required user input if a ditch is defined; default=0	6.4.3
	Recharge Rate	
Recharge Rate (m/yr)	All source types (WMU, structural fills and roadways): Monte Carlo based on distribution of soil types and location-specific climate conditions	6.4.4

LAU = land application unit LF = landfill SI = surface impoundment WP = waste pile

6.4.1 Infiltration Rates for WMUs

Several methodologies were used to estimate infiltration:

- **Landfills, waste piles, and land application units (no-liner, single-liner [landfill, waste pile only]).** The HELP model (Schroeder et al, 1994) was used to compute infiltration rates. A complete description of how the HELP model was used to develop infiltration rates is presented in Appendix A of the *EPACMTP Parameters/Data Background Document* (U.S. EPA, 2003b).
- **Landfills and waste piles (composite liner).** Infiltration rates were compiled from leak-detection-system flow rates reported for actual composite-lined waste units (TetraTech, 2001).
- **Surface impoundments (no liner, single liner).** Infiltration through the bottom of the impoundment is calculated internally by EPACMTP, as described in **Section 3.1.2**.
- **Surface impoundments (composite liner).** The Bonaparte equation (Bonaparte et al., 1989) was used to calculate the infiltration rate assuming circular (pin-hole) leaks with a uniform leak size of 6 mm^2, and using the distribution of leak densities (number of leaks per hectare) assembled from the survey of composite-lined units (TetraTech, 2001).

Tables 6-6 through **6-9** summarize the liner assumptions and infiltration rate calculations for landfills, waste piles, surface impoundments, and land application units, respectively. The remainder of **Section 6.4.1** provides background on how the HELP model was used in conjunction with data from climate stations across the United States to develop nationwide recharge and infiltration rate distributions and provides detailed discussion of how infiltration rates for different liner designs were developed for each type of WMU.

The HELP model is a quasi-two-dimensional hydrologic model for computing water balances of landfills, cover systems, and other solid waste management facilities (Schroeder et al., 1994). The HELP model is primarily a vertical flow model with some lateral flow in permeable drainage layers. Potential evapotranspiration is modeled by a modified Penman method. Transient values are calculated and may be able to be extracted; however, IWEM and EPACMTP are based on steady-state flow, and thus, long-term infiltration rates are generated with HELP. The primary purpose of the model is to assist in the comparison of design alternatives. The HELP model uses weather, soil, and design data to compute a water balance for landfill systems accounting for the effects of surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and leakage through soil, geomembrane or composite liners. The HELP model can simulate landfill systems consisting of various combinations of vegetation, cover soils, waste cells, lateral drain layers, low permeability barrier soils, and synthetic geomembrane liners.

For IWEM evaluations, HELP Versions 3.03 and 3.07 were used. An existing database of no-liner infiltration for landfills, waste piles and land application units, and recharge rates for 97 climate stations in the lower 48 contiguous states (ABB, 1995), representing 25 climatic regions, that was developed with HELP version 3.03, was used as a starting point. To develop the IWEM evaluations, five climate stations (located in Alaska, Hawaii, and Puerto Rico) were added to ensure coverage throughout all of the United States. **Figure 6-6** shows the locations of the 102 climate stations.

Table 6-6. Methodology Used to Compute Infiltration for Landfills

	No Liner	Single Liner	Composite Liner
Method	HELP model simulations to compute an empirical distribution of infiltration rates for a 2-ft (0.6-m) thick cover of three native soil cover types using nationwide coverage of climate stations. Soil-type specific infiltration rates for a specific site are assigned by using the infiltration rates for respective soil types at the nearest climate station.	HELP model simulations to compute an empirical distribution of infiltration rates through a single clay liner using nationwide coverage of climate stations. Infiltration rates for a specific site were obtained by using the infiltration rate for the nearest climate station.	Compiled from literature sources (TetraTech, 2001) for composite liners
Final Cover	Monte Carlo selection from distribution of soil cover types: 2-ft (0.6-m) thick native soil (one of three soil types: silty clay loam, silt loam, or sandy loam) with a range of mean hydraulic conductivities (4.2×10^{-5} cm/s to 7.2×10^{-4} cm/s).	3-ft (0.9-m) thick clay cover with a hydraulic conductivity of 1×10^{-7} cm/sec and a 10-ft (3-m) thick waste layer. On top of the cover, a 1-ft (0.3-m) layer of loam to support vegetation and drainage and a 1-ft (0.3-m) percolation layer.	No cover modeled; the composite liner is the limiting factor in determining infiltration
Liner Design	No liner	3-ft (0.9-m) thick clay liner with a hydraulic conductivity of 1×10^{-7} cm/sec. No leachate collection system. Assumes constant infiltration rate (assumes no increase in hydraulic conductivity of liner) over modeling period.	1.5-mm high-density polyethylene layer with either an underlying geosynthetic clay liner with maximum hydraulic conductivity of 5×10^{-9} cm/sec, or a 3-ft (0.9-m) compacted clay liner with maximum hydraulic conductivity of 1×10^{-7} cm/sec. Assumes same infiltration rate (i.e., no increase in hydraulic conductivity of liner) over modeling period.
IWEM Infiltration Rate	Monte Carlo selection from HELP generated location- specific values.	Monte Carlo selection from HELP generated location-specific values.	Monte Carlo selection from distribution of leak detection system flow rates.

Table 6-7. Methodology Used to Compute Infiltration for Surface Impoundments

	No Liner	Single Liner	Composite Liner
Method	EPACMTP SI module for infiltration through consolidated sludge and native soil layers with a unit-specific ponding depth from EPA's SI Study (U.S. EPA, 2001).	EPACMTP module for infiltration through a layer of consolidated sludge and a single clay liner with unit-specific ponding depth from EPA's SI study.	Bonaparte equation (Bonaparte et al., 1989) for pin-hole leaks using distribution of leak densities for units installed with formal construction quality assurance programs
Ponding Depth	Unit-specific based on EPA's SI study.	Unit-specific based on EPA's SI study.	Unit-specific based on EPA's SI study.
Liner Design	None. However, barrier to infiltration is provided by layer of consolidated sludge at the bottom of the impoundment, and a layer of clogged native soil below the consolidated sludge. The sludge thickness is assumed to be constant over the modeling period. The hydraulic conductivity of the consolidated sludge is between 1.3×10^{-7} and 1.8×10^{-7} cm/sec. The hydraulic conductivity of the clogged native material is assumed to be 0.1 of the unaffected native material in the vadose zone.	3-ft (0.9-m) thick clay liner with a hydraulic conductivity of 1×10^{-7} cm/sec. No leachate collection system. Assumes no increase in hydraulic conductivity of liner over modeling period. Additional barrier is provided by a layer of consolidated sludge at the bottom of the impoundment, see no-liner column.	1.5-mm high-density polyethylene layer with either an underlying geosynthetic clay liner with maximum hydraulic conductivity of 5×10^{-9} cm/sec, or a 3-ft (0.9-m) compacted clay liner with maximum hydraulic conductivity of 1×10^{-7} cm/sec. Assumptions: ▪ Constant infiltration rate (i.e., no increase in hydraulic conductivity of liner) over modeling period; ▪ Geomembrane liner is limiting factor that determines infiltration rate.
IWEM Infiltration Rate	Calculated by EPACMTP based on Monte Carlo selection of unit-specific ponding depth.	Calculated based on Monte Carlo selection of unit-specific ponding depth	Calculated based on Monte Carlo selection of unit-specific ponding depth and distribution of leak densities

Table 6-8. Methodology Used to Compute Infiltration for Waste Piles

	No Liner	Single Liner	Composite Liner
Method	HELP model simulations to compute distribution of infiltration rates for a 10-ft (3-m) thick layer of waste, using three waste permeabilities (copper slag, coal bottom ash, coal fly ash) and nationwide coverage of climate stations. Waste-type-specific infiltration rates for a specific site are obtained by using the infiltration rates for respective waste types at the nearest climate station.	HELP model simulations to compute distribution of infiltration rates through 10-ft (3-m) waste layer using three waste permeabilities and nationwide coverage of climate stations. Infiltration rates for a specific site were obtained by using the infiltration rate for the nearest climate station.	Compiled from literature sources (TetraTech, 2001) for composite liners
Cover	None	None	None
Liner Design	No liner	3-ft (0.9-m) thick clay liner with a hydraulic conductivity of 1×10^{-7} cm/sec, no leachate collection system, and a 10-ft (3-m) thick waste layer. Assumes no increase in hydraulic conductivity of liner over unit's operational life.	1.5-mm high-density polyethylene layer with either an underlying geosynthetic clay liner with maximum hydraulic conductivity of 5×10^{-9} cm/sec, or a 3-ft (0.9-m) compacted clay liner with maximum hydraulic conductivity of 1×10^{-7} cm/sec. Assumptions: ▪ Same infiltration rate (i.e., no increase in hydraulic conductivity of liner) over unit's operational life; ▪ Geomembrane is limiting factor in determining infiltration rate.
IWEM Infiltration Rate	Monte Carlo selection from HELP generated location-specific values.	Monte Carlo selection from HELP generated location- specific values.	Monte Carlo selection from distribution of leak detection system flow rates

Table 6-9. Methodology Used to Compute Infiltration for Land Application Units

	No Liner	Single Liner	Composite Liner
Method	HELP model simulations to compute an empirical distribution of infiltration rates for a 0.5-ft (15-cm) thick sludge layer, underlain by a 3-ft (0.9-m) layer of three types of native soil using nationwide coverage of climate stations. Soil-type specific infiltration rates for a specific site are assigned by using the infiltration rates for respective soil types at the nearest climate station.	N/A	N/A
Liner Design	No liner	N/A	N/A
IWEM Infiltration Rate	Monte Carlo selection from HELP generated location specific values.	N/A	N/A

Figure 6-6. Locations of HELP climate stations.

The current version of HELP (version 3.07) was used for the additional modeling for the no-liner scenario. The results of Version 3.07 were compared to those of Version 3.03, and the differences in calculated infiltration rates were insignificant. This comparison was also used to verify a number of counter-intuitive infiltration rates that were generated with HELP Version 3.03. For some climate stations located in areas of the country with low precipitation rates, the net infiltration for unlined landfills did not always correlate with the relative permeability of the landfill cover. In some cases, a less permeable cover resulted in a higher modeled infiltration rate as compared to a more permeable cover. Examples can be seen in the detailed listing of infiltration data in **Appendix D**. Table D-1 shows that for a number of climate stations, including Albuquerque, Denver, and Las Vegas, the modeled infiltration rate for landfills with a silty clay loam cover is higher than the values corresponding to silt loam and sandy loam soil covers. In all these cases, the HELP modeling results for unlined landfills were determined to be correct and could be explained in terms of other water balance components, including surface run-off and evapotranspiration.

The first 97 climate stations were grouped into 25 climate regions based on ranges of average annual precipitation and pan evaporation, as shown in **Table 6-10**. For each modeled climate station, HELP provides a database of five years of climatic data. This climatic data was used, along with data on the regional soil type and WMU design characteristics, to calculate a water balance for each applicable liner design as a function of the amount of precipitation that reaches the top surface of the unit, minus the amount of runoff and evapotranspiration. The HELP model then computed the net amount of water that infiltrates through the surface, waste, and liner layers, based on the initial moisture content and the hydraulic conductivity of each layer.

In addition to climate factors and liner designs, the infiltration rates calculated by HELP are affected by landfill cover design, permeability of the waste material in waste pile, and land application unit soil type. For every climate station and WMU type, three HELP infiltration rates were calculated. The WMU location is a required user input, and the climate factors used in HELP are therefore also fixed; however, IWEM still accounts for local variability in landfill soil cover type and waste pile waste permeability.

The permeability of the soil used in the landfill cover affects the HELP-generated infiltration rates. A consistent set of soil properties were used in the infiltration (and recharge) rate calculations, as was done in the unsaturated zone fate and transport simulations (see **Section 6.5.2**). HELP was used to calculate infiltration for sandy loam, silty loam, and silty clay loam soils.

In the case of waste piles, which do not have a cover, the permeability of the waste material itself plays a role similar to that of a landfill cover in regulating infiltration rate. Waste piles were modeled with three different waste types, having different waste permeabilities, and each having equal likelihood of occurrence. The permeabilities for the three different waste types are discussed in **Section 6.1.2**.

Table 6-10. Grouping of Climate Stations by Average Annual Precipitation and Pan Evaporation (ABB, 1995)

City	State	Climate Region	
		Precipitation (m/yr)	Evaporation (m/yr)
Boise	ID	< 0.40	< 0.76
Fresno	CA		
Bismarck	ND	< 0.40	0.76 – 1.0
Denver	CO		
Grand Junction	CO		
Pocatello	ID		
Glasgow	MT		
Pullman	WA		
Yakima	WA		
Cheyenne	WY		
Lander	WY		
Rapid City	SD	< 0.40	1.0 – 1.3
Los Angeles	CA		
Sacramento	CA		
San Diego	CA		
Santa Maria	CA		
Ely	NV		
Cedar City	UT		
Albuquerque	NM	< 0.40	1.3 – 1.5
Las Vegas	NV	< 0.40	> 1.5
Phoenix	AZ		
Tucson	AZ		
El Paso	TX		
Medford	OR	0.40 – 0.61	0.76 – 1.0
Great Falls	MT		
Salt Lake City	UT		
Grand Island	NE	0.40 – 0.61	1.0 – 1.3
Flagstaff	AZ	0.40 – 0.61	1.3 – 1.5
Dodge City	KS	0.40 – 0.61	> 1.5
Midland	TX		
St. Cloud	MN	0.61 – 0.81	< 0.76
E. Lansing	MI	0.61 – 0.81	0.76 – 1.0
North Omaha	NE	0.61 – 0.81	1.0 – 1.3
Dallas	TX	0.61 – 0.81	1.3 – 1.5
Tulsa	OK		
Brownsville	TX		
Columbia	MO	0.81 – 1.0	0.76 – 1.0
Put-in-Bay	OH		
Madison	WI		
Columbus	OH		
Cleveland	OH		
Des Moines	IA		
E. St. Louis	IL		
Topeka	KS	0.81 – 1.0	1.0 – 1.3
Tampa	FL	0.81 – 1.0	1.3 – 1.5
San Antonio	TX		
Portland	ME	1.0 – 1.2	< 0.76
Hartford	CT		
Syracuse	NY		
Worchester	MA		
Augusta	ME		
Providence	RI		
Nashua	NH		
Ithaca	NY		
Boston	MA		
Schenectady	NY		
NY City	NY	1.0 – 1.2	0.76 – 1.0
Lynchburg	VA		
Philadelphia	PA		
Seabrook	NJ		
Indianapolis	IN		
Cincinnati	OH		
Bridgeport	CT		
Jacksonville	FL	1.0 – 1.2	1.0 – 1.3
Orlando	FL		
Greensboro	NC		
Watkinsville	GA		
Norfolk	VA		
Shreveport	LA		
Astoria	OR	> 1.2	< 0.76
New Haven	CT		
Plainfield	MA		

(continues)

Table 6-10. Grouping of Climate Stations (continued)

<table>
<tr><th rowspan="2">City</th><th rowspan="2">State</th><th colspan="2">Climate Region</th></tr>
<tr><th>Precipitation (m/yr)</th><th>Evaporation (m/yr)</th></tr>
<tr><td>Oklahoma City</td><td>OK</td><td>0.61 – 0.81</td><td>> 61.5</td></tr>
<tr><td>Bangor</td><td>ME</td><td rowspan="12">0.81 – 1.0</td><td rowspan="12">< 0.76</td></tr>
<tr><td>Concord</td><td>NH</td></tr>
<tr><td>Pittsburgh</td><td>PA</td></tr>
<tr><td>Portland</td><td>OR</td></tr>
<tr><td>Caribou</td><td>ME</td></tr>
<tr><td>Chicago</td><td>IL</td></tr>
<tr><td>Burlington</td><td>VT</td></tr>
<tr><td>Rutland</td><td>VT</td></tr>
<tr><td>Seattle</td><td>WA</td></tr>
<tr><td>Montpelier</td><td>VT</td></tr>
<tr><td>Sault St. Marie</td><td>MI</td></tr>
</table>

<table>
<tr><th rowspan="2">City</th><th rowspan="2">State</th><th colspan="2">Climate Region</th></tr>
<tr><th>Precipitation (m/yr)</th><th>Evaporation (m/yr)</th></tr>
<tr><td>Nashville</td><td>TN</td><td rowspan="5">> 1.2</td><td rowspan="5">0.76 – 1.0</td></tr>
<tr><td>Knoxville</td><td>TN</td></tr>
<tr><td>Central Park</td><td>NY</td></tr>
<tr><td>Lexington</td><td>KY</td></tr>
<tr><td>Edison</td><td>NJ</td></tr>
<tr><td>Atlanta</td><td>GA</td><td rowspan="6">> 1.2</td><td rowspan="6">1.0 – 1.3</td></tr>
<tr><td>Little Rock</td><td>AK</td></tr>
<tr><td>Tallahassee</td><td>FL</td></tr>
<tr><td>New Orleans</td><td>LA</td></tr>
<tr><td>Charleston</td><td>SC</td></tr>
<tr><td>W. Palm Beach</td><td>FL</td></tr>
<tr><td>Lake Charles</td><td>LA</td><td rowspan="2">> 1.2</td><td rowspan="2">1.3 – 1.5</td></tr>
<tr><td>Miami</td><td>FL</td></tr>
</table>

6.4.1.2 Infiltration Rates for Unlined Units

Landfill. The HELP model was used to simulate infiltration through closed landfills for each of the 102 climate station locations shown in Figure 6-6. A 2-ft (0.6-m) cover was included as the minimum Subtitle D requirement. Three different soil cover types were modeled: sandy loam, silty loam, and silty clay loam soils. **Table 6-11** presents the hydraulic parameters used in the HELP modeling for these three soil types.

Table 6-11. Hydraulic Parameters for the Modeled Soils

Soil Type	HELP Soil Number	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)
Sandy Loam	6	0.453	0.190	0.085	0.000720
Silt Loam	9	0.501	0.284	0.135	0.000190
Silty Clay Loam	12	0.471	0.342	0.210	0.000042

Other landfill design criteria included:

- A vegetation cover of "fair" grass — this is the quality of grass cover suggested by the HELP model for landfills where limitations to root zone penetration and poor irrigation techniques may limit grass quality.
- The evaporation zone thickness selected for each location was generally the depth suggested by the model for that location for a fair grass crop; however, the evaporation zone thickness was not allowed to exceed the soil thickness (2 ft, or 0.6 m).

- The leaf area index (LAI)[4] selected for each location was that of fair grass (2.0) unless the model indicated a lower maximum for that location.
- The landfill configuration was based on a facility with an area of 4,047 m^2 (1 acre) with a 2% top slope and a drainage length of 61 m (represents one side of a 4,047 m^2 square). Runoff was assumed to be possible from 100% of the cover.

Appendix D, Table D-1, presents the infiltration rate data for the 102 climate stations. The unlined landfill infiltration rate for each soil type at each of the 102 climate centers was used as the ambient regional recharge rate for that climatic center and soil type.

Surface Impoundment. Surface impoundment infiltration rates were calculated using the built-in surface impoundment module in EPACMTP (see **Section 3.1.2**). This means that for EPACMTP, the surface impoundment infiltration rate is not really an input parameter, rather the model calculates infiltration rates "on the fly" during the simulation, as a function of impoundment ponding depth and other surface impoundment characteristics. For unlined surface impoundments, the primary parameters that control the infiltration rate are the ponding depth in the impoundment, the thickness and permeability of any accumulated sediment layer at the base of the impoundment, and the presence of a "clogged" (i.e., reduced permeability) layer of native soil underneath the impoundment caused by the migration of solids from the impoundment. In addition, IWEM checks that the calculated infiltration rate does not result in an unrealistic degree of ground water mounding (see **Section 6.7**).
For IWEM, unit-specific data on surface impoundment ponding depths from EPA's *Surface Impoundment Study* (U.S. EPA, 2001) were used, along with an assumed fixed sediment layer thickness of 20 cm at the base of the impoundment. The resulting sediment layer permeability has a relatively narrow range of variation between 1.26×10^{-7} and 1.77×10^{-7} cm/s. The depth of clogging underneath the impoundment was assumed to be 0.5 m in all cases, and the saturated hydraulic conductivity of the clogged layer was assumed to be 10% of that of the native soil underlying the impoundment.

In the event that the surface impoundment is reported to have its base below the water table, the infiltration was calculated using Darcy's law based on the hydraulic gradient across and the hydraulic conductivity of the consolidated sediment at the bottom of the impoundment unit.

Waste Pile. For the purpose of estimating leaching rates, waste piles were considered to be similar to non-covered landfills with a total waste thickness of 3 m (10 ft). Therefore, the infiltration rates for unlined waste piles were generated with the HELP model using the same general procedures as for landfills, but with the following modifications:

- **No cover.** The leachate flux was modeled through active, uncovered piles, with a surface having no vegetation. The evaporative zone depth was taken as the suggested HELP model value for the "bare" condition at each climate center. The leaf area index was set to zero to eliminate transpiration.
- **Variable waste permeability.** For uncovered waste piles, the infiltration rates predicted by HELP model were sensitive to the permeability of the waste material itself. Based on these results, waste pile infiltration rates were simulated for three different waste pile

[4] HELP defines LAI as a dimensionless ratio of the leaf area of actively transpiring vegetation to the normal surface area of the land on which the vegetation is growing

materials: relatively high permeability, moderate permeability, and relatively low permeability. Parameters for the three waste types are presented in **Table 6-12**.

Table 6-12. Moisture Retention Parameters for the Modeled Waste Pile Materials

Waste Type	HELP Soil Number	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)
Low Permeability	30	0.541	0.187	0.047	0.00005
Moderate Permeability	31	0.578	0.076	0.025	0.00410
High Permeability	33	0.375	0.055	0.020	0.04100

Waste pile infiltration rates were calculated for all 102 climate stations and waste material permeabilities. **Appendix D**, Table D-2, presents the waste pile infiltration rate values for all climate stations and waste types.

Land Application Unit. Land application units were modeled with HELP using two soil layers. The top layer was taken to be 0.5 ft (15 cm) thick and represented the layer into which the waste was applied. The bottom layer was of the same material type as the top layer and was set at a thickness of 3 ft (0.9 m). Both of these layers were modeled as vertical percolation layers. The same three soil types used for landfills were also used for land application units.
The waste applied to the land application unit was assumed to be a sludge-type material with a high water content. A waste application rate of 18.4 cm/yr was assumed, with the waste having a solids content of 20% and a unit weight of 1,200 kg/m^3. Assuming that 100% of the water in the waste was available as free water, an excess water amount of 15 cm/yr, in addition to precipitation, would be available for percolation. HELP model analyses showed that the additional water available for percolation generally would have little effect on the simulated water balance and net infiltration, except for sites located in arid regions of the United States with very little natural precipitation. For more representative waste application rates, the effect disappeared because introducing additional moisture in the simulated water balance results in a commensurate increase in runoff and removal by evapotranspiration. The land application unit infiltration values are presented in **Appendix D**, Table D-3.

6.4.1.3 Infiltration Rates for Single-Lined Waste Units

IWEM includes infiltration rates for lined landfills, waste piles, and surface impoundments. In the case of land application units, only unlined units are considered.

Landfill. Infiltration rates were calculated for single-lined landfills using the HELP model and modeling the landfill as a four-layer system, consisting, from top to bottom of:

- 1-ft (0.3-m) percolation cover layer;
- 3-ft (0.9-m) compacted clay cover with hydraulic conductivity of 1×10^{-7} cm/s ;
- 10-ft (3-m) thick waste layer; and
- 3-ft (0.9-m) thick compacted clay liner with a hydraulic conductivity of 1×10^{-7} cm/sec.

The cover layer was simulated as a loam drainage layer supporting a "fair" cover crop with an evaporative zone depth equal to that associated with a fair cover crop at the climate center. The remaining conditions were identical to those described in **Section 6.4.1.2** for unlined landfills.

The grouping of climate stations into 25 regions of similar climatic conditions depicted in Table 6-10 were used to reduce the number of required HELP simulations. Infiltration rates were calculated for the 25 climate regions, and then the same value was assigned to each climate station in one region, rather than calculating rates for all of the 102 individual climate stations. To ensure a conservative result, the climate center with the highest average precipitation in each climate region was chosen to represent that region. **Appendix D**, Table D-4, shows the infiltration rate values for clay-lined landfills. The actual climate stations that were used in the HELP simulations for each climate region are shown in bold face in the table. Individual infiltration rates were calculated for the five new climate centers in Alaska, Hawaii, and Puerto Rico that were not assigned to a climate region.

The database of HELP-generated infiltration rates is used to provide estimates of landfill infiltration rates in IWEM when a user does not have site-specific data. The grouping of climate centers into regions for clay-lined units resulted in a number of apparent anomalies in which the suggested infiltration rate for a lined unit was higher than the unlined infiltration rate at the same climate station. This resulted from using the infiltration rate for the climate center with the highest annual precipitation in each region for clay-lined units, but then comparing it with a location-specific infiltration value for unlined units. These anomalies occurred only for climate stations in arid parts of the United States, and were noticeable only when the absolute magnitude of infiltration was low. To eliminate these counter-intuitive results, location-specific HELP infiltration rates for clay-lined units were calculated for 17 climate stations (listed at right). These location-specific infiltration rates for these 17 climate stations were then incorporated into the IWEM software, replacing the regional values developed for these stations.

Climate Stations with Location-Specific HELP Infiltration Rates for Clay-Lined Units

Phoenix, AZ	Rapid City, SD
Tucson, AZ	El Paso, TX
Denver, CO	Cedar City, UT
Grand Junction, CO	Salt Lake City, UT
Pocatello, ID	Pullman, WA
Great Falls, MT	Yakima, WA
Glasgow, MT	Cheyenne, WY
Ely, NV	Lander, WY
Las Vegas, NV	

Waste Pile. Infiltration rates for single-lined waste piles were calculated using the HELP model and modeling the waste pile as a two-layer system, consisting, from top to bottom, of:

- 10-ft (3-m) thick, uncovered, waste layer; and
- 3-ft (0.9-m) thick compacted clay liner with a hydraulic conductivity of 1×10^{-7} cm/sec.

Other parameters were set to the same values as in the unlined waste pile case. The same three waste material types were used. A bare surface was modeled for the evaporative zone depth.

The same grouping of climate stations in 25 climate regions as was previously discussed for landfills was used. **Appendix D**, Table D-4, shows the infiltration rate values for clay-lined waste piles. The actual climate centers that were used in the HELP simulations for each climate region are shown in bold face in the table. Individual infiltration rates were calculated for the five new climate centers, in Alaska, Hawaii, and Puerto Rico, which were not assigned to a climate region.

Analogous to the situation encountered for landfills, we found a number of apparent anomalies between waste pile infiltration rates for unlined as compared to clay-lined waste piles occurred with the regional infiltration values for clay-lined units. The occurrence of these anomalies for waste piles was also restricted to climate centers in arid parts of the United States, for which the absolute magnitude of infiltration was low. These were corrected in the same way as described above for landfills.

During the process of verifying the HELP-generated infiltration rates for clay-lined units, incorrect values for clay-lined waste piles assigned to the Lake Charles, LA and Miami, FL, climate stations were replaced. These two climate stations have high precipitation (Table 6-10), but were assigned low infiltration rates (see **Appendix D**, Table D-4). The HELP model was rerun for the clay-lined waste pile scenario for the three clay-lined waste pile scenarios: low, medium, and high waste permeability. The re-calculated infiltration rate values averaged 0.066 m/yr, as compared to the previously generated rate of 0.019 m/yr. The re-calculated values were incorporated in the IWEM software tool.

Surface Impoundment. For single-lined surface impoundments, infiltration rates were calculated by EPACMTP in the same manner as described in **Section 6.4.1.2** for unlined units, with the exception of that a 3-ft (0.9-m) compacted clay liner with a hydraulic conductivity of 1×10^{-7} cm/s was modeled at the bottom of the WMU. In addition, the effect of clogged native material was not included due to the filtering effects of the liner.

6.4.1.4 Infiltration Rates for Composite-Lined Units

For composite liners, data on liner integrity and leachate infiltration through composite liners were collected and compiled from the available literature (TetraTech, 2001). This section describes how those data were applied to develop the IWEM analyses.

Landfill and Waste Pile. Composite-lined landfills and waste piles were treated the same for the purpose of determining infiltration rates. For these WMUs, an infiltration rate distribution was developed from actual leak detection system flow rates reported for clay composite-lined landfill cells. The distribution of composite-lined landfill and waste pile infiltration rates was based on available monthly average leak detection system flow rates from 27 landfill cells reported by TetraTech (2001). The data and additional detail for the 27 landfill cells are provided in **Appendix D**, Table D-5. The data included monthly average leak detection system flow rates for 22 operating landfill cells and 5 closed landfill cells. The 27 landfill cells are located in eastern United States: 23 in the northeastern region, one in the mid-Atlantic region, and 3 in the southeastern region. Each of the landfill cells is underlain by a geomembrane/geosynthetic clay liner which consists of a geomembrane of thickness between 1 and 1.5 mm (with the majority, 22 of 27, being 1.5 mm thick), overlying a geosynthetic clay layer of reported thickness of 6 mm. The geomembrane is a flexible membrane layer made from high-density polyethylene. The geosynthetic clay liner is a composite barrier consisting of two geotextile outer layers with a uniform core of bentonite clay to form a hydraulic barrier. The liner system is underlain by a leak detection system.

A subset of the reported flow rates compiled by TetraTech (2001) was used in developing the composite liner infiltration rates for IWEM. Leak detection system flow rates for geomembrane/compacted clay composite-lined landfill cells were not included. For compacted clay liners (including composite geomembrane), there is the potential for water to be released during the consolidation of the clay liner and yield an unknown contribution of water to leak detection system flow. Thus, it is very difficult to determine how much of the leak detection system flow is due to liner leakage, versus due to clay consolidation. Leak detection system flow rates from three geomembrane/geosynthetic clay lined-cells were also omitted. For one cell, flow rate data were available for the cell's operating period and the cell's post-closure period. The average flow rate for the cell was 26 L/ha/day when the cell was operating and 59 L/ha/day when the cell was closed. These flow rates, which were among the highest reported, are difficult to interpret because the flow rate from the closed cell was over twice the flow rate from the open cell, a pattern inconsistent with the other open cell/closed cell data pairs we reviewed. For the two other cells, additional verification of the data may be needed in order to fully understand the reported flow rates.

The resulting cumulative probability distribution of infiltration rates for composite-lined landfills and waste piles for use in this application is based on the 27 remaining data points is presented in **Table 6-13**. Note that over 50% of the values are zero, that is, they have no measurable infiltration.

Table 6-13. Cumulative Frequency Distribution of Infiltration Rate for Composite-Lined Landfills and Waste Piles

Percentile	0	10	25	50	75	90	100
Infiltration Rate (m/yr)	0.0	0.0	0.0	0.0	7.30×10^{-5}	1.78×10^{-4}	4.01×10^{-4}

Surface Impoundment

Leakage through circular defects (pinholes) in a composite liner were calculated using the following equation developed by Bonaparte et al. (1989):

$$Q = 0.21a^{0.1}h^{0.9}K_s^{0.74} \tag{6-1}$$

where:

Q = steady-state rate of leakage through a single hole in the liner (m^3/s)
a = area of hole in the geomembrane (m^2)
h = head of liquid on top of geomembrane (m)
K_s = hydraulic conductivity of the low-permeability soil underlying the geomembrane (m/s).

This equation is applicable to cases where there is good contact between the geomembrane and the underlying compacted clay liner. For each surface impoundment unit, the infiltration rate was determined using the above equation based on the unit-specific ponding depth data (corresponding to h in the above equation) from the *Surface Impoundment Study* (U.S. EPA, 2001) in combination with a distribution of leak densities (expressed as number of leaks per hectare) compiled from 26 leak density values reported in TetraTech (2001). The leak densities are based on liners installed with formal Construction Quality Assurance programs.

The 26 sites with leak density data are mostly located outside the United States: 3 in Canada, 7 in France, 14 in United Kingdom, and 2 in unknown locations. The WMUs at these sites (8 landfills, 4 surface impoundments, and 14 unknown) are underlain by a layer of geomembrane of thickness varying from 1.14 to 3 mm. The majority of the geomembranes are made from high-density polyethylene (23 of 26) with the remaining 3 made from prefabricated bituminous geomembrane or polypropylene. One of the sites has a layer of compacted clay liner beneath the geomembrane, however, for the majority of the sites (25 of 26) material types below the geomembrane layer are not reported. The leak density data above were used for surface impoundments. The leak density distribution is shown in **Table 6-14**. Table D-6, **Appendix D**, provides additional detail.

Table 6-14. Cumulative Frequency Distribution of Leak Density for Composite-Lined Surface Impoundments

Percentile	0	10	20	30	40	50	60	70	80	90	100
Leak density (Num. leaks/ha)	0	0	0	0	0.7	0.915	1.36	2.65	4.02	4.77	12.5

To use the Bonaparte equation, a uniform leak size of 6 mm^2 was assumed. The leak size is the middle of a range of hole sizes reported by Rollin et al. (1999), who found that 25% of holes were less than 2 mm^2, 50% of holes were 2 to 10 mm^2, and 25% of holes were greater than 10 mm^2. The geomembrane was assumed to be underlain by a compacted clay liner whose hydraulic conductivity is 1×10^{-7} cm/s.

An infiltration rate calculation to estimate the range of infiltration resulting from the leaks in geomembrane was conducted to ascertain the plausibility of the leak density data. Because of the absence of documented infiltration data for surface impoundments, the infiltration data for landfills, described above for landfills and waste piles, were used as a surrogate infiltration data set for comparison purposes. Because the comparison was made on the basis of landfill data, the head of liquid above the geomembrane was set to 1 ft (0.3 m), which is a typical maximum design head for landfills. Calculation results are shown in Table D-6, **Appendix D**. The results indicate that the calculated leakage rates, based on the assumptions of above-geomembrane head, hole dimension, hydraulic conductivity of the barrier underneath the geomembrane, and good contact between the geomembrane and the barrier, agree favorably with the observed landfill flow rates reported in Table D-5, **Appendix D**. This result provided confidence that the leak density data could be used as a reasonable basis for calculating infiltration rates using actual impoundment ponding depths.

The resulting frequency distribution of calculated infiltration rates for composite- lined surface impoundments is presented in **Table 6-15**. In IWEM, the user is required to specify the unit's ponding depth. IWEM will then determine the unit's infiltration distribution using the Bonaparte equation and the leak density distribution in Table 6-13.

Table 6-15. Cumulative Frequency Distribution of Infiltration Rate for Composite-Lined Surface Impoundments

Percentile	0	10	25	50	75	90	100
Infiltration Rate (m/yr)	0.0	0.0	0.0	1.34×10^{-5}	1.34×10^{-4}	3.08×10^{-4}	4.01×10^{-3}

6.4.2 Infiltration Rates for Structural Fills

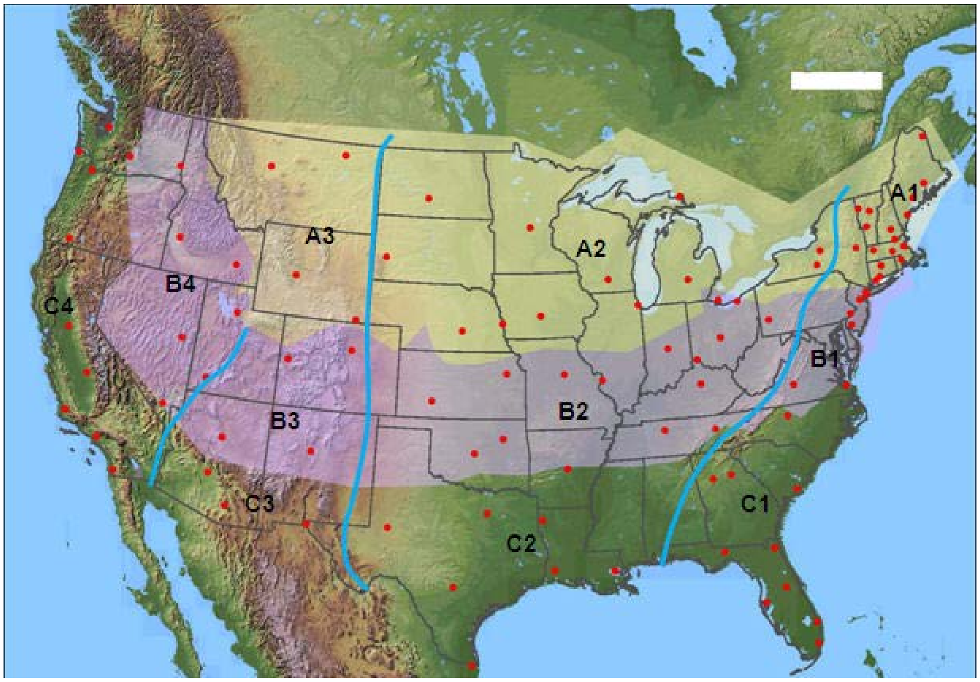
The HELP model (Schroeder et al, 1994) rates computed for unlined landfills were assumed to be representative of infiltration rates through structural fills. The hydraulic performance of a structural fill is often designed to behave similarly to the surrounding soils (NRMCA, n.d.). Therefore, in IWEM, recharge rates are assumed to be similar to the infiltration rates through unlined landfills (see **Section 6.4.4**). In the event that the surface material (or compaction of the structural fill materials) results in a less permeable medium, IWEM will use the effective hydraulic conductivity (a required input) to limit the HELP-derived or user-specified infiltration rate to one no greater than the hydraulic conductivity of the structural fill materials.

6.4.3 Infiltration Rates for Roadways

Subgrade infiltration is an input parameter for the IWEM roadway source module, required to define the mass flux emanating from the highway source area. Subgrade infiltration refers to water exiting from the subbase layer into the subgrade below. Subgrade infiltration is governed by pavement configuration, pavement hydraulic properties, climatic conditions, and drainage system. Nationwide, a multitude of combinations of the above four factors are possible. At present, there are very little subgrade infiltration data. To assist the IWEM user in estimating subgrade infiltration for different configurations, conditions, and settings, a procedure for estimating subgrade infiltration is presented in this section. The procedure involves dividing the United States into 12 climatic zones. For each zone, pre-determined infiltration rates for major types of pavement configuration with a range of material properties and climatic conditions are given. The 12 climatic zones are described in **Section 6.4.3.1**. Tabulated subgrade infiltration rates are discussed and presented in tables described in **Section 6.4.3.2**. A procedure to estimate subgrade infiltration rates for specific zones, configurations, and material properties is presented in **Section 6.4.3.3**. Finally, a procedure for estimating runoff and evaporation in climatic zones is presented in **Section 6.4.3.4**.

6.4.3.1 Climatic Zones

Following the report by Jackson and Puccinelli (2006), the environmental regions of interest in the United States may be defined based on three temperature ranges (i.e., deep freeze, moderate freeze, and no freeze) and precipitation ranges. According to Jackson and Puccinelli (2006), deep-freeze, moderate-freeze, and no-freeze geographical regions, defined in terms of freezing index, are shown in **Figure 6-7**. The freezing index is used as a measure of the combined duration and magnitude of below freezing temperatures occurring during any given freezing season (Tuhkanen, 1980). As defined by the U.S. Army Corps of Engineers, freezing index is the number of Celsius degree-days (above and below 0°C) between the highest and lowest points on the cumulative degree-days time curve for one freezing season. According to Jackson and Puccinelli (2006), the no-freeze region defines areas with a freezing index less than 50 °C-days, while the moderate-freeze is defined with a freezing index between 50 and 400 °C-days. The deep-freeze region consists of locations exhibiting a freezing index greater than 400 °C-days. Each region is further subdivided into four zones based on similarity in climate. Note that Alaska is in Zone A4, and Hawaii is in Zone C4.



Legend:
A Deep Freeze (4 subzones; Subzone A4, which includes only Alaska is not shown)
B Moderate-Freeze (4 subzones)
C No-Freeze (4 subzones with C4, including Hawaii, not shown)
● Climate station location

Figure 6-7. Climatic zones.

The EPACMTP in IWEM uses climate data from the HELP climate database, which includes 102 climate stations in 45 states and Puerto Rico (U.S. EPA, 2003b). For each zone in Figure 6-7, two climate stations located within the zone from the HELP climate database, with minimum and maximum precipitations, are selected. The selected 24 climate stations are listed in **Table 6-16**.

Table 6-16. Climatic Zones and Corresponding 5-year Average Annual Precipitations

Freezing Index	Zone[a]	Minimum 5-Year Average Precipitation for Zone		Maximum 5-Year Average Precipitation for Zone	
		Station[b]	(m/yr)	Station[b]	(m/yr)
Deep-freeze	A1	Montpelier, VT	0.88	New Haven, CT	1.3
	A2	Rapid City, SD	0.39	Syracuse, NY	1.2
	A3	Cheyenne, WY	0.28	Great Falls, MT	0.46
	A4[d]	Fairbanks, AK	0.24	Annette, AK	2.6
Moderate-freeze	B1	Philadelphia, PA	1.1	Edison, NJ	1.3
	B2	Dodge City, KS	0.5	Nashville, TN	1.4
	B3	Grand Junction, CO	0.18	Flagstaff, AZ	0.54
	B4	Las Vegas, NV	0.13	Salt Lake City, UT	0.41
No-freeze	C1	Tampa, FL	0.97	Tallahassee, FL	1.7
	C2	Midland, TX	0.41	New Orleans, LA	1.8
	C3	Phoenix, AZ	0.2	Tucson, AZ	0.26
	C4[4]	Fresno, CA	0.26	Astoria, OR	1.7

Notes:

[a] Zone geographical coverage is given in Figure 6-7.

[b] Two climate stations in each zone are selected: one with the lowest precipitation, and the other with the highest precipitation.

[c] Precipitation data are obtained from HELP model.

[d] Zone A4 comprises Alaska only. Hawaii is incorporated into Zone C4 (not shown in Figure 6-7).

6.4.3.2 Zone-Specific Subgrade Infiltration Rates

The default zone-specific subgrade infiltration rates included in IWEM were estimated for various pavement components using the HELP model (Schroeder et al, 1994). **Table 6-17** presents the material properties used as inputs to the HELP model to estimate default infiltration rates for IWEM for the various pavement components**.** (Note most of these variables are not inputs to IWEM.) The pavement components for various pavement types in Table 6-17 were represented by vertical-percolation layers as described by Schroeder et al (1994). However, for a special case of low-end portland cement concrete pavement top-course layers with hydraulic conductivity less than 10^{-6} cm/sec, the pavement layers were represented in the infiltration analysis by soil-liner layers (Schroeder et al, 1994). In addition, to avoid unrealistic ponding above the pavement represented by the soil-liner layers, a very thin vertical-percolation layer (0.25 cm) was placed on top of the uppermost soil-liner layer to limit the ponding elevation to the road surface elevation. In all cases, the pavement system was assumed to rest on top of a vertical-percolation layer with the hydraulic conductivity of at least 1.7×10^{-3} cm/sec. In each zone, the climate stations with the highest and lowest 5-year average precipitations were selected to provide an estimate of the range of infiltration variation within that zone. A comprehensive literature survey of hydraulic properties of asphalt concrete, portland cement concrete, base, subbase, and embankment has been undertaken by Apul et al. (2002). Ranges of hydraulic conductivity values for these pavement components, based on the values reported by Apul et al (2002) and references therein, are provided in Table 6-17 as a guide. The HELP model–estimated default subgrade infiltration rates using the zone-specific maximum and minimum precipitations (presented in Table 6-16) and the highest and lowest values of material properties (presented in

Table 6-17) are listed in **Tables 6-18, 6-19,** and **6-20** for the following pavement types and roadway components :

- **Table 6-18:** Asphaltic concrete pavement, portland cement concrete pavement, and Embankment
- **Table 6-19:** Unpaved shoulder, shoulder paved with asphaltic concrete, and shoulder paved with portland cement concrete
- **Table 6-20:** Unpaved median, median paved with asphaltic concrete, and median paved with portland cement concrete.

The selection of extreme values for these inputs and environmental variables in each climatic region is consistent with the objective of determining a bounding range of infiltration rates through various material configurations to support a screening level analysis.

For given precipitations in some zones, the differences between the respective high and low infiltration values are relatively small. This is due to the fact that, especially in zones with low precipitation, the amount of water available after runoff and evaporation can easily percolate into the pavement because the low values of hydraulic properties are comparable to or greater than the rate of infiltration. An inspection of Table 6-17 reveals that the infiltration values are dependent on precipitation, although the relationship may not be linear. For a given zone, if the precipitation at the user's site is different from the zone-specific values used in Table 6-17, the user may obtain preliminary estimates of the location-specific minimum and maximum subgrade infiltration rates by linearly interpolating between respective values associated with minimum and maximum precipitations in the table. For the user who wishes to further refine the infiltration values for specific sites and/or states, it is recommended that location-specific information be utilized to run the HELP model. Parameters suggested in Table 6-17 may be used in the case that pavement-specific data are not available. For the estimation of infiltration rates in embankments and ditches, it may be necessary to account for runoff that emanates from the pavements to the ditches and evaporation over the ditch surfaces, as discussed in Section C.2.2.4 of **Appendix C**.

Runoff rates (meters/year) estimated by the HELP model are given in **Tables 6-21, 6-22**, and **6-23** for the same pavement types and roadway components listed above for infiltration rates. Ditch evaporation data are not available. However, a range of evaporation rates based on evaporation from a non-vegetated soil surface (estimated using the HELP with an embankment as a surrogate soil area) and pan evaporation data from NOAA (1982) is given in **Tables 6-24** and **6-25**, respectively, and can be used for estimating evaporation rates for ditches.

Table 6-17. Material Properties Used in the HELP Model to Estimate Default Infiltration Rates for Roadway Module

	Layer	Description	Hydraulic Conductivity (cm/sec)	Air void (%)	Thickness (cm)[a]	Texture[b]	Total Porosity[c] (vol/vol)	Field Capacity[c] (vol/vol)	Wilting Point[c] (vol/vol)	Curve Number[d]
Flexible Pavement (asphaltic concrete pavement)										
Low-end[e]	L-1	Top course	1.00E-05	2[g]	22	-[h]	0.02	0.011	0.005	99
	L-2	Base course	4.30E-05	50	37	ML	0.50	0.280	0.130	N/A
	L-3	Subbase course	4.30E-05	50	46	ML	0.50	0.280	0.130	N/A
High-end[f]	H-1	Top course	48[i]	24	7.6	-[j]	0.24	0.020	0.007	97
	H-2	Base course	35	39	5.1	GP	0.39	0.032	0.013	N/A
	H-3	Subbase course	35	39	31	GP	0.39	0.032	0.013	N/A
Rigid Pavement (portland cement concrete pavement)										
Low-end	L-1	Top course	2.00E-10	1	33	-[h]	0.01	0.006	0.003	99
	L-2	Subbase course	4.30E-05	50	41	ML	0.50	0.280	0.130	N/A
High-end	H-1	Top course	48	35	20	-[j]	0.35	0.028	0.011	97
	H-2	Subbase course	35	39	10	GP	0.39	0.032	0.013	N/A
Shoulder (unpaved)										
Low-end	L-1	Base course	4.30E-05	50	28	ML	0.50	0.280	0.130	72
	L-2	Subbase course	4.30E-05	50	46	ML	0.50	0.280	0.130	N/A
High-end	H-1	Base course	35	39	5.1	GP	0.39	0.032	0.013	72
	H-2	Subbase course	35	39	25	GP	0.39	0.032	0.013	N/A
Shoulder (paved with asphaltic concrete)										
Low-end	L-1	Top course	1.00E-05	2	15	-[h]	0.02	0.011	0.005	99
	L-2	Base course	4.30E-05	50	28	ML	0.50	0.280	0.130	N/A
	L-3	Subbase course	4.30E-05	50	46	ML	0.50	0.280	0.130	N/A
High-end	H-1	Top course	48	24	7.6	-[j]	0.24	0.020	0.007	97
	H-2	Base course	35	39	5.1	GP	0.39	0.032	0.013	N/A
	H-3	Subbase course	35	39	25	GP	0.39	0.032	0.013	N/A
Shoulder (paved with portland cement concrete)										
Low-end	L-1	Top course	2.00E-10	1	29	-[h]	0.01	0.006	0.003	99
	L-2	Subbase course	4.30E-05	50	47	ML	0.50	0.280	0.130	N/A
High-end	H-1	Top course	48	1	15	-[j]	0.35	0.028	0.011	97
	H-2	Subbase course	35	39	11	GP	0.39	0.032	0.013	N/A
Median (unpaved)										
Low-end	L-1	Base course	4.30E-05	50	28	ML	0.50	0.280	0.130	72
	L-2	Subbase course	4.30E-05	50	46	ML	0.50	0.280	0.130	N/A
High-end	H-1	Base course	35	39	5.1	GP	0.39	0.032	0.013	72
	H-2	Subbase course	35	39	25	GP	0.39	0.032	0.013	N/A

(continued)

Table 6-17. Material Properties Used in the HELP Model to Estimate Default Infiltration Rates for Roadway Module

	Layer	Description	Hydraulic Conductivity (cm/sec)	Air void (%)	Thickness (cm)[a]	Texture[b]	Total Porosity[c] (vol/vol)	Field Capacity[c] (vol/vol)	Wilting Point[c] (vol/vol)	Curve Number[d]
Median (paved with asphaltic concrete)										
Low-end	L-1	Top course	1.00E-05	2[e]	22	-[f]	0.02	0.011	0.005	99
	L-2	Base course	4.30E-05	50	28	ML	0.50	0.280	0.130	N/A
	L-3	Subbase course	4.30E-05	50	46	ML	0.50	0.280	0.130	N/A
High-end	H-1	Top course	48[g]	24	7.6	-[h]	0.24	0.020	0.007	97
	H-2	Base course	35	39	5.1	GP	0.39	0.032	0.013	N/A
	H-3	Subbase course	35	39	25	GP	0.39	0.032	0.013	N/A
Median (paved with portland cement concrete)										
Low-end	L-1	Top course	2.00E-10	1	33	-[f]	0.01	0.006	0.003	99
	L-2	Base course	4.30E-05	50	28	ML	0.50	0.280	0.130	N/A
	L-3	Subbase course	4.30E-05	50	46	ML	0.50	0.280	0.130	N/A
High-end	H-1	Top course	48	35	20	-[h]	0.35	0.028	0.011	97
	H-2	Base course	35	39	5.1	GP	0.39	0.032	0.013	N/A
	H-3	Subbase course	35	39	25	GP	0.39	0.032	0.013	N/A
Embankment										
Low-end	L-1	Base course	4.30E-05	50	56	ML	0.50	0.280	0.130	72
High-end	H-1	Base course	35	39	56	GP	0.39	0.032	0.013	72

[a] Layer thicknesses were obtained from Jackson and Puccinelli (2006).

[b] Texture: the soil texture types are classified according to two standard systems–U.S. Department of Agriculture and Unified Soil Classification System. According to the latter, ML denotes silt; and GP denotes gravel.

[c] Source: Schroeder et al. (1996).

[d] Source: USDA (1986).

[e] Low-end: parameter set expected to yield minimum infiltration.

[f] High-end: parameter set expected to yield maximum infiltration.

[g] Air voids for top courses were based on Tables 6.1 and 7.1 of Apul et al. (2002) for asphaltic concrete and portland cement concrete, respectively. Air voids for base/subbase courses were based on HELP parameters for ML and GP (Table 1, HELP User's Guide).

[h] Soil texture type unavailable. Field capacity and permanent wilting point were determined from the total porosity using the ratios of field capacity/total porosity, and permanent wilting point/total porosity from ML.

[i] High hydraulic conductivity value for the top course is based on an assumption that each square meter of the pavement is traversed by three 5-cm wide fractures. A similar value may be obtained using Ridgway (1976) infiltration data and Equation 9.1 in Apul et al. (2002). High hydraulic conductivity for base and subbase courses were obtained from pg. 90 of Apul et al. (2002). Low hydraulic conductivity values were obtained from Apul et al. (2002).

[j] Soil texture type unavailable. Field capacity and permanent wilting point were determined from the total porosity using the ratios of field capacity/total porosity, and permanent wilting point/total porosity from GP.

Table 6-18. Infiltration Rates (m/yr) for Common Pavement Types: Pavements and Embankments

Region	Zone	Selected Station[a]	Within-Zone Precipitation	5-Year Average Precipitation (m/yr)[a]	Infiltration Rate for Asphaltic Concrete		Infiltration Rate for Portland Cement Concrete		Infiltration Rate for Embankment	
					HIGH[b]	LOW[b]	HIGH[b]	LOW[b]	HIGH[b]	LOW[b]
Deep-freeze	A1	Montpelier, VT	Lowest	0.88	0.25	0.12	0.27	3.0E-05	0.41	0.16
		New Haven, CT	Highest	1.3	0.39	0.17	0.42	4.1E-05	0.86	0.41
	A2	Rapid City, SD	Lowest	0.39	0.11	0.010	0.11	1.9E-05	0.19	0.018
		Syracuse, NY	Highest	1.2	0.34	0.14	0.35	3.6E-05	0.67	0.31
	A3	Cheyenne, WY	Lowest	0.28	0.062	0.011	0.068	2.0E-05	0.11	0.0043
		Great Falls, MT	Highest	0.46	0.13	0.0058	0.13	2.3E-05	0.21	0.031
	A4	Fairbanks, AK	Lowest	0.24	0.090	0.052	0.092	2.3E-05	0.11	0.02
		Annette, AK	Highest	2.6	1.0	0.33	1.1	6.1E-05	2.1	1.6
Moderate - freeze	B1	Philadelphia, PA	Lowest	1.1	0.35	0.16	0.37	3.8E-05	0.72	0.27
		Edison, NJ	Highest	1.3	0.39	0.17	0.41	3.8E-05	0.84	0.37
	B2	Dodge City, KS	Lowest	0.5	0.15	0.056	0.16	2.1E-05	0.30	0.064
		Nashville, TN	Highest	1.4	0.45	0.12	0.47	4.6E-05	1.0	0.49
	B3	Grand Junction, CO	Lowest	0.18	0.041	4.3E-05	0.017	2.3E-05	0.055	7.4E-05
		Flagstaff, AZ	Highest	0.54	0.15	0.0015	0.092	2.5E-05	0.25	0.069
	B4	Las Vegas, NV	Lowest	0.13	0.047	0.0015	0.025	1.2E-05	0.069	0.00076
		Salt Lake City, UT	Highest	0.41	0.14	0.0010	0.10	2.3E-05	0.20	0.053
No-freeze	C1	Tampa, FL	Lowest	0.97	0.27	0.046	0.30	3.3E-05	0.61	0.16
		Tallahassee, FL	Highest	1.7	0.47	0.067	0.50	3.6E-05	1.3	0.65
	C2	Midland, TX	Lowest	0.41	0.13	0.012	0.12	2.1E-05	0.25	0.050
		New Orleans, LA	Highest	1.8	0.47	0.060	0.50	3.8E-05	1.3	0.66
	C3	Phoenix, AZ	Lowest	0.2	0.060	0.0015	0.030	1.2E-05	0.096	0.00025
		Tucson, AZ	Highest	0.26	0.068	0.0015	0.028	1.9E-05	0.11	0.00025
	C4	Fresno, CA	Lowest	0.26	0.10	0.00025	0.056	1.5E-05	0.15	0.038
		Astoria, OR	Highest	1.7	0.79	0.29	0.81	5.1E-05	1.4	1.1

[a] Two climate stations in each subzone are selected: one with the lowest precipitation and one with the highest precipitation. Precipitation data are from the HELP model database.
[b] Material properties are those of the high- and low-end values of the respective ranges given in Table 6-16.

Table 6-19. Infiltration Rates (m/yr) for Common Pavement Types: Shoulders

Region	Zone	Selected Station[a]	Within-Zone Precipitation	5-Year Average Precipitation (m/yr)[a]	Infiltration Rate for Shoulder (unpaved)		Infiltration Rate for Shoulder (paved with asphaltic concrete)		Infiltration Rate for Shoulder (paved with portland cement concrete)	
					HIGH[b]	LOW[b]	HIGH[b]	LOW[b]	HIGH[b]	LOW[b]
Deep-freeze	A1	Montpelier, VT	Lowest	0.88	0.41	0.16	0.25	0.03	0.26	6.6E-05
		New Haven, CT	Highest	1.3	0.86	0.41	0.39	0.056	0.41	7.6E-05
	A2	Rapid City, SD	Lowest	0.39	0.19	0.017	0.11	0.0010	0.10	5.3E-05
		Syracuse, NY	Highest	1.2	0.67	0.31	0.34	0.047	0.35	7.1E-05
	A3	Cheyenne, WY	Lowest	0.28	0.11	0.004	0.062	0.0036	0.065	4.8E-05
		Great Falls, MT	Highest	0.46	0.21	0.030	0.13	0.00076	0.12	5.8E-05
	A4	Fairbanks, AK	Lowest	0.24	0.11	0.024	0.090	0.053	0.092	4.8E-05
		Annette, AK	Highest	2.6	2.1	1.6	1.0	0.23	1.1	1.2E-04
Moderate - freeze	B1	Philadelphia, PA	Lowest	1.1	0.72	0.27	0.35	0.044	0.37	9.1E-05
		Edison, NJ	Highest	1.3	0.84	0.37	0.39	0.053	0.41	1.0E-04
	B2	Dodge City, KS	Lowest	0.5	0.30	0.065	0.15	0.020	0.15	6.4E-05
		Nashville, TN	Highest	1.4	1.01	0.49	0.45	0.034	0.47	9.9E-05
	B3	Grand Junction, CO	Lowest	0.18	0.024	6.1E-05	0.026	7.6E-06	0.016	6.6E-05
		Flagstaff, AZ	Highest	0.54	0.18	0.068	0.11	0.00127	0.090	5.8E-05
	B4	Las Vegas, NV	Lowest	0.13	0.041	0.00076	0.035	0.00025	0.024	3.0E-05
		Salt Lake City, UT	Highest	0.41	0.16	0.053	0.14	0.00051	0.082	5.6E-05
No-freeze	C1	Tampa, FL	Lowest	0.97	0.61	0.16	0.27	0.014	0.29	7.4E-05
		Tallahassee, FL	Highest	1.7	1.3	0.65	0.47	0.017	0.49	9.1E-05
	C2	Midland, TX	Lowest	0.41	0.25	0.050	0.13	0.007	0.12	4.8E-05
		New Orleans, LA	Highest	1.8	1.3	0.66	0.47	0.015	0.50	9.7E-05
	C3	Phoenix, AZ	Lowest	0.2	0.056	5.6E-05	0.041	8.9E-05	0.026	3.3E-05
		Tucson, AZ	Highest	0.26	0.052	0.00025	0.042	0.00025	0.025	5.1E-05
	C4	Fresno, CA	Lowest	0.26	0.10	0.037	0.077	0.00025	0.058	3.8E-05
		Astoria, OR	Highest	1.7	1.4	1.1	0.79	0.22	0.81	0.00011

[a] Two climate stations in each subzone are selected: one with the lowest precipitation and one with the highest precipitation. Precipitation data are from the HELP model database.
[b] Material properties are those of the high- and low-end values of the respective ranges given in Table 6-16.

Table 6-20. Infiltration Rates (m/yr) for Common Pavement Types: Medians

Region	Zone	Selected Station[a]	Within-Zone Precipitation	5-Year Average Precipitation (m/yr)	Infiltration Rate for Median (unpaved)		Infiltration Rate for Median (paved with asphaltic concrete)		Infiltration Rate for Median (paved with portland cement concrete)	
					HIGH[b]	LOW[b]	HIGH[b]	LOW[b]	HIGH[b]	LOW[b]
Deep-freeze	A1	Montpelier, VT	Lowest	0.88	0.41	0.16	0.25	0.12	0.27	2.5E-05
		New Haven, CT	Highest	1.3	0.86	0.41	0.39	0.17	0.42	3.3E-05
	A2	Rapid City, SD	Lowest	0.39	0.19	0.017	0.11	0.0097	0.11	1.9E-05
		Syracuse, NY	Highest	1.2	0.67	0.31	0.34	0.14	0.35	2.8E-05
	A3	Cheyenne, WY	Lowest	0.28	0.11	0.0041	0.062	0.011	0.068	1.7E-05
		Great Falls, MT	Highest	0.46	0.21	0.030	0.13	0.0056	0.13	2.1E-05
	A4	Fairbanks, AK	Lowest	0.24	0.11	0.02	0.090	0.052	0.092	1.7E-05
		Annette, AK	Highest	2.6	2.1	1.6	1.0	0.33	1.1	4.6E-05
Moderate - freeze	B1	Philadelphia, PA	Lowest	1.1	0.72	0.27	0.35	0.16	0.37	3.6E-05
		Edison, NJ	Highest	1.3	0.84	0.37	0.39	0.17	0.41	3.6E-05
	B2	Dodge City, KS	Lowest	0.5	0.30	0.065	0.15	0.056	0.16	2.2E-05
		Nashville, TN	Highest	1.4	1.0	0.49	0.45	0.12	0.47	3.6E-05
	B3	Grand Junction, CO	Lowest	0.18	0.024	6.1E-05	0.026	4.3E-05	0.037	2.0E-05
		Flagstaff, AZ	Highest	0.54	0.18	0.068	0.11	0.0018	0.15	2.2E-05
	B4	Las Vegas, NV	Lowest	0.13	0.041	0.00076	0.035	0.0015	0.043	1.1E-05
		Salt Lake City, UT	Highest	0.41	0.16	0.053	0.14	0.0013	0.14	2.1E-05
No-freeze	C1	Tampa, FL	Lowest	0.97	0.61	0.16	0.27	0.047	0.30	2.5E-05
		Tallahassee, FL	Highest	1.7	1.3	0.65	0.47	0.069	0.50	3.3E-05
	C2	Midland, TX	Lowest	0.41	0.25	0.050	0.13	0.012	0.12	1.6E-05
		New Orleans, LA	Highest	1.8	1.3	0.66	0.47	0.060	0.50	2.8E-05
	C3	Phoenix, AZ	Lowest	0.2	0.056	5.6E-05	0.041	0.0015	0.057	1.0E-05
		Tucson, AZ	Highest	0.26	0.052	0.00025	0.042	0.00152	0.067	1.7E-05
	C4	Fresno, CA	Lowest	0.26	0.10	0.037	0.077	0.00025	0.096	1.3E-05
		Astoria, OR	Highest	1.7	1.4	1.1	0.79	0.29	0.82	3.8E-05

[a] Two climate stations in each subzone are selected: one with the lowest precipitation and one with the highest precipitation. Precipitation data are from the HELP model database.
[b] Material properties are those of the high- and low-end values of the respective ranges given in Table 6-16.

Table 6-21. Runoff Rates (m/yr) for Common Pavement Types: Pavements and Embankments

Region	Zone	Selected Station[a]	Within-Zone Precipitation	5-Year Average Precipitation (m/yr)[a]	Runoff Rate for Asphaltic Concrete		Runoff Rate for Portland Cement Concrete		Runoff Rate for Embankment	
					HIGH[b]	LOW[b]	HIGH[b]	LOW[b]	HIGH[b]	LOW[b]
Deep-freeze	A1	Montpelier, VT	Lowest	0.88	0.39	0.60	0.38	0.79	0.21	0.25
		New Haven, CT	Highest	1.3	0.58	0.94	0.57	1.2	0.10	0.17
	A2	Rapid City, SD	Lowest	0.39	0.10	0.21	0.10	0.33	0.0086	0.013
		Syracuse, NY	Highest	1.2	0.58	0.89	0.57	1.1	0.23	0.31
	A3	Cheyenne, WY	Lowest	0.28	0.055	0.13	0.055	0.23	0.00076	0.0013
		Great Falls, MT	Highest	0.46	0.11	0.25	0.11	0.39	0.022	0.026
	A4	Fairbanks, AK	Lowest	0.24	0.039	0.097	0.036	0.18	0.010	0.020
		Annette, AK	Highest	2.6	1.2	2.0	1.2	2.5	0.19	0.46
Moderate - freeze	B1	Philadelphia, PA	Lowest	1.1	0.46	0.78	0.45	1.1	0.073	0.12
		Edison, NJ	Highest	1.3	0.61	0.97	0.60	1.3	0.14	0.23
	B2	Dodge City, KS	Lowest	0.5	0.17	0.32	0.17	0.47	0.0033	0.015
		Nashville, TN	Highest	1.4	0.61	1.0	0.60	1.3	0.026	0.11
	B3	Grand Junction, CO	Lowest	0.18	0.019	0.062	0.019	0.15	0	0.00025
		Flagstaff, AZ	Highest	0.54	0.17	0.31	0.17	0.46	0.053	0.083
	B4	Las Vegas, NV	Lowest	0.13	0.028	0.073	0.029	0.13	0	0
		Salt Lake City, UT	Highest	0.41	0.082	0.21	0.081	0.36	0.007	0.014
No-freeze	C1	Tampa, FL	Lowest	0.97	0.37	0.68	0.37	0.95	0.010	0.039
		Tallahassee, FL	Highest	1.7	0.87	1.4	0.86	1.7	0.039	0.16
	C2	Midland, TX	Lowest	0.41	0.15	0.28	0.14	0.41	0.00025	0.0023
		New Orleans, LA	Highest	1.8	0.92	1.4	0.91	1.7	0.056	0.19
	C3	Phoenix, AZ	Lowest	0.2	0.042	0.11	0.042	0.19	0	0
		Tucson, AZ	Highest	0.26	0.055	0.14	0.055	0.25	0	0
	C4	Fresno, CA	Lowest	0.26	0.059	0.15	0.060	0.25	0	0.00076
		Astoria, OR	Highest	1.7	0.62	1.2	0.60	1.6	0.0066	0.12

[a] Two climate stations in each subzone are selected: one with the lowest precipitation and one with the highest precipitation. Precipitation data are from the HELP model database.
[b] Material properties are those of the high- and low-end values of the respective ranges given in Table 6-16.

Table 6-22. Runoff Rates (m/yr) for Common Pavement Types: Shoulders

Region	Zone	Selected Station[a]	Within-Zone Precipitation	5-Year Average Precipitation (m/yr)[a]	Runoff Rate for Shoulder (unpaved)		Runoff Rate for Shoulder (paved with asphaltic concrete)		Runoff Rate for Shoulder (paved with portland cement concrete)	
					HIGH[b]	LOW[b]	HIGH[b]	LOW[b]	HIGH[b]	LOW[b]
Deep-freeze	A1	Montpelier, VT	Lowest	0.88	0.21	0.25	0.39	0.60	0.38	0.79
		New Haven, CT	Highest	1.3	0.10	0.17	0.58	0.93	0.57	1.2
	A2	Rapid City, SD	Lowest	0.39	0.0086	0.013	0.10	0.20	0.10	0.33
		Syracuse, NY	Highest	1.2	0.23	0.31	0.58	0.88	0.57	1.1
	A3	Cheyenne, WY	Lowest	0.28	0.00076	0.0013	0.055	0.13	0.055	0.23
		Great Falls, MT	Highest	0.46	0.022	0.026	0.11	0.24	0.11	0.39
	A4	Fairbanks, AK	Lowest	0.24	0.010	0.020	0.039	0.097	0.036	0.18
		Annette, AK	Highest	2.6	0.19	0.46	1.2	2.0	1.2	2.5
Moderate - freeze	B1	Philadelphia, PA	Lowest	1.1	0.073	0.12	0.46	0.78	0.45	1.1
		Edison, NJ	Highest	1.3	0.14	0.23	0.61	0.97	0.60	1.3
	B2	Dodge City, KS	Lowest	0.5	0.0033	0.015	0.17	0.32	0.17	0.47
		Nashville, TN	Highest	1.4	0.026	0.11	0.61	1.0	0.60	1.3
	B3	Grand Junction, CO	Lowest	0.18	0	0.00025	0.019	0.061	0.019	0.15
		Flagstaff, AZ	Highest	0.54	0.054	0.083	0.17	0.30	0.17	0.46
	B4	Las Vegas, NV	Lowest	0.13	0	0	0.029	0.072	0.029	0.13
		Salt Lake City, UT	Highest	0.41	0.007	0.014	0.082	0.20	0.082	0.36
No-freeze	C1	Tampa, FL	Lowest	0.97	0.010	0.039	0.37	0.68	0.37	0.95
		Tallahassee, FL	Highest	1.7	0.039	0.16	0.87	1.4	0.86	1.7
	C2	Midland, TX	Lowest	0.41	0.00025	0.0023	0.15	0.28	0.14	0.41
		New Orleans, LA	Highest	1.8	0.056	0.18	0.92	1.4	0.91	1.7
	C3	Phoenix, AZ	Lowest	0.2	0	0	0.042	0.11	0.042	0.19
		Tucson, AZ	Highest	0.26	0	0	0.055	0.14	0.055	0.25
	C4	Fresno, CA	Lowest	0.26	0	0.00076	0.060	0.15	0.060	0.25
		Astoria, OR	Highest	1.7	0.0066	0.12	0.62	1.2	0.60	1.6

[a] Two climate stations in each subzone are selected: one with the lowest precipitation and one with the highest precipitation. Precipitation data are from the HELP model database.
[b] Material properties are those of the high- and low-end values of the respective ranges given in Table 6-16.

Table 6-23. Runoff Rates (m/yr) for Common Pavement Types: Medians

Region	Zone	Selected Station[a]	Within-Zone Precipitation	5-Year Average Precipitation (m/yr)[a]	Runoff Rate for Median (unpaved)		Runoff Rate for Median (paved with asphaltic concrete)		Runoff Rate for Median (paved with portland cement concrete)	
					HIGH[b]	LOW[b]	HIGH[b]	LOW[b]	HIGH[b]	LOW[b]
Deep-freeze	A1	Montpelier, VT	Lowest	0.88	0.21	0.25	0.39	0.60	0.38	0.79
		New Haven, CT	Highest	1.3	0.10	0.17	0.58	0.94	0.57	1.2
	A2	Rapid City, SD	Lowest	0.39	0.0086	0.013	0.10	0.21	0.10	0.33
		Syracuse, NY	Highest	1.2	0.23	0.31	0.58	0.89	0.57	1.1
	A3	Cheyenne, WY	Lowest	0.28	0.00076	0.0013	0.055	0.13	0.055	0.23
		Great Falls, MT	Highest	0.46	0.022	0.026	0.11	0.25	0.11	0.39
	A4	Fairbanks, AK	Lowest	0.24	0.010	0.020	0.039	0.097	0.036	0.18
		Annette, AK	Highest	2.6	0.19	0.46	1.2	2.0	1.2	2.5
Moderate - freeze	B1	Philadelphia, PA	Lowest	1.1	0.073	0.12	0.46	0.78	0.45	1.1
		Edison, NJ	Highest	1.3	0.14	0.23	0.61	0.97	0.60	1.3
	B2	Dodge City, KS	Lowest	0.5	0.0033	0.015	0.17	0.32	0.17	0.47
		Nashville, TN	Highest	1.4	0.026	0.11	0.61	1.0	0.60	1.3
	B3	Grand Junction, CO	Lowest	0.18	0	0.00025	0.019	0.062	0.019	0.15
		Flagstaff, AZ	Highest	0.54	0.054	0.083	0.17	0.31	0.17	0.46
	B4	Las Vegas, NV	Lowest	0.13	0	0	0.029	0.073	0.028	0.13
		Salt Lake City, UT	Highest	0.41	0.007	0.014	0.082	0.21	0.081	0.36
No-freeze	C1	Tampa, FL	Lowest	0.97	0.010	0.039	0.37	0.68	0.37	0.95
		Tallahassee, FL	Highest	1.7	0.039	0.16	0.87	1.4	0.86	1.7
	C2	Midland, TX	Lowest	0.41	0.00025	0.0023	0.15	0.28	0.14	0.41
		New Orleans, LA	Highest	1.8	0.056	0.18	0.92	1.4	0.91	1.7
	C3	Phoenix, AZ	Lowest	0.2	0	0	0.042	0.11	0.042	0.19
		Tucson, AZ	Highest	0.26	0	0	0.055	0.14	0.055	0.25
	C4	Fresno, CA	Lowest	0.26	0	0.00076	0.060	0.15	0.059	0.25
		Astoria, OR	Highest	1.7	0.0066	0.12	0.62	1.2	0.60	1.6

[a] Two climate stations in each subzone are selected: one with the lowest precipitation and one with the highest precipitation. Precipitation data are from the HELP model database.
[b] Material properties are those of the high- and low-end values of the respective ranges given in Table 6-16.

Table 6-24. Climatic Zones and Corresponding Embankment Evaporation Rates from HELP (m/yr)

Freezing Index	Zone[a]	Station[b]	5-Year Ave Evaporation[c]	
			Low-end Inputs	High-end Inputs
Deep-freeze	A1	Montpelier, VT	0.26	0.48
		New Haven, CT	0.30	0.68
	A2	Rapid City, SD	0.20	0.35
		Syracuse, NY	0.31	0.60
	A3	Cheyenne, WY	0.17	0.27
		Great Falls, MT	0.22	0.40
	A4[d]	Fairbanks, AK	0.11	0.18
		Annette, AK	0.36	0.57
Moderate-freeze	B1	Philadelphia, PA	0.31	0.71
		Edison, NJ	0.35	0.74
	B2	Dodge City, KS	0.20	0.42
		Nashville, TN	0.36	0.79
	B3	Grand Junction, CO	0.13	0.18
		Flagstaff, AZ	0.22	0.37
	B4	Las Vegas, NV	0.066	0.13
		Salt Lake City, UT	0.21	0.35
No-freeze	C1	Tampa, FL	0.35	0.76
		Tallahassee, FL	0.42	0.92
	C2	Midland, TX	0.16	0.36
		New Orleans, LA	0.41	0.94
	C3	Phoenix, AZ	0.10	0.19
		Tucson, AZ	0.14	0.25
	C4[d]	Fresno, CA	0.11	0.22
		Astoria, OR	0.27	0.47

Notes:

[a] Zone geographical coverage is given in Figure 6-7.

[b] Two climate stations in each subzone are selected: one with the lowest precipitation, and the other with the highest precipitation.

[c] Evaporation data are obtained from HELP model with embankment.

[d] Zone A4 comprises Alaska only. Hawaii is incorporated into Zone C4 (not shown in Figure 6-7).

Table 6-25. Climatic Zones and Corresponding Pan Evaporation Rate Ranges from NOAA (m/yr)

Freezing Index	Zone[a]	Station[b]	Pan Evaporation[c]	
Deep-freeze	A1	Montpelier, VT	0.57	1.1
		New Haven, CT	1.0	1.8
	A2	Rapid City, SD	1.2	1.3
		Syracuse, NY	0.57	1.1
	A3	Cheyenne, WY	1.0	1.8
		Great Falls, MT		
	A4[d]	Fairbanks, AK	1.3	
		Annette, AK		
Moderate-freeze	B1	Philadelphia, PA	1.3	
		Edison, NJ		
	B2	Dodge City, KS	1.2	2.4
		Nashville, TN	1.3	3.1
	B3	Grand Junction, CO	1.1	2.8
		Flagstaff, AZ	1.4	1.6
	B4	Las Vegas, NV	1.2	2.2
		Salt Lake City, UT	2.8	3.0
No-freeze	C1	Tampa, FL	1.0	3.1
		Tallahassee, FL	1.2	2.4
	C2	Midland, TX	1.3	3.1
		New Orleans, LA	1.1	2.8
	C3	Phoenix, AZ	1.4	1.6
		Tucson, AZ	1.2	2.2
	C4[d]	Fresno, CA	2.8	3.0
		Astoria, OR		

Notes:

[a] Zone geographical coverage is given in Figure 6-7.

[b] Two climate stations in each zone are selected: one with the lowest precipitation, and the other with the highest precipitation.

[c] Source of Pan Evaporation data: NOAA (1982).

[d] Zone A4 comprises Alaska only. Hawaii is incorporated into Zone C4 (not shown in Figure 6-7).

6.4.3.3 Procedure for Estimating Subgrade Infiltration in Climatic Zones

Using the information presented in the above sections, the IWEM user can estimate generic subgrade infiltration rates by following the steps below.

- **Step 1** Determine the appropriate climatic zone using Figure 6-7.
- **Step 2** Consists of two sub-steps:
  - ***Step 2a*** Determine the range (high–low) of subgrade infiltration from Tables 6-18 to 6-20 for a given pavement type (i.e., asphaltic concrete pavement, portland cement concrete pavement, unpaved shoulder, asphaltic concrete shoulder, portland cement concrete shoulder, unpaved median, asphaltic concrete median, portland cement concrete median, and embankment). For a given zone, if the precipitation at the user's site is between the zone-specific maximum and minimum values used in Tables 6-18 to 6-20, the user may obtain preliminary estimates of the location-specific minimum and maximum subgrade infiltration rates by linearly interpolating between respective

subgrade infiltration rates associated with minimum and maximum precipitations in the table. In the event that the high and low subgrade infiltration rates are not significantly different, the user may use the mean value instead of both the high and low values. Both high and low infiltration rates are recommended to bracket the range of uncertainty.

– ***Step 2b*** In the event that the climatic conditions, pavement configurations, and drainage systems at the user's site are different from those given in Tables 6-17 to 6-23 and that the user wishes refine the range of subgrade infiltration rate obtained from Step 2a to closely reflect the climatic conditions at the user's site, it is recommended that the user run the HELP model with site-specific climatic conditions and drainage configurations.

It should be noted that the pavement infiltration rate should not exceed lowest value of the saturated hydraulic conductivity of the underlying pavement layers. This principle is applicable to both the with-drainage and without-drainage pavement systems. The IWEM module performs this check.

6.4.3.4 Procedure for Estimating Runoff and Evaporation in Climatic Zones

If a ditch is present, it will be necessary to estimate runoff from the nearby pavement and evaporation from the ditch in order to estimate the exfiltration rate[5] from the ditch. Similar to the procedure outlined above in **Section 6.4.3.3**, based on a known climatic zone, the corresponding rates of runoff, soil evaporation, and pan evaporation can be obtained from Tables 6-21 to 6-23 (runoff), Table 6-24 (evaporation), and Table 6-25 (pan evaporation). However, as always, site-specific values for these parameters are preferred. If the ditch evaporation rate is not known, it is recommended that the user perform screening analyses with the soil evaporation rate (Table 6-24), pan evaporation rate (Table 6-25), and a mean value of the two rates.

6.4.4 Recharge Rates

The HELP model (Schroeder et al, 1994) was used to compute recharge rates for all sources. The factors related to soil type that affect the HELP-generated recharge rates are the permeability of the soil used in the landfill cover, and – in the case of recharge or for land application units – the permeability of the soil type in the vicinity of the source. HELP was used to calculate recharge for the three primary soil types across the United States (sandy loam, silty loam, and silty clay loam soils) and ambient climate conditions at 102 climate stations through the use of the HELP water-balance model as summarized in **Section 6.4.1**. We assumed the ambient regional recharge rate for a given climate center and soil type (for all source types) is the same as the corresponding unlined landfill infiltration rate.

6.5 Parameters Used to Describe the Unsaturated and Saturated Zones

Parameter values for the unsaturated and saturated zone modeling in IWEM were obtained from a number of data sources. A primary data source was the Hydrogeologic Database for Ground-water Modeling (HGDB), assembled by Rice University on behalf of the American Petroleum Institute (Newell, 1989). This database provides probability distributions of a number of key ground water modeling parameters for various types of subsurface environments.

[5] Exfiltration is defined as the process of water percolating down to the unsaturated zone from the bottom of a ditch.

For unsaturated zone modeling, a database of soil hydraulic properties for various soil types, assembled by Carsel and Parrish (1988), was used in combination with information from the Soil Conservation Service on the nationwide prevalence of different soil types across the United States.

Table 6-26 summarizes the parameters used to characterize subsurface parameters. The last column indicates where the user can find a detailed discussion of each parameter in this document. The *IWEM v3.1 User's Guide* (U.S. EPA, 2015a) provides additional guidance in selecting values for these parameters.

Table 6-26. Summary of IWEM Subsurface Parameters

Modeling Element	Description or Value	Section Reference
General Subsurface Parameters		
Subsurface environment	Optional user input; default is unknown subsurface environment	6.5.1
Depth to ground water (m)	Optional user input; default derived from subsurface environment if known, otherwise national average value (5.18 m)	6.5.1
Saturated Zone Hydraulic Conductivity (m/yr)	Optional user input; default derived from subsurface environment if known, otherwise national average (1890 m/y)	6.5.1
Saturated Zone Hydraulic Gradient	Optional user input; default derived from subsurface environment if known, otherwise national average (0.0057 m/m)	6.5.1
Saturated Zone Thickness (m)	Optional user input; default derived from subsurface environment if known, otherwise national average (10.1 m)	6.5.1
Unsaturated Zone Parameters		
Soil Hydraulic Parameters: (Hydraulic conductivity; saturated water content; residual water content; moisture retention curve parameters)	Distribution of values corresponding to three major soil types (sandy loam, silt loam, and silty clay loam). Probability of occurrence of each soil type based on nationwide distribution	6.5.2
Soil Bulk density (kg/L)	Assigned based on selected soil type (sandy loam, silt loam, or silty clay loam)	6.5.2
Soil Percent Organic Matter (%)	Distribution of values corresponding to three major soil types (sandy loam, silt loam, and silty clay loam). Probability of occurrence of each soil type based on nationwide distribution	6.5.2
Soil Temperature (°C)	Assigned based on Source location	6.5.2
Unsaturated Zone pH	Assumed to be same as saturated zone pH; nationwide distribution derived from STORET ground water quality database	6.5.2
Saturated Zone Parameters		
Saturated Zone Porosity	Derived from nationwide distribution of mean aquifer particle diameter	6.5.3
Saturated Zone Bulk Density (kg/L)	Derived from saturated zone porosity	6.5.3
Saturated Zone Fraction Organic Carbon	Nationwide distribution derived from STORET water quality database	6.5.3
Saturated Zone Temperature (°C)	Assigned based on Source location	6.5.3
Saturated Zone pH	Nationwide distribution derived from STORET water quality database	6.5.3

6.5.1 Subsurface Parameters

The database, HGDB, provides site-specific data on four key subsurface parameters:[6]

- Depth to ground water;
- Saturated zone thickness;
- Saturated zone hydraulic conductivity; and
- Saturated zone hydraulic gradient.

The data in this hydrogeological database were collected by independent investigators for approximately 400 hazardous waste sites throughout the United States.

In HGDB, the data are grouped into 12 subsurface environments, which are based on EPA's DRASTIC classification of hydrogeologic settings (U.S. EPA, 1987). **Table 6-27** lists the subsurface environments. The table includes a total of 13 categories; 12 are distinct subsurface environments, while the 13th category, which is labeled "other" or "unknown", was used for waste sites that could not be classified into one of the first 12 environments. The subsurface parameter values in this 13th category are simply averages of the parameter values in the 12 actual subsurface environments. Details on the individual parameter distributions for each subsurface environment are provided in the *EPACMTP Parameters/Data Background Document* (U.S. EPA, 2003b).

The key feature of this database is that it provides a set of correlated values of the four parameters for each of the 400 sites in the database. That is, the value of each parameter is associated with the three other subsurface parameters reported for the same site. These correlations were preserved, because having information on some parameters allows the development of more accurate estimates for missing parameter values.

In IWEM, the type of subsurface environment, as well as each of the four individual subsurface parameters (depth to ground water, saturated thickness, saturated hydraulic conductivity, and hydraulic gradient) are optional, site-specific user inputs. Depending on the extent of available site data, IWEM will use statistical correlations developed from the HGDB to estimate missing or unknown parameters. If site-specific values for all four parameters are known, then IWEM will use these values and in this case, information on the type of subsurface environment is not needed. If one or more of the four subsurface parameters are unknown, but the type of subsurface environment at the site is known, IWEM will use the known parameters to generate a probability distribution for the unknown parameters, using the statistical correlations that correspond to the type of environment at the site. If no site-specific hydrogeologic information is known, IWEM will treat the site as being in subsurface environment number 13 and assign values that are national averages.

[6] The database also provides data on ground water seepage velocity and on "vertical penetration depth" of a waste plume below the water table. These data were not used. EPACMTP calculates the ground water velocity directly, and the vertical penetration depth is not used in EPACMTP.

Table 6-27. HGDB Subsurface Environments (from Newell, 1989)

Region	Description
1	Metamorphic and Igneous
2	Bedded Sedimentary Rock
3	Till Over Sedimentary Rock
4	Sand and Gravel
5	Alluvial Basins Valleys and Fans
6	River Valleys and Floodplains with Overbank Deposit
7	River Valleys and Floodplains without Overbank Deposits
8	Outwash
9	Till and Till Over Outwash
10	Unconsolidated and Semi-consolidated Shallow Aquifers
11	Coastal Beaches
12	Solution Limestone
13	Other (Not classifiable)

6.5.2 Unsaturated Zone Parameters

Soil Hydraulic Parameters. Data on unsaturated hydraulic properties assembled by Carsel and Parrish (1988) were used in conjunction with information from the Soil Conservation Service on the nationwide prevalence of different soil types across the United States to model flow of infiltration water through the unsaturated zone. First, Soil Conservation Service soil mapping data were used to estimate the relative prevalence of light- (sandy loam), medium- (silt loam), and heavy-textured (silty clay loam) soils across the United States. The estimated percentages are shown in **Table 6-28**. The soil types used in the unsaturated zone modeling were also used in the HELP model to derive infiltration and recharge rates (see **Section 6.4**) in order to have a consistent set of soil modeling parameters. The Carsel and Parrish (1988) soil property data were used to determine the probability distributions of individual soil parameters for each soil type, and these distributions were used in the Monte Carlo modeling for IWEM. **Table 6-29** presents the unsaturated zone parameter values used in IWEM. The development of the distributions and use of the parameters presented in Table 6-29 is described in detail in Section 5.2.3 of the *EPACMTP Parameters/Data Background Document* (U.S. EPA, 2003b).

Table 6-28. Nationwide Distribution of Soil Types Represented in IWEM

Texture Category	Soil Conservation Service Soil Type	Relative Frequency (%)
Light textured	Sandy Loam	15.4
Medium textured	Silt Loam	56.6
Heavy textured	Silty Clay Loam	28.0

Table 6-29. Statistical Parameters for Soil Properties for Three Soil Types Used in IWEM Development (Carsel and Parrish, 1988)

Parameter[1]	Distribution Type[2]	Limits of Variation		Mean	Standard Deviation
		Minimum	Maximum		
Soil Type–Silty Clay Loam					
Ksat (cm/hr)	SB	0	3.5	0.017	2.921
θr	NO	0	0.115	0.089	0.0094
α (cm^{-1})	SB	0	0.15	.009	.097
β	NO	1.0	1.5	1.236	0.061
% OM	SB	0	8.35	0.11	5.91
ρb	Constant	-	-	1.67	-
θs	Constant	-	-	0.43	-
Soil Type–Silt Loam					
Ksat (cm/hr)	LN	0	15.0	0.343	0.989
θr	SB	0	0.11	0.068	0.071
α (cm^{-1})	LN	0	0.15	0.019	0.012
β	SB	1.0	2.0	1.409	1.629
% OM	SB	0	8.51	0.105	5.88
ρb	Constant	-	-	1.65	-
θs	Constant	-	-	0.45	-
Soil Type–Sandy Loam					
K_{sat} (cm/hr)	SB	0	30.0	2.296	24.65
θ_r	SB	0	0.11	0.065	0.074
α (cm^{-1})	SB	0	0.25	0.070	0.171
β	LN	1.35	3.00	1.891	0.155
% OM	SB	0	11.0	0.074	7.86
ρ_b	Constant	-	-	1.60	-
θ_s	Constant	-	-	0.41	-

[1] K_{sat} is saturated hydraulic conductivity; θ_r is residual water content; α, β are retention curve parameters; % OM is percent Organic Matter, ρ_b is bulk density; θ_s is saturated water content.

[2] NO is Normal (Gaussian) distribution; SB is Log ratio distribution where Y = ln [(x-A)/(B-x)], A < x < B; LN is Log normal distribution, Y = ln [x], where Y = normal distributed parameter

The parameters α, β, and θ_r in Table 6-29 are specific to the Mualem-Van Genuchten model that is employed in the EPACMTP unsaturated zone flow module described in **Section 4.1** (see the *EPACMTP Technical Background Document*, U.S. EPA, 2003a, for details).

Soil Bulk Density and Percent Organic Matter. These soil transport parameters are used to calculate the constituent-specific retardation coefficients, the unsaturated zone dispersivity, and the soil pH and temperature. The latter two parameters are used to calculate hydrolysis transformation rates; pH is also a key parameter for modeling transport of metals. Soil bulk density and percent organic matter were obtained from the Carsel and Parrish (1988) database and are presented in Table 6-29. These parameters are used to calculate the retardation factor in the constituent transport equation (see Equation 4-1 in **Section 4.1**). We used the data on the percent organic matter to calculate the fraction organic carbon, assuming that 58% of soil organic matter is organic carbon:[7]

$$f_{oc} = \frac{\% OM}{1.74 \times 100} \tag{6-2}$$

where:

f_{oc}	=	Mass fraction organic carbon in the soil (kg/kg)
$\% \ OM$	=	Percent organic matter (%)
1.74	=	Conversion factor (=1/0.58) (dimensionless)
100	=	Conversion factor (% to mass fraction).

Dispersivity in the unsaturated zone, α_{uz}, is calculated as a function of the travel distance (D_u,) between the base of the source and the water table, according to the following relationship:

$$\alpha_{uz} = 0.02 + (0.022 \times D_u) \tag{6-3}$$

where:

α_{uz}	=	longitudinal dispersivity in the unsaturated zone (m)
D_u	=	Depth of the unsaturated zone, from the base of the source to the water table (m).

This relationship is based on a regression analysis of field scale transport data presented by Gelhar et al. (1985). The maximum allowed value of dispersivity is capped at 1 m in IWEM. The development of Equation 6-3 is described in detail in Section 3.9 of the *EPACMTP Technical Background Document* (U.S. EPA, 2003a).

Soil temperature and pH were obtained from nationwide distributions. The same distributions were used for the entire subsurface, that is, both for the unsaturated zone and for the saturated zone. In IWEM, a nationwide aquifer pH distribution, derived from EPA's STORET database, was used. The pH distribution is an empirical distribution with a median value of 6.8 and lower and upper bounds of 3.2 and 9.7, respectively, as shown in **Table 6-30**. The development of the pH distribution in Table 6-30 is described in detail in Section 5.3.10 of the *EPACMTP Parameters/Data Background Document* (U.S. EPA, 2003b).

Table 6-30. Probability Distribution of Soil and Aquifer pH

Percentile	0	1	5	10	25	50	75	90	95	99	100
pH Value	3.20	3.60	4.50	5.20	6.07	6.80	7.40	7.90	8.2	8.95	9.7

As modeled in IWEM, soil and aquifer temperature affects the transformation rate of constituents that are subject to hydrolysis, through the effect of temperature on reaction rates (see **Section 6.6.1**). In the IWEM development, average annual temperatures in shallow ground water systems (Todd, 1980) were used to assign a temperature value to each climate center (Figure 6-6) in the modeling database, based on the climate center's geographical location. For each climate center, the assigned temperature was an average of the upper and lower values for that temperature region, as shown in **Figure 6-8**. In other words, all climate centers located in the band between 10°C and 15°C were assigned a temperature value of 12.5 °C.

[7] This is a typical value; see, for example, http://soilquality.org/indicators/total_organic_carbon.html.

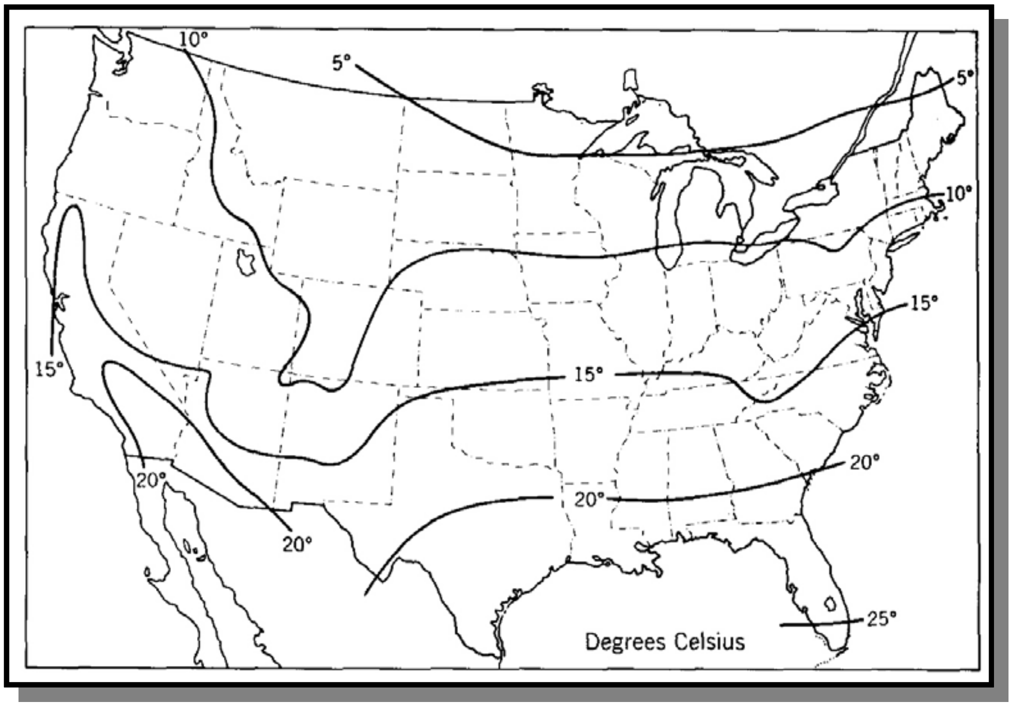


Figure 6-8. Ground water temperature distribution for shallow aquifers in the United States (from Todd, 1980).

IWEM Monte Carlo Methodology for Soil Parameters. In IWEM, soil properties are assumed to be uniform at each site. A new set of soil parameters is selected for each iteration in the Monte Carlo modeling process, but the soil properties were assumed uniform for a given simulation. However, the methodology for assigning soil types differed. In IWEM, the soil type is an optional site-specific user input parameter. Because the site location must always be entered by the user, the selection of the soil type determines the recharge rate, as well as the HELP-derived infiltration rates which the IWEM tool will use in the evaluation. Based on the selected soil type, the IWEM tool will randomly select values for the parameters in Table 6-29 from the probability distributions corresponding to the soil type. If the soil type is entered as “unknown,” the Monte Carlo process for the unsaturated zone parameters will randomly select one of the three possible soil types in accordance with their nationwide frequency of occurrence.

6.5.3 Saturated Zone Parameters

In addition to the four site-related subsurface parameters discussed in **Section 6.5.1**, IWEM requires a number of additional saturated zone transport parameters. They are: saturated zone porosity; saturated zone bulk density; longitudinal, transverse and vertical dispersivities; fraction organic carbon; aquifer temperature; and aquifer pH.

Saturated zone porosity is used in the calculation of the ground water seepage velocity; saturated zone porosity and bulk density are used in the calculation of constituent-specific retardation coefficients. IWEM uses default, nationwide distributions for aquifer porosity and bulk density, that is, they are not user inputs. Both were derived from a distribution of aquifer particle diameter presented by Shea (1974). This distribution is presented in **Table 6-31**. Using the data in Table 6-30 as an input distribution, IWEM calculates porosity, *N*, from particle diameter using an empirical relationship based on data reported by Davis (1969) as:

$$N = 0.261 - 0.0385 \times \ln(d) \tag{6-4}$$

where

N = Porosity (dimensionless)
d = Mean particle diameter (cm)
ln = Natural logarithm.

Additionally, relationships presented in McWorther and Sunada (1977) were used to establish relationships between total (N) and effective porosity (N_e) as a function of mean particle diameter, see **Table 6-32**. The development of Equation 6-4 and the distributions in Table 6-31 and Table 6-32 are described in detail in Section 5.3.2 of the *EPACMTP Parameters/Data Background Document* (U.S. EPA, 2003b).

Table 6-31. Empirical Distribution of Mean Aquifer Particle Diameter (from Shea, 1974)

Percentile	0.0	3.8	10.4	17.1	26.2	37.1	56.0	79.2	90.4	94.4	97.6	100
Particle Diameter (cm)	3.9×10^{-4}	7.8×10^{-4}	0.0016	0.0031	0.0063	0.0125	0.025	0.05	0.1	0.2	0.4	0.8

Table 6-32. Ratio Between Effective and Total Porosity as a Function of Particle Diameter (after McWorther and Sunada, 1977)

Mean Particle Diameter (cm)	N_e/N Range
$< 6.25\times10^{-3}$	0.03–0.77
$6.25\times10^{-3} – 2.5\times10^{-2}$	0.04–0.87
$2.5\times10^{-2} – 5.0\times10^{-2}$	0.31–0.91
$5.0\times10^{-2} – 10^{-1}$	0.58–0.94
$> 10^{-1}$	0.52–0.95

Dispersivity. IWEM calculates apparent saturated zone dispersivities as a function of the distance between the waste unit and the modeled ground water well, using regression relationships based on a compilation of field-scale dispersivity data in Gelhar et al. (1985). These relationships are:

$$\begin{aligned} \alpha_L(x) &= \alpha_L^{REF} \times (x/152.4)^{0.5} \\ \alpha_T &= \alpha_L/8 \\ \alpha_V &= \alpha_L/160 \end{aligned} \tag{6-5}$$

where

α_L = longitudinal dispersivity (m)
x = downgradient ground water travel distance (m)
α_L^{REF} = reference dispersivity value (m)
α_T = horizontal transverse dispersivity (m)
α_V = vertical transverse dispersivity (m).

A longitudinal dispersivity corresponding to a distance of 152.4 m was used as a reference to calculate dispersivity at different well distances, according to the probability distribution presented in **Table 6-33**. The development of Equation 6-5 and the distribution in Table 6-33 are described in detail in Section 5.3.8 of the *EPACMTP Parameters/Data Background Document* (U.S. EPA, 2003b).

Table 6-33. Cumulative Probability Distribution of Longitudinal Dispersivity at Reference Distance of 152.4 m

Percentile	0.0	1.00	70.0	100.0
Dispersivity, α_L^{REF} (m)	0.1	1.0	10.0	100.0

Bulk Density and Fraction Organic Carbon. Sorption of organic constituents was modeled using data such as the fraction organic carbon (f_{oc}), as discussed in **Section 4.1** (Equation 4-5). In the development of IWEM, a nationwide distribution obtained from values of dissolved organic carbon in EPA's STORET water quality database was used. The distribution was modeled as a Johnson SB frequency distribution (see *EPACMTP Parameters/Data Background Document*, U.S. EPA, 2003b) with a mean of 4.32×10^{-4}, a standard deviation of 0.0456, and lower and upper limits of 0.0 and 0.064, respectively.

Temperature and pH. Values of the ground water temperature and pH were determined in the same way as soil pH and temperature (see **Section 6.5.2**).

6.6 Parameters Used to Characterize the Chemical Fate of Constituents

For IWEM evaluations, the chemical fate of constituents as they are transported through the subsurface is presented in terms of an overall first-order decay coefficient, a retardation coefficient which reflects equilibrium sorption reactions, and for transformation daughter-products, a production term that represents the formation of daughter compounds due to the transformation of parent constituents. This section describes how constituent-specific parameter values were developed for these chemical fate processes. **Section 6.6.1** describes constituent transformation processes, while **Section 6.6.2** discusses all constituent degradation processes. **Section 6.6.3** describes how we modeled sorption processes.

Table 6-34 summarizes the parameters used to characterize the chemical fate of constituents. The last column indicates where the user can find a detailed discussion of each parameter in this document. The *IWEM v3.1 User's Guide* (U.S. EPA, 2015a) provides additional guidance in selecting values for these parameters.

Table 6-34. Summary of IWEM Chemical Fate Parameters

Modeling Element	Description or Value	Section Reference
	Constituent Transformation Parameters	
Hydrolysis Rate (yr^{-1})	IWEM accounts for hydrolysis transformation reactions using constituent-specific hydrolysis rate constants.	6.6.1
Overall (Bio-) degradation (yr^{-1})	Other types of (bio-) degradation processes can be entered as optional constituent-specific parameters.	6.6.1
	Constituent Sorption Parameters	
Soil-Water Partition Coefficient (K_d) (kg/L)	For organic constituents, equilibrium sorption is taken into account via constituent-specific organic carbon partition coefficients; for metals, effective equilibrium partition coefficients are generated using the MINTEQA2 geochemical speciation model.	6.6.2.1, 6.6.2.2

6.6.1 Constituent Transformation

For organic constituents, IWEM accounts for chemical and biological transformations by considering a first-order overall degradation coefficient in the transport analysis (see **Section 4.1**). The default hydrolysis rate coefficients in the IWEM constituent database can be replaced with a user-specified overall degradation rate that can account for any type of transformation process, including biodegradation.

Hydrolysis Rate. Hydrolysis refers to the transformation of chemical constituents through reactions with water. For organic constituents, hydrolysis can be one of the main degradation processes that occur in soil and ground water and is represented in the EPACMTP model by means of an overall first-order chemical decay coefficient. For modeling hydrolysis in IWEM, we used constituent-specific hydrolysis rate constants compiled at the EPA's Environmental Research Laboratory in Athens, GA (Kollig, 1993). These are listed in **Appendix B**.

The hydrolysis process as modeled in IWEM is affected by aquifer pH, aquifer temperature, and constituent sorption through the following equations. The tendency of each constituent to hydrolyze is expressed through constituent-specific acid-catalyzed, neutral, and base-catalyzed rate constants. The values of the rate constants are modified to account for the effect of aquifer temperature through the Arrhenius equation:

$$K_J^T = K_J^{T_r} \exp\left[\frac{E_a}{R}\left(\frac{1}{T_r+273} - \frac{1}{T+273}\right)\right] \quad (6\text{-}6)$$

where:

K_J^T	=	Hydrolysis rate constant for reaction process J at temperature T (1/mole/yr for acid or base catalyzed, and 1/yr for neutral)
$K_J^{T_r}$	=	Hydrolysis rate constant for reaction process J at reference temperature, T_r (1/mole/yr for acid or base catalyzed, and 1/yr for neutral)
J	=	*a* for acid-catalyzed, *b* for base-catalyzed, and *n* for neutral
T	=	Temperature of the subsurface (°C)
T_r	=	Reference temperature (°C)
273	=	Conversion factor from °C to K
R	=	Universal gas constant (1.987×10^{-3} Kcal/K-mole)
E_a	=	Arrhenius activation energy (Kcal/mole).

Next, the effect of pH on hydrolysis rates is incorporated via:

$$\lambda_1 = K_a^T[H^+] + K_n^T + K_b^T[OH^-] \quad (6\text{-}7)$$

where

λ_1	=	First-order decay rate for dissolved phase (1/yr)
K_a^T	=	Acid-catalyzed hydrolysis rate constant (1/mole/yr)
$[H^+]$	=	Hydrogen ion concentration (mole/L)
K_n^T	=	Neutral hydrolysis rate constant (1/yr)
K_b^T	=	Based-catalyzed hydrolysis rate constant (1/mole/yr)
$[OH^-]$	=	Hydroxyl ion concentration (mole/L).

$[H^+]$ and $[OH^-]$ are computed from the pH of the soil or aquifer using:

$$[H^+] = 10^{-pH} \quad (6\text{-}8)$$

$$[OH^-] = 10^{-(14-pH)} \quad (6\text{-}9)$$

The sorbed phase hydrolysis rate is calculated as:

$$\lambda_2 = 10K_a^T[H^+] + K_n^T \quad (6\text{-}10)$$

where:

λ_2	=	First-order hydrolysis rate for sorbed phase (1/yr)
K_a^T	=	Acid-catalyzed hydrolysis rate constant (1/mole/yr)
K_n^T	=	Neutral hydrolysis rate constant (1/yr)
10	=	Acid-catalyzed hydrolysis enhancement factor.

Finally, the overall first-order transformation rate for hydrolysis is calculated as:

$$\lambda = \frac{\lambda_1 N + \lambda_2 \rho_b K_d}{N + \rho_b K_d} \quad (6\text{-}11)$$

where:

λ	=	Overall first-order hydrolysis transformation rate (1/yr)
λ_1	=	Dissolved phase hydrolysis transformation rate (1/yr)
λ_2	=	Sorbed phase hydrolysis transformation rate (1/yr)
N	=	Porosity (water content in the unsaturated zone) (dimensionless)
ρ_b	=	Bulk density (L/kg)
K_d	=	Partition coefficient (kg/L).

Toxic hydrolysis daughter products were identified using the information on hydrolysis transformation pathways presented in Kollig (1993).

Biodegradation and Overall Degradation Rate. Many organic constituents may be subject to biodegradation in the subsurface, and the IWEM tool allows the user to provide a constituent-specific overall degradation coefficient, which can include either aerobic or anaerobic biodegradation. However, IWEM does not specifically simulate biodegradation reactions. The IWEM user must, therefore, ensure that the value entered is representative of actual site conditions, and that the transformation reactions can be adequately characterized as a first-order rate process (i.e., process that can be represented in terms of a characteristic half-life). The overall degradation rate parameter that is used as an IWEM input is related to the constituent's subsurface half-life and is expressed as:

$$\lambda = \frac{0.693}{t_{1/2}} \quad (6\text{-}12)$$

where

λ	=	IWEM degradation rate input value (1/yr)
0.693	=	Natural log of 2 (dimensionless)
$t_{1/2}$	=	Constituent half-life (yr).

6.6.2 Constituent Sorption

In addition to physical and biological transformation processes, the transport of constituents can be affected by a wide range of complex geochemical reactions. From a practical view, the important aspect of these reactions is the removal of solute from solution, irrespective of the process. For this reason, IWEM lumps the cumulative effects of the geochemical processes into a single term (i.e., solid-water partition coefficient), which is one of several parameters needed to describe the degree a constituent's mobility is retarded relative to ground water. In the EPACMTP fate and transport model upon which IWEM is based, this process is defined by the retardation factor defined in **Section 4.1** (Equation 4-5). The remainder of this section describes the procedures that IWEM uses to model sorption for organic constituents and inorganic constituents, specifically, metals.

6.6.2.1 Sorption Modeling for Organic Constituents

For organic constituents, K_d values are calculated as the product of the constituent-specific K_{oc} and the fraction organic carbon in the soil or ground water:

$$K_d = K_{oc} \times f_{oc} \tag{6-13}$$

where

K_d = partition coefficient (L/kg)
K_{oc} = normalized organic carbon distribution coefficient (kg/L)
f_{oc} = fractional organic carbon content (dimensionless).

K_{oc} values for IWEM constituents are listed in **Appendix B**. For IWEM, the fraction organic carbon in the unsaturated zone was calculated from the percent organic matter in the soil as shown in Equation 6-2 (see **Section 6.5.2**).

In the saturated zone modeling, direct values for f_{oc} were based on the nationwide data on the fraction organic carbon in ground water (see **Section 6.5.3**).

6.6.2.2 Sorption Modeling for Inorganic Constituents

Partition coefficients (K_d) for inorganics in IWEM are selected from non-linear sorption isotherms estimated using the geochemical speciation model, MINTEQA2. For a particular inorganic species, K_d values in a soil or aquifer are dependent upon the species concentration and various geochemical characteristics of the soil or aquifer and the associated porewater. The approach and development of non-linear sorption isotherms and their use in EPACMTP are described in detail in Appendix G of the *EPACMTP Technical Background Document* (U.S. EPA, 2003a) and in Appendix B of the *EPACMTP Parameters/Data Background Document* (U.S. EPA, 2003b).

Geochemical parameters that have the greatest influence on the magnitude of K_d include the pH of the system and the nature and concentration of sorbents associated with the soil or aquifer matrix. In the subsurface beneath a disposal facility, the concentration of leachate constituents may also influence K_d. Although the dependence of metal partitioning on the total metal concentration and on pH and other geochemical characteristics is apparent from partitioning studies reported in the scientific literature, the reported K_d values for individual metals do not cover the range of metal concentrations or geochemical conditions relevant in the IWEM scenarios. For this reason, the Agency chose to use an equilibrium speciation model, MINTEQA2, to estimate inorganic metal partition coefficients for the IWEM development.

From input data consisting of total concentrations of the inorganic chemicals, the model calculates the fraction of a constituent that is dissolved, adsorbed, and precipitated at equilibrium. The ratio of the adsorbed fraction to the dissolved fraction is the dimensionless partition coefficient. The dimensionless partition coefficient for each inorganic species was converted to K_d with units of L/kg by normalizing the mass of soil (in kg) with one liter of porewater in which it is equilibrated (U.S. EPA, 2003a,b). Isotherms are generated when the equilibrium metal distribution between sorbed and dissolved fraction are estimated for a series of input total concentrations.

Using MINTEQA2, the list of inorganic species for which adsorption isotherms were developed are listed on the right side. For these inorganic species, two sets of isotherms are provided in IWEM based on the characterization of leachate data used for MINTEQ2 modeling (discussed below).

Aluminum (Al^{3+})
Antimony (Sb^{5+})
Arsenic (As^{3+}, As^{5+})
Barium (Ba)
Beryllium (Be)
Boron (B)
Cadmium (Cd)
Chromium (Cr^{3+}, Cr^{6+})
Cobalt (Co)
Copper (Cu)
Fluoride (F)
Iron (Fe^{2+})
Manganese (Mn^{2+})
Mercury (Hg)
Lead (Pb)
Molybdenum (Mo^{5+})
Nickel (Ni)
Selenium (Se^{4+}, Se^{6+})
Silver (Ag)
Thallium (Tl^{1+})
Vanadium (V^{5+})
Zinc (Zn)

MINTEQA2 Input Parameters. The expected natural variability in Kd for a particular metal was accounted for in the MINTEQA2 modeling by including variability in important input parameters upon which Kd depends. The input parameters for which variability was incorporated include ground water compositional type, pH, concentration of sorbents, and concentration of metal (U.S. EPA, 2003a,b). In addition, the concentration of representative anthropogenic organic acids that may be present in leachate from a waste site were varied.

Two ground water compositional types were modeled– one with composition representative of a carbonate-terrain system and one representative of a non-carbonate system. The two ground water compositional types are correlated with the subsurface environment (see **Section 6.5.1**, Table 6-27). The carbonate type corresponds to the "solution limestone" subsurface environment setting. The other 11 subsurface environments in IWEM are represented by the non-carbonate ground water type. If the subsurface environment is "unknown," then IWEM will also assume it is a non-carbonate type. For both ground water types, a representative, charge-balanced ground water chemistry specified in terms of major ion concentrations and natural pH was selected from the literature. The carbonate system was represented by a sample reported in a limestone aquifer. This ground water had a natural pH of 7.5 and was saturated with respect to calcite. The non-carbonate system was represented by a sample reported from an unconsolidated sand and gravel aquifer with a natural pH of 7.4, selected because it is the most frequently occurring of the 12 subsurface environments in HGDB.

Two types of adsorbents were used in modeling the K_d values: ferric oxide and particulate organic matter **(**U.S. EPA, 2003a, b). Mineralogically, the ferric oxide was assumed to be goethite (FeOOH). To represent the interactions of protons and metals with the goethite surface, a database of sorption reactions for goethite reported by Mathur (1995) was used with the diffuse-layer sorption model in MINTEQA2. The concentration of sorption sites used in the model runs was based on a measurement of ferric iron extractable from soil samples using hydroxylamine hydrochloride as reported in EPRI (1986). This method of Fe extraction is intended to provide a measure of the exposed amorphous hydrous oxide of Fe present as mineral coatings and discrete particles and available for surface reaction with pore water. The variability in ferric oxide content represented by the variability in extractable Fe from these samples was included in the modeling by selecting low, medium and high ferric oxide concentrations corresponding to the 17th, 50th, and 83rd percentiles of the sample measurements. The specific surface area and site density used in the diffuse-layer model were as prescribed by Mathur. Although the same distribution of extractable ferric oxide sorbent was used in the saturated and unsaturated zones, the actual concentration of sorbing sites corresponding to the low, medium, and high ferric oxide settings in MINTEQA2 was different in the two zones because the phase ratio was different (4.57 kg/L in the unsaturated zone; 3.56 kg/L in the saturated zone).

The concentration of the second adsorbent, percent organic matter was obtained from organic matter distributions already present in the IWEM modeling database. In the unsaturated zone, low, medium, and high concentrations for components representing percent organic matter in the MINTEQA2 model runs were based on the distribution of solid organic matter for the silt loam soil type. (The silt loam soil type is intermediate in weight percent organic matter in comparison with the sandy loam and silty clay loam soil types and is also the most frequently occurring soil type among the three.) The low, medium, and high percent organic matter concentrations used in the saturated zone MINTEQA2 model runs were obtained from the organic matter distribution for the saturated zone. For both the ferric oxide and percent organic matter adsorbents, the amount of sorbent included in the MINTEQA2 modeling was scaled to correspond with the phase ratio in the unsaturated and saturated zones.

A dissolved organic matter distribution for the saturated zone was obtained from the EPA's STORET database. This distribution was used to provide low, medium, and high dissolved organic matter concentrations for the MINTEQA2 model runs. The low, medium, and high dissolved organic matter values were used exclusively with the low, medium, and high values, respectively, of percent organic matter. In the unsaturated zone, there was no direct measurement of dissolved organic matter available. The ratio of percent organic matter to dissolved organic matter for the three concentration levels (low, medium, and high) in the unsaturated zone was assumed to be the same as for the saturated zone. In MINTEQA2, the percent organic matter and dissolved organic matter components were modeled using the Gaussian distribution model. This model includes a database of metal- dissolved organic matter reactions (Susetyo et al., 1991). Metal reactions with percent organic matter were assumed to be identical in their mean binding constants with the dissolved organic matter reactions.

As mentioned above, two sets of isotherms are provided in IWEM based on the characteristic of the leachate data used for MINTEQ2 modeling. For the first case, sorption isotherms were developed using leachate data that represent acid conditions at the base of a landfill resulting from decaying organic matter (U.S EPA, 2003a, b). Many organic acids found in landfill leachate have significant metal-complexing capacity that may influence metal mobility. Representative carboxylic acids for leachate from industrial WMUs were included in the MINTEQA2 modeling. An analysis of total organic carbon in landfill leachate by Gintautas et al. (1993) was used to select and quantify the organic acids. The low, medium, and high values for the representative acids in the modeling were assigned based on the lowest, the average, and the highest measured total organic carbon among the six landfill leachates analyzed. Because leachate from industrial WMUs is expected to be lower in organic matter than in municipal landfills, only the low and medium leachate organic acids values were included in IWEM. The isotherms developed using this leachate are available for all WMUs, structural fill, and roadway modules.

For the second set, the agency developed nonlinear sorption isotherms based on leachate data specific to coal combustion residuals (CCRs) disposal sites, which is known to span a broad pH range – from acidic pH =2 to highly alkaline pH =13 (U.S.EPA, 2014b). This dataset contains Kds for CCR waste types that include ash, ash and coal, flue gas desulfurization (FGD), and fluidized bed combustion (FBC). The user is referred to Appendix H of the (U.S. EPA, 2014b) for detailed discussion of the development of CCR-specific isotherms using MINTEQA2. These isotherms[8] are available for the roadway module only in this version of IWEM.

MINTEQA2 Modeling and Results. The MINTEQA2 modeling was conducted separately for each metal in three steps for the unsaturated zone, and these were repeated for the saturated zone:

- Sorbents were pre-equilibrated with ground waters: Each of nine possible combinations of the two ferric oxide and percent organic matter sorbent concentrations (low ferric oxide, low percent organic matter; low ferric oxide, medium percent organic matter; etc.) were equilibrated with each of the two ground water types (carbonate and non-carbonate). Because the sorbents adsorb some ground water constituents (calcium, magnesium, sulfate, fluoride), the input total concentrations of these constituents were adjusted so that their equilibrium dissolved concentrations in the model were equal to their original (reported) ground- water dissolved concentrations. This step was conducted at the natural pH of each ground water, and calcite was imposed as an equilibrium mineral for the carbonate ground water type. Small additions of inert ions were added to maintain charge balance.
- The pre-equilibrated systems were titrated to new target pHs. Each of the nine pre-equilibrated systems for each ground water type were titrated with sodium hydroxide to raise the pH or with nitric acid to lower the pH. Nine target pHs spanning the range 4.5 to 8.2 were used for the non-carbonate ground water. Three target pHs spanning the range 7.0 to 8.0 were used for the carbonate ground water. Titration with acid or base to adjust the pH allowed charge balance to be maintained.
- Leachable organic acids and the constituent metal were added. Each of the 81 pre-equilibrated, pH-adjusted systems of the non-carbonate ground water and the 27 pre-equilibrated, pH-adjusted systems of the carbonate ground water were equilibrated with two concentrations (low and medium) of leachable organic acids. The equilibrium pH was not imposed in MINTEQA2; pH was calculated and reflected the acid and metal additions. The constituent metal was added as a metal salt (e.g., $PbNO_3$) at a series of 44 total concentrations spanning the range 0.001 mg/L to 10,000 mg/L of metal. Equilibrium composition and K_d were calculated at each of the forty-four total metal concentrations to produce an isotherm of sorbed metal versus metal concentration. The isotherm can also be expressed as K_d versus metal concentration.

This modeling resulted in 81 isotherms for the non-carbonate environment and 27 isotherms for the carbonate environment for the unsaturated zone. A like number of isotherms for each environment was produced for the saturated zone. Each isotherm corresponds to a particular setting of ferric oxide sorbent concentration, percent organic matter sorbent (and associated dissolved organic matter) concentration, leachate acid concentration, and pH. An example isotherm for chromium (VI) is shown in **Figure 6-9**.

[8] Only CCR-specific sorption isotherms are provide for aluminum, boron, and iron ions, thus these constituents are not available for WMUs and structural fill modules.

For chromium, arsenic, and selenium, isotherms were calculated for two environmentally relevant oxidation states. The different oxidation states of these metals have different geochemical behavior, and in the case of chromium also distinctly different toxicological behavior. Chromium (III) exhibits behavior typical of a cation, but chromium (VI) behaves as an anion (chromate). Chromium (III) and chromate are most strongly sorbed at opposite ends of the pH spectrum: sorption of Chromium (III) tends to increase with pH over the pH range 4 to 8, whereas sorption of chromate tends to decrease with pH over this range.

The two oxidation states of arsenic and selenium also exhibit differences in sorption behavior. Therefore, both forms of arsenic and selenium are incorporated in IWEM. The user may select the more mobile species for a more conservative evaluation. The more mobile oxidation state was determined by running EPACMTP with both sets of isotherms for these metals. The results indicate that arsenic (III) and selenium (VI) are the more mobile forms.

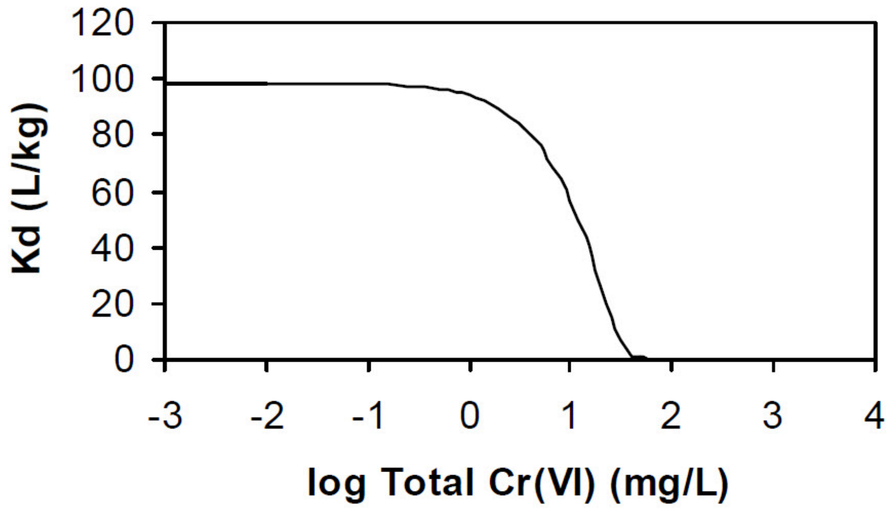


Figure 6-9. Unsaturated zone isotherm for chromium (VI) (non-carbonate environment, low leachate organic acids, medium ferric oxide, high percent organic matter, pH 6.3).

6.7 Screening Procedures EPA Used to Eliminate Unrealistic Parameter Combinations in the Monte Carlo Process

Inherent to the Monte Carlo process is that parameter values are drawn from multiple data sources and then combined in each iteration of the modeling process. Because the parameter values are drawn randomly from their individual probability distributions, it is possible that parameters are combined in ways that are physically infeasible and that violate the validity of the EPACMTP flow and transport model. Therefore, a number of checks were implemented to eliminate or reduce these occurrences as much as possible.

As a relatively simple measure, upper and lower limits are specified on individual parameter values to ensure that their randomly generated values are within physically realistic limits. Where possible, data sources were used that contained multiple parameters, and the Monte Carlo process was implemented in a way that preserved the existing correlations among the parameters.

Upper and lower limits were implemented on secondary parameters whose values are calculated (derived) internally in the Monte Carlo module as functions of the primary EPACMTP input parameters (see the *EPACMTP Parameters/Data Background Document*, U.S. EPA, 2003b). A set of screening procedures was also implemented to ensure that infiltration rates and the resulting predicted ground water mounding would remain physically plausible. Specifically, parameter values generated in each Monte Carlo iteration were screened for the following conditions:

- Infiltration and recharge so high that they cause the water table to come into contact with the bottom of landfills, waste piles, structural fills, roadways or rise above the ground surface;
- Water level in a surface impoundment unit below the water table, causing flow into the surface impoundment;
- Infiltration rate from a surface impoundment exceeds the saturated hydraulic conductivity of the soil underneath.

These screening procedures are discussed in more detail below. Mathematical details of the screening algorithms are presented in the *EPACMTP Technical Background Document* (U.S. EPA, 2003a).

The logic diagram for the infiltration screening procedure is presented in **Figure 6-10**, and **Figure 6-11** provides a graphical illustration of the screening criteria. The numbered criteria checks in Figure 6-10 correspond to the numbered diagrams in Figure 6-11. Note that high infiltration rates are most likely with (unlined) surface impoundments. Therefore, the screening procedure is the most involved for surface impoundment WMUs.

Figure 6-10(a) depicts the screening procedures for landfills, waste piles, land application units, structural fills and average, effective infiltration rate through roadways. For these source types, after user-supplied default and randomly generated parameters are selected for each Monte Carlo simulation, IWEM calculates the estimated water table mounding that would result from the selected combination of parameter values. The combination of parameters is accepted if the calculated maximum water table elevation (the ground water “mound”) remains below the bottom of these source types or the ground surface elevation at the site, whichever is lower. If the criterion is not satisfied, the randomly selected parameters for the simulation are rejected and a new data set is selected.

For surface impoundments, there are two additional screening steps, as depicted in Figure 6-10(b). At each Monte Carlo iteration, the user-supplied and default parameters are used to determine whether the surface impoundment unit is hydraulically connected to the water table. If the base of the surface impoundment is below the water table, the surface impoundment unit is said to be hydraulically connected to the water table (see Figure 6-11, Criterion 1). This scenario is rejected and a new set of random parameters is generated if the hydraulically connected surface impoundment is an inseeping type, that is, the water surface in the surface impoundment is below the water table (see Figure 6-11, Criterion 1(b)). As long as the elevation of the waste water surface in the impoundment is above the water table, the first criterion is passed (Figure 6-11, Criterion 1(a)).

If the base of the unit is located above the ambient water table, that is, before any adjustment to the water table elevation to account for mounding is made, the unit is said to be hydraulically separated from the water table (see Figure 6-11, Criterion 2). However, in this case, it is necessary to ensure that the calculated infiltration rate does not exceed the maximum feasible infiltration rate. The maximum feasible infiltration rate is the maximum infiltration that allows the water table to be hydraulically separated from the surface impoundment. In other words, the infiltration rate does not allow the crest of the local ground water mound to be higher than the base of the surface impoundment. This limitation allows IWEM to determine a conservative infiltration rate that is based on the free-drainage condition at the base of the surface impoundment. The infiltration rate is no longer conservative if the water table is allowed to be in hydraulic contact with the base of the surface impoundment. If the maximum feasible infiltration rate (I_{max}) is exceeded, IWEM will set the infiltration rate to this maximum value.

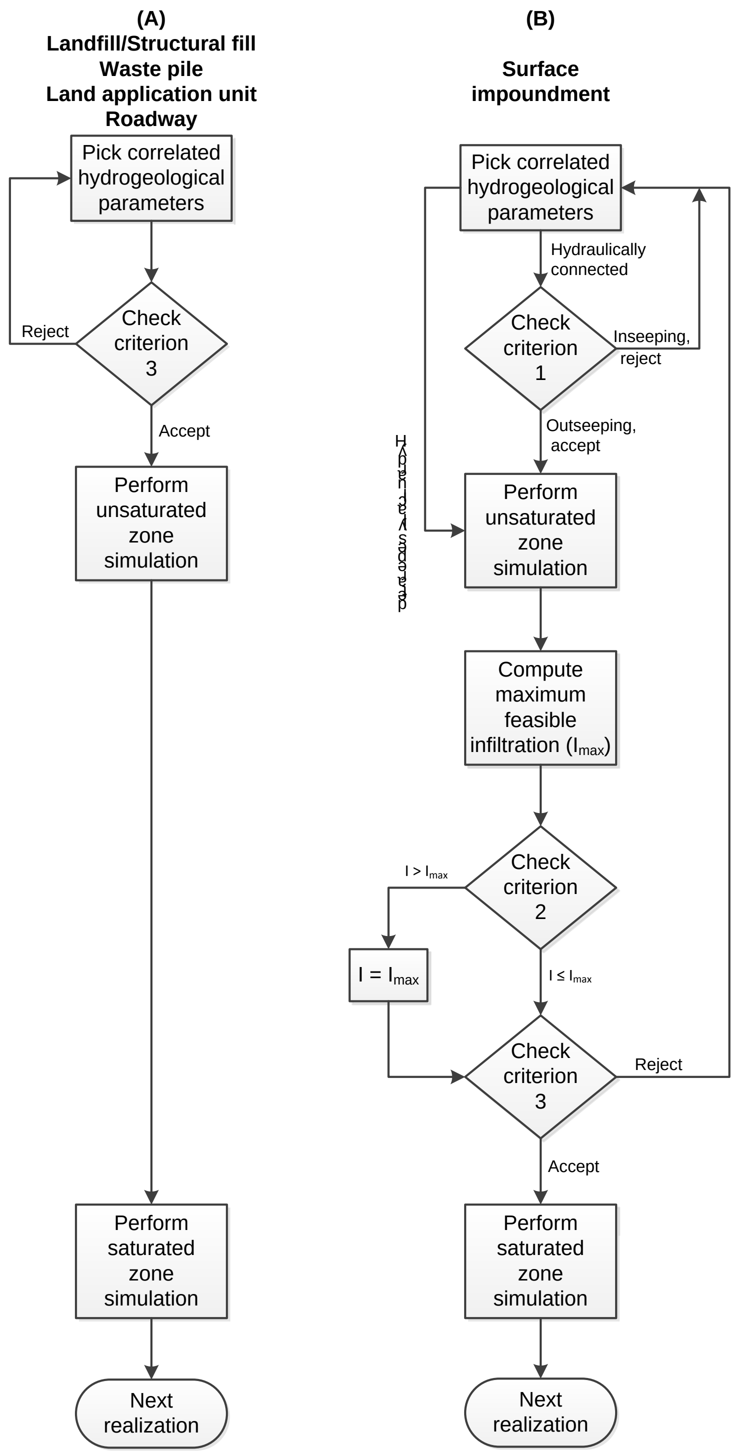


Figure 6-10. Flowchart describing the infiltration screening procedure.

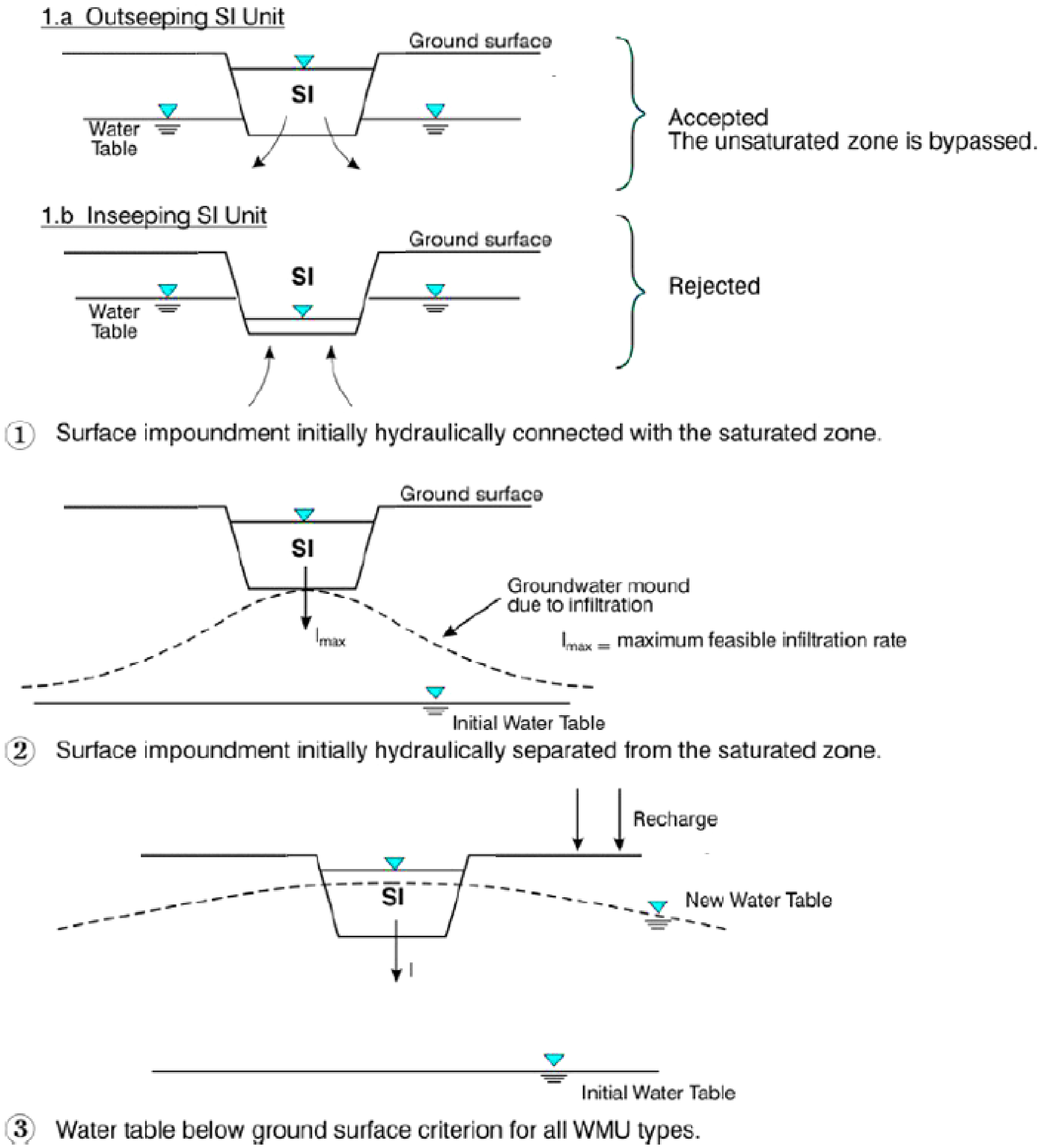


Figure 6-11. Infiltration screening criteria.

IWEM handles the screening in this order to accommodate the internal software logic in EPACMTP. If the surface impoundment is a hydraulically connected type based on the user-supplied information on the impoundment and water table positions, EPACMTP will simulate this system by bypassing the unsaturated zone module. On the other hand, if the hydraulic connection results from water table mounding, i.e., the original water table elevation is below the impoundment, EPACMTP cannot easily handle this situation, and the scenario is therefore rejected.

Once the infiltration limit has been imposed, the third criterion is checked to ensure that any ground water mounding does not result in a rise of the water table mound above the ground surface, in the same manner as done for other types of sources.

In the IWEM software, the parameter constraints are checked after all inputs have been specified, but before the actual EPACMTP Monte Carlo simulations are initiated. The first check applies when the user provides all input parameters as site-specific values. In this case, the software checks that the combination of input values does not violate the infiltration and water table elevation constraints. The second check applies when some inputs are set to site-specific values, while default probability distributions are used for other inputs. In this case, it is possible that the combination of fixed, site-specific values with national or regional distributions, results in a high frequency of rejections in the EPACMTP simulations. An example would be simulating an unlined surface impoundment at a site where the depth to ground water is set to a very small value. This combination is likely to lead to a large number of rejections in the EPACMTP Monte Carlo simulation due to violation of the ground water mounding constraint. This, in turn, may result in very long EPACMTP run times. It also indicates that IWEM may not be appropriate for that site.

IWEM therefore checks the user inputs through a probabilistic screening routine that generates random combinations of EPACMTP parameter values in accordance with the specified inputs and measures the number of rejections. This routine will check that 20,000 acceptable parameter combinations can be generated in 100,000 or less random iterations. If the inputs fail this test, the software will report the most frequently violated constraint and suggest potential remedies in the user inputs.

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7.0 Reference Ground Water Concentrations

This section presents the reference ground water concentrations (RGCs) that IWEM uses for the screening evaluation. An IWEM evaluation can accommodate three types of RGCs:

- Maximum Contaminant Levels (MCLs)
- Health-based numbers (HBNs)
- Other standards (e.g., state standards).

7.1 Maximum Contaminant Levels

MCLs are included in IWEM for 59 constituents for which values are available. MCLs are the highest level of contaminants allowed in public drinking water and are established under the Safe Drinking Water Act. In developing MCLs, EPA considers not only a constituent's health effects, but also additional factors, such as the cost of treatment. The constituent-specific MCL values included in IWEM are provided in **Table 7-1**, and were obtained from the Regional Screening Level Generic Tables (U.S. EPA, 2015b). The values in Table 7-1 are current as of January 2015; however, the IWEM user is urged to check for the latest values.

Table 7-1. MCLs Included in IWEM (Current as of January 30, 2015)[2]

CAS No.	Chemical Name	MCL (mg/L)
7440-36-0	Antimony	0.006
22569-72-8	Arsenic (III)[a]	0.01
15584-04-0	Arsenic (V)[a]	0.01
7440-39-3	Barium	2
71-43-2	Benzene	0.005
50-32-8	Benzo{a}pyrene	0.0002
7440-41-7	Beryllium	0.004
117-81-7	Bis(2-ethylhexyl)phthalate	0.006
75-27-4	Bromodichloromethane	0.08
88-85-7	Butyl-4,6-dinitrophenol,2-sec-	0.007
7440-43-9	Cadmium	0.005
56-23-5	Carbon tetrachloride	0.005
57-74-9	Chlordane[b]	0.002
108-90-7	Chlorobenzene	0.1
124-48-1	Chlorodibromomethane	0.08
67-66-3	Chloroform	0.08
16065-83-1	Chromium (III)	0.1
18540-29-9	Chromium (VI)	0.1
7440-50-8	Copper	1.3
106-46-7	Dichlorobenzene 1,4-	0.075
96-12-8	Dibromo-3-chloropropane 1,2-	0.0002

(continued)

[2] The latest MCLs can be found at http://water.epa.gov/drink/contaminants/#List

CAS No.	Chemical Name	MCL (mg/L)
95-50-1	Dichlorobenzene 1,2-	0.6
107-06-2	Dichloroethane 1,2-	0.005
75-35-4	Dichloroethylene 1,1-	0.007
156-59-2	Dichloroethylene cis-1,2-	0.07
156-60-5	Dichloroethylene trans-1,2-	0.1
94-75-7	Dichlorophenoxyacetic acid 2,4-	0.07
78-87-5	Dichloropropane 1,2-	0.005
72-20-8	Endrin	0.002
100-41-4	Ethylbenzene	0.7
106-93-4	Ethylene dibromide	5E-05
6984-48-8	Fluoride	4
58-89-9	HCH (Lindane) gamma-	0.0002
76-44-8	Heptachlor	0.0004
1024-57-3	Heptachlor epoxide	0.0002
118-74-1	Hexachlorobenzene	0.001
77-47-4	Hexachlorocyclopentadiene	0.05
7439-92-1	Lead	0.015
7439-97-6	Mercury	0.002
72-43-5	Methoxychlor	0.04
75-09-2	Methylene Chloride	0.005
87-86-5	Pentachlorophenol	0.001
1336-36-3	Polychlorinated biphenyls (Aroclors)	0.0005
10026-03-6	Selenium (IV)[c]	0.05
7782-49-2	Selenium (VI)	0.05
100-42-5	Styrene	0.1
1746-01-6	TCDD 2,3,7,8-	3E-08
127-18-4	Tetrachloroethylene	0.005
7440-28-0	Thallium	0.002
108-88-3	Toluene	1
8001-35-2	Toxaphene (chlorinated camphenes)	0.003
75-25-2	Tribromomethane	0.08
120-82-1	Trichlorobenzene 1,2,4-	0.07
71-55-6	Trichloroethane 1,1,1-	0.2
79-00-5	Trichloroethane 1,1,2-	0.005
79-01-6	Trichloroethylene,1,1,2-	0.005
93-72-1	Trichlorophenoxy)propionic acid 2-(2,4,5- (Silvex)	0.05
75-01-4	Vinyl chloride	0.002
1330-20-7	Xylenes (total)	10

[a] Not in Regional Screening Level tables, used value for 7440-38-2 Arsenic, Inorganic as surrogate.

[b] Not in Regional Screening Level tables, used value for 12789-03-6 Chlordane as surrogate.

[c] Not in Regional Screening Level tables, used value for 7782-49-2 Selenium as surrogate.

7.2 Health-Based Numbers

HBNs are the constituent concentrations in ground water that would generally be expected not to cause adverse noncancer health effects in the general population (including sensitive subgroups), or not to result in an additional incidence of cancer in more than some specified fraction of individuals exposed to the constituent (e.g., one in one million) via ingestion, inhalation, or dermal exposure. Calculated HBNs are no longer included in IWEM, but the reader can obtain or calculate their own HBNs and enter them for use in an IWEM evaluation. Not all IWEM constituents have an MCL; thus, for those chemicals, a user-specified HBN or other standard (see **Section 7.3**) is the only evaluation option.

A good online source for HBNs is the "Regional Screening Levels for Chemical Contaminants at Superfund Sites" (http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/index.htm). The Regional Screening Levels site is the product of an interagency effort between the U.S. Department of Energy's Oak Ridge National Laboratory and EPA Regions 3, 6, and 9. The site provides screening levels for more than 700 chemicals for various exposure pathways, as well as a link to the *Regional Screening Levels User's Guide*, which documents all input assumptions and equations used to develop the health-based screening levels.

In addition to health-based screening levels, the Regional Screening Levels website also provides a link to a screening level calculator, the latest toxicity values (e.g., Reference Doses and Cancer Slope Factors), exposure factors, and physical and chemical properties. The reader can use the calculator to develop site-specific HBNs using different assumptions for toxicity values, chemical properties, and exposure factors. Using the Regional Screening Levels Calculator, the reader can also calculate screening levels for chemicals not included in the Regional Screening Levels generic tables and database, provided that the reader can identify and justify input data for toxicity, exposure factors, and chemical properties data.

When the IWEM user enters an HBN, the user will also be required to enter the associated exposure duration. This enables IWEM to average results over the appropriate exposure duration to estimate the RGC. All user-specified cancer HBNs must have the same value for exposure duration for all pathways for a particular chemical (but it can vary from chemical to chemical). Likewise, all user-specified non-cancer HBNs must have the same value for exposure duration for all pathways for a particular chemical. However, the exposure durations for cancer and non-cancer HBNs do not have to be the same.

7.3 Other Standards

The IWEM user can also enter a different standard (such as a state standard) or other user-defined RGCs and associated exposure duration. This allows the user to enter a different standard than the MCL (for example, a California EPA standard or other state standard) if state standards are more stringent than the MCL. The reader can usually find state drinking water standards by searching "[state] drinking water standards" online. For example, California standards can be found at http://www.cdph.ca.gov/certlic/drinkingwater/Pages/MCLsandPHGs.aspx. Not all states have their own standards, preferring to use the federal MCLs.

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8.0 How Does IWEM Make Recommendations?

The objective of the ground water fate and transport model is to determine the extent of dilution and attenuation a constituent may undergo as it migrates from a source to a ground water well and thereby estimate the constituent concentration at the well. The level of dilution and attenuation helps determine the magnitude of exposure concentration that can be compared to RGCs. This section describes the methods used to develop the basis for the recommendations in IWEM.

8.1 Making Recommendations Corresponding to a 90th Percentile Exposure Concentration

Every single simulation of EPACMTP in the Monte Carlo process results in an estimate concentration at the modeled ground water well. Because the estimated ground water concentrations are compared to health-based RGCs, which reflect specific exposure duration assumptions, the ground water concentrations calculated in IWEM represent maximum time-averaged values, as depicted conceptually in **Figure 8-1**

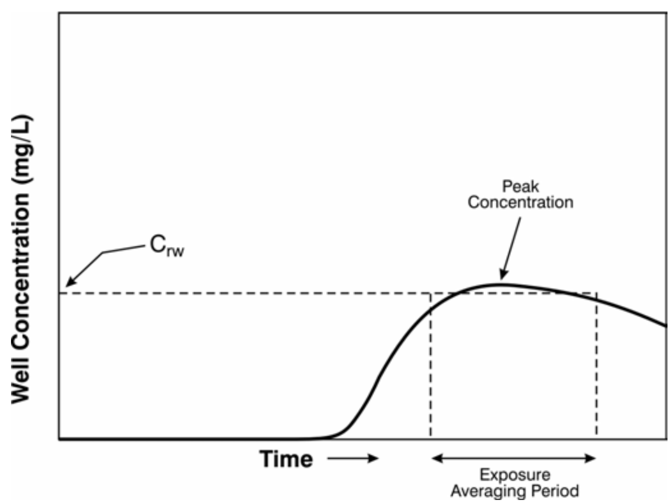

Figure 8-1. Determination of time-averaged ground water well concentration.

Depending on the type of RGC, the IWEM tool uses different averaging times in calculating ground water well concentrations, as follows:

- **MCL:** Peak ground water well concentration
- **User-specified HBNs:** Specified exposure duration
- **Other standards:** Specified exposure duration.

The EPACMTP simulation runs until the observed ground water concentration of a constituent at the well peaks and falls below a model specified concentration (10^{-16} mg/l). The maximum time averaged concentration is calculated around this peak based on a user-specified exposure duration as depicted in Figure 8-1. However, in certain cases (e.g., low infiltration rate, deep unsaturated zone, strongly sorbing constituents), the peak ground water concentration would not occur up to a maximum of 10,000 years after the simulation started. For such cases, EPACMTP would stop the simulation and returns a maximum time-averaged concentration up to 10,000 years.

All user-specified cancer HBNs must have the same value for exposure duration for all pathways for a particular chemical (but it can vary from chemical to chemical). For instance, if cancer HBNs are provided for both inhalation and ingestion exposure pathways, the exposure duration for both HBNs must be the same, for example 30 years. Likewise, all user-supplied non-cancer HBNs must have the same value for exposure duration for all pathways for a particular chemical. However, the exposure durations for cancer and non-cancer HBNs do not have to be the same.

At the conclusion of a Monte Carlo simulation consisting of 10,000 iterations, the 10,000 values of estimated ground water concentration for each specific time-averaging period are sorted from low to high into a cumulative distribution function (CDF), see **Figure 8-2**. The CDF represents the range in the expected location-specific ground water concentration due to uncertainty and variability in the local conditions.

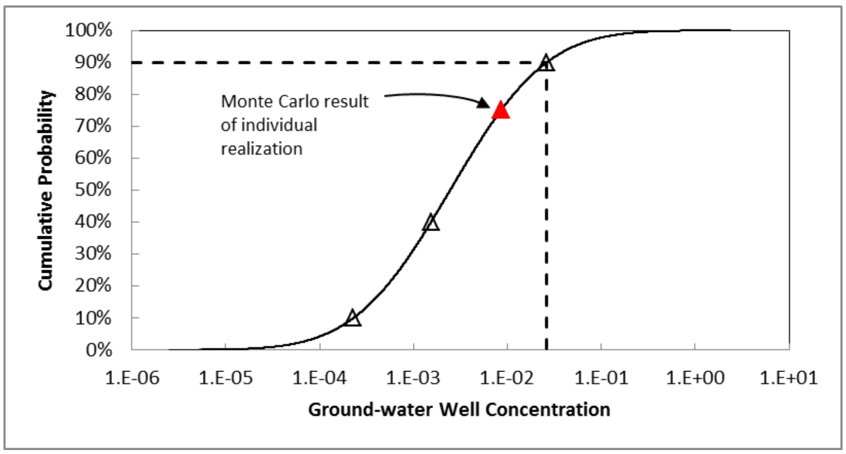

Figure 8-2. Example cumulative distribution function of well concentrations.

For the development of the IWEM tool, EPA selected the 90th percentile of the estimated ground water concentration cumulative distribution function as the point of comparison. This was done to allow conservative decisions to be made quickly with large degree of confidence that the results of the evaluation are adequately protective of human health and the environment, given the selected RGC and the degree of uncertainty inherent in the data and the analyses. In addition, this approach was also consistent with the recommendation of the *Guidance for Risk Characterization* (U.S. EPA, 1995). Therefore, IWEM evaluations are based on a high-end exposure assessment that is used to describe the risk or hazard for individuals in small, but definable segments of the population.

EPA's *Guidance for Risk Characterization* advises that "conceptually, high-end exposure means exposure above about the 90th percentile of the population distribution, but not higher than the individual in the population who has the highest exposure." Use of the 90th percentile protection level in IWEM implies that, of the modeled scenarios, 90% result in well concentrations that are lower than the specified RGC, and thus, are considered protective for at least 90% of the cases.

8.2 Making Liner Recommendations for WMUs

The recommended liner design is the minimum liner (i.e., unlined is being the first, followed by a clay liner, then a composite liner) for which the estimated ground water concentrations of all constituents is less than their specified RGC. For land application, only the "no liner" scenario is considered (because land application units do not typically have liners). Therefore, the model evaluates whether wastes can be protectively land applied, based on leachate constituent concentrations.

After conducting an IWEM evaluation, the user can choose to implement the recommendation by designing the unit based on the liner recommendations given by IWEM, or to continue to a more detailed site-specific analysis.

When interpreting IWEM liner recommendations, the following key risk assessment issues should be kept in mind:

- All HBNs correspond to a specified target risk (for carcinogens) or a target hazard quotient (for noncarcinogens). Thus, ***the recommendations will only be protective relative to those target risks or hazard quotients*** (and the other assumptions underlying the HBNs).
- IWEM evaluations do not consider combined exposure from the different pathways evaluated (ingestion of drinking water, inhalation of constituents volatilized from ground water during household use, or dermal exposure while showering). Nor do they consider the potential for additive exposure to multiple constituents. Therefore, use caution when evaluating multiple constituents that have similar fate and transport characteristics (e.g., similar K_ds and hydrolysis rates), as well as constituents with non-cancer health effects associated with the same target organ. The additive exposures could result in risks or hazard quotients above the targets of the selected HBNs.
- Usually, exposures below a noncancer RGC (i.e., hazard quotient <1) are not likely to be associated with adverse health effects, and are therefore less likely to be of regulatory concern. As the frequency and/or magnitude of the exposures exceeding the noncancer RGC (hazard quotient >1), the probability of adverse effects in a human population increases. However, it should not be categorically concluded that all exposures below a noncancer RGC are "acceptable" (or will be risk-free) and that all exposures in excess of a noncancer RGC are "unacceptable" (or will result in adverse effects).

As with all modeling, the model output, interpretation of the results, and the recommendations should be taken with the consideration of the assumptions underlying the model and the adequacy of the input data. In addition, IWEM liner recommendations should be implemented in consultation with state authorities to ensure compliance with state regulations, which may require more protective measures than the IWEM results recommend. Alternatively, if the waste has only one, or very few "problem" constituents that call for a more stringent and costly liner system (or which make land application inappropriate), it may make sense to evaluate pollution prevention, recycling, and treatment efforts for those specific constituents. If site-specific conditions seem likely to support the use of a liner design different from the one recommended (or suggest a different conclusion regarding the appropriateness of land application of a waste), a full site-specific ground water fate and transport analysis may be needed.

8.3 Determining the Appropriateness of Reused Industrial Materials in a Structural Fill

For structural fills, IWEM estimates a 90th percentile well concentration from the Monte Carlo simulation results, as described in **Section 8.1**. Like WMUs, IWEM compares that well concentration to the specified RGCs. If the estimated 90th percentile well concentration is lower than the specified RGC for all modeled constituents, IWEM considers the reuse of industrial material in a structural fill design may be appropriate, given the RGCs. However, if the 90th percentile well concentration of any of the modeled constituents is greater than its corresponding RGC, then IWEM determines that the reuse of industrial materials in a structural fill may not be appropriate. As with all modeling, the model output, interpretation of the results, and the recommendations should be taken with the consideration of the assumptions underlying the model and the adequacy of the input data. It is recommended that the user consult with the state authorities on the appropriateness of the IWEM design scenario, results, and recommendation based on state requirements.

8.4 Determining the Appropriateness of Reused Industrial Materials in a Roadway

For roadways, IWEM calculates a 90th percentile well concentration for each strip of the roadway (as described in **Section 8.1**), and then sums those concentrations across all strips to estimate an overall 90^{th} percentile well concentration. If the sum of 90th percentile concentrations exceeds the maximum leachate concentration specified across all strips, the sum is set equal to the maximum leachate concentration. IWEM then compares that overall well concentration to the specified RGCs. If the overall estimated 90th percentile well concentration is lower than the specified RGC for all modeled constituents, IWEM considers the reuse of industrial materials in the modeled roadway design may be appropriate. As with all modeling, the model output, interpretation of the results, and the recommendations should be taken with the consideration of the assumptions underlying the model and the adequacy of the input data.

IWEM can model only one segment of roadway at a time. If multiple segments are needed to fully evaluate a section of road, the segments must be run separately and a combined result calculated outside of IWEM. Briefly, this involves obtaining the 90th percentile exposure level for each constituent for each segment from the detailed results screen. Those values are then summed across segments for each constituent, and the resulting overall exposure level can then be compared to the RGC for each constituent. If the overall exposure concentration is less than the RGC for all modeled constituents, the reuse of industrial materials in the roadway design is appropriate, based on the specified RGCs. If any exposure concentrations exceed the specified RGC, then such application of industrial materials is not appropriate. Example 4 in Appendix C of the *IWEM v3.1 User's Guide* deals with a multi-segment problem and demonstrates this summary procedure.

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Appendix A: Glossary

A

Adsorption isotherm: The relationship between the concentration of constituent in solution and the amount adsorbed at constant temperature.

Adsorption: Adherence of molecules in solution to the surface of solids.

Advection: The process whereby solutes are transported by the bulk mass of flowing fluid.

Alluvium: The general name for all sediments, including clay, silt, sand, gravel or similar unconsolidated material deposited in a sorted or semi-sorted condition by a stream or other body of running water, in a streambed, floodplain, delta, or at the base of a mountain slope as a fan.

Anisotropy: The condition of having different properties in different directions.

Aquifer system: A body of permeable material that functions regionally as a water-yielding unit; it comprises two or more permeable beds separated at least locally by confining beds that impede ground water movement but do not greatly affect the regional hydraulic continuity of the system; includes both saturated and unsaturated parts of permeable material.

Aquifer: A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Area of influence of a well: The area surrounding a pumping or recharging well within which the potentiometric surface has been changed.

B

Base: A layer of material in an asphalt roadway that is located directly under the surface or paved layer. Typically, from bottom to top, the layers of a roadway are subgrade, grade, subbase, base, and pavement.

Breakthrough curve: A graph of concentration versus time at a fixed location.

Beneficial Reuse: The reuse of industrial waste or byproducts in a product or application that provides functional benefits, thus conserving natural resources that would otherwise be used.

C

Cation exchange capacity: The sum total of exchangeable cations that a porous medium can absorb. Expressed in moles of ion charge per kilogram of soil.

Confined aquifer: An aquifer bounded above and below by impermeable beds or by beds of distinctly lower permeability than that of the aquifer itself; an aquifer containing confined ground water.

Confined: A modifier that describes a condition in which the potentiometric surface is above the top of the aquifer.

Confining unit: A body of impermeable or distinctly less permeable material which separates water-bearing layers.

D

Darcian velocity: The rate of ground water flow per unit area of porous or fractured media measured perpendicular to the direction of flow. See specific discharge.

Darcy's law: An empirical law which states that the velocity of flow through porous medium is directly proportional to the hydraulic gradient.

Desorption: Removal of a substance adsorbed to the surface of an adsorbent. Also, the reverse process of sorption.

Diffusion coefficient: The rate at which solutes are transported at the microscopic level due to variations in the solute concentrations within the fluid phases.

Diffusion: Spreading of solutes from regions of higher concentration to regions of lower concentration caused by the concentration gradient. In slow-moving ground water, this can be a significant mixing process.

Dispersion coefficient: A measure of the tendency of a plume of dissolved constituents in ground water to spread. Equal to the sum of the coefficients of mechanical dispersion and molecular diffusion in a porous medium.

Dispersion, longitudinal: Process whereby some of the water molecules and solute molecules travel more rapidly than the average linear velocity and some travel more slowly. Results in the spreading of the solute in the direction of the bulk flow.

Dispersion, transverse: Process whereby some of the water molecules and solute molecules spread in directions perpendicular to the bulk flow.

Dispersivity: A geometric property of a porous medium that determines the dispersion characteristics of the medium by relating the components of pore velocity to the dispersion coefficient.

Distribution coefficient: The quantity of a constituent sorbed by a solid per unit weight of solid divided by the quantity dissolved in water per unit volume of water.

Ditch: Part of a roadway that receives drainage and runoff.

Drain: A special type of roadway layer that moves water from underneath the roadway to a ditch. See also permeable base.

E

Embankment: A raised area at the edge of a road. An embankment is a type of strip in IWEM.

Evapotranspiration: The combined loss of water from a given area by evaporation from the land and transpiration from plants.

Exfiltration: In IWEM, the rate of water leaving the bottom of any component of the roadway, including the ditch.

Exposure pathway: The course a chemical or physical agent takes from a source to an exposed organism. An exposure pathway describes a unique mechanism by which an individual or population is exposed to chemicals or physical agents at, or originating from, a site. Each exposure pathway includes a source or release from a source, an exposure point, and an exposure route. If the exposure point differs from the source, transport/exposure medium (e.g., water) or media (in case of intermedia transfer) also is included.

Exposure point concentration: An estimate of the arithmetic average concentration of a contaminant at exposure point.

Exposure point: A location of potential contact between an organism and a chemical or physical agent.

F

Fill: A screened earthen material used to create a strong and stable base. In roadway applications, fill is often used for abutments or slabs, backfill for retaining structures, or filling of trenches and other excavations that will support roadways or other structures when completed.

Flow velocity: The rate of ground water flow per unit area of porous or fractured media measured perpendicular to the direction of flow. See specific discharge.

Flow, steady: A characteristic of a flow system where the magnitude and direction of specific discharge are constant in time at any point. See also flow, unsteady.

Flow, uniform: A characteristic of a flow system where specific discharge has the same magnitude and direction at any point.

Flow, unsteady: A characteristic of a flow system where the magnitude and/or direction of the flow rate changes with time.

Flowable fill: A liquid-like material that is self-compacting and self-leveling, and is used as a substitute for conventional compacted fill material.

Flux: The rate of ground water flow per unit area of porous or fractured media measured perpendicular to the direction of flow. See specific discharge.

Fracture: A break or crack in the bedrock.

Freezing degree-day: A measure of the departure of the mean daily temperature above and below 32°F, positive if above and negative if below.

Freezing season: The period of time between the highest point and the succeeding lowest point on the time curve of cumulative degree-days above and below 32°F; the opposite of thawing season.

G

Geohydrologic system: The geohydrologic units within a geologic setting, including any recharge, discharge, interconnections between units, and any natural or human-induced processes or events that could affect ground water flow within or among those units. See ground water system.

Geohydrologic unit: An aquifer, a confining unit, or a combination of aquifers and confining units comprising a framework for a reasonably distinct geohydrologic system. See hydrogeologic unit.

Grade: A capping layer added to the subgrade in a roadway to protect it in new construction. Typically, from bottom to top, the layers of a roadway are subgrade, grade, subbase, base, and pavement.

Ground water, confined: Ground water under pressure significantly greater than atmospheric and whose upper limit is the bottom of a confining unit.

Ground water: Water present below the land surface in a zone of saturation. Ground water is the water contained within an aquifer.

Ground water discharge: Flow of water out of the zone of saturation.

Ground water flow: The movement of water in the zone of saturation.

Ground water flux: The rate of ground water flow per unit area of porous or fractured media measured perpendicular to the direction of flow. See specific discharge.

Ground water mound: A raised area in a water table or potentiometric surface created by ground water recharge.

Ground water recharge: The process of water addition to the saturated zone or the volume of water added by this process.

Ground water system: A ground water reservoir and its contained water. Also, the collective hydrodynamic and geochemical processes at work in the reservoir.

Ground water table: That surface below which rock, gravel, sand or other material is saturated. It is the surface of a body of unconfined ground water at which the pressure is atmospheric. Also called water table; synonymous with phreatic surface.

Ground water travel time: The time required for a unit volume of ground water or solute to travel between two locations. The travel time is the length of the flow path divided by the pore water velocity. If discrete segments of the flow path have different hydrologic properties, the total travel time will be the sum of the travel times for each discrete segment.

Ground water, unconfined: Water in an aquifer that has a water table. See also ground water, confined.

Gutter: A channel that captures runoff (overland flow) from a roadway, preventing some or all of it from reaching the ditch

H

Health-based number: The maximum constituent concentration in ground water that is expected to not usually cause adverse noncancer health effects in the general population (including sensitive subgroups), or that will not result in an additional incidence of cancer in more than approximately one in one million individuals exposed to the contaminant.

Heterogeneity: A characteristic of a medium in which material properties vary throughout the medium.

Homogeneity: A characteristic of a medium in which material properties are identical throughout the medium.

Hydraulic conductivity: A coefficient of proportionality describing the rate at which water can move through an aquifer or other permeable medium. Synonymous with permeability.

Hydraulic gradient: Slope of the water table or potentiometric surface.

Hydraulic head: The level to which water rises in a well with reference to a datum such as sea level.

Hydrodynamic dispersion: The spreading of the solute front during ground water plume transport resulting from both mechanical dispersion and molecular diffusion. Synonymous with mechanical dispersion.

Hydrogeologic unit: Any soil or rock unit or zone that by virtue of its porosity or permeability, or lack thereof, has a distinct influence on the storage or movement of ground water.

Hydrologic properties: Those properties of a rock that govern the entrance of water and the capacity to hold, transmit, and deliver water. Hydrologic properties include porosity, effective porosity, and permeability.

Hydrolysis: The splitting (lysis) of a compound by a reaction with water. Example are the reaction of salts with water to produce solutions that are not neutral, and the reaction of an ester with water.

Hydrostratigraphic unit: See hydrogeologic unit.

I

Igneous rocks: Rocks that solidified from molten or partly molten materials, that is from a magma or lava.

Immiscible: The chemical property of two or more phases that, at mutual equilibrium, cannot dissolve completely in one another, for example, oil and water.

Impermeable: A characteristic of some geologic material that limits its ability to transmit significant quantities of water under the head differences ordinarily found in the subsurface.

Infiltration: The downward entry of water into the soil or rock (i.e., percolation), specifically from a waste management unit. See also percolation and recharge.

Isotropy: The condition in which the property or properties of interest are the same in all directions.

L

Layer: A portion of the depth of a roadway that corresponds to a separate material; a material layer.

Leachate: A liquid that has percolated through waste and has extracted dissolved or suspended materials.

Leaching: Separation or dissolving out of soluble constituents from a waste by percolation of water.

Leaching duration: The period of time that leachate is released from a source.

M

Matrix diffusion: The tendency of solutes to diffuse from the larger pores in the system into small pores inside the solid matrix from where they can be removed only very slowly.

Matrix: The solid particles in a porous system and their spatial arrangement. Often used in contrast to the pore space in a porous system.

Maximum Contaminant Level (MCL): Legally enforceable standards regulating the maximum allowed amount of certain chemicals in drinking water.

Mechanical dispersion: The process whereby solutes are mechanically mixed during advective transport caused by the velocity variations at the microscopic level. Synonymous with hydrodynamic dispersion.

Median: The part of a roadway that separates the travel lanes in one direction from those in the other. A median is a type of strip in IWEM.

Metamorphic rocks: Any rock derived from pre-existing rocks by mineralogical, chemical, and/or structural changes, essentially in the solid state, in response to marked changes in temperature, pressure, shearing stress, and chemical environment, generally at depth in the Earth's crust.

Miscible: The chemical property of two or more fluid phases that, when brought together, have the ability to mix and form one phase.

Model: A simplified representation of a physical system obeying certain specified conditions, whose behavior is used to understand the real world system. Often, the model is a mathematical representation, programmed into a computer.

Moisture content: The ratio of either (a) the weight of water to the weight of solid particles expressed as moisture weight percentage or (b) the volume of water to the volume of solid particles expressed as moisture volume percentage in a given volume of porous medium. See water content.

Molecular diffusion: The process in which solutes are transported at the microscopic level due to variations in the solute concentrations within the fluid phases. See diffusion.

Monte Carlo simulation: A method that produces a statistical estimate of a quantity by taking many random samples from an assumed probability distribution, such as a normal distribution. The method is typically used when experimentation is infeasible or when the actual input values are difficult or impossible to obtain.

Mounding: Commonly, an outward and upward expansion of the free water table caused by surface infiltration or recharge.

O

Outwash deposits: Stratified drift deposited by meltwater streams flowing away from melting ice.

Overburden: The layer of fragmental and unconsolidated material including loose soil, silt, sand and gravel overlying bedrock, which has been either transported from elsewhere or formed in place.

P

Paved Area: The travel lanes in a roadway; the part vehicles drive on. The paved area is a type of strip in IWEM.

Pavement: A type of roadway layer that consists of paving material such as asphalt. Typically, from bottom to top, the layers of a roadway are subgrade, grade, subbase, base, and pavement.

Percolation: The downward entry of water into the soil or rock and ultimately the saturated zone. In IWEM, there are two types: infiltration (through the waste management unit) and recharge (through the soil outside the waste management unit footprint).

Permeability: The property of a porous medium to transmit fluids under a hydraulic gradient.

Permeable: The property of a porous medium to allow the easy passage of a fluid through it.

Permeable Base: The permeable base is a layer of high permeability materials that serve to divert water and any dissolved constituents in the water from further downward migration. In the IWEM software, the permeable base is called a drain. A ditch must be included in the design before a drain can be included, as the ditch serves as the destination for diverted waters.

pH: A numerical measure of the acidity or alkalinity of water ranging from 0 to 14. Neutral waters have pH near 7. Acidic waters have pH less than 7 and alkaline waters have pH greater than 7.

Pore-water velocity: Average velocity of water particles. Equals the Darcian velocity divided by the effective porosity. Synonymous with seepage velocity.

Porosity, effective: The ratio, usually expressed as a percentage, of the total volume of voids (or pores) available for fluid transmission to the total volume of the porous medium.

Porosity: The ratio, usually expressed as a percentage, of the total volume of voids (or pores) of a given porous medium to the total volume of the porous medium.

Portland Cement Concrete: Hydraulic cement (cement that not only hardens by reacting with water but also forms a water-resistant product) produced by pulverizing clinkers consisting essentially of hydraulic calcium silicates, usually containing one or more of the forms of calcium sulfate as an inter ground addition.

R

Receptor: The potentially exposed individual for the exposure pathway considered.

Recharge: The downward entry of water to the saturated zone; also the water added. In IWEM, recharge is the result of natural precipitation around a waste management unit.

Retardation factor: The ratio of the average linear velocity of ground water to the velocity of a dissolved constituent. A value greater than one indicates that the constituent moves more slowly than water, usually caused by sorption.

Risk assessment: The process used to determine the risk posed by contaminants released into the environment. Elements include identification of the contaminants present in the environmental media, assessment of exposure and exposure pathways, assessment of the toxicity of the contaminants present at the site, characterization of human health risks, and characterization of the impacts or risks to the environment.

Risk: The probability that a constituent will cause an adverse effect in exposed humans or to the environment.

Road segment: A length of roadway being modeled in IWEM.

Roadway: A road, including not just the paved road surface, but other structures such as a median, road shoulders, embankments, and ditches.

S

Saturated Zone: The part of the water bearing layer of rock or soil in which all spaces, large or small, are filled with water.

Sedimentary rocks: Rocks formed from consolidation of loose sediments such as clay, silt, sand, and gravel.

Seepage velocity: See pore-water velocity.

Shoulder: Part of a roadway that is adjacent to the travel lane(s) but may not be paved. A shoulder is a type of strip in IWEM.

Slope: The ratio of the change in elevation to the distance over which the elevation change is measured. For a roadway, slope is measured along the direction of travel; for a ditch, along the direction of flow.

Soil bulk density: The mass of dry soil per unit bulk soil.

Soil moisture: Subsurface liquid water in the unsaturated zone expressed as a fraction of the total porous medium volume occupied by water. It is less than or equal to the porosity.

Solubility: The total amount of solute species that will remain indefinitely in a solution maintained at constant temperature and pressure in contact with the solid crystals from which the solutes were derived.

Solute transport: The net flux of solute (dissolved constituent) through a hydrogeologic unit controlled by the flow of subsurface water and transport mechanisms.

Sorption: A general term used to encompass the process of adsorption.

Source term: The kinds and amounts of constituents that make up the source of a potential release.

Specific discharge: The rate of discharge of ground water per unit area of a porous medium measured at right angle to the direction of flow. Synonymous with Darcian velocity, or (specific) flux.

Strip: A portion of the width of a roadway; include both the actual road and strips along the side or down the middle that are not actual driving surface (such as shoulder or median).

Structural Fill: The use of industrial wastes and related byproducts as substitutes for earthen materials to support parking lots, roads, airstrips, tanks/vaults, and buildings; to construct highway embankments and bridge abutments; to fill borrow pits, mines, and other landscape irregularities; and to change the landscape for development or reclamation projects. Structural fills may be either flowable or compacted; IWEM can model both.

Subbase: The layer of aggregate material laid on top of the subgrade or grade, on which the base course layer is laid. Typically, from bottom to top, the layers of a roadway are subgrade, grade, subbase, base, and pavement.

Subgrade: The layer of naturally occurring material a road is built upon. Typically, from bottom to top, the layers of a roadway are subgrade, grade, subbase, base, and pavement.

T

Till: Till consists of a generally unconsolidated, unsorted, unstratified heterogeneous mixture of clay, silt, sand, gravel and boulders of different sizes and shapes. Till is deposited directly by and underneath glacial ice without subsequent reworking by meltwater.

Toxicity: The degree to which a chemical substance elicits a deleterious or adverse effect on a biological system of an organism exposed to the substance over a designated time period.

Transient flow: See flow, unsteady.

Transmissivity: The rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient. It is equal to an integration of the hydraulic conductivities across the saturated part of the aquifer perpendicular to the flow paths.

Transport: Conveyance of dissolved constituents and particulates in flow systems. See also solute transport.

U

Unconfined aquifer: An aquifer that has a water table.

Unconfined: A condition in which the upper surface of the zone of saturation forms a water table under atmospheric pressure.

Unconsolidated deposits: Deposits overlying bedrock and consisting of soil, silt, sand, gravel and other material which have either been formed in place or have been transported in from elsewhere.

Unsaturated flow: The movement of water in a porous medium in which the pore spaces are not filled to capacity with water.

Unsaturated zone: The subsurface zone between the water table and the land surface where some of the spaces between the soil particles are filled with air.

V

Vadose zone: See unsaturated zone.

Volatiles: Substances with relatively large vapor pressures that easily volatilize when in contact with air.

W

Water content: The amount of water lost from the soil after drying it to constant weight at 105 °C, expressed either as the weight of water per unit weight of dry soil or as the volume of water per unit bulk volume of soil. See also moisture content.

Water table aquifer: See unconfined aquifer.

Water table: The upper surface of a zone of saturation except where that surface is formed by a confining unit. The water pressure at the water table equals atmospheric pressure.

Well: A bored, drilled or driven shaft, or a dug hole extending from the ground surface into the ground water, that is used to inject (injection well) or extract ground water. Well screen. A cylindrical filter used to prevent sediment from entering a water well. There are several types of well screens, which can be ordered in various slot widths, selected on the basis of the grain size of the aquifer material where the well screen is to be located. In very fine grained aquifers, a zone of fine gravel or coarse sand may be required to act as a filter between the screen and the aquifer.

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Appendix B: List of IWEM Waste Constituents and Default Physical and Chemical Property Data

Table B-1 lists the 231 chemicals in IWEM and their default physical and chemical properties.

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Table B-1. Constituent Physical and Chemical Properties

CAS	Constituent Name	Molecular Weight[a] (g/mol)	Solubility[b] (mg/L)	Log K_{oc}[c] (log[mL/g])	Hydrolysis Rate Constants[c] Acid Catalyzed (K_a) (1/mol/yr)	Neutral (K_n)	Base Catalyzed (K_b) (1/mol/yr)	Diffusion Coefficient in Air (D_a) (m^2/yr)	Diffusion Coefficient in Water[d] (D_w) (m^2/yr)	Henry's Law Coefficent (HLC) (atm-m^3/mol)
83-32-9	Acenaphthene	154.21	4.24	3.75	0	0	0			
75-07-0	Acetaldehyde [Ethanal]	44.10	1E+06	-0.21	0	0	0	404	0.0426	7.89E-05
67-64-1	Acetone (2-propanone)	58.08	1E+06	-0.59	0	0	0	334	0.0363	3.88E-05
75-05-8	Acetonitrile (methyl cyanide)	41.05	1E+06	-0.71	0	0	45	423	0.0445	3.46E-05
98-86-2	Acetophenone	120.15	6,130	1.26	0	0	0			
107-02-8	Acrolein	56.06	213,000	-0.22	0	6.68E+8	0	353	0.0385	1.22E-04
79-06-1	Acrylamide	71.08	640,000	-0.99	31.50	0.018	0	337	0.0397	1.00E-09
79-10-7	Acrylic acid [propenoic acid]	72.10	1E+06	-1.84	0	0	0	325	0.0378	1.17E-07
107-13-1	Acrylonitrile	53.06	74,000	-0.09	500	0	5,200	360	0.0388	1.03E-04
309-00-2	Aldrin	364.91	0.18	6.18	0	0	0	71.9	0.0184	1.70E-04
107-18-6	Allyl alcohol	58.10	1E+06	1.47	0	0	0			
7429-90-5	Aluminum (CCR waste only)	26.98	1E+06							
62-53-3	Aniline (benzeneamine)	93.13	36,000	0.60	0	0	0	262	0.0319	1.90E-06
120-12-7	Anthracene	178.23	0.043	4.21	0	0	0			
7440-36-0	Antimony	121.76	1E+06							
22569-72-8	Arsenic (III)	74.92	1E+06							
15584-04-0	Arsenic (V)	74.92	1E+06							
7440-39-3	Barium	137.33	1E+06							
56-55-3	Benz{a}anthracene	228.29	0.0094	5.34	0	0	0	161	0.0186	3.35E-06
71-43-2	Benzene	78.11	1,750	1.80	0	0	0	282	0.0325	5.55E-03
92-87-5	Benzidine	184.24	500	1.26	0	0	0	112	0.0239	3.88E-11
50-32-8	Benzo{a}pyrene	252.31	0.00162	5.80	0	0	0	80.4	0.0208	1.13E-06
205-99-2	Benzo{b}fluoranthene	252.31	0.0015	5.80	0	0	0	150	0.0174	1.11E-04
100-51-6	Benzyl alcohol	108.14	40,000	0.78	0	0	0			
100-44-7	Benzyl chloride	126.59	525	2.84	0	410	0	200	0.0278	4.15E-04
7440-41-7	Beryllium	9.01	1E+06							
111-44-4	Bis(2-chloroethyl)ether	143.01	17,200	0.80	0	0.23	0	179	0.0275	1.80E-05
39638-32-9	Bis(2-chloroisopropyl)ether	171.07	1,310	2.39	0	0	0	126	0.0233	1.34E-04
117-81-7	Bis(2-ethylhexyl)phthalate	390.56	0.34	7.13	0	0	1,400	54.6	0.0132	1.02E-07
7440-42-8	Boron (CCR waste only)	10.81	1E+06							

CAS	Constituent Name	Molecular Weight[a] (g/mol)	Solubility[b] (mg/L)	Log K_{oc}[c] (log[mL/g])	Hydrolysis Rate Constants[c] Acid Catalyzed (K_a) (1/mol/yr)	Neutral (K_n)	Base Catalyzed (K_b) (1/mol/yr)	Diffusion Coefficient in Air (D_a) (m^2/yr)	Diffusion Coefficient in Water[d] (D_w) (m^2/yr)	Henry's Law Coefficent (HLC) (atm-m^3/mol)
75-27-4	Bromodichloromethane	163.83	6,740	1.77	0	0	50,000	178	0.0337	1.60E-03
74-83-9	Bromomethane	94.94	15,200	0.76	0	9.46	0	315	0.0426	6.24E-03
106-99-0	Butadiene 1,3-	54.09	735	2.06				315	0.0325	7.36E-02
71-36-3	Butanol n-	74.12	74,000	0.50	0	0	0			
85-68-7	Butyl benzyl phthalate	312.36	2.69	4.23	0	0	120,000			
88-85-7	Butyl-4,6-dinitrophenol,2-sec- (Dinoseb)	240.22	52	2.02	0	0	0			
7440-43-9	Cadmium	112.41	1E+06							
75-15-0	Carbon disulfide	76.13	1,190	1.84	0	0	31,500	334	0.0410	3.03E-02
56-23-5	Carbon tetrachloride	153.82	793	2.41	0	0.017	0	180	0.0308	3.04E-02
57-74-9	Chlordane	409.78	0.056	5.89	0	0	37.7	67.8	0.0172	4.86E-05
126-99-8	Chloro-1,3-butadiene 2- (Chloroprene)	88.54	1,740	1.74	0	0	0	265	0.0315	1.19E-02
106-47-8	Chloroaniline p-	127.57	5,300	1.61	0	0	0			
108-90-7	Chlorobenzene	112.56	472	2.58	0	0	0	227	0.0299	3.70E-03
510-15-6	Chlorobenzilate	325.19	11.1	4.04	0	0	2.80E+06	68.8	0.0173	7.24E-08
124-48-1	Chlorodibromomethane	208.28	2,600	1.91	0	0	25,000	115	0.0334	7.83E-04
75-00-3	Chloroethane [Ethyl chloride]	64.50	5,680	0.51	0	0	0	328	0.0366	8.82E-03
67-66-3	Chloroform	119.38	7,920	1.58	0	0.0001	2,740	243	0.0344	3.67E-03
74-87-3	Chloromethane	50.49	5,330	0.91	0	0	0	391	0.0429	8.82E-03
95-57-8	Chlorophenol 2-	128.56	22,000	1.82	0	0	0	208	0.0299	3.91E-04
107-05-1	Chloropropene 3- (Allyl Chloride)	76.53	3,370	1.13	0	40	0	295	0.0341	1.10E-02
16065-83-1	Chromium (III) (Chromic Ion)	52.00	1E+06							
18540-29-9	Chromium (VI)	52.00	1E+06							
218-01-9	Chrysene	228.29	0.0016	5.34	0	0	0	82.3	0.0213	9.46E-05
7440-48-4	Cobalt	58.93	1E+06							
7440-50-8	Copper	63.55	1E+06							
108-39-4	Cresol m-	108.14	22,700	1.76	0	0	0	230	0.0294	8.65E-07
95-48-7	Cresol o-	108.14	26,000	1.76	0	0	0	239	0.0311	1.20E-06
106-44-5	Cresol p-	108.14	21,500	1.76	0	0	0	228	0.0291	7.92E-07
1319-77-3	Cresols	324.42	23,400	2.12	0	0	0	232	0.0299	9.52E-07

CAS	Constituent Name	Molecular Weight[a] (g/mol)	Solubility[b] (mg/L)	Log K_{oc}[c] (log[mL/g])	Hydrolysis Rate Constants[c]			Diffusion Coefficient in Air (D_a) (m^2/yr)	Diffusion Coefficient in Water[d] (D_w) (m^2/yr)	Henry's Law Coefficent (HLC) (atm-m^3/mol)
					Acid Catalyzed (K_a) (1/mol/yr)	Neutral (K_n)	Base Catalyzed (K_b) (1/mol/yr)			
98-82-8	Cumene	120.19	61.3	3.40	0	0	0	190	0.0248	1.16E+00
108-93-0	Cyclohexanol	100.16	43,000	1.11	0	0	0	239	0.0295	1.02E-04
108-94-1	Cyclohexanone	98.14	5,000	1.82	0	0	0			
72-54-8	DDD	320.05	0.09	5.89	0	0.025	22,000			
72-55-9	DDE	318.03	0.12	6.64	0	0	0			
50-29-3	DDT p,p'-	354.49	0.025	6.59	0	0.060	310,000	57.7	0.014	8.10E-06
2303-16-4	Diallate	270.22	40	4.17	0	0.1	8,000			
53-70-3	Dibenz{a,h}anthracene	278.35	0.00249	6.52	0	0	0	74.4	0.0190	1.47E-08
96-12-8	Dibromo-3-chloropropane 1,2-	236.33	1,230	1.94	0	0.004	120,000	101	0.0281	1.47E-04
95-50-1	Dichlorobenzene 1,2-	147.00	156	3.08	0	0	0	177	0.0281	1.90E-03
106-46-7	Dichlorobenzene 1,4-	147.00	73.8	3.05	0	0	0	173	0.0274	2.40E-03
91-94-1	Dichlorobenzidine 3,3'-	253.13	3.11	3.32	0	0	0	150	0.0173	4.00E-09
75-71-8	Dichlorodifluoromethane (Freon 12)	120.91	280	2.16	0	0	0	240	0.0341	3.43E-01
75-34-3	Dichloroethane 1,1-	98.96	5,060	1.46	0	0.0113	0.378	264	0.0334	5.62E-03
107-06-2	Dichloroethane 1,2-	98.96	8,520	1.13	0	0.0096	54.7	269	0.0344	9.79E-04
75-35-4	Dichloroethylene 1,1-	96.94	2,250	1.79	0	0	0	272	0.0347	2.61E-02
156-59-2	Dichloroethylene cis-1,2-	96.94	3,500	1.70	0	0	0			
156-60-5	Dichloroethylene trans-1,2-	96.94	6,300	1.60	0	0	0			
120-83-2	Dichlorophenol 2,4-	163.00	4,500	2.49	0	0	0			
94-75-7	Dichlorophenoxyacetic acid 2,4-(2,4-D)	221.04	677	0.68	0	0	0			
78-87-5	Dichloropropane 1,2-	112.99	2,800	1.67	0	0	0	231	0.0307	2.80E-03
542-75-6	Dichloropropene 1,3-(mixture of isomers)	110.97	2,800	1.43	0	0	0	241	0.0319	1.77E-02
10061-01-5	Dichloropropene cis-1,3-	110.97	2,720	1.80	0	40	0	241	0.0322	2.40E-03
10061-02-6	Dichloropropene trans-1,3-	110.97	2,720	1.80	0	40	0	241	0.0319	1.80E-03
60-57-1	Dieldrin	380.91	0.195	5.08	0	0.063	0	73.5	0.0190	1.51E-05
84-66-2	Diethyl phthalate	222.24	1,080	1.99	0	0	310,000			
56-53-1	Diethylstilbestrol	268.35	0.0956	4.09	0	0	0			
60-51-5	Dimethoate	229.25	25,000	0.13	0	1.68	4.48E+06			
119-90-4	Dimethoxybenzidine 3,3'-	0.00	60	1.49	0	0	0			

CAS	Constituent Name	Molecular Weight[a] (g/mol)	Solubility[b] (mg/L)	Log K_{oc}[c] (log[mL/g])	Hydrolysis Rate Constants[c] Acid Catalyzed (K_a) (1/mol/yr)	Neutral (K_n)	Base Catalyzed (K_b) (1/mol/yr)	Diffusion Coefficient in Air (D_a) (m^2/yr)	Diffusion Coefficient in Water[d] (D_w) (m^2/yr)	Henry's Law Coefficent (HLC) (atm-m^3/mol)
68-12-2	Dimethyl formamide N,N- [DMF]	73.10	1E+06	-0.99	0	0	0	307	0.0353	7.39E-08
57-97-6	Dimethylbenz{a}anthracene 7,12-	256.35	0.025	6.64	0	0	0	149	0.0172	3.11E-08
119-93-7	Dimethylbenzidine 3,3'-	212.29	1,300	2.55	0	0	0			
105-67-9	Dimethylphenol 2,4-	122.17	7,870	2.29	0	0	0			
84-74-2	Di-n-butyl phthalate	278.35	11.2	4.37	0	0	1.80E+06			
99-65-0	Dinitrobenzene 1,3-	168.11	861	1.31	0	0	0			
51-28-5	Dinitrophenol 2,4-	184.11	2,787	-0.09	0	0	0			
121-14-2	Dinitrotoluene 2,4-	182.14	270	1.68	0	0	0	118	0.0249	9.26E-08
606-20-2	Dinitrotoluene 2,6-	182.14	182	1.40	0	0	0			
117-84-0	Di-n-octyl phthalate	390.56	0.02	7.60	0	0	520,000			
123-91-1	Dioxane 1,4-	88.11	1E+06	-0.81	0	0	0	276	0.0331	4.80E-06
122-39-4	Diphenylamine	169.23	35.7	3.30	0	0	0			
122-66-7	Diphenylhydrazine 1,2-	184.24	68	2.82	0	0	0	108	0.0229	1.53E-06
298-04-4	Disulfoton	274.39	16.3	2.94	0	2.3	54,000			
115-29-7	Endosulfan (Endosulfan I & II mixture)	406.92	0.51	3.55	0	0	0			
72-20-8	Endrin	380.91	0.25	4.60	0	0.055	0			
106-89-8	Epichlorohydrin	92.52	65,900	-0.53	25,000	30.9	0	280	0.0350	3.04E-05
106-88-7	Epoxybutane 1,2-	72.11	95,000	0.90				294	0.0331	1.80E-04
110-80-5	Ethoxyethanol 2-	90.12	1E+06	-0.54	0	0	0	258	0.0308	1.23E-07
111-15-9	Ethoxyethanol acetate 2-	132.16	229,000	0.70	0	0	0	180	0.0252	1.80E-06
141-78-6	Ethyl acetate	88.11	80,300	0.35	3,500	0.0048	3.40E+06			
60-29-7	Ethyl ether	74.12	56,800	0.55	0	0	0			
97-63-2	Ethyl methacrylate	114.14	3,671	1.27	0	0	1.10E+06			
62-50-0	Ethyl methanesulfonate	124.15	6,300	-0.27	0	1,250	0			
100-41-4	Ethylbenzene	106.17	169	3.00	0	0	0	216	0.0267	7.88E-03
106-93-4	Ethylene dibromide (1,2-Dibromoethane)	187.86	4,180	1.42	0	0.63	0	136	0.0331	7.43E-04
107-21-1	Ethylene glycol	62.10	1E+06	-1.50	0	0	0	369	0.0429	6.00E-08
75-21-8	Ethylene oxide	44.10	1E+06	-1.10	290,000	21	0	423	0.0460	1.48E-04

CAS	Constituent Name	Molecular Weight[a] (g/mol)	Solubility[b] (mg/L)	Log K_{oc}[c] (log[mL/g])	Hydrolysis Rate Constants[c] Acid Catalyzed (K_a) (1/mol/yr)	Neutral (K_n)	Base Catalyzed (K_b) (1/mol/yr)	Diffusion Coefficient in Air (D_a) (m^2/yr)	Diffusion Coefficient in Water[d] (D_w) (m^2/yr)	Henry's Law Coefficent (HLC) (atm-m^3/mol)
96-45-7	Ethylene thiourea	102.15	62,000	0.00	0	0	0	274	0.0319	3.08E-10
206-44-0	Fluoranthene	202.26	0.206	4.63	0	0	0			
16984-48-8	Fluoride	19.00								
50-00-0	Formaldehyde	30.03	550,000	-1.30	0	0	0	527	0.0549	3.36E-07
64-18-6	Formic acid	46.03	1E+06	-2.70	0	0	0			
98-01-1	Furfural	96.10	110,000	0.80	0	0	0	269	0.0337	4.00E-06
319-85-7	HCH beta-	290.83	0.24	3.43	0	0	0	87.4	0.0233	7.43E-07
58-89-9	HCH (Lindane) gamma-	290.83	6.8	3.40	0	1.05	1.73E+06	86.4	0.023	1.40E-05
319-84-6	HCH alpha-	290.83	2	3.43	0	0	0	86.7	0.0232	1.06E-05
76-44-8	Heptachlor	373.32	0.18	5.21	0	61	0	70.3	0.018	1.10E-03
1024-57-3	Heptachlor epoxide	389.32	0.2	4.90	0	0.063	0	69.1	0.0176	9.50E-06
87-68-3	Hexachloro-1,3-butadiene	260.76	3.23	4.46	0	0	0	84.2	0.0222	8.15E-03
118-74-1	Hexachlorobenzene	284.78	0.005	5.41	0	0	0	91.5	0.0248	1.32E-03
77-47-4	Hexachlorocyclopentadiene	272.77	1.8	4.72	0	24.8	0	85.8	0.0228	2.70E-02
55684-94-1	Hexachlorodibenzofurans [HxCDFs]	374.87	8.25E-06	7.00	0	0	0	138	0.0133	1.43E-05
34465-46-8	Hexachlorodibenzo-p-dioxins [HxCDDs]	390.86	4E-06	6.38	0	0	0	135	0.013	1.10E-05
67-72-1	Hexachloroethane	236.74	50	3.61	0	0	0	101	0.0280	3.89E-03
70-30-4	Hexachlorophene	406.91	140	5.00	0	0	0			
110-54-3	Hexane n-	86.20	12.4	2.95	0	0	0	230	0.0256	1.43E-02
7783-06-4	Hydrogen Sulfide	34.08	437							
193-39-5	Indeno{1,2,3-cd}pyrene	276.34	2.2E-05	6.26	0	0	0	141	0.0164	1.60E-06
7439-89-6	Iron (CCR waste only)	55.85	1E+06							
78-83-1	Isobutyl alcohol	74.12	85,000	0.44	0	0	0			
78-59-1	Isophorone	138.21	12,000	1.90	0	0	0	166	0.0238	6.64E-06
143-50-0	Kepone	490.64	7.6	4.15	0	0	0			
7439-92-1	Lead	207.20	1E+06							
7439-96-5	Manganese	54.90	1E+06							
7439-97-6	Mercury	200.59	0.0562		0	0	0	225	0.0949	1.14E-02
126-98-7	Methacrylonitrile	67.09	25,400	0.22	500	0	5,200	304	0.0334	2.47E-04

CAS	Constituent Name	Molecular Weight[a] (g/mol)	Solubility[b] (mg/L)	Log K_{oc}[c] (log[mL/g])	Hydrolysis Rate Constants[c] Acid Catalyzed (K_a) (1/mol/yr)	Neutral (K_n)	Base Catalyzed (K_b) (1/mol/yr)	Diffusion Coefficient in Air (D_a) (m^2/yr)	Diffusion Coefficient in Water[d] (D_w) (m^2/yr)	Henry's Law Coefficent (HLC) (atm-m^3/mol)
67-56-1	Methanol	32.04	1E+06	-1.08	0	0	0	498	0.0520	4.55E-06
72-43-5	Methoxychlor	345.65	0.045	4.90	0	0.69	12,000			
109-86-4	Methoxyethanol 2-	76.10	1E+06	0.95	0	0	0	300	0.0347	8.10E-08
110-49-6	Methoxyethanol acetate 2-	118.13	1E+06	0.00	0	0	0	208	0.0275	3.11E-07
78-93-3	Methyl ethyl ketone	72.11	223,000	-0.03	0	0	0	289	0.0322	5.59E-05
108-10-1	Methyl isobutyl ketone	100.16	19,000	0.87	0	0	0	220	0.0264	1.38E-04
80-62-6	Methyl methacrylate	100.12	15,000	0.74	0	0	0	237	0.0292	3.37E-04
298-00-0	Methyl parathion	263.20	55	2.47	0	2.8	0			
1634-04-4	Methyl tert-butyl ether [MTBE]	88.15	51,300	1.05	0	0	0	238	0.0272	5.87E-04
56-49-5	Methylcholanthrene 3-	268.36	0.00323	7.00	0	0.017	0	76	0.0194	9.40E-07
74-95-3	Methylene bromide (Dibromomethane)	173.83	11,930	1.21	0	0	0			
75-09-2	Methylene Chloride (Dichloromethane)	84.93	13,000	0.93	0	0.001	0.6	315	0.0394	2.19E-03
7439-98-7	Molybdenum	95.90	1E+06							
91-20-3	Naphthalene	128.17	31	3.11	0	0	0	191	0.0264	4.83E-04
7440-02-0	Nickel	58.69	1E+06							
98-95-3	Nitrobenzene	123.11	2,090	1.51	0	0	0	215	0.0298	2.40E-05
79-46-9	Nitropropane 2-	89.09	17,000	0.23	0	0	0	267	0.0322	1.23E-04
55-18-5	Nitrosodiethylamine N-	102.14	93,000	-0.03	0	0	0	233	0.0288	3.63E-06
62-75-9	Nitrosodimethylamine N-	74.08	1E+06	0.45	0	0	0	312	0.0363	1.20E-06
924-16-3	Nitroso-di-n-butylamine N-	158.24	1,270	2.09	0	0	0	133	0.0215	3.16E-04
621-64-7	Nitroso-di-n-propylamine N-	130.19	9,890	1.03	0	0	0	178	0.0245	2.25E-06
86-30-6	Nitrosodiphenylamine N-	198.22	35.1	2.84	0	0	0	89.6	0.0227	5.00E-06
10595-95-6	Nitrosomethylethylamine N-	88.11	19,700	1.03	0	0	0	265	0.0315	1.40E-06
100-75-4	Nitrosopiperidine N-	114.15	76,500	-0.02	0	0	0	220	0.0290	2.80E-07
930-55-2	Nitrosopyrrolidine N-	100.12	1E+06	-0.57	0	0	0	252	0.0319	1.20E-08
152-16-9	Octamethyl pyrophosphoramide	286.25	1E+06	-0.51	1,900	0	0			
56-38-2	Parathion (ethyl)	291.26	6.54	3.15	0	2.4	3.70E+06			
608-93-5	Pentachlorobenzene	250.34	1.33	5.39	0	0	0			

CAS	Constituent Name	Molecular Weight[a] (g/mol)	Solubility[b] (mg/L)	Log K_{oc}[c] (log[mL/g])	Hydrolysis Rate Constants[c]			Diffusion Coefficient in Air (D_a) (m^2/yr)	Diffusion Coefficient in Water[d] (D_w) (m^2/yr)	Henry's Law Coefficent (HLC) (atm-m^3/mol)
					Acid Catalyzed (K_a) (1/mol/yr)	Neutral (K_n)	Base Catalyzed (K_b) (1/mol/yr)			
30402-15-4	Pentachlorodibenzofurans [PeCDFs]	340.42	0.00024	4.93	0	0	0	144	0.0142	5.00E-06
36088-22-9	Pentachlorodibenzo-p-dioxins [PeCDDs]	356.42	0.000118	6.30	0	0	0	141	0.0138	2.60E-06
82-68-8	Pentachloronitrobenzene (PCNB)	295.34	0.55	4.57	0	0	0			
87-86-5	Pentachlorophenol	266.34	1,950	3.06	0	0	0	93	0.0253	2.44E-08
108-95-2	Phenol	94.11	82,800	1.23	0	0	0	263	0.0325	3.97E-07
62-38-4	Phenyl mercuric acetate	336.74	2,000	0.00	0	0	0			
108-45-2	Phenylenediamine 1,3-	108.14	2.55E+06	-0.30	0	0	0			
298-02-2	Phorate	260.36	50	2.64	0	62	0			
85-44-9	Phthalic anhydride	148.12	6,200	1.56	0	490,000	0	188	0.0308	1.63E-08
1336-36-3	Polychlorinated biphenyls (Aroclors)		0.07	6.19	0	0	0	73.5	0.0189	2.60E-03
23950-58-5	Pronamide	256.13	32.8	2.63	59	0	610			
75-56-9	Propylene oxide [1,2-Epoxypropane]	58.10	405,000	1.40	0	0	0	347	0.0382	1.23E-04
129-00-0	Pyrene	202.26	0.135	4.92	0	0	0			
110-86-1	Pyridine	79.10	1E+06	0.34	0	0	0	294	0.0344	8.88E-06
94-59-7	Safrole	162.19	810.67	2.34	0	0	0			
10026-03-6	Selenium (IV)	78.96	1E+06							
7782-49-2	Selenium (VI)	78.96	1E+06							
7440-22-4	Silver	107.87	1E+06							
57-24-9	Strychnine and salts	334.42	160	1.90	0	0	0			
100-42-5	Styrene	104.15	310	2.84	0	0	0	225	0.0278	2.75E-03
95-94-3	Tetrachlorobenzene 1,2,4,5-	215.89	0.595	4.28	0	0	0			
51207-31-9	Tetrachlorodibenzofuran 2,3,7,8-	305.98	0.000692	6.62	0	0	0	152	0.0153	1.54E-05
1746-01-6	Tetrachlorodibenzo-p-dioxin 2,3,7,8-	321.97	7.91E-06	6.10	0	0	0	148	0.0148	7.92E-05
630-20-6	Tetrachloroethane 1,1,1,2-	167.85	1,100	2.71	0	0.0137	11,300	152	0.0287	2.42E-03
79-34-5	Tetrachloroethane 1,1,2,2-	167.85	2,970	2.07	0	0.0051	15,900,000	154	0.0293	3.45E-04

CAS	Constituent Name	Molecular Weight[a] (g/mol)	Solubility[b] (mg/L)	Log K_{oc}[c] (log[mL/g])	Hydrolysis Rate Constants[c] Acid Catalyzed (K_a) (1/mol/yr)	Neutral (K_n)	Base Catalyzed (K_b) (1/mol/yr)	Diffusion Coefficient in Air (D_a) (m^2/yr)	Diffusion Coefficient in Water[d] (D_w) (m^2/yr)	Henry's Law Coefficent (HLC) (atm-m^3/mol)
127-18-4	Tetrachloroethylene	165.83	200	2.21	0	0	0	159	0.0298	1.84E-02
58-90-2	Tetrachlorophenol 2,3,4,6-	231.89	100	2.32	0	0	0			
3689-24-5	Tetraethyl dithiopyrophosphate (Sulfotep)	322.31	25	3.51	0	84	9,000,000			
7440-28-0	Thallium	204.38	1E+06							
137-26-8	Thiram [Thiuram]	240.40	30	2.83	0	0	0			
108-88-3	Toluene	92.14	526	2.43	0	0	0	246	0.0291	6.64E-03
95-80-7	Toluenediamine 2,4-	122.17	33,700	0.02	0	0	0	243	0.0282	7.92E-10
95-53-4	Toluidine o-	107.15	16,600	1.24	0	0	0	228	0.0290	2.72E-06
106-49-0	Toluidine p-	107.15	782	1.24	0	0	0			
8001-35-2	Toxaphene (chlorinated camphenes)		0.74	4.31	0	0.070	28,000	68.1	0.0173	6.00E-06
75-25-2	Tribromomethane (Bromoform)	252.73	3,100	2.05	0	0	10,000	113	0.0328	5.35E-04
76-13-1	Trichloro-1,2,2-trifluoro-ethane 1,1,2-	187.38	170	2.97	0	0	0	119	0.0271	4.81E-01
120-82-1	Trichlorobenzene 1,2,4-	181.45	34.6	3.96	0	0	0	125	0.0265	1.42E-03
71-55-6	Trichloroethane 1,1,1-	133.40	1,330	2.16	0	0.64	2.40E+06	204	0.0303	1.72E-02
79-00-5	Trichloroethane 1,1,2-	133.40	4,420	1.73	0	2.73E-05	49,500	211	0.0315	9.13E-04
79-01-6	Trichloroethylene (Trichloroethylene 1,1,2-)	131.39	1,100	2.10	0	0	0	217	0.0322	1.03E-02
75-69-4	Trichlorofluoromethane (Freon 11)	137.37	1,100	2.11	0	0	0	207	0.0319	9.70E-02
95-95-4	Trichlorophenol 2,4,5-	197.45	1,200	2.93	0	0	0			
88-06-2	Trichlorophenol 2,4,6-	197.45	800	2.25	0	0	0	99	0.0255	7.79E-06
93-72-1	Trichlorophenoxy)propionic acid 2-(2,4,5- (Silvex)	269.51	140	1.74	0	0	0			
93-76-5	Trichlorophenoxyacetic acid 2,4,5-	255.48	268	1.43	0	0	0			
96-18-4	Trichloropropane 1,2,3-	147.43	1,750	1.66	0	0.0170	3,600	181	0.0291	4.09E-04
121-44-8	Triethylamine	101.20	55,000	1.31	0	0	0	209	0.0247	1.38E-04
99-35-4	Trinitrobenzene (Trinitrobenzene 1,3,5-) sym-	213.11	350	1.05	0	0	0			

CAS	Constituent Name	Molecular Weight[a] (g/mol)	Solubility[b] (mg/L)	Log K_{oc}[c] (log[mL/g])	Hydrolysis Rate Constants[c] Acid Catalyzed (K_a) (1/mol/yr)	Neutral (K_n)	Base Catalyzed (K_b) (1/mol/yr)	Diffusion Coefficient in Air (D_a) (m^2/yr)	Diffusion Coefficient in Water[d] (D_w) (m^2/yr)	Henry's Law Coefficent (HLC) (atm-m^3/mol)
126-72-7	Tris(2,3-dibromopropyl)phosphate	697.61	8	3.19	0	0.088	300,000			
7440-62-2	Vanadium	50.94	1E+06							
108-05-4	Vinyl acetate	86.10	20,000	0.45	0	0	0	268	0.0315	5.11E-04
75-01-4	Vinyl chloride	62.50	2,760	1.04	0	0	0	337	0.0378	2.70E-02
108-38-3	Xylene m-	106.17	161	3.09	0	0	0	216	0.0267	7.34E-03
95-47-6	Xylene o-	106.17	178	3.02	0	0	0	218	0.0270	5.19E-03
106-42-3	Xylene p-	106.17	185	3.12	0	0	0	216	0.0267	7.66E-03
1330-20-7	Xylenes (total)	318.50	175	3.08	0	0	0	217	0.0268	6.73E-03
7440-66-6	Zinc	65.39	1E+06							

Note: Data sources for chemical property values are indicated in the column headings; exceptions are noted in parentheses for individual chemical values.
[a] http://chemfinder.cambridgesoft.com (CambridgeSoft)
[b] U.S. EPA (1997)
[c] Kollig (1993)
[d] Calculated based on Water 9 (U.S. EPA, 2001)
[e] SRC (1999)
[f] Calculated based on U.S. EPA (2000a)
[g] HSDB (NLM , 2001)
[h] MI DEQ (nd)
[i] Calculated based on U.S. EPA (1987)
[j] U.S. EPA (1999)
[k] U.S. EPA (2000b)
[l] Calculated from l using regression equation log[Koc] = 1.029 x log[Kow] - 0.18; presented in Table 10.2 of deMarsily (1986)
[m] Lyman et al. (1990)

Appendix C: Formulation of the Roadway Module

C.1 General Conceptualization

The roadway in the Industrial Waste Management Evaluation Model (IWEM) is conceptualized as illustrated in **Figure C-1**, which depicts a typical roadway with a segment constructed with industrial materials. For the purposes of model simplicity, that segment is assumed to be nearly linear and thus can be approximated by the straight line segment AB. If the segment to be modeled is long and meandering, it must be subdivided into several nearly linear segments that can each be represented by a straight line.

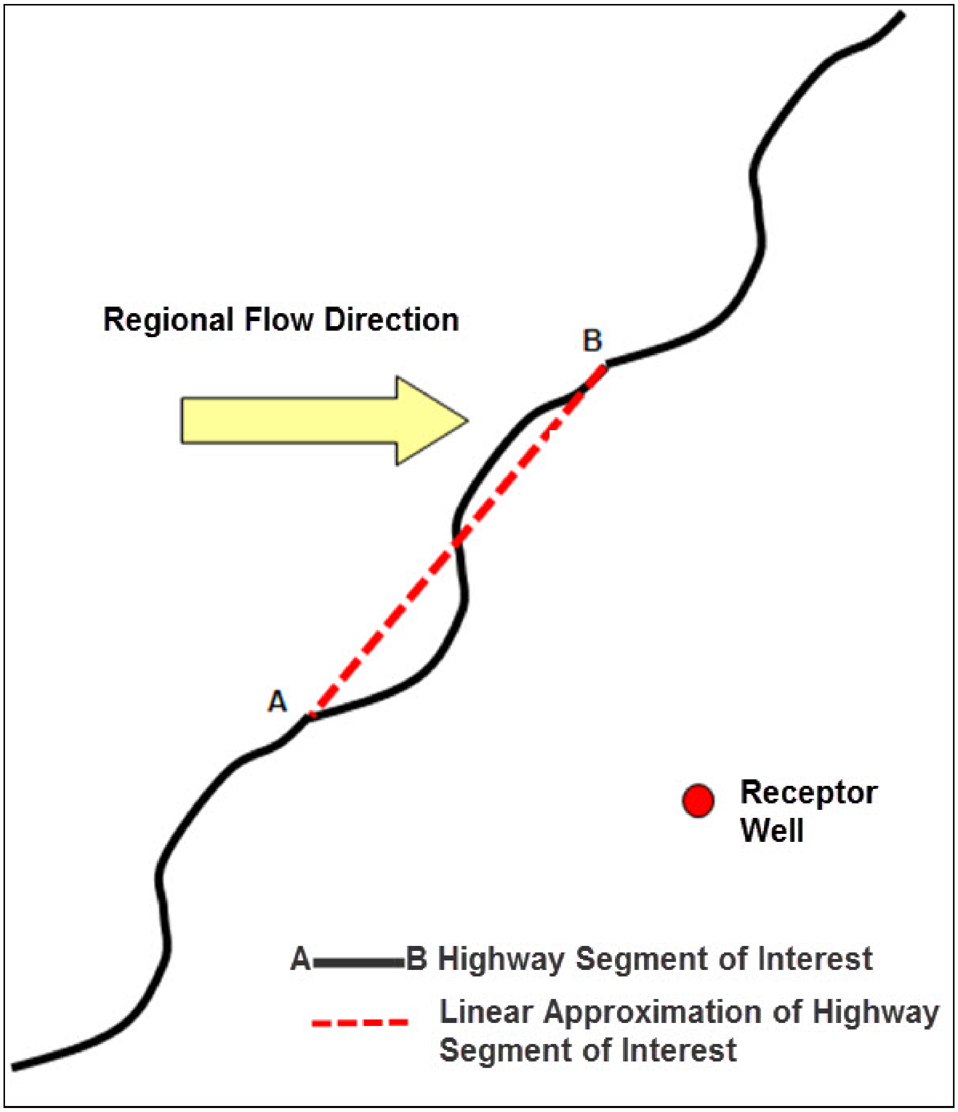


Figure C-1. A typical roadway with a recycled-material segment.

Figure C-2 shows a typical cross section of a roadway, that may comprise several components (e.g., lane, shoulder, ditch). For the model, each component was idealized as a column, referred to henceforth as the roadway-source column. In the vertical direction, as shown in **Figure C-3**, each roadway-source column included materials starting vertically upward from a reference datum (which could be the top of subgrade), to the surface of a pavement(or a road shoulder, an embankment, a ditch). As shown in Figure C-3, each roadway-source column was underlain by a corresponding vadose-zone column.

A roadway-source column was assumed to be uniform in terms of parameters and properties along the length of interest (i.e., the modeled segment shown in Figure C-1). Therefore, a roadway-source column becomes a roadway-source strip in three dimensions. **Figure C-4** shows an example of a roadway cross section comprising three roadway-source strips representing, respectively, a median, a travel lane, and a ditch. Note that a more typical roadway may consist of up to fifteen roadway-source strips: for example, left shoulder, left-travel lane, median, right-travel lane, and right shoulder in Figure C-3. More strips are possible to account for drainage ditches and berms and different configurations of layers; the IWEM roadway module limits the total number of roadway-source strips to 15. An example of only three roadway-source strips is used here as a basis for further discussion. Each roadway-source strip may consist of several layers, depending on how a given roadway was constructed. A travel lane strip may be composed of a pavement layer (portland cement concrete or asphalt concrete), a base-course layer, a subbase layer, and a subgrade layer. A median may comprise a base layer, a subbase layer, and a subgrade layer. An unpaved road shoulder may have only one layer—a subgrade layer. With this type of conceptualization, one can easily see that each roadway-source strip was equivalent to the existing waste management units (WMUs) source modules that are available within EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP). However, the WMUs module in IWEM can accommodate only sources with a square footprint and one layer.

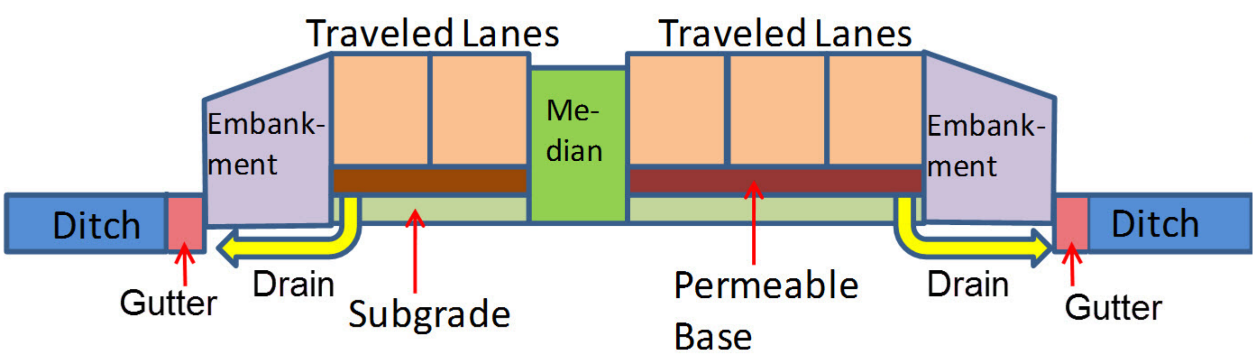


Figure C-2. A typical cross section of a roadway.

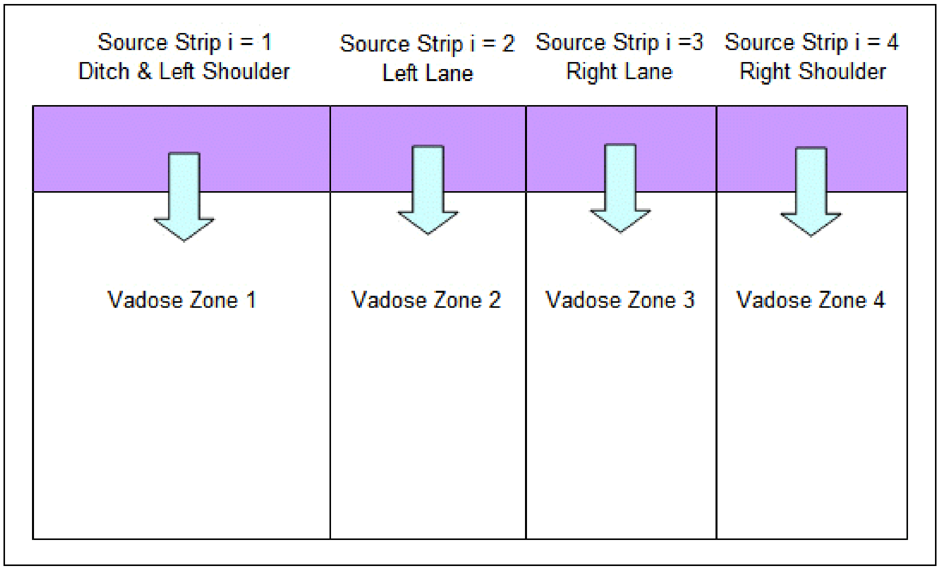


Figure C-3. Modules of IWEM corresponding to multiple roadway-source strips.

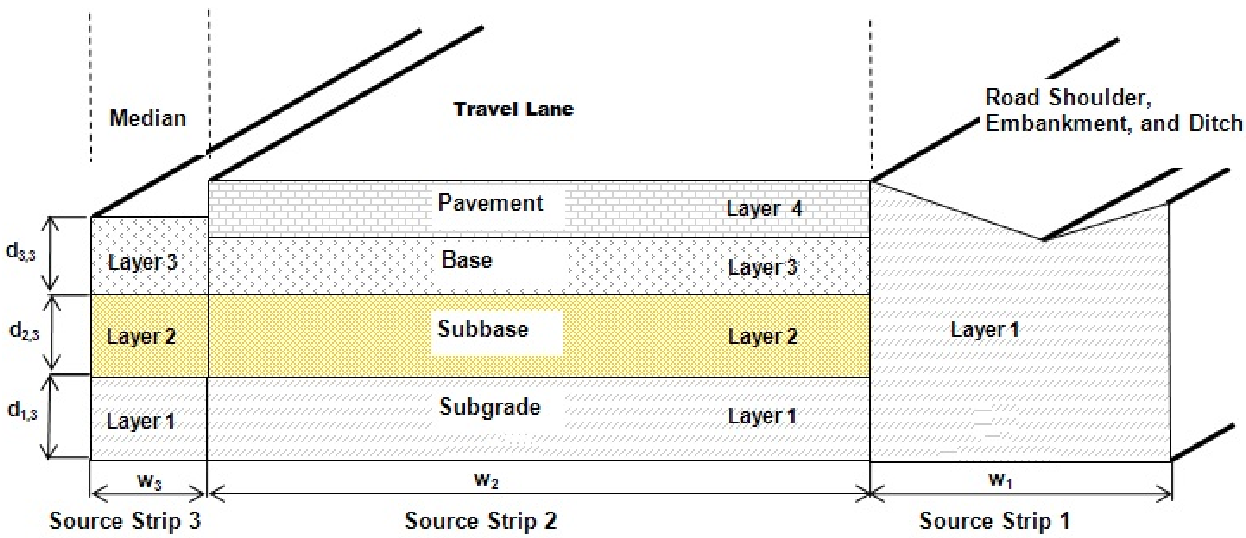


Figure C-4. An example of layering in roadway-source strips.

The roadway axis may not be normal to the regional flow direction. **Figure C-5** shows an idealized (straight line) roadway segment with several laterally contiguous rectangular roadway-source strips oriented at a positive angle α with respect to a line orthogonal to the regional flow direction. The current aquifer transport module can handle only the case where α = 0°. To handle a general case with |α| > 0°, the result of the existing aquifer transport module must be modified after the simulation. A general approach, which is discussed in **Section C.2.2.2**, is that the reference x-y coordinate system is transformed into the x´-y´ coordinate system, shown in **Figure C-6**, which aligns with both the roadway axis and the regional flow direction. A further transformation to the x″-y″ coordinate system (see Figure C-6) results in an orthogonal system consistent with the existing aquifer transport module for describing the fate and transport of contaminants in the transformed domain. It should be noted that the IWEM software asks the user to provide a positive angle θ, which represents the angle between the down-gradient roadway edge and the regional flow direction and is defined by the relationship $\theta = 90° - \alpha$. The equations that define the transformation from the x-y coordinate system to the x″-y″ coordinate system encoded into the IWEM software account for this change in angle representation.

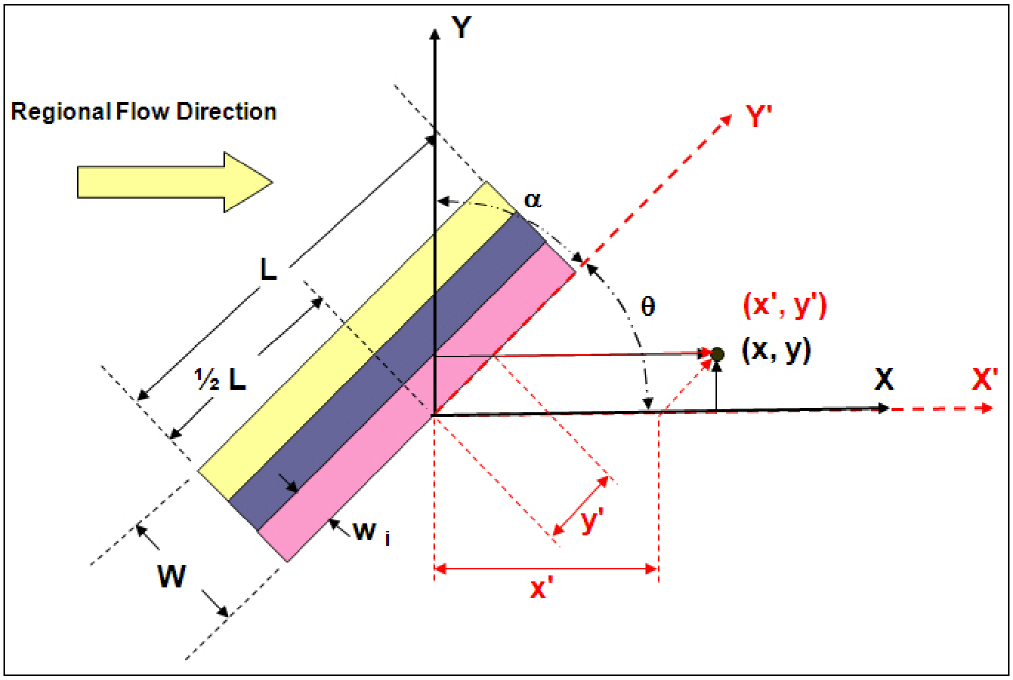


Figure C-5. Non-orthogonal source.

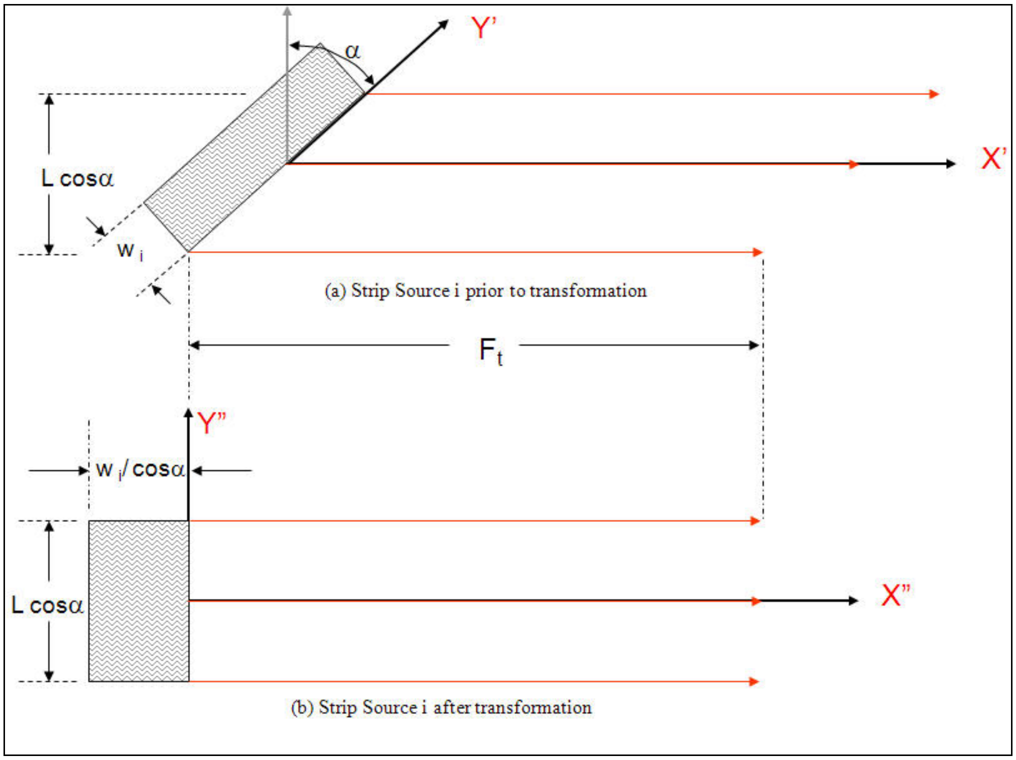


Figure C-6. Roadway-source strip *i* (a) in its original form; and (b) after transformation, where F_t is the plume front position at time *t*.

C.2 Formulation

A detailed mathematical formulation for the general conceptualization of the roadway, as described in **Section C.1**, is presented here. The formulation is based on a number of simplifying assumptions, which are listed in **Section C.2.1**. The formulation is presented in **Section C.2.2**.

C.2.1 List of Assumptions

The general assumptions for EPACMTP (U.S. EPA 2003a, b, c, d) relevant to the IWEM's roadway module are listed below:

- The rate of percolation through the unsaturated zone is constant over time.
- Flow and transport through the unsaturated zone is in the vertical, downward direction and assumed to be one-dimensional; flow is assumed to be steady, and transport is transient.
- Flow through the homogeneous saturated zone is assumed to be uniform, steady, and one-dimensional; transport is assumed to be three dimensional and transient.
- Material properties do not vary in time.

As the primary sources of industrial materials used in roadway construction are combustion byproducts, the constituents of concern are essentially metals, which generally exhibit non-linear sorption behavior. EPACMTP provides an analytical solution for one-dimensional transport of a solute with non-linear sorption (See Appendix B.2 in U.S. EPA [2003a]), which requires the simplification of the leaching profile to a constant magnitude, finite pulse (i.e., a square pulse). In addition, a database of empirical non-linear sorption isotherms (See Appendix G in U.S. EPA [2003a]) developed specifically for combustion byproducts is incorporated into the IWEM software and available to the user. The metals transport capability provided by EPACMTP and its accompanying assumptions have governed the development of the roadway module formulation and the primary assumption that leachate profiles are conceptualized as square pulses.

For more details on the assumptions incorporated into the EPACMTP, see **Section 4.3**. In addition to these general assumptions for EPACMTP, the following IWEM specific assumptions are used in the formulation:

- In the region of interest, the general regional ground water flow pattern is assumed not to be affected by the presence of a traversing roadway. It follows from this assumption that infiltration from the traversing roadway is on the same order of magnitude as regional recharge. Furthermore, the areal coverage of the roadway contributing infiltration is assumed very small compared to the total regional area contributing recharge, so that any difference between the infiltration and recharge rates does not significantly influence the regional flow field.
- For a screening-level analysis, lateral communication between roadway-source strips is assumed to be insignificant.
- A single, long-term average infiltration rate is assumed to percolate through each roadway-source strip.
- Leaching begins at the end of pavement construction.

- Material properties of each roadway-source strip do not vary in time.

C.2.2 Mathematical Formulation

The formulation presented here refers to drainage systems that are integrated into the roadway cross-section as "permeable bases." The IWEM software refers to these drainage systems as "**drains**." Please be mindful of these synonyms when reading through this section.

This section describes the mathematical formulation for multiple material layers (**Section C.2.2.1**); source geometry and non-orthogonality of regional flow field (**Section C.2.2.2**); multiple material layers with a drainage system (**Section C.2.2.3**); runoff from top of pavement and discharge from a permeable base that constitutes the drainage system, or drain (**Section C.2.2.4**); roadside drainage areas, ditches, or streams (**Section C.2.2.5**); single and multiple road segments (**Section C.2.2.6**); single and dual drainage systems (**Section C.2.2.7**); and a discussion on the versatility of the roadway module (**Section C.2.2.8**).

C.2.2.1 Multiple Material Layers

For the IWEM roadway source module, a pulse source scenario was assumed based on two reasons. First, IWEM is a screening-level analysis, therefore the simplicity and conservatism of a pulse source type is an appropriate assumption. Second, a pulse source is appropriate for metals, which are anticipated to be the predominant constituents of concern in recycled industrial materials.

Using Figure C-4 as reference and assuming that leachate is generated from layer *k* of roadway-source strip *i* in a pulse-like manner, the leachate concentration in layer *k* of roadway source strip *i* can be calculated as follows:

$$C_{L,ki} = C^0_{L,ki} \qquad where\ t_{0,ki} \le t \le t_{p,ki} + t$$
$$C_{L,ki} = 0 \qquad where\ t > t_{p,ki} + t \qquad \text{(C-1)}$$

where:

$C_{L,ki}$ = Leachate concentration in layer *k* of roadway-source strip *i* (M/L^3)
$C^0_{L,ki}$ = Initial leachate concentration in layer *k* of roadway-source strip *i* (M/L^3)
$t_{0,ki}$ = Time at which leachate leaves the bottom surface of roadway-source strip *i* (T)
t = Time (T)
$t_{p,ki}$ = Pulse duration for layer *k* of roadway-source strip *i* (T)

Note that in Equation (C-1) and the ensuing equations, constituent indices are dropped for the sake of generality.

Leachate from a given layer is assumed to leave the bottom surface of roadway-source strip *i* immediately after the pulse from the layer below has completely left the strip. Each layer with leachable material contributes to the final release, with leachate from the lowest layer leaving the bottom of the roadway cross-section first.

In this manner, leaching occurs downward in a series of sequential pulses that never overlap or dilute as dissolved constituent mass migrates to and through the bottom layer. There are no gaps between pulses. Numbering the layers beginning with the bottom-most layer, it can be stated that

$$t_{0,ki} = \sum_{j=1}^{k-1} t_{p,ji} \qquad \text{(C-2)}$$

where:

$t_{0,ki}$ = Time at which leachate leaves the bottom surface of roadway-source strip *i* (T)
t = Time (T)
$t_{p,ji}$ = Pulse duration for layer *j* of roadway-source strip *i* (T)

With infiltration rate I_i, the pulse duration for pavement layer *k* of roadway-source strip *i* is given by

$$t_{p,ki} = \frac{M_{0,ki}}{w_i \, L \, I_i \, C^0_{L,ki}} \qquad \text{(C-3)}$$

where:

$t_{p,ki}$ = Pulse duration for layer *k* of roadway-source strip *i* (T)
$M_{0,ki}$ = Initial total mass in pavement layer *k* of roadway-source strip *i* (M)
w_i = Width of roadway-source strip *i* (L)
L = Length of roadway-source strip *i* (L)
I_i = Infiltration rate for roadway-source strip *i* (L/T)
$C^0_{L,ki}$ = Initial leachate concentration in layer *k* of roadway-source strip *i* (M/L^3)

For a source with multiple layers, the duration of leaching may be derived from the mass balance principle. The initial total mass of a constituent at the time leaching begins is given by

$$M_{0,ki} = w_i \, L \, d_{k,i} \, C^0_{Total,k,i} \, \rho^0_{Bulk,k,i} \qquad \text{(C-4)}$$

where:

$M_{0,ki}$ = Initial total mass in pavement layer *k* of roadway-source strip *i* (M)
w_i = Width of roadway-source strip *i* (L)
L = Length of roadway-source strip *i* (L)
$d_{k,i}$ = Thickness of layer *k* and roadway-source strip *i* (L)
$C^0_{Total,k,i}$ = Initial total constituent concentration (M/M) in layer *k* and roadway-source strip *i*
$\rho^0_{Bulk,k,i}$ = Initial bulk density (M/L^3) in layer *k* and roadway-source strip *i*

Leachate from layer 1 is assumed to leave the bottom surface of the strip instantaneously at time = 0, and the pulse duration of layer *k* is assumed not to exist if the constituent of interest is absent from layer *k*. Hence

$$t_{0,1i} = 0, \qquad t_{p,ki} = 0, when\ C^0_{L,ki} = 0 \tag{C-5}$$

where:

$t_{0,1i}$	=	Time at which leachate leaves the bottom surface of roadway-source strip *i* (T)
$t_{p,ki}$	=	Pulse duration for layer *k* of roadway-source strip *i* (T)
$C^0_{L,ki}$	=	Initial leachate concentration in layer *k* of roadway-source strip *i* (M/L^3)

C.2.2.2 Source Geometry and Non-orthogonality of Regional Flow Field

Regional Flow Field

Based on the assumptions that

- in the region of interest, the general regional ground water flow pattern is not affected by the presence of a traversing roadway;
- infiltration from the traversing roadway is on the order of regional recharge, and;
- the areal coverage of the roadway is very small compared to the total regional area so that the difference between the infiltration and recharge does not cause significant impact on the regional flow field; the regional flow field may be approximated by a solution with infiltration equal to recharge.

As a result of these assumptions, there is no distortion in the flow field in the vicinity of the roadway.

Treatment of a Rectangular and Non-orthogonal Source

Source Geometry

In the case of roadway-source module, the source is rectangular. It is necessary to re-specify the source geometry in IWEM, from rectangular to square. Re-specification of the source geometry is relatively straightforward and is handled as a pre-processing step prior the fate and transport simulations.

Non-Orthogonality between the Source Orientation and the Regional Flow Field

In general, a roadway may be oriented in such a way that the roadway axis is not orthogonal to the regional ground water flow direction. To accommodate the non-orthogonality of the roadway source, it is necessary to transform the transport domain in such a way that the roadway becomes orthogonal to the regional ground water flow direction and is approximately rectangular in the transformed domain. Transformation details are given in **Appendix F**. A summary of the transformation is given below.

For the current aquifer module, the reference frame for transport in a horizontal plane is the system of x-y axes shown in Figure C-4. The inclination angle, θ, which is equal to 90° – α (α being the conjugate inclination angle), is incorporated into the analysis via the following transformation:

$$C'_i\,(x,y,z,t) = C'_i\,(x',y',z,t) = C'_i\,(x'',y'',z,t) \tag{C-6}$$

$$\begin{aligned} x' &= x - y\tan\alpha, x' \geq 0;\ \alpha < \frac{\pi}{2} \\ y' &= y/\cos\alpha \\ x'' &= x' \\ y'' &= y'\cos\alpha \end{aligned} \tag{C-7}$$

where:

C'_i	=	Concentration in the transport domains emanating from roadway-source strip i (M/L^3)
x	=	Distance along the flow direction measured from the midpoint of the down gradient face of the strip of interest (L)
y	=	Distance normal to the flow direction measured from the midpoint of the down gradient face of the strip of interest (L)
z	=	Depth measured from the water table (L)
t	=	Time (T)
x'	=	Distance along the flow direction measured from the down gradient face of the strip of interest in the transformed domain (L)
y'	=	Distance measured from the x′ along the direction parallel to the axis of the roadway (L)
x''	=	Distance along the flow direction measured from the down gradient face of the strip of interest in the transformed domain (L)
y''	=	Distance normal to the flow direction measured from the midpoint of the down gradient face of the strip of interest in the transformed domain (L)
α	=	conjugate inclination angle = 90°– θ (the inclination angle)

With the transformation in Equations (C-6) and (C-7), the source in **Figure C-5** is transformed into the one shown in **Figure C-**6. Note also that in the transformed domain, the dimensions of the roadway source are also accordingly transformed (compare Figures C-5 and C-6). The above transformation has two limitations: (i) it is an approximate transformation and does not account for source end effects, and (ii) the angle of inclination must remain below 90° and therefore, the regional flow direction is not allowed to be completely parallel to the roadway axis. Suggested analytical procedures to overcome the end effects, and the case with the angle of inclination, θ, equal to 0°, are given in **Appendix F**.

The rationale for the above transformations is given diagrammatically in Figures C.5 and C.6. The objective of these transformations is to take advantage of the existing IWEM flow and transport modules developed for a rectangular source in a rectangular coordinate system, where the width of the source is aligned along the flow direction and its length normal to the flow direction. In Figure C-5, the transformation from the x-y to the x′-y′ coordinate systems is to render the y′ axis parallel to the roadway axis. In Figure C-6, a front location at time *t* in the x″-y″

coordinate system and the corresponding front in the x′-y′ coordinate system are shown. Based on the corresponding front locations, it can be stated without proof that the transformation is valid for advection-dominated systems. When a roadway of interest is very long (length >> width), lateral dispersion across stream tubes is expected to be relatively small as the lateral concentration gradient approaches zero. In addition, when the roadway is very long, the end effects (in Figure C-6, the ends of the roadway segment are not parallel to the x, x′, and x″ axes) are relatively small and, as a result, errors arising from the orientation of the roadway ends are relatively small compared to the amount of mass released by the entire length of the roadway.

It should be noted also that contaminant fluxes from each roadway-source strip are determined using strip-specific infiltration. Modifications to IWEM will manage roadway-source strip-specific fluxes and coordinate the presentation of these data to EPACMTP.

In Figure C-6, one can recognize that the configuration conforms to the existing aquifer module. However, it will be necessary to modify the inputs to EPACMTP and the simulated results of EPACMTP to include coordinate and dimensional transformations.

The enhanced transport module was verified against a numerical model. Verification results are given in **Appendix G**.

C.2.2.3 Multiple Material Layers with a Drainage System

Subsurface drainage systems were originally included in roadway cross-sections to alleviate moisture-related stress in pavements such as rutting, stripping, cracking, and pumping. As a result, the roadway pavement life could be extended threefold by proper installation and maintenance of subsurface pavement drainage systems (Christopher and McGuffey, 1997; Apul et al., 2002). Many states adopted the use of such drain systems such as permeable bases to remove water that percolated through pavement.

> In IWEM, a ditch is a required element in a roadway design if a drainage system is included. The ditch serves as the destination of any waters diverted through the drainage system, as well as any runoff not captured by a gutter. Ditches are discussed in **Section C.2.2.4**.

Recently, the introduction of industrial materials, with the potential to release constituents into the environment, into the design and construction of new roadways created additional motivation to consider including controlled diversion of moisture away from the roadway. In addition, permeable bases could also serve as a leachate capturing system to divert water percolating through the cracks of a pavement made with industrial materials. This will help prevent leachate from infiltrating further into the unsaturated zone. Captured leachate can be channeled from permeable base into localized bioretention facilities, where it can be treated before the water allowed to infiltrate into the soil. The roadway module in IWEM provides the option to integrate the permeable drainage layers as part of the roadway design scenario, while accounting lateral transport of contaminants.

A typical permeable base pavement section, shown in **Figure C-7**, is provided to help visualize pavement drainage components. A common design approach in subsurface drainage systems is the installation of a permeable base, which serves to remove infiltration water. This highly permeable layer is at least 7 to 10 centimeters thick and extends under the full width of the roadway exposed to traffic loads. Permeable bases are used in both Portland cement concrete and asphalt concrete pavements (see **Figure C-8**). The permeable base may be located just above the subgrade or above the base (Van Sambeek, 1989). The permeable layer may also be used without another base. A filter reinforcement layer is typically placed between the permeable base and natural soils to prevent infiltration of fines into the subbase and the migration of subbase into the permeable base. In the field, a filter layer may consist of a dense-graded subbase, or geotextile may be used as the filter layer (Christopher, 1998).

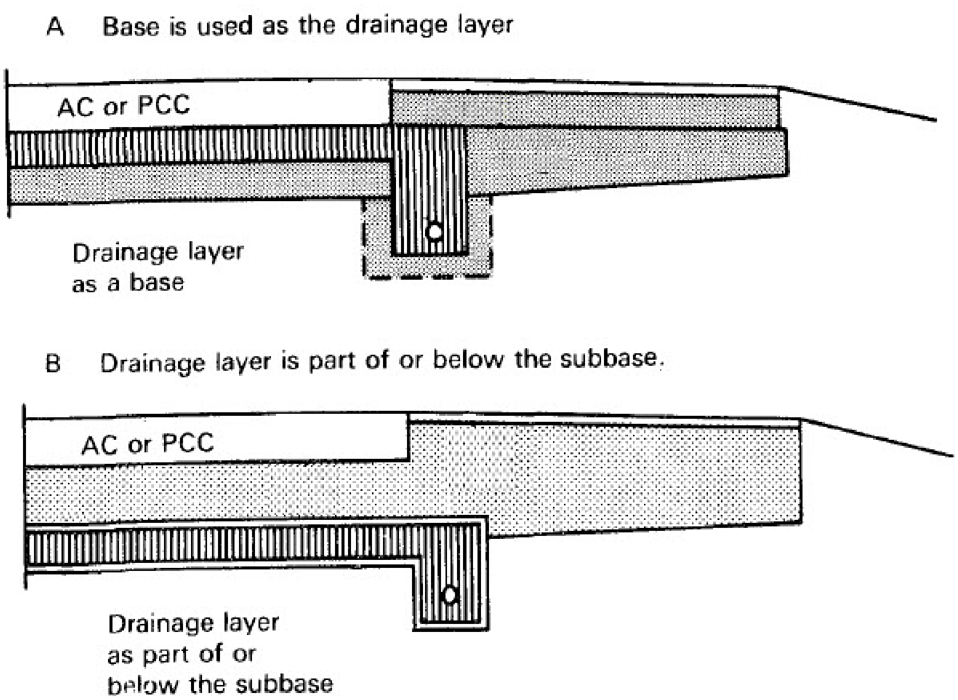


Figure C-7. Typical permeable base pavement sections: (a) base used as drainage layer (b) drainage layer is part of or below the subbase (from AASHTO, 1993).

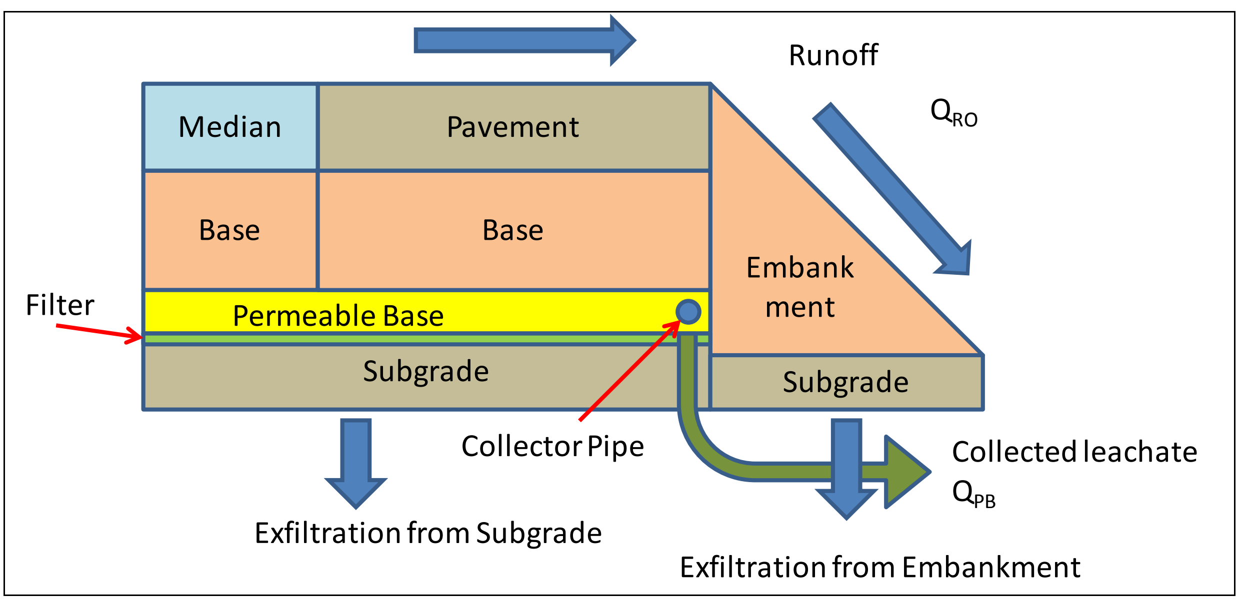


Figure C-8. General configuration of the highway module with a drainage system.

In Figure C-8, a pavement underlain by a drainage system, as in Figure C-4, is represented by contiguous columns. However, in this case, the base course is underlain by a drainage system comprising a permeable base on top of a filter layer, which rests above a subgrade layer of the same material. Although it is not depicted in Figure C-8, a roadside ditch is required to receive runoff and leachate collected by the permeable base.

At any given time, *t*, the contaminant flux that enters the permeable base layer, is described by

$$F_{PB} = L\sum_{i=1}^{N_C} w_i\, I_i \sum_{k=1}^{N_L} C_{L,ki}^{0}\left(H\left(t-t_{0,ki}\right)-H\left(t-\left[t_{0,ki}+t_{p,ki}\right]\right)\right) \qquad \text{(C-8)}$$

and the average infiltration rate from all columns is given by

$$I_{PB} = \frac{1}{\sum_{i=1}^{N_C} w_i}\sum_{i=1}^{N_C} w_i\, I_i \qquad \text{(C-9)}$$

where:

F_{PB} = Mass flux from pavement layers above the permeable base (M/T)
N_C = Number of columns above the permeable base (dimensionless)
L = Length of roadway-source strip *i* (L)
w_i = Width of roadway-source strip *i* (L)
I_i = Infiltration rate for roadway-source strip *i* (L/T)
N_L = Number of layers in respective column above the permeable base (dimensionless)
$C^0_{L,ki}$ = Initial leachate concentration in layer *k* of roadway-source strip *i* (M/L^3)
$H(t)$ = Heaviside's unit function, = 0 when $t < 0$, = 1 when $t \geq 0$ (dimensionless)
I_{PB} = Average infiltration rate pavement columns above the permeable base (L/T)

Equation C-8 is derived based on the following in assumptions:

- Leachate from a given layer is assumed to leave the bottom of the layer just above the permeable base immediately after the pulse from the layer below has completely left the same layer just above the permeable base;
- Any layers that do not contribute to leachate concentrations are ignored; and
- Water and mass flux are constant for each individual pulse from a layer.

Equation C-9 represents a weighted average of infiltration rates through each strip above a drain.

In the event that the layer beneath the permeable base has relatively low hydraulic conductivity, the mass in the permeable base will be transported laterally to a collector pipe. In this case, the infiltration from the permeable base to the layer below is limited by the hydraulic conductivity of the underlying layer. The water flow rate diverted to the collector pipe is given by

$$Q_{PB} = \left(I_{PB} - I'_{PB}\right) L \sum_{i=1}^{N_C} w_i \qquad \text{(C-10)}$$

where:

Q_{PB} = Water flux from collector pipe in the permeable base (L^3/T)
I_{PB} = Infiltration rate from the layer above permeable base to the permeable base (L/T)
I'_{PB} = Infiltration rate from the permeable base to the subgrade layer below (L/T)
= I_{PB}, if $I_{PB} < K_{SG}$

= K_{SG}, if $I_{PB} > K_{SG}$

L = Length of roadway-source strip *i* (L)

w_i = Width of roadway-source strip *i* (L)

With infiltration rate I_{PB} from the layer above, the pulse duration for the permeable base is given by

$$t_{p,PB} = \frac{M_{0,PB}}{I_{PB}\, L \sum_{i=1}^{N_C} w_i\, C^0_{L,PB}} \tag{C-11}$$

$$M_{0,PB} = L \sum_{i=1}^{N_C} w_i\, d_{PB}\, C^0_{Total,PB}\, \rho^0_{Bulk,PB} \tag{C-12}$$

where:

$t_{p,\,PB}$ = Time required for the contaminant to completely leach from the permeable base (T)

$M_{0,\,PB}$ = Initial total mass in permeable base (M)

I_{PB} = Infiltration rate from the layer above the permeable base to the permeable base (L/T)

L = Length of roadway-source strip *i* (L)

w_i = Width of roadway-source strip *i* (L)

$C^0_{L,PB}$ = Initial leachate concentration in the permeable base (M/L^3)

d_{PB} = Thickness of permeable base (L)

$C^0_{Total,\,PB}$ = Initial total constituent concentration in permeable base (M/M)

$\rho^0_{Bulk,\,PB}$ = Initial bulk density in permeable base (M/L^3)

The pulse duration, Equation C-11, is derived by dividing the total mass of constituent in the permeable base by the rate at which mass leaves the permeable base. The mass flux is equal to the product of the per-unit-area infiltration rate, the area through which infiltration passes and the leachate concentration from the permeable base.

Equation C-12 defines the total mass of constituent in the permeable base as the product of the volume of material used in the permeable base and the initial total concentration of leachable constituent in the material.

The concentration of contaminant that leaves the permeable base via the collector pipe or to the layer below is estimated from the mass flux from the pavement (Equation C-8) divided by the water flux into the permeable base from the layers above, and the leachate flux from the materials in the permeable base, thus

$$C_{PB} = \frac{1}{\sum_{i=1}^{N_C} w_i\, I_i} \sum_{i=1}^{N_C} w_i\, I_i \sum_{k=1}^{N_L} C^0_{L,ki}\left(H\left(t - t_{0,ki}\right) - H\left(t - \left[t_{0,ki} + t_{p,ki}\right]\right)\right) + C^0_{L,PB}\left(H(0) - H\left(t - t_{p,PB}\right)\right) \tag{C-13a}$$

The time-average concentration for C_{PB} is

$$\overline{C}_{PB} = \frac{1}{\Delta t_{PB}} \left(\frac{1}{\sum_{i=1}^{N_C} w_i \, I_i} \sum_{i=1}^{N_C} w_i \, I_i \, \sum_{k=1}^{N_L} C^0_{L,ki} \, t_{p,ki} \; + \; C^0_{L,PB} \, t_{p,PB} \right) \tag{C-13b}$$

$$\overline{C_{PB}} = 0, \; t > \Delta t_{PB}$$

$$\Delta t_{PB} = \frac{1}{\sum_{i=1}^{N_C} w_i} \sum_{i=1}^{N_C} w_i \sum_{k=1}^{N_L} t_{p,ki} + t_{p,PB} \tag{C-13c}$$

where:

C_{PB} = Concentration of efflux from the permeable base (M/L^3)

t_{PB} = Concentration averaging period (T)

$\overline{C}_{PB}$ = Time-average concentration of efflux from the permeable base (M/L^3)

Similar to the derivation in the previous section, with N_{LB} layers below the permeable base, the time taken to leach out contaminant from all the layers below the permeable base is given by

$$t_{SG} = \sum_{j=1}^{N_{LB}} t_{p,SG,j} \tag{C-14}$$

$$t_{0,SG,j} = \sum_{m=1}^{j-1} t_{p,SG,m} \tag{C-15}$$

$$t_{p,SG,j} = \frac{M_{0,SG,j}}{L \, I'_{PB} \, C^0_{L,SG,j} \sum_{i=1}^{N_C} w_i} \tag{C-16}$$

$$M_{0,SG,j} = L \, d_{SG,j} \, C^0_{Total,SG,j} \rho^0_{Bulk,SG,j} \sum_{i=1}^{N_C} w_i \tag{C-17}$$

where:

t_{SG} = Time required for the contaminant immediately below the permeable base to travel to the bottommost extent of the subgrade layer (T)

$t_{p,SG,j}$ = Time required for the contaminant to completely leach from subgrade layer *j* (T)

$t_{0,SG,j}$ = Time at which leachate from subgrade layer *j* begins to leave the bottom surface of the subgrade (T)

$M_{0,\, SG\, j}$ = Initial total mass in subgrade layer *j* (M)

$d_{SG,i}$ = Thickness of subgrade layer *j* (L)

$C^0_{Total,\, SG,\, j}$ = Initial total constituent concentration (M/M) in subgrade layer *j*

$\rho^0_{Bulk,\, SG,\, j}$ = Initial bulk density (M/L^3) in subgrade layer *j*

With N_{LB} subgrade layers below the permeable base, the concentration that leaves to bottom of the subgrade layer is given by

$$\begin{aligned} C_{SG} = & \frac{1}{\sum_{i=1}^{N_C} w_i I_i} \sum_{i=1}^{N_C} w_i I_i \sum_{k=1}^{N_L} C^0_{L,ki} \Big(H\big(t - t_{SG} - t_{p,PB} - t_{0,ki}\big) - H\big(t - t_{SG} - t_{p,PB} - [t_{0,ki} + t_{p,ki}]\big)\Big) \\ & + C^0_{L,PB} \Big(H\big(t_{SG}\big) - H\big(t - t_{SG} - t_{p,PB}\big)\Big) + \\ & + \sum_{j=1}^{N_{LB}} C^0_{L,j} \Big(H\big(t - t_{0,SG,j}\big) - H\big(t - [t_{0,SG,j} + t_{p,SG,j}]\big)\Big) \end{aligned} \tag{C-18}$$

where:

C_{SG}	=	Concentration that leaves to the bottom of the subgrade layer (M/L^3)
N_C	=	Number of columns above the permeable base (dimensionless)
w_i	=	Width of roadway-source strip *i* (L)
I_i	=	Infiltration rate for roadway-source strip *i* (L/T)
N_L	=	Number of layers in respective column above the permeable base (dimensionless)
$C^0_{L,ki}$	=	Initial leachate concentration in layer *k* of roadway-source strip *i* (M/L^3)
$H(t)$	=	Heaviside's unit function, = 0 when t < 0, = 1 when t ≥ 0 (dimensionless)
t_{SG}	=	Time required for the contaminant immediately below the permeable base to travel to the bottommost extent of the subgrade layer (T)
$t_{p,PB}$	=	Time required for the contaminant to completely leach from permeable base (T)
$t_{0,ki}$	=	Time at which leachate leaves layer *k* of roadway-source strip *i* (T)
$t_{p,ki}$	=	Pulse duration for layer *k* of roadway-source strip *i* (T)
$C^0_{L,PB}$	=	Initial leachate concentration in the permeable base (M/L^3)
N_{LB}	=	Number of layers in respective column below the permeable base (dimensionless)
$C^0_{L,j}$	=	Initial leachate concentration in subgrade layer *j* (M/L^3)
$t_{0,SG,j}$	=	Time at which leachate from subgrade layer *j* begins to leave the bottom surface of the subgrade (T)
$t_{p,SG,j}$	=	Time required for the contaminant to completely leach from subgrade layer *j* (T)

Note that in Equation (C-18), the travel time of all pulses above the filter layer (immediately below the permeable base) is delayed by $t_{SG} + t_{p,PB}$ and the travel time of the pulse from the permeable base is delayed by $t_{p,PB}$.

C.2.2.4 Runoff from Top of Pavement and Discharge from Permeable Base

As shown in Figure C-7, runoff from the pavement surface and collected leachate from the permeable base may drain into a roadside ditch. The runoff is divided into two categories: divertible and indivertible. The divertible runoff flux from the pavement is estimated from

$$Q_{DRO} = \sum_{i=1}^{N_{CBG}} RO_i \times w_i \times L \qquad \text{(C-19)}$$

where:

Q_{DRO} = Divertible runoff water flux before a gutter (L^3/T)
N_{CBG} = Number of strips with divertible runoff to gutter
RO_i = Runoff rate per unit area of strip *i* (L/T)
w_i = Width of roadway-source strip *i* (L)
L = Length of roadway-source strip *i* (L)

Parts of the surface runoff and permeable base fluxes may also be diverted or lost. For the surface runoff, the total flux that reaches the roadside ditch consists of the remainder of divertible runoff and indivertible runoff. The effective runoff flux and collected leachate flux from the permeable base that may reach the roadside ditch, as shown in **Figure C-9**, may be described by:

$$\begin{aligned} Q'_{DRO} &= K_{DRO} \times Q_{DRO} \\ Q'_{RO} &= Q'_{DRO} + \sum_{j=1}^{N_{CAG}} RO_j \times w_j \times L \\ Q'_{PB} &= K_{PB} \times Q_{PB} \end{aligned} \qquad \text{(C-20)}$$

where:

Q'_{DRO} = Remaining divertible runoff water flux (L^3/T) that reaches the ditch
K_{DRO} = Divertible runoff coefficient (dimensionless), varying from 0 to 1.
Q_{DRO} = Divertible runoff water flux before a gutter (L^3/T)
Q'_{RO} = Total effective runoff water flux (L^3/T) that reaches the ditch
N_{CAG} = Number of strips with indivertible runoff
RO_i = Runoff rate per unit area of strip *i* (L/T)
w_i = Width of roadway-source strip *i* (L)
L = Length of roadway-source strip *i* (L)
Q'_{PB} = Effective water flux from collector pipe in the permeable base (L^3/T) that reaches the ditch
K_{PB} = Water flux coefficient (dimensionless), varying from 0 to 1
Q_{PB} = Water flux from collector pipe in the permeable base (L^3/T)

Note that equations C-19 and C-20 are not used if no drain is specified in the roadway design.

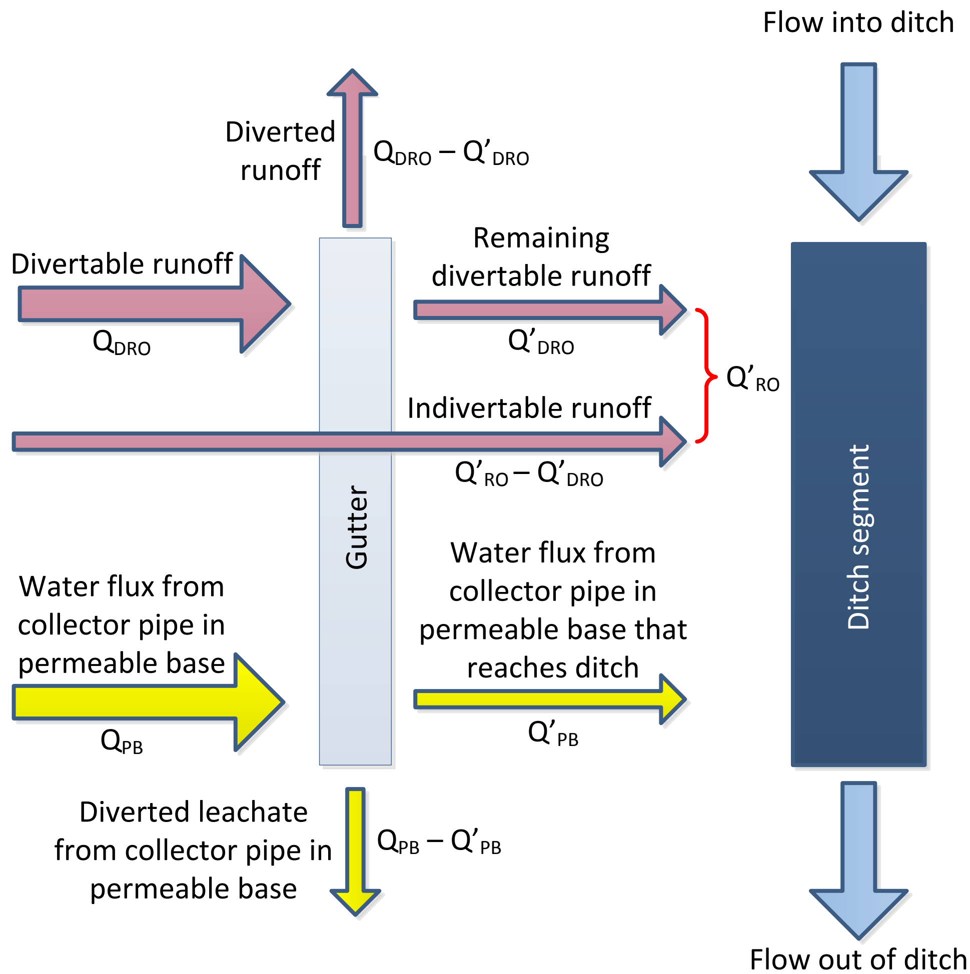


Figure C-9. Paths for runoff and collected leachate from permeable base.

C.2.2.5 Roadside Drainage Areas, Ditches, or Streams

A typical roadway may be flanked by a drainage ditch or a stream with flowing/stagnant water on either side. In this document, the term ditch will be used throughout. A typical ditch cross section is shown in **Figure C-10,** along with mass influxes and effluxes. The ditch is assumed to be adjacent to the embankment of a road segment, which consists of an assemblage of travel lane columns and an embankment column (**Figure C-11**).

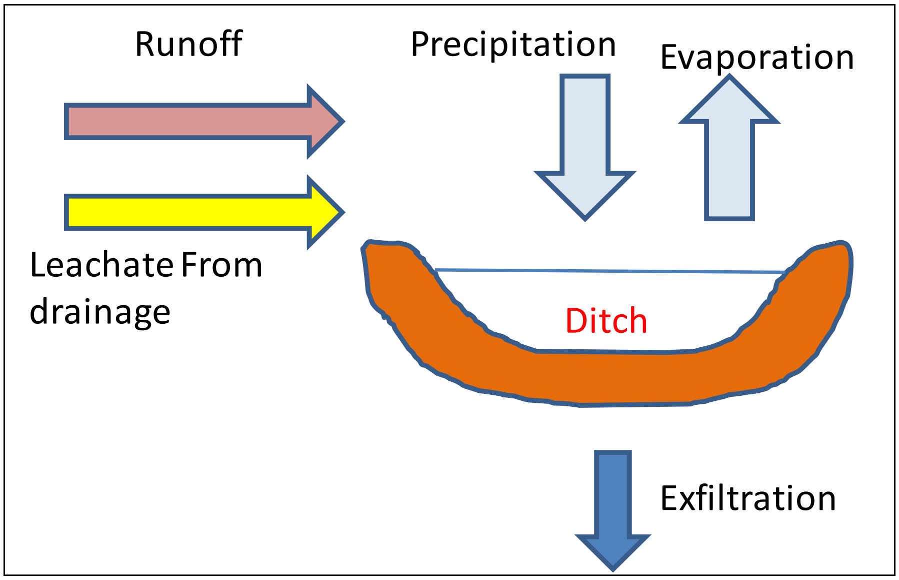


Figure C-10. Fluxes to and from a ditch and the ditch cross section.

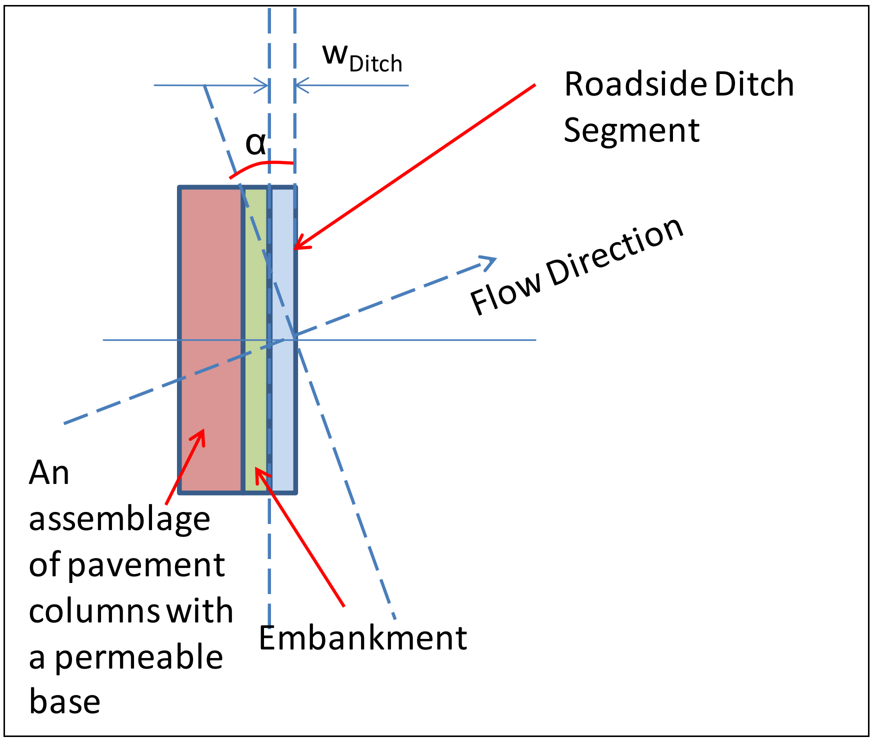


Figure C-11. A plan view showing highway source term components.

The ditch area may or may not be water-filled. In arid areas, the roadside ditch may be mostly dry. For the roadway analysis, it is assumed that there are two possible roadside sources that derive contaminant mass from the pavement assemblage: water-filled ditches and dry ditches. These two source types are discussed below.

Water-Filled Ditches

Water-filled ditches are assumed to be water-filled on a long-term basis. The water may be flowing or remain stagnant. Water that flows into the ditches is derived from discharge from the permeable base and runoff. In this analysis, no contaminant mass is assumed to be transported by runoff. Water leaves the ditch by outflow to the downstream ditch segment (if the water is flowing) and by exfiltration. Exfiltration is defined as the process of water percolating down to the unsaturated zone from the bottom of the ditch.

Based on the principle of mass conservation, it can be stated that

$$Q'_{PB}\,\overline{C}_{PB} + Q_{In}\,C_{In} = Q_{Out}\,C_{Out} + Q_{DExfil}\,C_{DExfil} \tag{C-21}$$

where:

- Q'_{PB} = Effective water flux from collector pipe in the permeable base (L^3/T) that reaches the ditch
- $\overline{C}_{PB}$ = Time-average concentration of efflux from the permeable base (M/L^3)
- Q_{In} = Ditch inflow rate from upstream (L^3/T)
- C_{In} = Contaminant concentration of ditch inflow (M/L^3)
- Q_{Out} = Ditch outflow rate to downstream (L^3/T)
- C_{Out} = Contaminant concentration of ditch outflow (M/L^3)
- Q_{DExfil} = Exfiltration rate from the ditch (L^3/T)
- C_{DExfil} = Contaminant concentration of ditch exfiltration (M/L^3)

Based on an assumption that

$$C_{out} = C_{DExfil} \tag{C-22}$$

Contaminant concentration in the exfiltration from a given ditch can be described as

$$C_{DExfil} = \frac{Q'_{PB}\,\overline{C}_{PB} + Q_{in}\,C_{in}}{Q_{out} + Q_{DExfil}} \tag{C-23}$$

where:

- C_{DExfil} = Contaminant concentration of ditch exfiltration (M/L^3)
- Q'_{PB} = Effective water flux from collector pipe in the permeable base (L^3/T) that reaches the ditch
- $\overline{C}_{PB}$ = Time-average concentration of efflux from the permeable base (M/L^3)
- Q_{In} = Ditch inflow rate from upstream (L^3/T)
- C_{In} = Contaminant concentration of ditch inflow (M/L^3)
- Q_{Out} = Ditch outflow rate to downstream (L^3/T)
- Q_{DExfil} = Exfiltration rate from the ditch (L^3/T)

Note that in the ditch associated with the upstream-most segment of the ditch, $C_{In} = 0$. Q_{Out} from the current segment becomes Q_{In} for the downstream ditch segment.

Assuming steady-state flow, from the principle of mass conservation, Q_{Out} is given by

$$Q_{out} = Q_{in} + Q'_{RO} + Q'_{PB} + Q_{Precip} - Q_{Evap} - Q_{DExfil} \quad \text{(C-24)}$$

where:

Q_{Out} = Ditch outflow rate to downstream (L^3/T)
Q_{In} = Ditch inflow rate from upstream (L^3/T)
Q'_{RO} = Total effective runoff water flux (L^3/T) that reaches the ditch
Q'_{PB} = Effective water flux from collector pipe in the permeable base (L^3/T) that reaches the ditch
Q_{Precip} = Precipitation flux (L^3/T)
Q_{Evap} = Evaporation flux (L^3/T)
Q_{DExfil} = Exfiltration rate from the ditch (L^3/T)

The evaporation, precipitation, and exfiltration fluxes are determined from

$$Q_{Evap} = w_{Ditch}\, L\, E_p \quad \text{(C-25)}$$

$$Q_{Precip} = w_{Ditch}\, L\, P \quad \text{(C-26)}$$

where:

Q_{Evap} = Evaporation flux (L^3/T)
Q_{Precip} = Precipitation flux (L^3/T)
w_{Ditch} = Ditch width (L)
L = Length of ditch (L)
E_P = Evaporation rate over the ditch (L/T)
P = Precipitation rate over the ditch (L/T)

Assuming that the water table is located below the bottom layer underlying the ditch, Q_{DExfil} is approximated by

$$Q_{DExfil} = w_{Ditch}\, L\, K_{Bed}\, \frac{H_{Str} + T_{Bed}}{T_{Bed}} \quad \text{(C-27)}$$

where:

Q_{DExfil} = Exfiltration rate from the ditch (L^3/T)
w_{Ditch} = Ditch width (L)
L = Length of ditch (L)
K_{Bed} = Vertical hydraulic conductivity of the ditch bed (L/T)
H_{Str} = Depth of water in the ditch (L)
T_{Bed} = Thickness of the ditch bed (L)

Of interest is the case in which $Q_{In} = Q_{Out}$, using Equations (C-24) and (C-27), one obtains

$$H_{Str} = \left(Q'_{RO} + Q'_{PB} + Q_{Precip} - Q_{Evap}\right)\frac{T_{Bed}}{w_{Ditch}\ L\,K_{Bed}} - T_{Bed} \qquad \text{(C-28a)}$$

where:

H_{Str}	=	Depth of water in the ditch (L)
Q'_{RO}	=	Total effective runoff water flux (L^3/T) that reaches the ditch
Q'_{PB}	=	Effective water flux from collector pipe in the permeable base (L^3/T) that reaches the ditch
Q_{Precip}	=	Precipitation flux (L^3/T)
Q_{Evap}	=	Evaporation flux (L^3/T)
T_{Bed}	=	Thickness of the ditch bed (L)
w_{Ditch}	=	Ditch width (L)
L	=	Length of ditch (L)
K_{Bed}	=	Vertical hydraulic conductivity of the ditch bed (L/T)

To safeguard against possibly unrealistic values of H_{Str}, the estimated water depth is limited to H_{Str}^{Limit}. In the event that H_{Str} is negative, the ditch is regarded as dry (see subsection below on dry ditches), and the following equations are not applicable. In the event that H_{Str}, is limited to H_{Str}^{Limit}, Q_{DExfil} is given by:

$$Q_{DExfil} = Q'_{RO} + Q'_{PB} + Q_{Precip} - Q_{Evap} \qquad \text{(C-28b)}$$

where:

Q_{DExfil}	=	Exfiltration rate from the ditch (L^3/T)
Q'_{RO}	=	Total effective runoff water flux (L^3/T) that reaches the ditch
Q'_{PB}	=	Effective water flux from collector pipe in the permeable base (L^3/T) that reaches the ditch
Q_{Precip}	=	Precipitation flux (L^3/T)
Q_{Evap}	=	Evaporation flux (L^3/T)

Q_{In} and Q_{Out} may be may be calculated from cross-sectional average velocity along the ditch, which, in turn, may be estimated using Manning's equation, thus

$$V = \frac{k}{n} R^{0.667}\, S^{0.5} \qquad \text{(C-29)}$$

where:

V	=	Cross-section average water velocity (L/T)
k	=	Conversion factor = 1 if V is in m/s, = 1.486 for V in ft/s
n	=	Manning's coefficient
R	=	Hydraulic radius (area/wetted perimeter) (L)
S	=	Slope of the water surface (dimensionless)

S is assumed to be equal to streambed slope and *should be set to zero in the case of stagnant water*.

Hydraulic radius R is given by

$$R = \frac{w_{Ditch} H_{Str}}{w_{Ditch} + 2 H_{Str}} \tag{C-30}$$

where:

R	=	Hydraulic radius (area/wetted perimeter) (L)
w_{Ditch}	=	Ditch width (L)
H_{Str}	=	Depth of water in the ditch (L)

Based on the assumption that $Q_{In} = Q_{Out}$, the water flux along the ditch is determined from

$$Q_{In} = Q_{Out} = V\ w_{Ditch}\ H_{Str} \tag{C-31}$$

where:

Q_{In}	=	Ditch inflow rate from upstream (L^3/T)
Q_{Out}	=	Ditch outflow rate to downstream (L^3/T)
V	=	Cross-section average water velocity (L/T)
w_{Ditch}	=	Ditch width (L)
H_{Str}	=	Depth of water in the ditch (L)

Dry Ditches

In arid areas where the roadside ditch is mostly dry, it is likely that Q_{DExfil} is negative. In the event that Q_{DExfil} is negative, it is assumed that the some or all Q'_{RO} and Q'_{PB} are discharged to the roadside without forming a surface water body. It is also assumed that the infiltration can be estimated using the following relationship:

$$\frac{Q'_{RO} + Q'_{PB} + Q_{Precip}}{Q_{DExfil} + Q_{Rech}} = \frac{Q_{Precip}}{Q_{Rech}} \tag{C-32}$$

where:

Q'_{RO}	=	Total effective runoff water flux (L^3/T) that reaches the ditch
Q'_{PB}	=	Effective water flux from collector pipe in the permeable base (L^3/T) that reaches the ditch
Q_{Precip}	=	Precipitation flux (L^3/T)
Q_{DExfil}	=	Exfiltration rate from the ditch (L^3/T)
Q_{Rech}	=	Recharge flux (L^3/T)

Q_{Rech} is calculated as

$$Q_{Rech} = R_{Rech} \times w_{Ditch} \times L \tag{C-33}$$

where:

Q_{Rech}	=	Recharge flux (L^3/T)
R_{Rech}	=	Recharge flux per unit area (L/T)
w_{Ditch}	=	Ditch width (L)
L	=	Length of ditch (L)

Note that R_{Rech} is available in the EPACMTP database.

From Equation (C-32), one obtains the following:

$$Q_{DExfil} = (Q'_{RO} + Q'_{PB} + Q_{Precip}) \frac{Q_{Rech}}{Q_{Precip}} - Q_{Rech} \tag{C-34}$$

where:

Q_{DExfil} = Exfiltration rate from the ditch (L^3/T)
Q'_{RO} = Total effective runoff water flux (L^3/T) that reaches the ditch
Q'_{PB} = Effective water flux from collector pipe in the permeable base (L^3/T) that reaches the ditch
Q_{Precip} = Precipitation flux (L^3/T)
Q_{Rech} = Recharge flux (L^3/T)

However, Q_{DExfil} is limited to

$$Q_{DExfil} \le w_{Ditch} \, L \, K_{TopSoil} \tag{C-35}$$

where:

Q_{DExfil} = Exfiltration rate from the ditch (L^3/T)
w_{Ditch} = Ditch width (L)
L = Length of ditch (L)
$K_{TopSoil}$ = Vertical hydraulic conductivity of the top soil (L/T)

In the case that Q_{DExfil} from Equation (C-33) is greater than the right-hand side of Equation (C-35), it is limited to the right-hand side of Equation (C-34), and the excess flux is assumed lost to evaporation. The resultant contaminant concentration in the ditch area is estimated using Q_{DExfil} from Equation (C-35), thus

$$C_{DExfil} = \frac{\overline{C}_{PB} \times Q'_{PB}}{Q_{DExfil} + Q_{Rech}} \tag{C-36}$$

where:

C_{DExfil} = Contaminant concentration of ditch exfiltration (M/L^3) the ditch
$\overline{C}_{PB}$ = Time-average concentration of efflux from the permeable base (M/L^3)
Q'_{PB} = Effective water flux from collector pipe in the permeable base (L^3/T) that reaches the ditch
Q_{DExfil} = Exfiltration rate from the ditch (L^3/T)
Q_{Rech} = Recharge flux (L^3/T)

C.2.2.6 Single and Multiple Road Segments

Single Road Segment

Each roadway-source strip is treated as an individual source, and a number of individual EPACMTP simulations for all the strips and layers must be performed. The fate and transport effects observed at receptor locations are estimated by summing the 90th percentile exposure concentrations for all layers for each constituent. These strips and layers constitute a composite source or a single roadway segment source. The summing of contributions from all strips and layers for a single road segment source is managed by IWEM. The maximum value of the resulting aggregate exposure concentration for each constituent is limited by the maximum leachate concentration provided by the user for that constituent.

Multiple Road Segments

If several road segments are modeled, each segment must be treated as a composite source consisting of strips and layers, as described above. Contaminant concentrations at receptor wells resulting from contributions from all composite sources are determined by the method of superposition. In other words, concentration of a contaminant at a receptor well location is the sum of concentration contributions from all segments. Aggregation of concentrations from all segments must be performed by the user outside IWEM.

The road constructed with recycled materials (with contaminants) may be longitudinally divided into several contiguous segments, as shown in **Figure C-12**. To account for contaminants carried by the flowing water in the roadside ditch, additional ditch segments farther downstream than the road segments may be required. Between two connecting ditch segments, C_{Out} of the upstream segment becomes C_{In} for the downstream segment. In other words,

$$C_{Out}^{l-1} = C_{In}^{l} \qquad \text{(C-37)}$$

where:

C^{l-1}_{Out} = Concentration in the outflow of the *l*-1st ditch segment (M/L^3)
C^{1}_{In} = Concentration in the inflow of the *l*-th ditch segment (M/L^3)

Assuming that there is no influx of contaminant at the upstream-most segment of the ditch, using Equation (C-23) recursively, it can be shown that:

For the first segment:

$$C_{Out}^{1} = \frac{Q'_{PB}\,\overline{C}_{PB}}{Q_{out} + Q_{DExfil}} \qquad \text{(C-38a)}$$

For the second segment:

$$C_{Out}^{2} = \frac{Q_{In}\,Q'_{PB}\,\overline{C}_{PB} + Q'_{PB}\,\overline{C}_{PB}\left(Q_{out} + Q_{DExfil}\right)}{\left(Q_{out} + Q_{DExfil}\right)^2} \qquad \text{(C-38b)}$$

For the *n*-th segment:

$$C_{Out}^{n} = \frac{Q'_{PB}\,\overline{C}_{PB}\sum_{l=1}^{n}\left[Q_{In}^{n-l+1}\left(Q_{out} + Q_{DExfil}\right)^{l-1}\right]}{\left(Q_{out} + Q_{DExfil}\right)^n} \qquad \text{(C-38c)}$$

where:

C^{1}_{Out} = Concentration in the outflow of the 1st ditch segment (M/L^3)
C^{2}_{Out} = Concentration in the outflow of the 2nd ditch segment (M/L^3)
C^{n}_{Out} = Concentration in the outflow of the nth ditch segment (M/L^3)

Q'_{PB} = Effective water flux from collector pipe in the permeable base (L^3/T) that reaches the ditch
$\overline{C}_{PB}$ = Time-average concentration of efflux from the permeable base (M/L^3)
Q_{Out} = Ditch outflow rate to downstream (L^3/T)
Q_{DExfil} = Exfiltration rate from the ditch (L^3/T)
Q_{In} = Ditch inflow rate from upstream (L^3/T)

The required number of ditch segments beyond the road segments may be user-defined or dependent on pre-specified criteria. All the segments are assumed to be subject to the same water fluxes (runoff and permeable base discharge) from all road segments. As shown in Figure C-12, in each segment, the effective runoff and permeable base fluxes are the same for all segments; however, the concentration from the permeable base, C_{PB}, is zero in road segments constructed by conventional materials (without contaminants).

Let $C^n_{Out}(t)$ be the outflow concentration in the ditch segment corresponding to the last road segment (*n*-th segment). As the contaminant moves through the ditch, its concentration continually and gradually diminishes through the loss to the ditch exfiltration and through the addition of contaminant-free water from runoff, precipitation, and permeable base. With the addition of $L_{Segment}$ ditch segments beyond the road segments, using the mass conservation equation (Equation C-23) with $C_{PB} = 0$ recursively, the exfiltration concentration in this segment may be shown to be

$$C^{L_{Segment}}_{DExfil} = \left(\frac{Q_{In}}{Q_{Out} + Q_{DExfil}} \right)^{L_{Segment}} C^n_{Out}(t) \qquad \text{(C-39)}$$

where:

$C^{L_{Segment}}_{DExfil}$ = Exfiltration concentration in the ditch segment beyond the road segment (M/L^3)
Q_{In} = Ditch inflow rate from upstream (L^3/T)
Q_{Out} = Ditch outflow rate to downstream (L^3/T)
Q_{DExfil} = Exfiltration rate from the ditch (L^3/T)
$L_{Segment}$ = Number of ditch segments beyond the road segments (unitless)
$C^n_{Out}(t)$ = Outflow concentration in the ditch segment corresponding to the last (*n*th) road segment (M/L^3)

In order that the following condition is satisfied:

$$C^{L_{Segment}}_{DExfil} \leq C_{Crit} \qquad \text{(C-40)}$$

where:

$C^{L_{Segment}}_{DExfil}$ = Exfiltration concentration in the ditch segment beyond the road segment (M/L^3)
C_{Crit} = Criterion for exfiltration concentration (M/L^3)

The minimum number of ditch segments beyond the road segments must be at least

$$L_{Segment} \geq \frac{\log\left[\dfrac{C^n_{Out}}{C_{Crit}}\right]}{\log\left[\dfrac{Q_{In}}{Q_{Out} + Q_{DExfil}}\right]} \quad \text{(C-41)}$$

where:

$L_{Segment}$ = Number of ditch segments beyond the road segments (unitless)
C^n_{Out} = Outflow concentration in the ditch segment corresponding to the last (*n*th) road segment (M/L^3)
C_{Crit} = Criterion for exfiltration concentration (M/L^3)
Q_{In} = Ditch inflow rate from upstream (L^3/T)
Q_{Out} = Ditch outflow rate to downstream (L^3/T)
Q_{DExfil} = Exfiltration rate from the ditch (L^3/T)

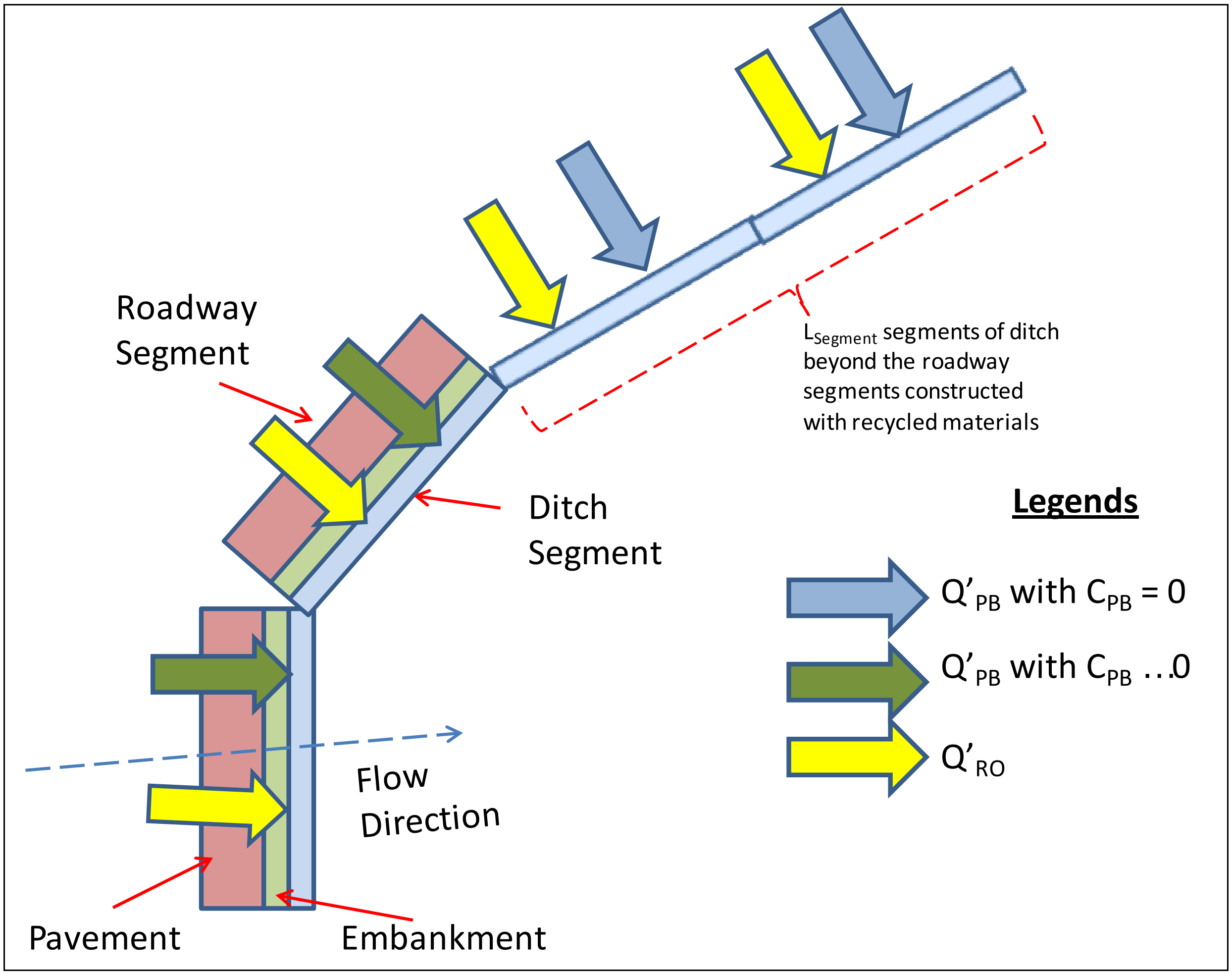


Figure C-12. Concatenated roadway segments and ditch segments (with and without roadway segments).

C.2.2.7 Single and Dual Drainage Systems

The derivation in the foregoing subsection assumes that there is only one drainage ditch along the roadway. In the event that the roadway is flanked by two drainage ditches, one on either side, it is assumed that the two ditches receive drainage from two different permeable bases, as shown in **Figure C-13**. It should be noted that the number of permeable bases is restricted to two. Runoff and drainage in two different systems is directed to respective drainage ditches.

C.2.2.8 Versatility of the IWEM Roadway Module

The IWEM Roadway module may be utilized to simulate leachate from a major berm or embankment constructed using recycled materials, as shown in **Figure C-14**. In the case shown in the figure, the berm may be represented by a single or multiple columns. Ditch-side berms, as shown in **Figure C-15,** may also be included in the roadway analyses. Other similar structural fills, such as backfills of retaining structures, and landfill caps may also be analyzed using the IWEM module.

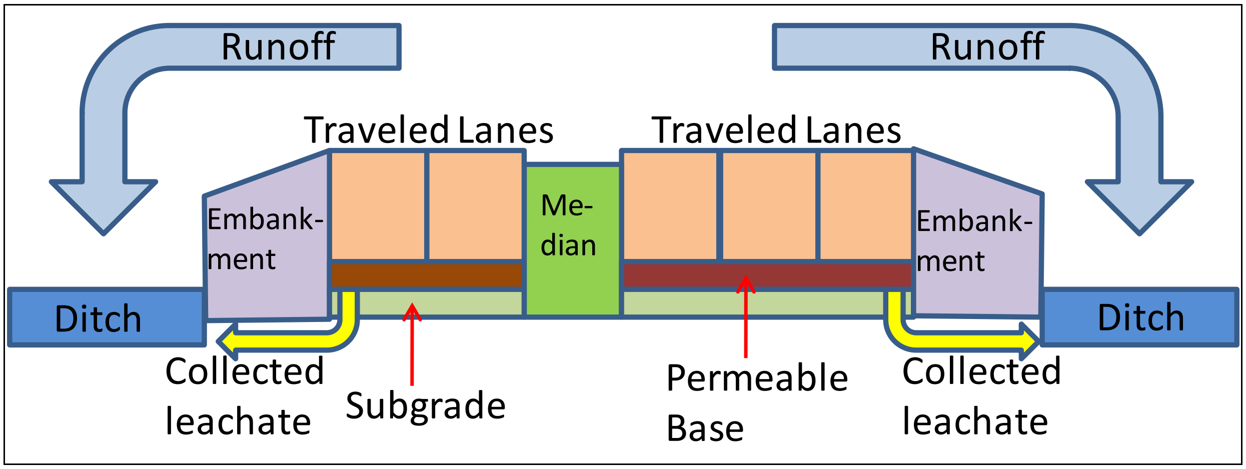


Figure C-13. A symmetric roadway segment with two symmetric assemblages with identical properties and drainage configurations.

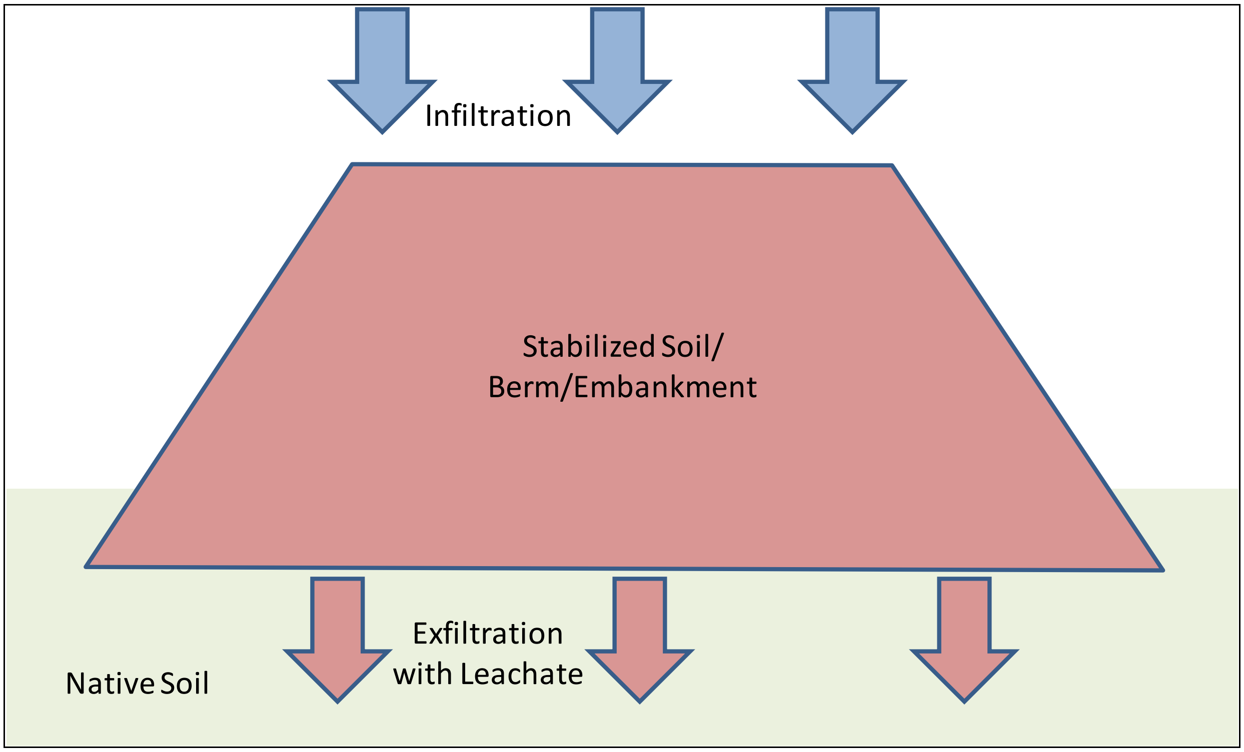
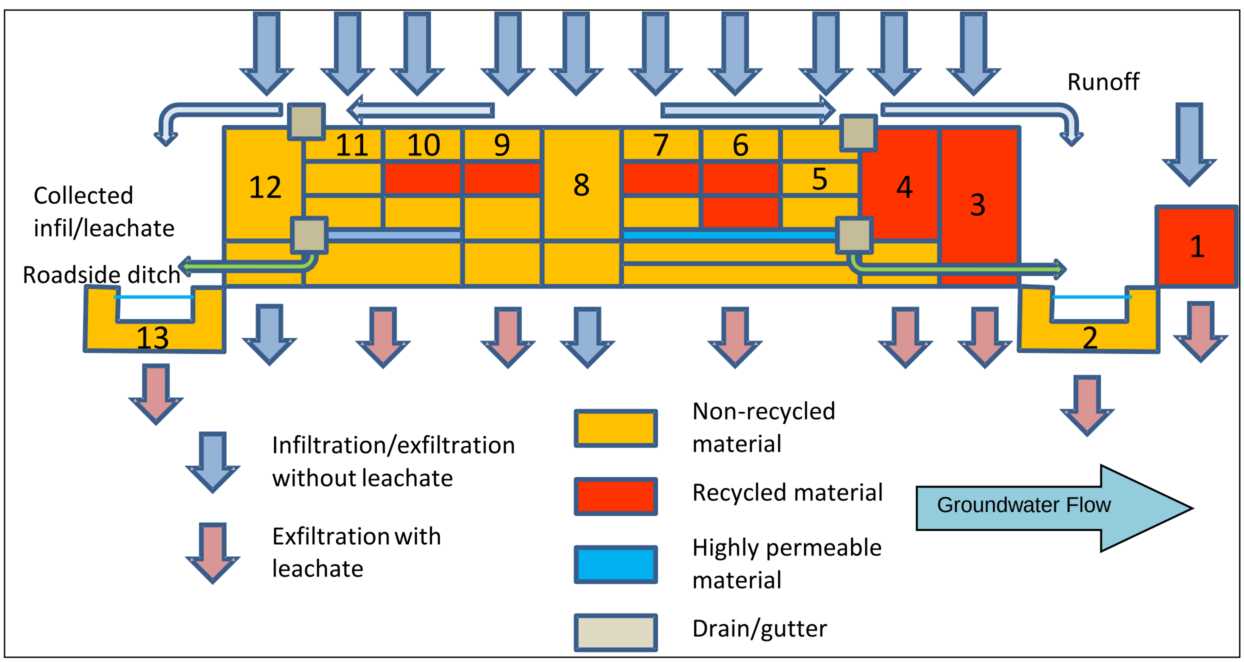


Figure C-14. A major berm/embankment.



Strip numbering conforms to IWEM specifications – beginning numbering at the down-gradient edge.
IWEM limits the maximum number of strips and layers to 15 and 5, respectively.

Figure C-15. An asymmetric roadway segment with two drainage configurations and a ditch-side berm (represented by Column 1).

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Appendix D: Infiltration Rate Data for WMUs and Structural Fills

This appendix provides the infiltration rates derived with the Hydrologic Evaluation of Landfill Performance (HELP) model (Schroeder et al, 1994) for landfills (unlined landfill rates are also used for structural fills) (**Table D-1**), waste piles (**Table D-2**), and land application units (**Table D-3**). In addition, **Tables D-4** and **D-5** provide, respectively, the flow rate data from (TetraTech, 2001) used to develop infiltration rates for composite liners for landfills and waste piles and the leak density data (TetraTech, 2001) used to develop infiltration rates for composite liners for surface impoundments. **Table D-6** presents a comparison of composite liner infiltration rates using different methods for landfills. **Figure D-1** shows that comparison graphically. For the interested reader, a detailed description of how the HELP model was used to develop infiltration and recharge rates is provided in Appendix A of the *EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP): Parameter/Data Background Document* (U.S. EPA, 2003).

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Table D-1. HELP-Derived Infiltration Rates for Landfills and Structural Fills (m/yr)

ID	City	State	No Liner (landfills, structural fills)			Clay Liner (landfills)
			Silt loam	Sandy loam	Silty clay loam	
19	Albuquerque	NM	0.00E+00	0.00E+00	3.00E-04	0.00E+00
98	Annette	AK	1.68E+00	1.84E+00	1.46E+00	3.38E-02
82	Astoria	OR	1.08E+00	1.15E+00	9.65E-01	5.26E-02
95	Atlanta	GA	3.42E-01	3.99E-01	2.82E-01	4.77E-02
62	Augusta	ME	2.12E-01	2.70E-01	1.67E-01	4.45E-02
44	Bangor	ME	1.47E-01	2.05E-01	1.23E-01	4.32E-02
99	Bethel	AK	5.64E-02	7.21E-02	5.54E-02	2.95E-02
7	Bismarck	ND	2.39E-02	3.00E-02	1.96E-02	1.88E-02
2	Boise	ID	8.00E-04	9.40E-03	3.80E-03	4.61E-03
67	Boston	MA	2.33E-01	2.38E-01	1.54E-01	4.45E-02
75	Bridgeport	CT	1.95E-01	2.46E-01	1.62E-01	4.44E-02
35	Brownsville	TX	5.49E-02	1.05E-01	3.84E-02	2.41E-02
43	Burlington	VT	1.36E-01	1.78E-01	1.17E-01	4.32E-02
41	Caribou	ME	1.08E-01	1.49E-01	8.86E-02	4.32E-02
18	Cedar City	UT	0.00E+00	8.00E-04	0.00E+00	6.69E-05
86	Central Park	NY	3.36E-01	4.17E-01	2.74E-01	4.86E-02
93	Charleston	SC	2.61E-01	3.29E-01	2.12E-01	4.77E-02
10	Cheyenne	WY	5.00E-04	1.30E-03	8.60E-03	2.38E-05
42	Chicago	IL	7.98E-02	1.14E-01	6.20E-02	4.32E-02
74	Cincinnati	OH	1.55E-01	2.21E-01	1.54E-01	4.44E-02
52	Cleveland	OH	7.80E-02	1.21E-01	8.23E-02	4.09E-02
55	Columbia	MO	1.53E-01	1.99E-01	1.22E-01	4.09E-02
51	Columbus	OH	7.65E-02	1.16E-01	6.63E-02	4.09E-02
38	Concord	NH	1.59E-01	2.06E-01	1.37E-01	4.32E-02
36	Dallas	TX	5.99E-02	1.07E-01	5.31E-02	2.41E-02
3	Denver	CO	8.00E-04	8.00E-04	3.60E-03	1.83E-05
53	Des Moines	IA	1.14E-01	1.64E-01	1.16E-01	4.09E-02
29	Dodge City	KS	1.35E-02	3.45E-02	2.26E-02	9.44E-03
32	E. Lansing	MI	1.09E-01	1.45E-01	1.10E-01	3.74E-02
54	E. St. Louis	IL	1.44E-01	1.68E-01	7.04E-02	4.09E-02
88	Edison	NJ	3.12E-01	3.91E-01	2.49E-01	4.86E-02
23	El Paso	TX	7.60E-03	1.30E-02	8.10E-03	1.03E-04
16	Ely	NV	0.00E+00	0.00E+00	3.00E-04	3.54E-05
100	Fairbanks	AK	1.04E-02	2.34E-02	1.17E-02	9.40E-03
28	Flagstaff	AZ	2.39E-02	6.30E-02	2.26E-02	2.41E-02

ID	City	State	No Liner (landfills, structural fills)			Clay Liner (landfills)
			Silt loam	Sandy loam	Silty clay loam	
1	Fresno	CA	3.07E-02	3.68E-02	3.81E-02	4.61E-03
6	Glasgow	MT	9.90E-03	7.40E-03	9.90E-03	6.69E-05
27	Grand Island	NE	4.42E-02	6.27E-02	3.23E-02	1.96E-02
4	Grand Junction	CO	0.00E+00	0.00E+00	3.00E-04	2.70E-05
25	Great Falls	MT	3.60E-03	6.90E-03	7.40E-03	1.02E-04
77	Greensboro	NC	3.26E-01	3.90E-01	2.71E-01	3.62E-02
59	Hartford	CT	1.71E-01	2.23E-01	1.41E-01	4.45E-02
101	Honolulu	HI	5.23E-02	9.45E-02	3.66E-02	4.83E-03
73	Indianapolis	IN	1.30E-01	1.86E-01	1.06E-01	4.44E-02
66	Ithaca	NY	1.68E-01	2.14E-01	1.39E-01	4.45E-02
78	Jacksonville	FL	1.51E-01	2.11E-01	1.10E-01	3.62E-02
85	Knoxville	TN	4.11E-01	4.46E-01	3.54E-01	4.86E-02
96	Lake Charles	LA	3.65E-01	4.64E-01	2.82E-01	4.92E-02
11	Lander	WY	3.30E-03	5.30E-03	9.40E-03	1.28E-04
20	Las Vegas	NV	0.00E+00	0.00E+00	1.80E-03	6.89E-05
87	Lexington	KY	3.29E-01	3.97E-01	2.70E-01	4.86E-02
90	Little Rock	AK	3.53E-01	4.34E-01	2.82E-01	4.77E-02
12	Los Angeles	CA	7.87E-02	9.50E-02	6.99E-02	1.26E-03
69	Lynchburg	VA	3.08E-01	3.61E-01	2.57E-01	4.44E-02
50	Madison	WI	9.12E-02	1.40E-01	6.86E-02	4.09E-02
24	Medford	OR	2.07E-01	2.31E-01	2.10E-01	4.32E-02
97	Miami	FL	1.45E-01	2.20E-01	1.02E-01	4.92E-02
30	Midland	TX	1.80E-02	2.54E-02	1.35E-02	9.44E-03
47	Montpelier	VT	1.06E-01	1.48E-01	8.79E-02	4.32E-02
65	Nashua	NH	2.27E-01	2.81E-01	1.94E-01	4.45E-02
89	Nashville	TN	4.67E-01	5.40E-01	3.77E-01	4.86E-02
83	New Haven	CT	3.52E-01	4.63E-01	2.86E-01	5.26E-02
92	New Orleans	LA	5.89E-01	7.45E-01	4.50E-01	4.77E-02
70	New York City	NY	2.44E-01	2.94E-01	1.97E-01	4.44E-02
80	Norfolk	VA	3.12E-01	0.00E+00	2.69E-01	3.62E-02
33	North Omaha	NE	6.71E-02	7.95E-02	5.36E-02	2.91E-02
37	Oklahoma City	OK	6.12E-02	9.42E-02	3.89E-02	2.46E-02
76	Orlando	FL	1.02E-01	1.70E-01	8.05E-02	3.62E-02
71	Philadelphia	PA	2.01E-01	2.61E-01	1.64E-01	4.44E-02
21	Phoenix	AZ	0.00E+00	3.00E-04	3.00E-04	1.69E-05
39	Pittsburg	PA	8.94E-02	1.31E-01	7.92E-02	4.32E-02

ID	City	State	No Liner (landfills, structural fills)			Clay Liner (landfills)
			Silt loam	Sandy loam	Silty clay loam	
84	Plainfield	MA	1.90E-01	2.54E-01	1.52E-01	5.26E-02
5	Pocatello	ID	0.00E+00	0.00E+00	0.00E+00	5.50E-04
40	Portland	OR	4.17E-01	4.39E-01	3.93E-01	4.32E-02
64	Portland	ME	2.29E-01	2.84E-01	1.87E-01	4.45E-02
63	Providence	RI	2.13E-01	2.86E-01	1.75E-01	4.45E-02
8	Pullman	WA	6.90E-03	1.32E-02	8.40E-03	2.27E-04
49	Put-in-Bay	OH	5.08E-02	1.00E-01	4.95E-02	4.09E-02
17	Rapid City	SD	5.00E-04	7.10E-03	3.30E-03	6.40E-05
45	Rutland	VT	1.21E-01	1.60E-01	1.01E-01	4.32E-02
13	Sacramento	CA	1.02E-01	8.76E-02	9.45E-02	1.26E-03
26	Salt Lake City	UT	1.30E-02	2.69E-02	1.85E-02	5.10E-04
58	San Antonio	TX	1.10E-01	1.65E-01	8.20E-02	2.53E-02
14	San Diego	CA	2.21E-02	3.40E-02	2.41E-02	1.26E-03
102	San Juan	PR	1.27E-01	1.92E-01	9.45E-02	1.93E-02
15	Santa Maria	CA	9.47E-02	1.15E-01	8.41E-02	1.26E-03
48	Sault St. Marie	MI	1.65E-01	2.10E-01	1.44E-01	4.32E-02
68	Schenectady	NY	1.47E-01	1.93E-01	1.22E-01	4.45E-02
72	Seabrook	NJ	1.81E-01	2.43E-01	1.43E-01	4.44E-02
46	Seattle	WA	4.38E-01	4.58E-01	4.08E-01	4.32E-02
81	Shreveport	LA	2.30E-01	2.94E-01	1.84E-01	3.62E-02
31	St. Cloud	MN	6.02E-02	8.31E-02	5.54E-02	3.42E-02
60	Syracuse	NY	2.55E-01	3.25E-01	2.12E-01	4.45E-02
91	Tallahassee	FL	5.91E-01	7.31E-01	4.56E-01	4.77E-02
57	Tampa	FL	6.58E-02	1.03E-01	4.75E-02	2.53E-02
56	Topeka	KS	1.05E-01	1.48E-01	7.62E-02	3.50E-02
22	Tucson	AZ	0.00E+00	3.00E-04	5.00E-04	2.23E-05
34	Tulsa	OK	6.86E-02	1.01E-01	4.65E-02	2.41E-02
94	W. Palm Beach	FL	2.61E-01	3.49E-01	1.78E-01	4.77E-02
79	Watkinsville	GA	2.89E-01	3.56E-01	2.33E-01	3.62E-02
61	Worchester	MA	2.02E-01	2.59E-01	1.70E-01	4.45E-02
9	Yakima	WA	0.00E+00	2.30E-03	3.00E-04	1.15E-04

Table D-2. HELP-Derived Infiltration Rates for Waste Piles (m/yr)

ID	City	State	No Liner[a]			Clay Liner[a]		
			Low Permea-bility Waste	Medium Permea-bility Waste	High Permea-bility Waste	Low Permea-bility Waste	Medium Perma-bility Waste	High Permea-bility Waste
19	Albuquerque	NM	2.54E-04	2.54E-04	2.54E-04	1.60E-03	1.51E-02	7.43E-03
98	Annette	AK	1.54E+00	1.81E+00	1.88E+00	1.35E-01	1.36E-01	1.35E-01
82	Astoria	OR	1.21E+00	1.21E+00	1.21E+00	1.32E-01	1.35E-01	1.35E-01
95	Atlanta	GA	5.16E-01	5.16E-01	5.16E-01	1.18E-01	1.35E-01	1.35E-01
62	Augusta	ME	3.14E-01	3.14E-01	3.14E-01	1.19E-01	1.29E-01	1.28E-01
44	Bangor	ME	2.57E-01	2.57E-01	2.57E-01	1.13E-01	1.27E-01	1.27E-01
99	Bethel	AK	5.02E-02	7.25E-02	1.23E-01	3.52E-02	3.64E-02	6.60E-02
7	Bismarck	ND	2.59E-02	2.59E-02	2.59E-02	1.24E-02	6.89E-02	9.50E-02
2	Boise	ID	2.54E-04	2.54E-04	2.54E-04	1.36E-02	4.34E-02	6.06E-02
67	Boston	MA	3.22E-01	3.22E-01	3.22E-01	1.19E-01	1.29E-01	1.28E-01
75	Bridgeport	CT	3.69E-01	3.69E-01	3.69E-01	1.06E-01	1.34E-01	1.33E-01
35	Brownsville	TX	2.27E-01	2.27E-01	2.27E-01	4.97E-03	1.33E-01	1.32E-01
43	Burlington	VT	2.13E-01	2.13E-01	2.13E-01	1.13E-01	1.27E-01	1.27E-01
41	Caribou	ME	1.88E-01	1.88E-01	1.88E-01	1.13E-01	1.27E-01	1.27E-01
18	Cedar City	UT	2.54E-04	2.54E-04	2.54E-04	4.82E-03	8.26E-04	5.32E-03
86	Central Park	NY	5.23E-01	5.23E-01	5.23E-01	1.26E-01	1.35E-01	1.35E-01
93	Charleston	SC	4.83E-01	4.83E-01	4.83E-01	1.18E-01	1.35E-01	1.35E-01
10	Cheyenne	WY	4.32E-03	4.32E-03	4.32E-03	1.37E-03	2.92E-04	7.07E-03
42	Chicago	IL	1.68E-01	1.68E-01	1.68E-01	1.13E-01	1.27E-01	1.27E-01
74	Cincinnati	OH	3.10E-01	3.10E-01	3.10E-01	1.06E-01	1.34E-01	1.33E-01
52	Cleveland	OH	1.82E-01	1.82E-01	1.82E-01	6.88E-02	1.32E-01	1.32E-01
55	Columbia	MO	3.10E-01	3.10E-01	3.10E-01	6.88E-02	1.32E-01	1.32E-01
51	Columbus	OH	1.72E-01	1.72E-01	1.72E-01	6.88E-02	1.32E-01	1.32E-01
38	Concord	NH	2.35E-01	2.35E-01	2.35E-01	1.13E-01	1.27E-01	1.27E-01
36	Dallas	TX	2.58E-01	2.58E-01	2.58E-01	4.97E-03	1.33E-01	1.32E-01
3	Denver	CO	7.62E-04	7.62E-04	7.62E-04	1.97E-03	1.28E-03	3.66E-03
53	Des Moines	IA	2.51E-01	2.51E-01	2.51E-01	6.88E-02	1.32E-01	1.32E-01
29	Dodge City	KS	1.01E-01	1.01E-01	1.01E-01	3.26E-03	1.06E-01	1.19E-01
32	E. Lansing	MI	1.36E-01	1.36E-01	1.36E-01	4.81E-02	1.15E-01	1.11E-01
54	E. St. Louis	IL	2.63E-01	2.63E-01	2.63E-01	6.88E-02	1.32E-01	1.32E-01
88	Edison	NJ	4.90E-01	4.90E-01	4.90E-01	1.26E-01	1.35E-01	1.35E-01
23	El Paso	TX	2.31E-02	2.31E-02	2.31E-02	5.81E-03	2.63E-03	6.74E-03
16	Ely	NV	2.54E-04	2.54E-04	2.54E-04	5.89E-03	1.12E-03	3.61E-03
100	Fairbanks	AK	7.67E-03	1.67E-02	7.77E-02	9.80E-03	1.18E-02	4.07E-02

ID	City	State	No Liner[a]			Clay Liner[a]		
			Low Permea-bility Waste	Medium Permea-bility Waste	High Permea-bility Waste	Low Permea-bility Waste	Medium Perma-bility Waste	High Permea-bility Waste
28	Flagstaff	AZ	4.04E-02	4.04E-02	4.04E-02	1.05E-02	1.23E-01	1.23E-01
1	Fresno	CA	4.22E-02	4.22E-02	4.22E-02	1.36E-02	4.34E-02	6.06E-02
6	Glasgow	MT	3.66E-02	3.66E-02	3.66E-02	5.35E-04	2.25E-04	2.34E-02
27	Grand Island	NE	9.63E-02	9.63E-02	9.63E-02	4.22E-02	1.35E-01	1.34E-01
4	Grand Junction	CO	2.54E-04	2.54E-04	2.54E-04	4.59E-03	1.66E-03	1.98E-03
25	Great Falls	MT	2.59E-02	2.59E-02	2.59E-02	1.94E-03	4.66E-03	3.34E-02
77	Greensboro	NC	4.84E-01	4.84E-01	4.84E-01	8.04E-02	1.27E-01	1.27E-01
59	Hartford	CT	2.79E-01	2.79E-01	2.79E-01	1.19E-01	1.29E-01	1.28E-01
101	Honolulu	HI	5.01E-02	1.08E-01	1.98E-01	3.23E-02	4.94E-02	8.71E-02
73	Indianapolis	IN	2.69E-01	2.69E-01	2.69E-01	1.06E-01	1.34E-01	1.33E-01
66	Ithaca	NY	2.61E-01	2.61E-01	2.61E-01	1.19E-01	1.29E-01	1.28E-01
78	Jacksonville	FL	4.09E-01	4.09E-01	4.09E-01	8.04E-02	1.27E-01	1.27E-01
85	Knoxville	TN	5.42E-01	5.42E-01	5.42E-01	1.26E-01	1.35E-01	1.35E-01
96	Lake Charles	LA	6.07E-01	6.07E-01	6.07E-01	4.89E-02	5.58E-02	9.27E-02
11	Lander	WY	2.03E-03	2.03E-03	2.03E-03	4.19E-03	1.25E-03	2.00E-02
20	Las Vegas	NV	2.54E-04	2.54E-04	2.54E-04	5.15E-03	1.79E-03	7.97E-03
87	Lexington	KY	4.52E-01	4.52E-01	4.52E-01	1.26E-01	1.35E-01	1.35E-01
90	Little Rock	AK	5.38E-01	5.38E-01	5.38E-01	1.18E-01	1.35E-01	1.35E-01
12	Los Angeles	CA	1.33E-01	1.33E-01	1.33E-01	0.00E+00	5.56E-02	7.18E-02
69	Lynchburg	VA	2.69E-01	2.69E-01	2.69E-01	1.06E-01	1.34E-01	1.33E-01
50	Madison	WI	2.02E-01	2.02E-01	2.02E-01	6.88E-02	1.32E-01	1.32E-01
24	Medford	OR	2.50E-01	2.50E-01	2.50E-01	1.26E-01	1.33E-01	1.31E-01
97	Miami	FL	4.23E-01	4.23E-01	4.23E-01	4.89E-02	5.58E-02	9.27E-02
30	Midland	TX	7.57E-02	7.57E-02	7.57E-02	3.26E-03	1.06E-01	1.19E-01
47	Montpelier	VT	1.76E-01	1.76E-01	1.76E-01	1.13E-01	1.27E-01	1.27E-01
65	Nashua	NH	3.34E-01	3.34E-01	3.34E-01	1.19E-01	1.29E-01	1.28E-01
89	Nashville	TN	6.14E-01	6.14E-01	6.14E-01	1.26E-01	1.35E-01	1.35E-01
83	New Haven	CT	5.42E-01	5.42E-01	5.42E-01	1.32E-01	1.35E-01	1.35E-01
92	New Orleans	LA	8.49E-01	8.49E-01	8.49E-01	1.18E-01	1.35E-01	1.35E-01
70	New York City	NY	3.99E-01	3.99E-01	3.99E-01	1.06E-01	1.34E-01	1.33E-01
80	Norfolk	VA	4.54E-01	4.54E-01	4.54E-01	8.04E-02	1.27E-01	1.27E-01
33	North Omaha	NE	1.62E-01	1.62E-01	1.62E-01	2.02E-02	1.26E-01	1.27E-01
37	Oklahoma City	OK	2.42E-01	2.42E-01	2.42E-01	7.47E-03	1.31E-01	1.30E-01
76	Orlando	FL	3.84E-01	3.84E-01	3.84E-01	8.04E-02	1.27E-01	1.27E-01
71	Philadelphia	PA	3.53E-01	3.53E-01	3.53E-01	1.06E-01	1.34E-01	1.33E-01

ID	City	State	No Liner[a]			Clay Liner[a]		
			Low Permea-bility Waste	Medium Permea-bility Waste	High Permea-bility Waste	Low Permea-bility Waste	Medium Perma-bility Waste	High Permea-bility Waste
21	Phoenix	AZ	2.54E-04	2.54E-04	2.54E-04	4.73E-03	2.01E-03	7.62E-04
39	Pittsburg	PA	1.72E-01	1.72E-01	1.72E-01	1.13E-01	1.27E-01	1.27E-01
84	Plainfield	MA	3.03E-01	3.03E-01	3.03E-01	1.32E-01	1.35E-01	1.35E-01
5	Pocatello	ID	2.54E-04	2.54E-04	2.54E-04	5.86E-03	1.50E-03	3.19E-02
40	Portland	OR	5.06E-01	5.06E-01	5.06E-01	1.13E-01	1.27E-01	1.27E-01
64	Portland	ME	3.25E-01	3.25E-01	3.25E-01	1.19E-01	1.29E-01	1.28E-01
63	Providence	RI	3.48E-01	3.48E-01	3.48E-01	1.19E-01	1.29E-01	1.28E-01
8	Pullman	WA	2.54E-04	2.54E-04	2.54E-04	9.27E-03	1.43E-02	3.44E-02
49	Put-in-Bay	OH	1.48E-01	1.48E-01	1.48E-01	6.88E-02	1.32E-01	1.32E-01
17	Rapid City	SD	1.35E-02	1.35E-02	1.35E-02	9.92E-04	1.14E-03	1.92E-02
45	Rutland	VT	2.13E-01	2.13E-01	2.13E-01	1.13E-01	1.27E-01	1.27E-01
13	Sacramento	CA	1.23E-01	1.23E-01	1.23E-01	0.00E+00	5.56E-02	7.18E-02
26	Salt Lake City	UT	1.93E-02	1.93E-02	1.93E-02	9.11E-03	1.05E-02	3.68E-02
58	San Antonio	TX	2.95E-01	2.95E-01	2.95E-01	2.00E-02	1.34E-01	1.33E-01
14	San Diego	CA	6.58E-02	6.58E-02	6.58E-02	0.00E+00	5.56E-02	7.18E-02
102	San Juan	PR	1.50E-01	2.88E-01	4.44E-01	6.37E-02	7.93E-02	1.11E-01
15	Santa Maria	CA	1.51E-01	1.51E-01	1.51E-01	0.00E+00	5.56E-02	7.18E-02
48	Sault St. Marie	MI	2.37E-01	2.37E-01	2.37E-01	1.13E-01	1.27E-01	1.27E-01
68	Schenectady	NY	2.75E-01	2.75E-01	2.75E-01	1.19E-01	1.29E-01	1.28E-01
72	Seabrook	NJ	3.41E-01	3.41E-01	3.41E-01	1.06E-01	1.34E-01	1.33E-01
46	Seattle	WA	5.31E-01	5.31E-01	5.31E-01	1.13E-01	1.27E-01	1.27E-01
81	Shreveport	LA	4.46E-01	4.46E-01	4.46E-01	8.04E-02	1.27E-01	1.27E-01
31	St. Cloud	MN	1.52E-01	1.52E-01	1.52E-01	2.64E-02	1.26E-01	1.26E-01
60	Syracuse	NY	4.10E-01	4.10E-01	4.10E-01	1.19E-01	1.29E-01	1.28E-01
91	Tallahassee	FL	8.22E-01	8.22E-01	8.22E-01	1.18E-01	1.35E-01	1.35E-01
57	Tampa	FL	2.72E-01	2.72E-01	2.72E-01	2.00E-02	1.34E-01	1.33E-01
56	Topeka	KS	2.47E-01	2.47E-01	2.47E-01	1.74E-02	1.31E-01	1.30E-01
22	Tucson	AZ	2.54E-04	2.54E-04	2.54E-04	6.41E-03	7.53E-03	1.69E-03
34	Tulsa	OK	2.49E-01	2.49E-01	2.49E-01	4.97E-03	1.33E-01	1.32E-01
94	W. Palm Beach	FL	5.64E-01	5.64E-01	5.64E-01	1.18E-01	1.35E-01	1.35E-01
79	Watkinsville	GA	4.67E-01	4.67E-01	4.67E-01	8.04E-02	1.27E-01	1.27E-01
61	Worchester	MA	3.31E-01	3.31E-01	3.31E-01	1.19E-01	1.29E-01	1.28E-01
9	Yakima	WA	2.54E-04	2.54E-04	2.54E-04	4.86E-03	4.74E-03	2.84E-02

[a] Low, Medium, and High denote representative waste types with different hydraulic conductivities:
Low = Fine-grained waste (e.g., fly ash), Hydraulic conductivity is $5x10^{-5}$ cm/sec
Medium = Medium-grained waste (e.g., bottom ash), Hydraulic conductivity is 0.0041 cm/sec
High = Coarse-grained waste (e.g., slag), Hydraulic conductivity is 0.041 cm/sec

Table D-3. HELP-Derived Infiltration Rates for Land Application Units (m/yr)

ID	City	State	No Liner		
			Silty loam	Sandy loam	Silty clay loam
19	Albuquerque	NM	0.00E+00	0.00E+00	3.00E-04
98	Annette	AK	1.80E+00	1.98E+00	1.52E+00
82	Astoria	OR	1.08E+00	1.15E+00	9.65E-01
95	Atlanta	GA	3.42E-01	3.99E-01	2.82E-01
62	Augusta	ME	2.12E-01	2.70E-01	1.67E-01
44	Bangor	ME	1.47E-01	2.05E-01	1.23E-01
99	Bethel	AK	1.85E-01	1.98E-01	1.78E-01
7	Bismarck	ND	2.39E-02	3.00E-02	1.96E-02
2	Boise	ID	8.00E-04	9.40E-03	3.80E-03
67	Boston	MA	2.33E-01	2.38E-01	1.54E-01
75	Bridgeport	CT	1.95E-01	2.46E-01	1.62E-01
35	Brownsville	TX	5.49E-02	1.05E-01	3.84E-02
43	Burlington	VT	1.36E-01	1.78E-01	1.17E-01
41	Caribou	ME	1.08E-01	1.49E-01	8.86E-02
18	Cedar City	UT	0.00E+00	8.00E-04	0.00E+00
86	Central Park	NY	3.36E-01	4.17E-01	2.74E-01
93	Charleston	SC	2.61E-01	3.29E-01	2.12E-01
10	Cheyenne	WY	5.00E-04	1.30E-03	8.60E-03
42	Chicago	IL	7.98E-02	1.14E-01	6.20E-02
74	Cincinnati	OH	1.55E-01	2.21E-01	1.54E-01
52	Cleveland	OH	7.80E-02	1.21E-01	8.23E-02
55	Columbia	MO	1.53E-01	1.99E-01	1.22E-01
51	Columbus	OH	7.65E-02	1.16E-01	6.63E-02
38	Concord	NH	1.59E-01	2.06E-01	1.37E-01
36	Dallas	TX	5.99E-02	1.07E-01	5.31E-02
3	Denver	CO	8.00E-04	8.00E-04	3.60E-03
53	Des Moines	IA	1.14E-01	1.64E-01	1.16E-01
29	Dodge City	KS	1.35E-02	3.45E-02	2.26E-02
32	E. Lansing	MI	1.09E-01	1.45E-01	1.10E-01
54	E. St. Louis	IL	1.44E-01	1.68E-01	7.04E-02
88	Edison	NJ	3.12E-01	3.91E-01	2.49E-01
23	El Paso	TX	7.60E-03	1.30E-02	8.10E-03
16	Ely	NV	0.00E+00	0.00E+00	3.00E-04
100	Fairbanks	AK	1.46E-01	1.48E-01	1.45E-01
28	Flagstaff	AZ	2.39E-02	6.30E-02	2.26E-02

ID	City	State	No Liner		
			Silty loam	Sandy loam	Silty clay loam
1	Fresno	CA	3.07E-02	3.68E-02	3.81E-02
6	Glasgow	MT	9.90E-03	7.40E-03	9.90E-03
27	Grand Island	NE	4.42E-02	6.27E-02	3.23E-02
4	Grand Junction	CO	0.00E+00	0.00E+00	3.00E-04
25	Great Falls	MT	3.60E-03	6.90E-03	7.40E-03
77	Greensboro	NC	3.26E-01	3.90E-01	2.71E-01
59	Hartford	CT	1.71E-01	2.23E-01	1.41E-01
101	Honolulu	HI	5.41E-02	9.83E-02	3.63E-02
73	Indianapolis	IN	1.30E-01	1.86E-01	1.06E-01
66	Ithaca	NY	1.68E-01	2.14E-01	1.39E-01
78	Jacksonville	FL	1.51E-01	2.11E-01	1.10E-01
85	Knoxville	TN	4.11E-01	4.46E-01	3.54E-01
96	Lake Charles	LA	3.65E-01	4.64E-01	2.82E-01
11	Lander	WY	3.30E-03	5.30E-03	9.40E-03
20	Las Vegas	NV	0.00E+00	0.00E+00	1.80E-03
87	Lexington	KY	3.29E-01	3.97E-01	2.70E-01
90	Little Rock	AK	3.53E-01	4.34E-01	2.82E-01
12	Los Angeles	CA	7.87E-02	9.50E-02	6.99E-02
69	Lynchburg	VA	3.08E-01	3.61E-01	2.57E-01
50	Madison	WI	9.12E-02	1.40E-01	6.86E-02
24	Medford	OR	2.07E-01	2.31E-01	2.10E-01
97	Miami	FL	1.45E-01	2.20E-01	1.02E-01
30	Midland	TX	1.80E-02	2.54E-02	1.35E-02
47	Montpelier	VT	1.06E-01	1.48E-01	8.79E-02
65	Nashua	NH	2.27E-01	2.81E-01	1.94E-01
89	Nashville	TN	4.67E-01	5.40E-01	3.77E-01
83	New Haven	CT	3.52E-01	4.63E-01	2.86E-01
92	New Orleans	LA	5.89E-01	7.45E-01	4.50E-01
70	New York City	NY	2.44E-01	2.94E-01	1.97E-01
80	Norfolk	VA	3.12E-01	0.00E+00	2.69E-01
33	North Omaha	NE	6.71E-02	7.95E-02	5.36E-02
37	Oklahoma City	OK	6.12E-02	9.42E-02	3.89E-02
76	Orlando	FL	1.02E-01	1.70E-01	8.05E-02
71	Philadelphia	PA	2.01E-01	2.61E-01	1.64E-01
21	Phoenix	AZ	0.00E+00	3.00E-04	3.00E-04
39	Pittsburg	PA	8.94E-02	1.31E-01	7.92E-02

ID	City	State	No Liner		
			Silty loam	Sandy loam	Silty clay loam
84	Plainfield	MA	1.90E-01	2.54E-01	1.52E-01
5	Pocatello	ID	0.00E+00	0.00E+00	0.00E+00
40	Portland	OR	4.17E-01	4.39E-01	3.93E-01
64	Portland	ME	2.29E-01	2.84E-01	1.87E-01
63	Providence	RI	2.13E-01	2.86E-01	1.75E-01
8	Pullman	WA	6.90E-03	1.32E-02	8.40E-03
49	Put-in-Bay	OH	5.08E-02	1.00E-01	4.95E-02
17	Rapid City	SD	5.00E-04	7.10E-03	3.30E-03
45	Rutland	VT	1.21E-01	1.60E-01	1.01E-01
13	Sacramento	CA	1.02E-01	8.76E-02	9.45E-02
26	Salt Lake City	UT	1.30E-02	2.69E-02	1.85E-02
58	San Antonio	TX	1.10E-01	1.65E-01	8.20E-02
14	San Diego	CA	2.21E-02	3.40E-02	2.41E-02
102	San Juan	PR	1.49E-01	2.16E-01	1.05E-01
15	Santa Maria	CA	9.47E-02	1.15E-01	8.41E-02
48	Sault St. Marie	MI	1.65E-01	2.10E-01	1.44E-01
68	Schenectady	NY	1.47E-01	1.93E-01	1.22E-01
72	Seabrook	NJ	1.81E-01	2.43E-01	1.43E-01
46	Seattle	WA	4.38E-01	4.58E-01	4.08E-01
81	Shreveport	LA	2.30E-01	2.94E-01	1.84E-01
31	St. Cloud	MN	6.02E-02	8.31E-02	5.54E-02
60	Syracuse	NY	2.55E-01	3.25E-01	2.12E-01
91	Tallahassee	FL	5.91E-01	7.31E-01	4.56E-01
57	Tampa	FL	6.58E-02	1.03E-01	4.75E-02
56	Topeka	KS	1.05E-01	1.48E-01	7.62E-02
22	Tucson	AZ	0.00E+00	3.00E-04	5.00E-04
34	Tulsa	OK	6.86E-02	1.01E-01	4.65E-02
94	W. Palm Beach	FL	2.61E-01	3.49E-01	1.78E-01
79	Watkinsville	GA	2.89E-01	3.56E-01	2.33E-01
61	Worchester	MA	2.02E-01	2.59E-01	1.70E-01
9	Yakima	WA	0.00E+00	2.30E-03	3.00E-04

Table D-4. Flow Rate Data Used to Develop Composite Liner Infiltration Rates for Landfills and Waste Piles (from TetraTech, 2001)

All data are for high density polyethylene geomembrane/geosynthetic clay liner and municipal solid waste.

Landfill Cell ID[a]	Cell Type	Average Monthly Leak Detection System Flow Rate		Site Parameters			Landfill Cell Construction/Operation Information							Source of Data[b]
		(L/ha/d)	(m/y)	Location	Average Annual Rainfall (mm)	Subsurface Soil Type	Cell Area (ha)	Geomembrane Liner Thickness (mm)	Geosynthetic Clay or Compacted Clay Liner Thickness (mm)	Maximum Height of Waste (m)	End Construction Date	Waste Placement Start Date	Final Closure Date	
G228	Open	5.85	2.14E-04	Mid-Atlantic	NA	NA	51	1.5	NA	NA	1988	1989	NA	Eithe & Koerner(1997)
G232	Open	11	4.02E-04	Northeast	990	Silty Clay	4.7	1.5	6	NA	May-92	May-92	Jul-94	EPA (1998)
G233	Open	0	0.00E+00	Northeast	1040	Sand & Gravel	2	1.5	6	24	Jun-88	Jul-88	Feb-91	EPA (1998)
G234	Open	2	7.30E-05	Northeast	1040	Sand & Gravel	2	1.5	6	24	Jun-88	Jul-88	Feb-91	EPA (1998)
G235	Open	4	1.46E-04	Northeast	1040	Sand & Gravel	1.7	1.5	6	24	Aug-88	Sep-88	Apr-93	EPA (1998)
G236	Open	1	3.65E-05	Northeast	1040	Sand & Gravel	1.7	1.5	6	24	Aug-88	Sep-88	Apr-93	EPA (1998)
G237	Open	2	7.30E-05	Northeast	1040	Sand & Gravel	2.8	1.5	6	24	Sep-88	Oct-88	–	EPA (1998)
G238	Open	0	0.00E+00	Northeast	1040	Sand & Gravel	3.9	1.5	6	24	Dec-88	Dec-88	–	EPA (1998)
G239	Open	2	7.30E-05	Northeast	1040	Sand & Gravel	2.6	1.5	6	24	Jan-89	Feb-89	–	EPA (1998)
G240	Open	0	0.00E+00	Northeast	1040	Sand & Gravel	3.8	1.5	6	24	Jul-89	Jul-89	–	EPA (1998)
G241	Open	0	0.00E+00	Northeast	1040	Sand & Gravel	3.3	1.5	6	24	Dec-89	Dec-89	–	EPA (1998)
G242	Open	0	0.00E+00	Northeast	1040	Sand & Gravel	3.9	1.5	6	24	Feb-90	Jul-90	–	EPA (1998)
G243	Open	0	0.00E+00	Northeast	1040	Sand & Gravel	3	1.5	6	24	Feb-90	Feb-90	–	EPA (1998)
G244	Open	0	0.00E+00	Northeast	1040	Sand & Gravel	4	1.5	6	24	Oct-90	Oct-90	–	EPA (1998)
G245	Open	0	0.00E+00	Northeast	1040	Sand & Gravel	3	1.5	6	24	Jan-91	Jan-91	–	EPA (1998)
G246	Open	0	0.00E+00	Northeast	1040	Sand & Gravel	2.8	1.5	6	24	Apr-92	Apr-92	–	EPA (1998)
G247	Open	0	0.00E+00	Northeast	1040	Sand & Gravel	2.8	1.5	6	24	May-92	May-92	–	EPA (1998)
G248	Open	0	0.00E+00	Northeast	1040	Sand & Gravel	4.5	1.5	6	24	Jan-93	Jan-93	–	EPA (1998)

Landfill Cell ID[a]	Cell Type	Average Monthly Leak Detection System Flow Rate		Site Parameters			Landfill Cell Construction/Operation Information							Source of Data[b]
		(L/ha/d)	(m/y)	Location	Average Annual Rainfall (mm)	Subsurface Soil Type	Cell Area (ha)	Geomembrane Liner Thickness (mm)	Geosynthetic Clay or Compacted Clay Liner Thickness (mm)	Maximum Height of Waste (m)	End Construction Date	Waste Placement Start Date	Final Closure Date	
G249	Open	2	7.30E-05	Northeast	760	Sand	3.8	1.5	250	41	Sep-92	Dec-92	–	EPA (1998)
G250	Open	6	2.19E-04	Southeast	1090	NA	4	1.5	6	28	Dec-90	Feb-91	–	EPA (1998)
G251	Open	0	0.00E+00	Southeast	1090	NA	2.4	1.5	6	30	Jan-93	Jan-93	–	EPA (1998)
G252	Open	0	0.00E+00	Southeast	1090	NA	2.8	1.5	6	30	Jan-93	Jan-93	–	EPA (1998)
G232	Closed	2	7.30E-05	Northeast	990	Silty Clay	4.7	1	6	NA	May-92	May-92	Jul-94	EPA (1998)
G233	Closed	0	0.00E+00	Northeast	1040	Sand & Gravel	2	1	6	24	Jun-88	Jul-88	Feb-91	EPA (1998)
G234	Closed	0	0.00E+00	Northeast	1040	Sand & Gravel	2	1	6	24	Jun-88	Jul-88	Feb-91	EPA (1998)
G235	Closed	1	3.65E-05	Northeast	1040	Sand & Gravel	1.7	1	6	24	Aug-88	Sep-88	Apr-93	EPA (1998)
G236	Closed	0	0.00E+00	Northeast	1040	Sand & Gravel	1.7	1	6	24	Aug-88	Sep-88	Apr-93	EPA (1998)

Key:
– = not applicable
NA = not available

Data Sources:
Eithe and Koerner (1997)
U.S. EPA (1998)

[a] Cell ID as reported by Tetra Tech (2001)

Table D-5. Leak Density Data Used to Develop Composite Liner Infiltration Rates for Surface Impoundments (from TetraTech, 2001)

Site ID[a]	Date	Area (m^2)	Location	Waste Type	WMU type	Type of Geomembrane Liner[b]	Thickness of Geomembrane (mm)	Quality of Material Beneath Geomembrane	Holes	Knife Cuts/Tears	Seam or Weld Defects	Total Leaks	Range of Hole Size (mm)	Leak Density (leaks/ha)	Source[c]
L1	1995	18500	France	domestic	landfill	HDPE	2	high	0	0	5	5	NA	2.7	Rollin et al. (1999)
L2	1996	14926	France	domestic	landfill	HDPE	2	high	4	0	2	6	NA	4.02	Rollin et al. (1999)
L3	1994	13480	France	HW	landfill	HDPE	2	high	1	1	1	3	NA	2.23	Rollin et al. (1999)
L4	1995	11652	France	HW	landfill	HDPE	2	high	1	2	2	5	NA	4.29	Rollin et al. (1999)
L5	1997	8200	France	HW	landfill	HDPE	2	high	0	0	0	0	NA	0	Rollin et al. (1999)
L6	1998	9284	France	HW	landfill	HDPE	2	high	0	1	0	1	NA	1.08	Rollin et al. (1999)
L7	1995	67100	Canada	waste water treatment	pond	PBGM	3	high	3	0	2	5	NA	0.75	Rollin et al. (1999)
L8	1995	66150	Canada	waste water treatment	pond	PBGM	3	high	1	1	7	9	NA	1.36	Rollin et al. (1999)
L9	1997	11460	Canada	black liqueur	pond	PP	1.14	high	2	2	2	6	NA	5.24	Rollin et al. (1999)
L10	1998	18135	France	domestic	landfill	HDPE	2	high	0	3	3	6	NA	3.31	Rollin et al. (1999)
L86	Apr-96	9416	UK	NA	NA	HDPE	NA	NA	0	0	0	0	–	0	McQuade and Needham (1999)
L103	Oct-96	4980	UK	NA	NA	HDPE	NA	NA	0	0	0	0	–	0	McQuade and Needham (1999)
L110	Jan-97	11720	UK	NA	NA	HDPE	NA	NA	0	2	1	3	–	2.6	McQuade and Needham (1999)
L114	Jan-97	7000	UK	NA	NA	HDPE	NA	NA	0	3	1	4	–	5.7	McQuade and Needham (1999)
L136	Oct-97	13526	UK	NA	NA	HDPE	NA	NA	0	1	0	1	30x50	0.7	McQuade and Needham (1999)
L144	May-98	5608	UK	NA	NA	HDPE	NA	NA	0	0	0	0	–	0	McQuade and Needham (1999)

Site ID[a]	Date	Area (m^2)	Location	Waste Type	WMU type	Type of Geomembrane Liner[b]	Thickness of Geomembrane (mm)	Quality of Material Beneath Geomembrane	Holes	Knife Cuts/Tears	Seam or Weld Defects	Total Leaks	Range of Hole Size (mm)	Leak Density (leaks/ha)	Source[c]
L152	Aug-98	3742	UK	NA	NA	HDPE	NA	NA	0	0	0	0	–	0	McQuade and Needham (1999)
L159	NA	15000	UK	NA	NA	HDPE	NA	NA	0	0	0	0	–	0	McQuade and Needham (1999)
L160	NA	10000	UK	NA	NA	HDPE	NA	NA	0	0	0	0	–	0	McQuade and Needham (1999)
L176	May-98	13500	UK	NA	NA	HDPE	NA	NA	1	0	0	1	NA	0.7	McQuade and Needham (1999)
L177	Sep-96	15000	UK	NA	NA	HDPE	NA	NA	0	0	0	0	–	0	McQuade and Needham (1999)
L178	Apr-97	7500	UK	NA	NA	HDPE	NA	NA	0	1	0	1	–	1.3	McQuade and Needham (1999)
L179	Sep-98	5000	UK	NA	NA	HDPE	NA	NA	0	0	0	0	–	0	McQuade and Needham (1999)
L180	Sep-98	13200	UK	NA	NA	HDPE	NA	NA	0	0	0	0	–	0	McQuade and Needham (1999)
L181	NA	48600	NA	waste water containment	pond	HDPE	1.5	NA	NA	NA	NA	21	NA	4.3	Laine (1991)
L182	NA	8000	NA	HW	landfill	HDPE/CCL	2	NA	NA	NA	NA	10	NA	12.5	Laine (1991)

NA = not available; – = not applicable
[a] Cell ID as reported by Tetra Tech (2001)
[b] HDPE = high density polyethylene; PBGM = pre-fabricated bituminous geomembrane; PP = polypropylene; CCL = compacted clay liner
[c] Data Sources:
Laine (1991)
McQuade and Needham (1999)
Rollin, et al. (1999)

Table D-6. Comparison of Composite Liner Infiltration Rates Calculated Using Bonaparte Equation and Infiltration Rates for Composite-Lined Landfill Cells

Percentile	Calculated Infiltration (m/yr)	Observed Infiltration (m/yr)
0	0	0
10	0	0
20	0	0
30	0	0
40	1.05E-05	0
50	1.37E-05	0
60	2.03E-05	2.19E-05
70-	3.96E-05	7.30E-05
80	6.01E-05	7.30E-05
90	7.13E-05	1.73E-04
100	1.87E-04	4.02E-04

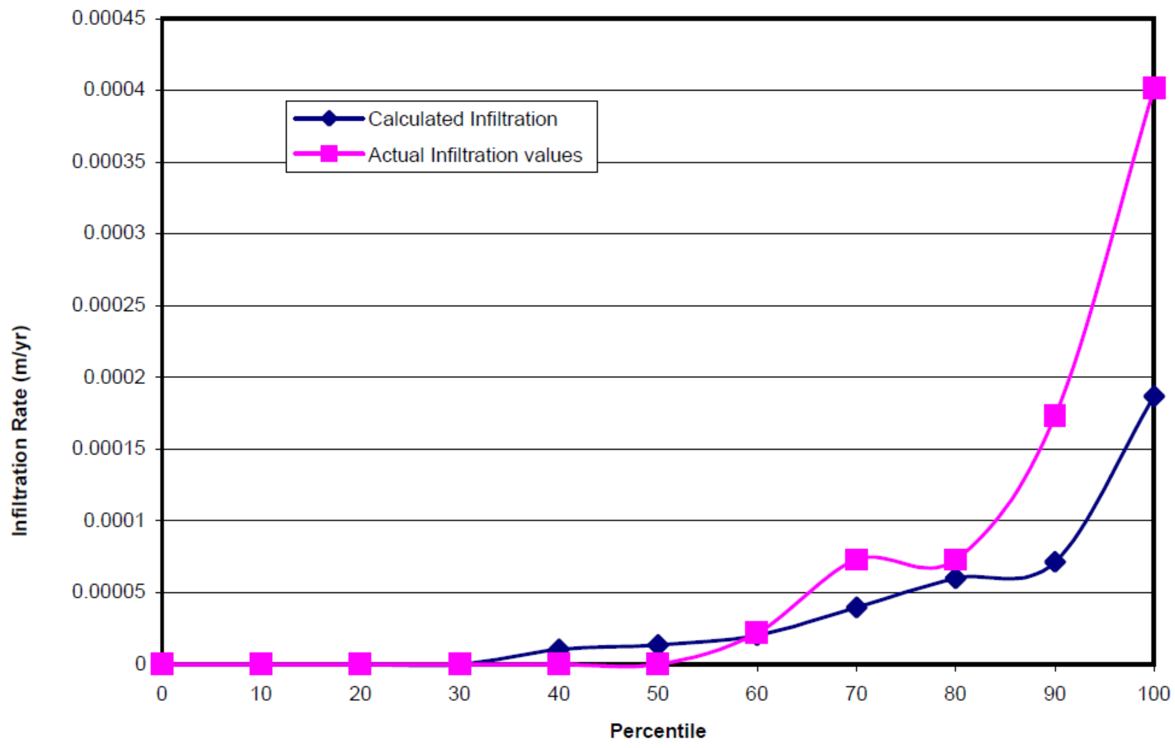

Figure D-1. Infiltration rate comparison (Head =0.3 m, Hole Area = 6 mm²).

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Appendix E: Infiltration Rates through Pavements

E.1 Introduction

The Industrial Waste Management Evaluation Model (IWEM) simulates the migration of contaminants from a roadway source to a down-gradient receptor well. To use the roadway source module, IWEM requires that the user provide infiltration rates through a roadway pavement; Infiltration rate is one of the key parameters influencing the downward migration of contaminants of concern. Recognizing the importance of this parameter, the EPA has developed infiltration rates for various types of roadway materials and provided them in IWEM as default values. The user may either consider using these values or provide the model their own site-specific infiltration rates. The main objective of this section is to discuss the approach used to develop long-term infiltration rates through various types of roadway material in a number of climatic zones.

A description of the approach used is presented in **Section E.2**. The data available in the literature are reviewed in **Section E.3**. The models used and the verification results are presented in **Sections E.4** and **E.5**, respectively.

E.2 General Approach

Infiltration rates through the roadway pavements are essential to predict the transport of contaminants from the roadways to the down-gradient receptor wells. However, sources of empirical data on infiltration rates through roadway pavements are limited. Therefore, mathematical models, as described in **Sections E.4** and **E.5**, were used to help generate the required infiltration rates included in IWEM. To ensure that the models could be reliably used to estimate infiltration rates, the models were first verified against available infiltration data from actual field observations. The verified models were then utilized to generate infiltration rates for various types of pavements in different climatic zones.

E.3 Available Infiltration Data for Pavements

E.3.1 Pavement Overview

A typical highway cross-section is presented in **Figure E-1**. As shown in the figure, a typical cross section consists of two or more travel lanes, two road shoulders/embankments, and a median in the middle between the travel lanes. It may also include ditches and gutters. Pavement is a major component of the travel lane that acts as a means to dissipate vehicular loads from its traffic surface (the surface course) to the subgrade. The subgrade could be either native soil, modified native soil (through densification or other treatments), or fill/embankment materials. There are two major types of pavement (Apul et al., 2002): flexible pavement and rigid pavement.

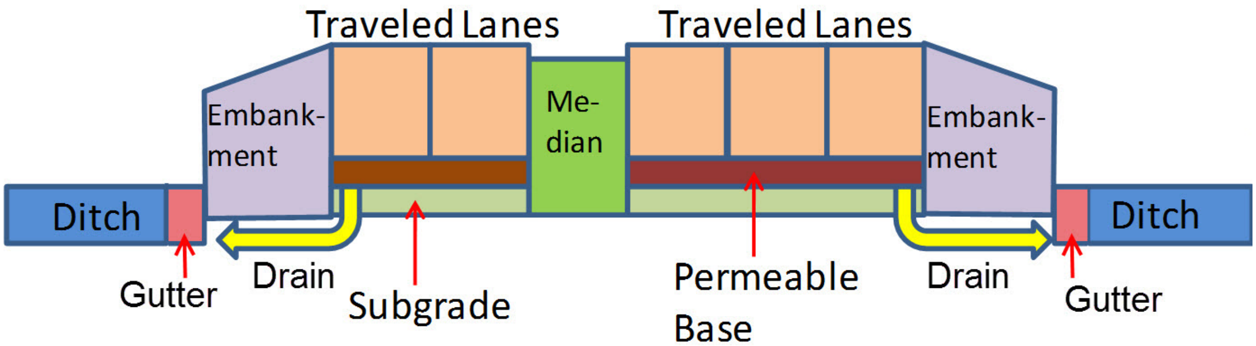


Figure E-1. A typical cross section of a roadway.

Flexible pavements consist of a combination of layers that includes an asphalt surface (wearing surface) constructed over a granular or asphalt base and a subbase. The entire pavement structure is constructed over the subgrade. Pavements can be constructed using hot mix or cold mix asphalt. Rigid pavements or portland cement concrete pavements consist of a portland cement concrete slab that is usually supported by a granular or stabilized base and a subbase. In some cases, the portland cement concrete slab may be overlaid with a layer of asphalt concrete. A typical pavement structure is shown in **Figure E-2**. A pavement is typically attached to an engineered drainage system because pavement failures are attributable to elevated moisture conditions. **Figure E-3** shows examples of the many types of subsurface highway drainage.

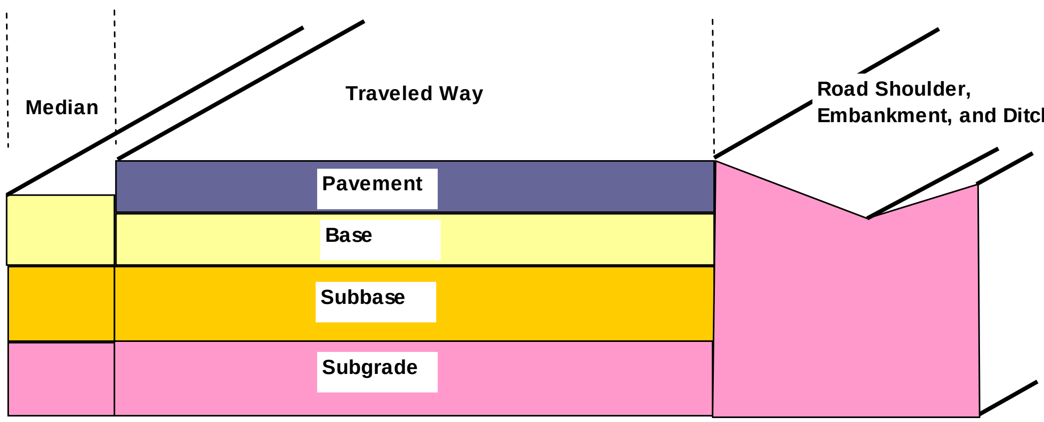


Figure E-2. Typical pavement layers.

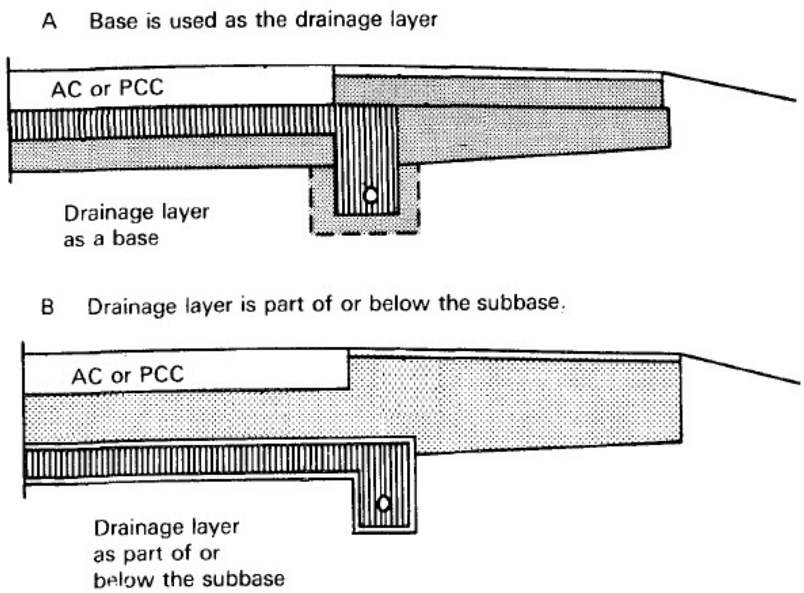


Figure E-3. Typical permeable base pavement sections: (a) base used as drainage layer; (b) drainage layer is part of or below the subbase (from AASHTO, 1993).

E.3.2 Infiltration Data

Infiltration-related data are relatively limited and available in two general categories: indirect short-term data and direct long-term data. Indirect short-term data normally involve water collected at drain outlets during rainfall or storm events. The duration of data collection varies from a few hours to a day depending on the respective duration of precipitation or storm event.

For drains with surface inlets, the difference between precipitation and the amount of water that passes through the drain system accounts for the sum of evaporation and surface runoff not captured by the surface drainage system, and downward percolation into the pavement. Subgrade infiltration (exfiltration or downward percolation at the base of pavement structure) may not begin until late in the rainfall event as the saturation condition in the pavement structure may not exceed field capacity until that time. Based on indirect measurements in a highway litter management pilot study conducted by Caltrans (2000) in Los Angeles County, CA, the amount of collected drained water varies from 62 to 89 percent of precipitation. In a controlled pilot study, the amount of 85 and 94 percent at two sites in Austin, Texas, was obtained by Irish et al. (1995).

For drains with subsurface inlets that may be connected to the base and/or subbase layers, the drainage data obtained by Ahmed et al. (1997) in Indiana indicate that the collected drained water varied between 0.1 to 70 percent of precipitation depending on the conditions of the pavement surface. Data in Indiana obtained by Feng et al. (1999) from three types of pavements indicate a relatively uniform value of 8 percent. Recently, indirectly measured short-term drainage data from a number of road sections in Minnesota indicate a variation between 2 to 35 percent of precipitation (Minnesota DOT, 2007; Apul, 2007). For data collected from subsurface drain outlets, the difference between precipitation and the amount of collected drained water accounts for evaporation, surface runoff, and subgrade infiltration at the bottom of pavement structure.

Therefore, the above limited data sets cannot be used to explicitly determine subgrade infiltration from the bottom of the pavement structure because it will be necessary to estimate runoff and evaporation in order to estimate short-term subgrade infiltration. In the IWEM document, the term "infiltration" refers to water exiting from the subbase layer (the bottom of the source) into the subgrade material (the top of the vadose zone) below. This infiltration is referred to as "subgrade infiltration" in this document to distinguish it from top-of-pavement infiltration, which refers to water entering the pavement surface from precipitation and runoff.

Long-term data normally involve multiple-year monitoring of subgrade infiltration from pavement structures above subgrade. In the literature, long-term subgrade infiltration monitoring data are very limited. Rainwater et al. (2001) provide subgrade infiltration data for three sites with asphaltic concrete pavements in Tennessee over a monitoring period of 3 years. In this case, one-square meter free-tension lysimeters were placed below an asphalt-stabilized base layer and above an unbound aggregate base layer. The experiment resulted in subgrade infiltration rates ranging from 0 to 1 percent of the total rainfall. These small subgrade infiltration rates may be due to the relatively new pavement surfaces and the presence of subsurface drainage systems above the lysimeters. A relatively comprehensive experiment was conducted at various road sections constructed with recycled materials along Wisconsin State Highway 60 (Li et al., 2005). Data on subgrade infiltration were provided by Li et al. (2005). In this experiment, lysimeters were placed below the subbase layer at each section. Both subgrade infiltration rate and contaminant concentrations leaching from the recycled materials were monitored. The subgrade infiltration rates were observed to vary from approximately 5 to 7 percent of total rainfall over a 5-year period. This experiment is described in more detail in **Section E-5**.

E.4 Descriptions of Models

Contaminant release and transport is directly affected by the presence and flow of water in pavements (Apul et al., 2007). While pavements are often considered impervious structures, roads constructed with portland cement concrete or asphalt concrete surface courses can experience water entry to the base layer through cracks (Ridgeway, 1976; Ahmed et al., 1997). The extent and rate of infiltration into the pavement structure also depends on rain intensity. If the infiltration capacity of the cracks is exceeded, then some of the rain becomes runoff and does not influence the mobility of the contaminants in pavements.

Two models were considered to simulate flow through pavements and estimate default infiltration rates for IWEM's roadway module. The movement of fluid through pavements may be simulated using a variably saturated flow model. Or, another approach, runoff and infiltration through the pavement surface may also be simulated by a water-budget model. The latter may also be used to approximate fluid fluxes through pavement structures that eventually exit through the bottom. These two types of models are described below.

E.4.1 Variability-Saturated Flow Model

The environment within pavement structures is variably saturated because of the temporal variability of meteoric fluid that enters the pavements through cracks and fractures. Simulation of flow and transport in pavements has been based on an implicit assumption that the hydraulic behavior of a fractured pavement may be approximated by that of an equivalent porous medium. Based on this assumption, the flow may be described by the following equations (Bear, 1972).

$$\frac{\partial}{\partial x_i}\left(k_{rw}K_{ij}\frac{\partial h}{\partial x_j}\right) - W = \phi\frac{\partial S_w}{\partial t} + S_w S_s\frac{\partial h}{\partial t} \qquad \text{(E-1)}$$

where

x_i, x_j = Cartesian coordinates (i, j = 1, 2, 3)
K_{ij} = Intrinsic permeability tensor
k_{rw} = Relative permeability, which is a function of water saturation
W = Volumetric flux per unit volume and represents sources and/or sinks
N = Drainable porosity taken to be equal to the specific yield
S_w = Degree of saturation of water, which is a function of the pressure head
S_s = Specific storage of the porous material
t = Time

Equation (E-1) may be solved by many flow and transport codes. The computer code used in this study, MODFLOW-SURFACT (HydroGeoLogic, 2011), is an enhanced version of the U.S. Geological Survey's modular three-dimensional ground water flow code (McDonald and Harbaugh, 1988). The code has been selected for the following reasons:

- The Menu Bar allows the user to perform common file operations;
- It can handle variably saturated flow and transport, including equilibrium sorption, and first-order degradation;
- It has been extensively verified and documented (HydroGeoLogic, 2011); and,
- It has been implemented in many different settings (e.g., Guvanasen et al., 2004; Tu et al., 2006).

E.4.2 Water Budget Model

This type of model is based solely on a water budget and does not address the physical aspects of flow and transport in a variably saturated environment. In 1994, EPA developed a quasi-two-dimensional hydrologic model for conducting water balance analyses of landfills, cover systems, and other solid waste containment facilities (Schroeder et al., 1994 a, b). The model is referred to as the Hydrologic Evaluation of Landfill Performance (HELP) model. The model accepts weather, soil, and design data and uses solution techniques that account for the effects of surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and leakage through soil, geomembrane, or composite liners. Landfill systems, including various combinations of vegetation, cover soils, waste cells, lateral drain layers, low-permeability barrier soils, and synthetic geomembrane liners, may be modeled. The model facilitates rapid estimation of the amounts of runoff, evapotranspiration, drainage, leachate collection, and liner leakage that may be expected to result from the operation of a wide variety of landfill designs. The HELP model was used to develop infiltration and recharge rates for landfills and other waste management units used in conjunction with the EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP) (U.S. EPA, 2003a-b), the ground water flow and transport engine used by IWEM. A detailed description of how the HELP model was used to develop infiltration and recharge rates is provided in Appendix A of the EPACMTP *Parameter/Data Background Document* (U.S. EPA 2003b).

Because the layering of landfill cover, waste materials, and liner is similar to the layering in pavement structures, HELP is also applicable to water-balance analyses of roadways.

E.5 Verification Results

In order to demonstrate that the MODFLOW-SURFACT and HELP models can be used to simulate flow in pavements, the two models were verified against infiltration data collected from pavement sections in Wisconsin, described by Li et al. (2005).

The test sections were constructed along a 1.4-km stretch of Wisconsin State Highway 60 near Lodi, WI, on soft subgrade. One of the test sections was constructed with bottom ash from a dry-bottom furnace at Alliant Energy's Columbia Power Station that burns sub-bituminous coal from the Wyoming Powder River Basin. The bottom ash is a coarse-grained material that is classified as well-graded sand in the Unified Soil Classification System and A-3 in the American Association of State Highway and Transportation Officials system (see **Figure E-4**).

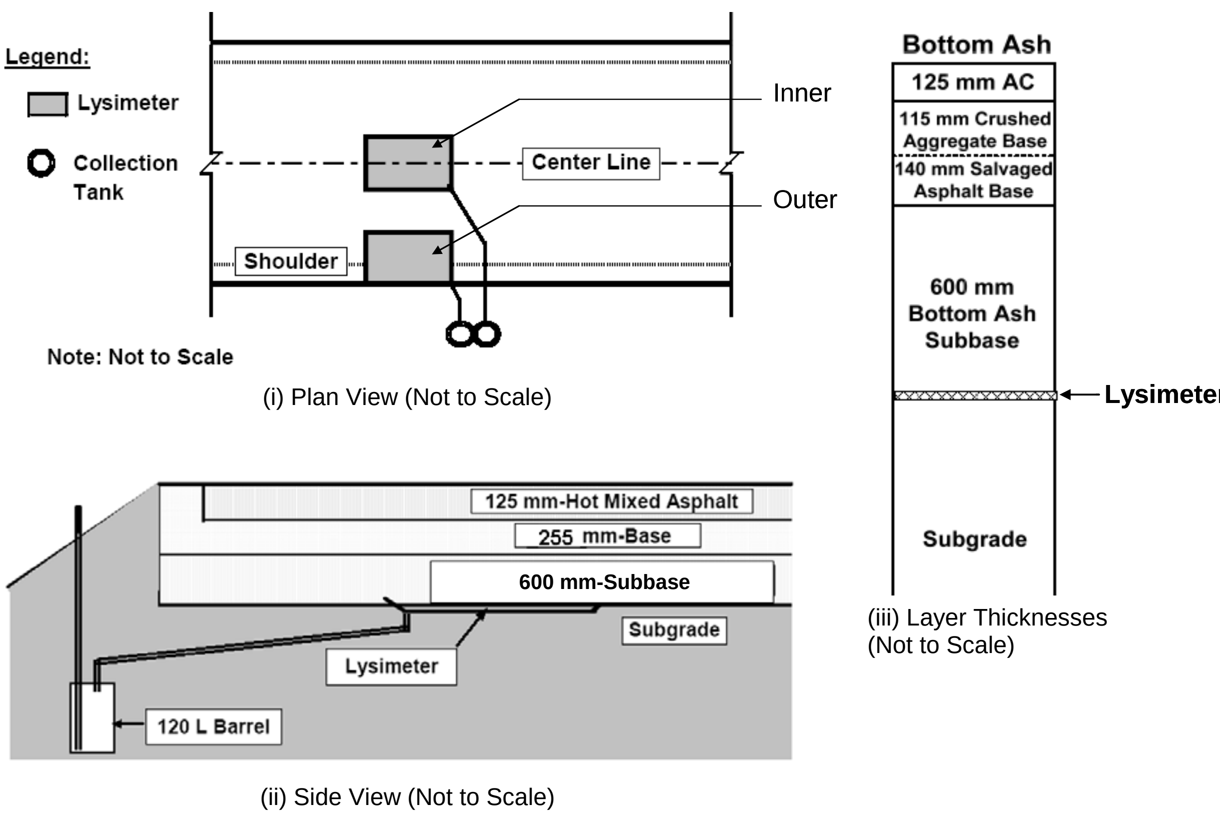


Figure E-4. Wisconsin State Highway 60 test section, experimental set up (from Li et al., 2005, and Sauer et al., 2005).

Two pan lysimeters (3.57 m × 4.75 m) were placed beneath the bottom subbase, immediately above the subgrade, to monitor the quality and quantity of water discharged from the base of the pavement. One lysimeter was located directly under the centerline of the highway, and the other was located underneath the edge of the pavement, with one-half of the lysimeter under the highway shoulder. Water collected by the lysimeters drains to 120-L high-density polyethylene (HDPE) drums located below ground surface adjacent to the highway (see Figure E-4 (ii)). Samples were collected from these lysimeters over a 5-year period. During each sampling event, water contained in each drum was removed with a pump, the total volume of the water in the drum was recorded, and samples were collected for chemical analysis for the concentrations of cadmium, chromium, selenium, and silver. Infiltration data at the bottom of the subbase layer measured by lysimeters between September 2000 and September 2005 are presented in **Figure E-5**. The median of infiltration rate over the 5-year observation period is approximately 0.15 mm/day (averaged from two lysimetes) or approximately 6.5 percent of total precipitation (2.3 mm/day or 865 mm/year). A summary of the volumetric leachate flux at the STH 60 Field Site is presented in **Table E-1**.

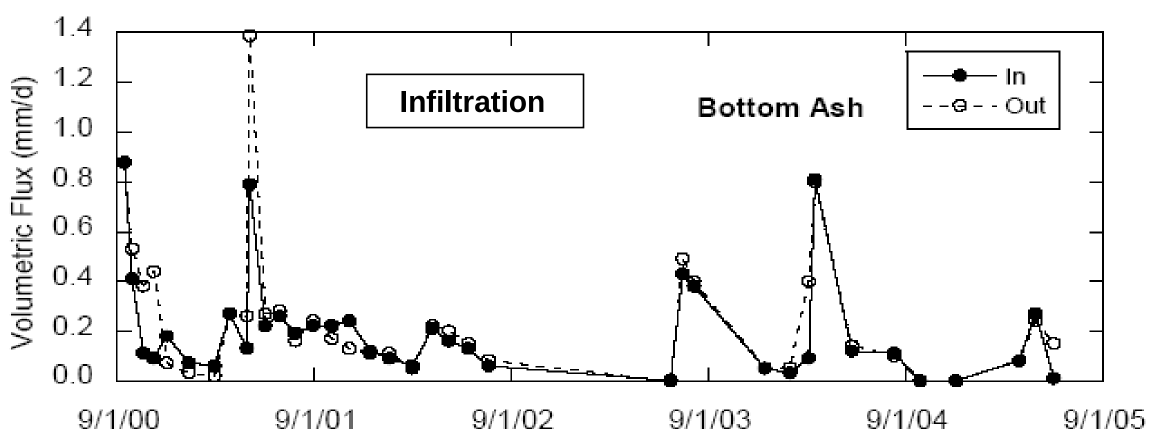


Figure E-5. Subgrade infiltration data (from Li et al., 2005).

Table E-1. Volumetric Leachate Flux at the STH60 Field Site

Flux Condition	Lysimeters	
	Inside (centerline)	**Outside (shoulder)**
Q50, 50th Percentile Infiltration rate (mm/day)	0.13	0.16
Q90, 90th Percentile Infiltration rate (mm/day)	0.43	0.53
QAp, Annual infiltration Rate (mm/day)	2.35	2.35
Q50/QAp	0.06	0.07
Q90/QAp	0.18	0.23

Source: Li et al. (2005)

E.5.1 Variability-Saturated Flow Model

A cross-section of State Highway 60 simulated by the model is depicted in **Figure E-6**. Because of symmetry, only one half of the cross-section was modeled. The cross section is 12.4 m wide. It consists of a 5.0-m wide asphalt concrete pavement, and a 1.6-m wide shoulder. The embankment was assumed to extend for 5.8 m from the outer edge of the shoulder. In the document by Li et al. (2005), slope values of the various components of the test section were not available. In the simulation, slopes consistent with highway engineering practice were used. The slopes of the pavement, shoulder, and embankment were assumed to be 2, 4, and 10 percent, respectively. These are typical slopes used in highway engineering practice (Apul et al., 2007). The model was discretized into 62 layers and 62 columns (**Figure E-7**). At this test section, there is no subsurface drainage system installed.

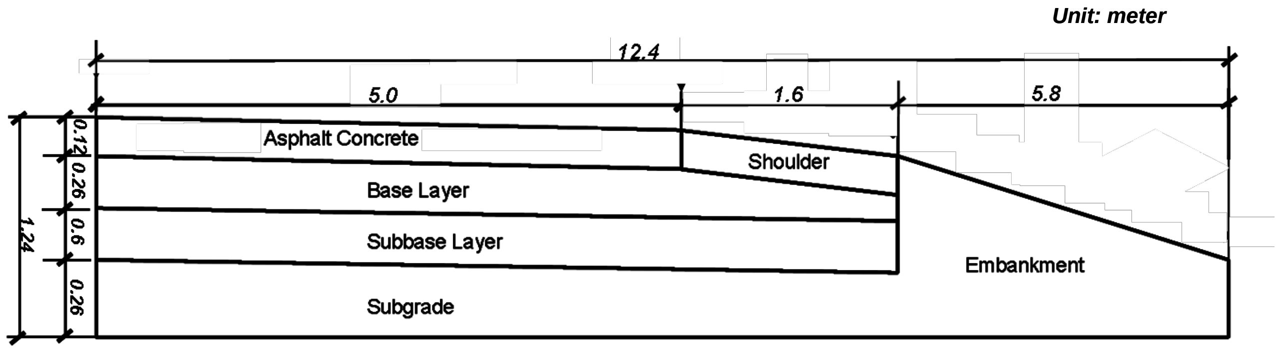


Figure E-6. Model cross-section of State Highway 60 (not to scale, all dimensions in meters).

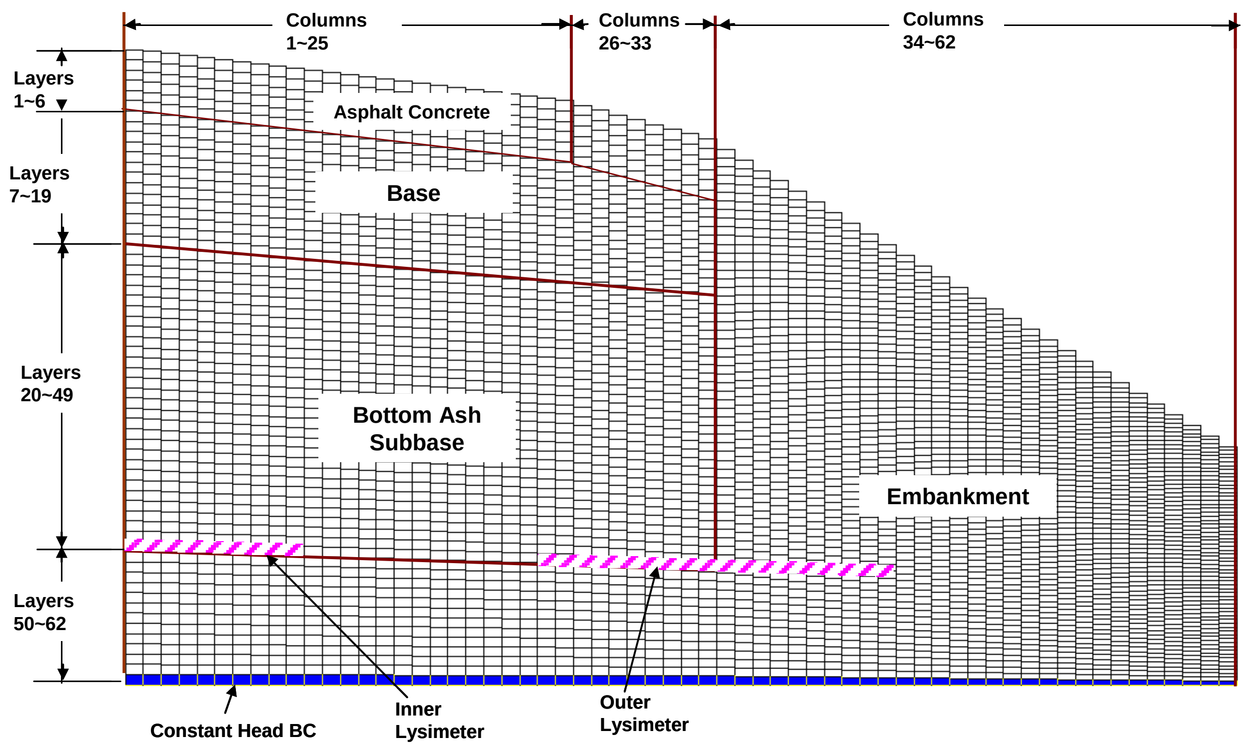


Figure E-7. Model grid corresponding to the cross-section in Figure E-6.

The pavement included four layers with different material types: asphalt concrete (pavement surface), crushed aggregate (top base course), salvaged asphalt (bottom base course), and bottom ash (subbase). The thicknesses of the four pavement layers are shown in Figure E-4(iii). The material type for subgrade was not reported and was assumed to be sand for simulation purposes. The relative permeability and saturation terms (k_{rw} and S_w, respectively) in Equation (4-1) were described using van Genuchten's characteristic functions (van Genuchten, 1980), which are dependent on two material-dependent parameters, α and β. These two parameters, along with other material properties used in the simulation, are given in **Table E-2**.

Table E-2. Material and Properties Used in Simulation: Flow Parameters

Material	Thickness (Inches [mm])	Layer		Hydraulic Conductivity (cm/sec)	Total Porosity (vol/vol)	α[a] (1/cm)	β[a] (unitless)	Residual Saturation (Vol/vol)
		Top	Bottom					
Asphalt concrete [b]	4.9 [125]	1	6	1.00E+01	0.03	1.000	2.19	0.02
Crushed aggregate base [c]	4.5 [115]	7	12	1.505E-03	0.3	0.063	1.3	0.06
Salvaged asphalt base [c]	5.5 [140]	13	19	1.505E-03	0.3	0.063	1.3	0.06
Bottom ash subbase [d]	23.6 [600]	20	49	4.63E-01	0.3	0.0431	3.1	0.02
Subgrade below lysimeters [e]	Remaining	50	62	8.25E-02	0.3	0. 145	2.68	0.05

[a] van Genuchten parameters (van Genuchten, 1980)

[b] Hydraulic properties of fractured asphalt concrete from Stormont and Zhou (2001) – gravel

[c] Hydraulic properties of base materials from Apul et al. (2007) – asphalt aggregate base

[d] Hydraulic properties of bottom ash subbase from Stormont and Zhou (2001) – medium sand

[e] Hydraulic properties of embankment and subgrade from Carsel and Parrish (1988) – sand

Infiltration into the pavement was assumed to be uniform over the entire asphalt concrete surface. This assumption is based on a premise that the pavement hydraulic behavior may be approximated by that of an equivalent porous medium. The pavement hydraulic properties were assumed to be uniform throughout the pavement cross-section. These properties were obtained from the literature. References are provided at the bottom of Table E-2.

Because runoff and evaporative loss information was not available, it was not possible to estimate the amount of water infiltrating into the pavement. For the simulation, the monthly top-of-pavement infiltration rate was adjusted until the simulated subgrade infiltration (exfiltration at the bottom of the subbase layer) was in reasonable agreement with the observed fluxes at the two lysimeters (**Figure E-8**).

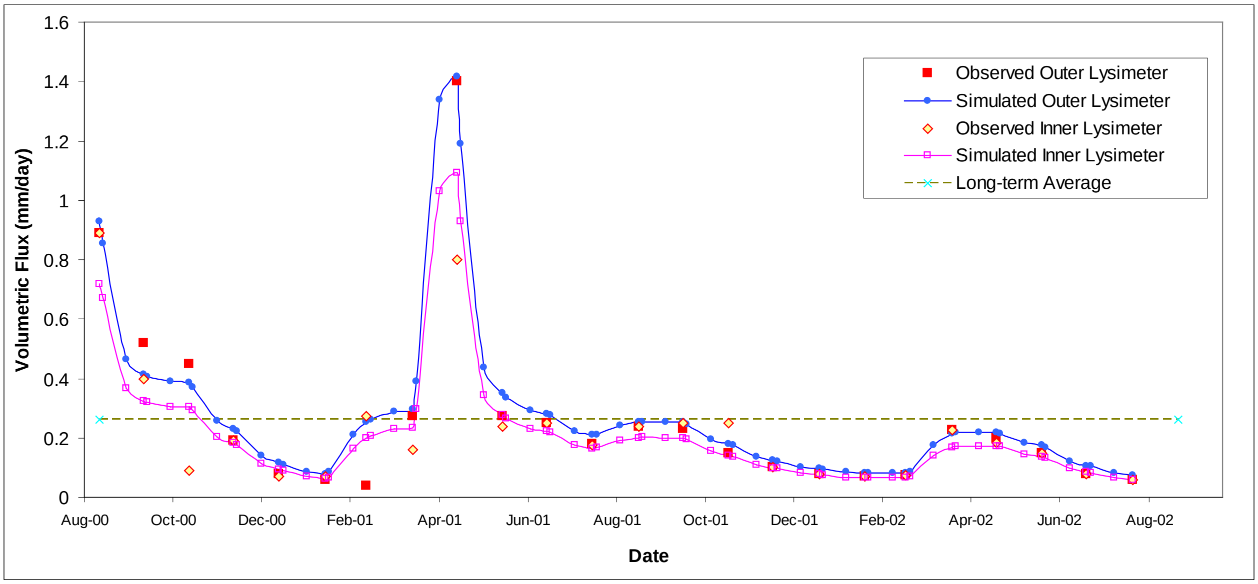


Figure E-8. Comparison between simulated and observed subgrade infiltrations (exfiltration from subbase) at the bottom of the subbase layer.

Precipitation data are compared against top-of-pavement infiltration and subgrade infiltration (subbase exfiltration) in **Figure E-9**. In the figure, it can be seen that, during the same month, top-of-pavement infiltration tends to be slightly larger than subgrade infiltration. The difference between the two rates could be due to possible lateral flow around the lysimeters to the embankment. In addition, it can also be seen that the two rates are generally much smaller than precipitation.

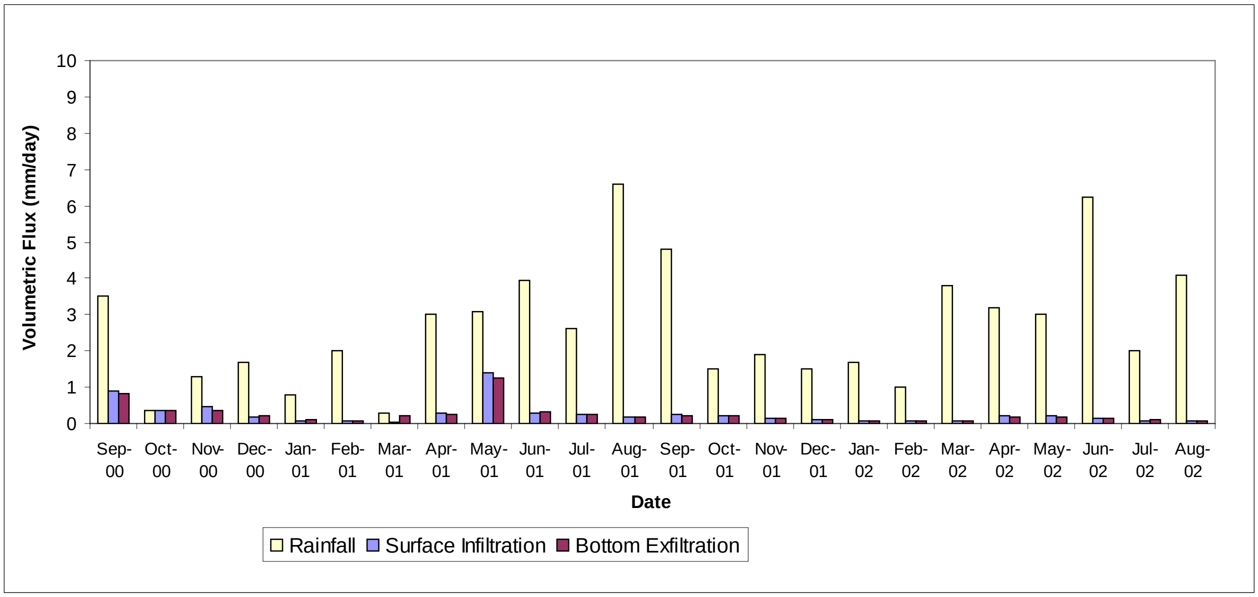


Figure E-9. Surface infiltration and bottom exfiltration (subgrade infiltration) vs. precipitation.

The results shown in Figure E-9 also suggest that storage effects within the STH 60 experimental section are relatively small and, as a consequence, infiltration tends to occur soon after precipitation events. Short-term data from pavements with subsurface drains indicate that water in the drains generally appears soon after the onset of rainstorm events, thereby suggesting that the lag time between the start of top-of-pavement infiltration and the onset of subgrade infiltration is very small, on the order of hours.

E.5.2 Water Budget Model

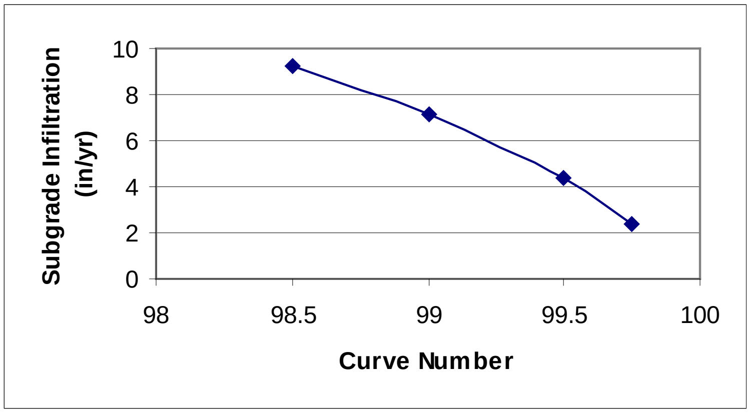
The water budget HELP model can be used to estimate the infiltration rate through pavement. The HELP model utilizes pavement properties, surface conditions, and climatic conditions (see **Section E.4.2**). The HELP model was evaluated by applying it to the setting, similar to that described in **Section E.5.1**. Using the input parameters in **Table E-3** and the material properties contained in Table E-2, the HELP-model-based subgrade infiltration rate is approximately 2.42 inches/year (6.1 cm/yr), which is a close approximation of the measured subgrade infiltration rate of approximately 2.35 inches/year (6.0 cm/yr or 0.16 mm/day).[2]

[2] Note that the HELP model uses English system units, not metric. For clarity, therefore, units here are given in the English units used, and metric equivalents are shown in parentheses.

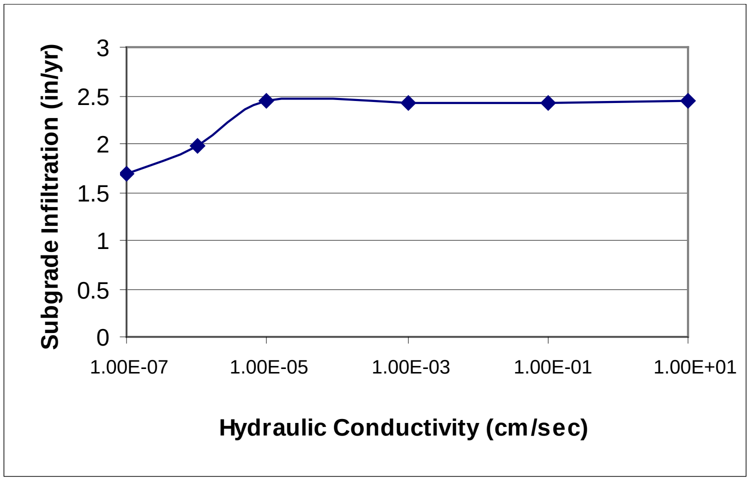
Table E-3. HELP Model Parameters and Results

Input Parameters	
Maximum Leaf Index	0
Curve Number (CN)	99.75
Root Zone Depth	0.10 in (0.25 cm)
Precipitation	32.07 in/yr (81 cm/yr)
Water Budget of Average Annual Totals for Years 1974 through 1978	
Evapotranspiration	2.01 in/yr (5.1 cm/yr)
Runoff	27.58 in/yr (70 cm/yr)
Change in Water Storage	0.05 in/yr (0.13 cm/yr)
Subgrade Infiltration	2.42 in/yr (6.1 cm/yr)

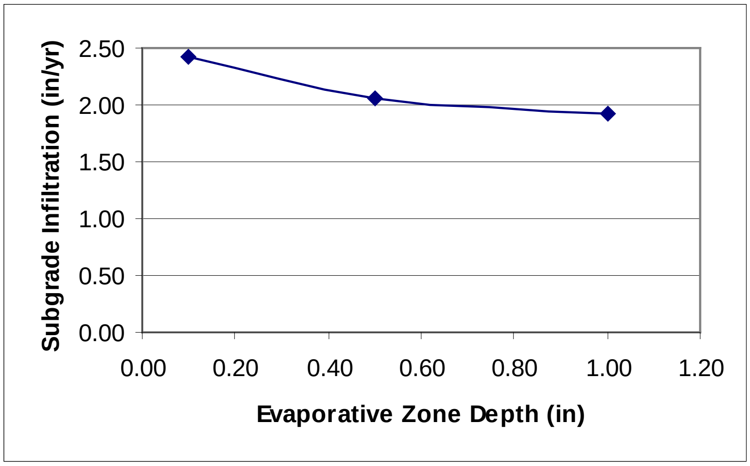
It was found that appropriate parameters were required to obtain simulated subgrade infiltration close to the observed subgrade infiltration. To determine appropriate ranges of parameters, material properties and surface conditions were varied to examine the HELP model sensitivity to input parameters. Among the three key parameters (curve number [Chow et al., 1988], saturated hydraulic conductivity, and evaporation depth), the curve number was found to be most influential to the subgrade infiltration rate. The curve number describes the imperviousness of a surface; the higher the number, the more impervious the surface. Although curve numbers up to 98 are recommended in the literature for pavement surface, a curve number value greater than 99 was found to generate more realistic subgrade infiltration rates (see **Figure E-10**, graph a). Figure E-10, graph b, shows that saturated hydraulic conductivity in the range shown is not a sensitive factor for subgrade infiltration. In the figure, it can be seen that saturated hydraulic conductivity begins to decrease subgrade infiltration when it is below a certain threshold value. Above this threshold value, infiltration remains constant and impact on runoff is very small. Evaporative zone depth is an important factor to evaporation as it dictates the amount of evaporative loss that may occur (see Figure E-10, graph c)—the more evaporative loss, the smaller the subgrade infiltration. As a result, a small value (less than 0.5 inches[about 1 cm]) of evaporative zone depth should be used. It was found that infiltration is not sensitive to layer thickness. The insensitivity to pavement thickness implies that the storage effects in pavements are small. This finding is consistent with results obtained from the variably saturated flow model reported in **Section E.5.1**. All the analyses reported here are based on HELP-determined, long-term average steady-state moisture profiles at the beginning of the simulations because they are likely to be the average conditions found in the field.



a) Effect of Curve Number (Evaporative Zone Depth=0.1 in, Hydraulic Conductivity = 10^{-3} cm/sec)



b) Effect of Hydraulic Conductivity (Curve Number = 99.75, Evaporative Zone Depth=0.1 in)



c) Effect of Evaporative Zone Depth (Curve Number= 99.75, Hydraulic Conductivity = 10^{-3} cm/sec)

Figure E-10. Sensitivity of HELP-determined bottom exfiltration to: a) curve number; b) hydraulic conductivity; and c) evaporation zone depth.

E.6 Summary

To use the roadway source term in IWEM, the user is required to provide infiltration rate through roadway pavements. Recognizing the importance of this parameter and coupled with the difficulty for the user to obtain reliable values from literature, the EPA provided in IWEM estimated infiltration rates in various roadway materials. The main objective of this section was to present the general approach used to determine physics-based, long-term subgrade infiltration rates at the bottom of various types of pavements in a number of climatic zones. Subgrade infiltration refers to water that exits the subbase layer (the bottom of the source) and percolates into the subgrade material (the top of the vadose zone), below.

Because the infiltration data through the roadway pavements are limited, mathematical models, described in **Sections E-4** and **E-5**, were used to help generate the required infiltration rates. In order to ensure that the models could be reliably used to estimate infiltration rates, the models were first verified against available infiltration data from actual field observations. The verified models were then utilized to generate infiltration rates for various types of pavements in different climatic zones.

For the purposes of subgrade infiltration estimation, six climatic zones were defined using the freezing index and precipitation as demarcation criteria. For each of these zones infiltration rates for several types of pavements and respective ranges of material properties were estimated using the water-budget HELP model. A procedure to utilize the estimated subgrade infiltration rates corresponding to given climatic conditions is presented in **Section 6.4.3**.

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Appendix F: A Discussion on the Formulation of the Non-Orthogonality between the Highway Axis and the Regional Ground Water Flow Direction

F.1 Introduction

Given the general settings of roadways, it is possible that the centerline axis of a roadway may not be directly perpendicular to the regional ground water flow direction. **Figure F-1** shows an idealized (straight line) highway segment with several laterally contiguous rectangular highway-source strips oriented at an angle α with respect to the normal of the regional ground water flow direction. However, the current aquifer transport module in the EPA's Composite Model for Leachate Migration and Transformation Products (EPACMTP) code (U.S. EPA, 2003a, b, c, d) adopted in the Industrial Waste Management Evaluation Model (IWEM) can handle only the case with α = 0°. In order to handle a general case with α > 0°, the results of the existing aquifer transport module must be modified post simulation. A general approach, which is discussed in **Appendix C** , is that the reference x-y coordinate system is transformed into the x′-y′ coordinate system, which aligns with both the highway axis and the regional flow direction (see Figure F-1). The latter is, in turn, transformed into the x″-y″ coordinate system, which is rectilinear, as shown in **Figure F-2**. Once transformed, the existing aquifer transport module can be used to describe fate and transport of contaminants in the transformed domain.

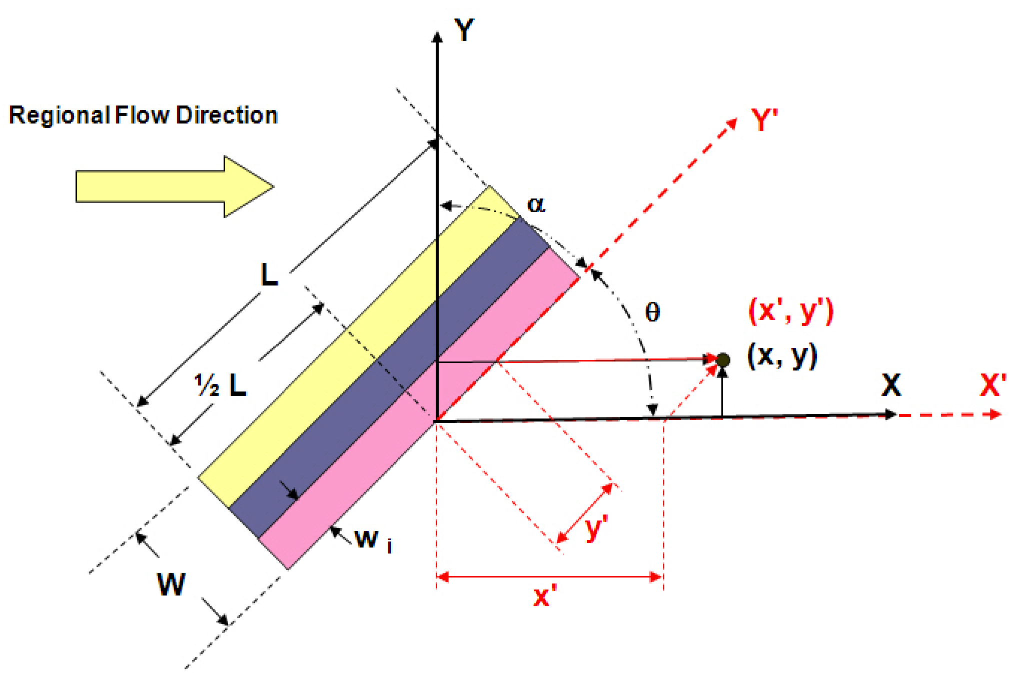

Figure F-1. Non-orthogonal source.

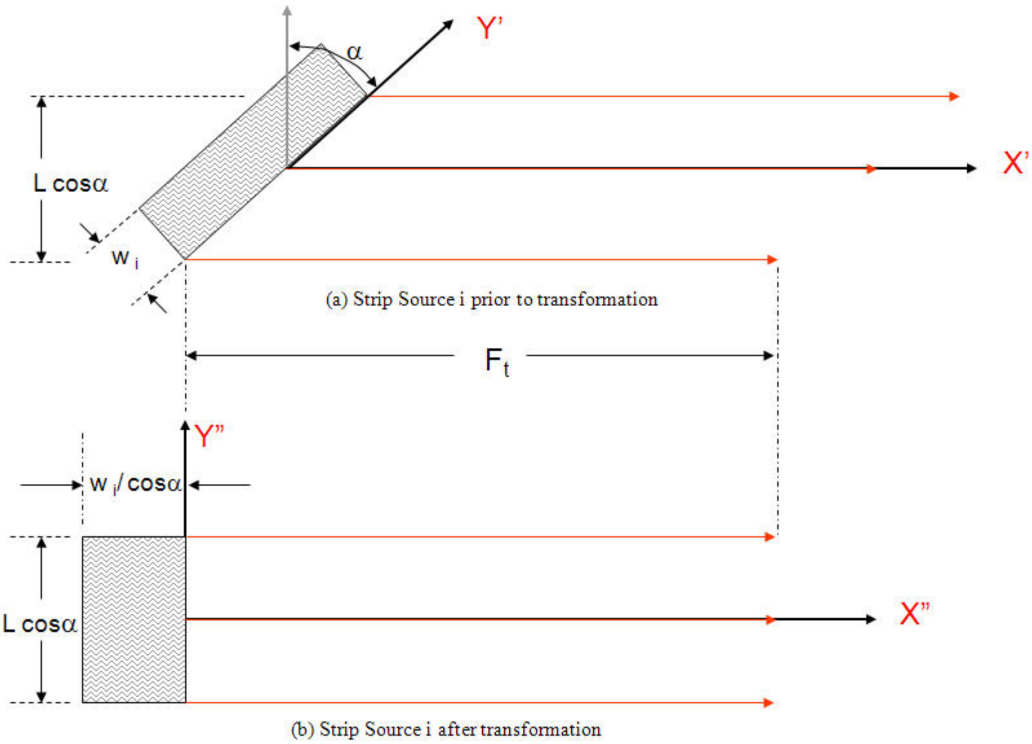

Figure F-2. Transformed orthogonal source for strip *i*.

With the approximation of the source subject to a non-orthogonal flow direction, as shown in Figures F-1 and F-2, it is necessary to address the issue of the accuracy of the transport module. In this note, the factors that may affect the accuracy of the transport module using the transformation are discussed in detail in **Section F.2.** Recommended analysis procedures to obtain conservatively accurate simulation results are given in **Section F.3**.

F.2 Formulation

F.2.1 Source Geometry and Non-Orthogonality of Regional Flow Field

F.2.1.1 Regional Flow Field

Based on the assumptions listed below, the regional flow field may be approximated by a solution with infiltration equal to recharge.

- in the region of interest, the general regional ground water flow pattern is not affected by the presence of a traversing highway;
- infiltration from the traversing highway is on the order of regional recharge; and,
- the areal coverage of the highway is very small compared to the total regional area so that the difference between the infiltration and recharge does not cause significant impact on the regional flow field.

As a result of these assumptions, there is no distortion in the flow field in the vicinity of the highway.

F.2.1.2 Treatment of a Rectangular and Non-orthogonal Source

In general, a highway may be oriented in such a way that the highway axis is not orthogonal to the regional ground water flow direction. To accommodate the non-orthogonality of the highway source, it is necessary to transform the transport domain in the following manner.

For the current aquifer module, the reference frame for transport in a horizontal plane is the system of x-y axes shown in Figure F-1. The complementary inclination angle α (= 90° - θ, where θ is the inclination angle) is incorporated into the analysis via the following two successive transformations:

$$C_i^{'}(x,y,z,t) = C_i^{'}(x^{'},y^{'},z^{'},t) = C_i^{'}(x^{"},y^{"},z^{"},t) \tag{F-1}$$

where:

$$\begin{aligned} x^{'} &= x - y\tan\alpha; \quad x^{'} \geq 0, \alpha < \frac{\pi}{2} \\ y^{'} &= y\sec\alpha \\ x^{"} &= x^{'} \\ y^{"} &= y^{'}\cos\alpha = y \\ z^{"} &= z^{'} = z \end{aligned} \tag{F-2}$$

C'_i	=	Concentration in the transport domains emanating from highway-source strip *i* (M/L^3)
x	=	Distance along the flow direction measured from the midpoint of the down gradient face of the strip of interest (L)
y	=	Distance normal to the flow direction measured from the midpoint of the down gradient face of the strip of interest (L)
x′	=	Distance along the flow direction measured from the down gradient face of the strip of interest in the transformed domain (L)
y′	=	Distance measured from the x′ axis along the direction parallel to the axis of the highway (L)
x″	=	Distance along the flow direction measured from the down gradient face of the strip of interest in the transformed domain (L)
y″	=	Distance normal to the flow direction measured from the midpoint of the down gradient face of the strip of interest in the transformed domain (L)
z, z′, z″	=	Depth measured from the water table (L)

With the transformation in Equations (F-1) and (F-2), the source in Figure F-1 is approximately transformed into the one shown in Figure F-2. Note also that in the transformed domain, the dimensions of the highway source are also accordingly transformed (compare Figures F-1 and F-2).

The above transformation has two limitations:

- It is an approximate transformation and does not account for source end effects (see **Section F.2.4** for a detailed discussion on the end effects), and
- The complementary angle of inclination must remain below 90°; therefore, the regional flow direction is not allowed to be parallel to the highway axis.

The objective of these transformations is to take advantage of the existing IWEM flow and transport modules developed for rectangular coordinate systems in which the source is always rectangular , with its width along to the flow direction and its length normal to the flow direction. In Figure F-1, the transformation from the x-y to the x′-y′ coordinate systems is to render the y′ axis parallel to the highway axis. As an illustration of the transformation on the advective transport process, in Figure F-2, a front location at time *t* of a plume emanating from the leading (downgradient) edge of the source in the x′-y′ coordinate system and the corresponding front of the corresponding plume in the x″-y″ coordinate system are shown. The transformation enables the plume in the x′-y′ system to be mapped onto the x″-y″ system. A detailed derivation in **Section F.2.2**, below, indicates that the transformation is valid for all transport processes (retardation, advection, dispersion, and decay) in the existing transport module.

F.2.2 Transport Equation in the Transformed Domains

In the original frame of reference x-y-z, the transport equation may be written as follows:

$$\frac{\partial R_d C'}{\partial t} + u_x \frac{\partial C'}{\partial x} = D_{xx} \frac{\partial^2 C'}{\partial x^2} + D_{yy} \frac{\partial^2 C'}{\partial y^2} + D_{zz} \frac{\partial^2 C'}{\partial z^2} - \lambda C' \qquad \text{(F-3)}$$

In the transformed frame of reference x’-y’-z’, Equation (F-3) becomes

$$\frac{\partial R_d C'}{\partial t} + u_x \frac{\partial C'}{\partial x'} = D_{xx} \frac{\partial^2 C'}{\partial x'^2} + \frac{1}{\cos^2 \alpha} D_{yy} \frac{\partial^2 C'}{\partial y'^2} + D_{zz} \frac{\partial^2 C'}{\partial z'^2} - \lambda C' \qquad \text{(F-4)}$$

In the transformed frame of reference x”-y”-z”, Equation (F-4) becomes

$$\frac{\partial R_d C'}{\partial t} + u_x \frac{\partial C'}{\partial x''} = D_{xx} \frac{\partial^2 C'}{\partial x''^2} + D_{yy} \frac{\partial^2 C'}{\partial y''^2} + D_{zz} \frac{\partial^2 C'}{\partial z''^2} - \lambda C' \qquad \text{(F-5)}$$

Where:

R_d = Retardation factor (unitless)
D_{xx} = Horizontal longitudinal dispersion coefficient along the x direction (L^2/T)
D_{yy} = Horizontal transverse dispersion coefficient along the x direction (L^2/T)
D_{zz} = Vertical transverse dispersion coefficient along the x direction (L^2/T)
λ = Decay constant (1/T)

Based on the transformations given in Equation (2.2), it can be stated that:

$$\begin{aligned} \frac{\partial C'}{\partial x} &= \frac{\partial C'}{\partial x'} = \frac{\partial C'}{\partial x''} \\ \frac{\partial C'}{\partial y} &\approx \frac{1}{\cos\alpha}\frac{\partial C'}{\partial y'} = \frac{\partial C'}{\partial y''} \\ \frac{\partial C'}{\partial z} &= \frac{\partial C'}{\partial z'} = \frac{\partial C'}{\partial z''} \end{aligned} \qquad \text{(F-6)}$$

assuming that the longitudinal concentration gradient is much smaller than the lateral concentration gradient. The terms in Equation (F-6) are used in transforming Equation (F-3) to Equations (F-4) and (F-5).

Note that Equations (F-3), (F-4), and (F-5) are identically bounded at infinity in the x and y directions. In other words, concentration becomes zero at infinity. In the z direction, identical flux conditions (input flux at the water table, and no advective and dispersive fluxes at the base of the aquifer) are identically applied to all equations. Note also that the retardation factor, dispersion coefficients, and decay constant are assumed to be uniform throughout the flow and transport domain.

A comparison between Equations (F-3) and (F-5) reveals that the transformed transport equation is identical in form to the original transport equation (Equation F-3). The identicality between the two equations implies that Equation (F-1) is correct. The two equations will give identical solutions at a homologous position, provided that all other constraints and boundary conditions are identical.

F.2.3 Transformation of Source and Permissible Complementary Inclination Angle

The rectangular source shown in Figure F-1 is reproduced in **Figure F-3** as Rectangle ABCD to illustrate the transformation process and to describe the end effects. The rectangle after transformation from x-y to x”-y” becomes a parallelogram, as shown in **Figure F-4**. The parallelogram in Figure F-4 is further simplified and approximated by a rectangular source, as shown in Figure F-2. Note that the area of the source remains invariant and equals to LW.

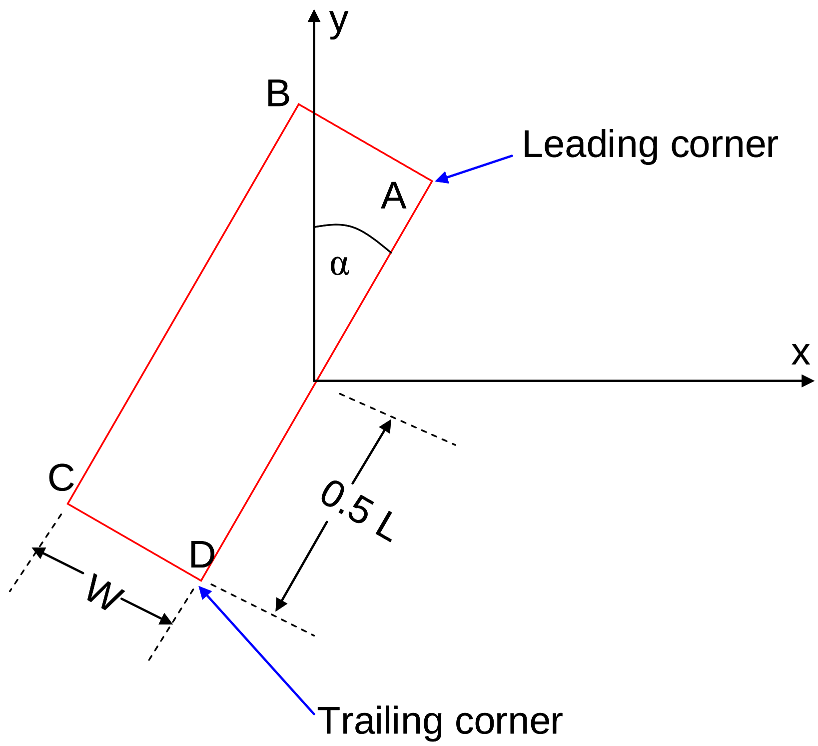

Figure F-3. Source before transformation in x-y coordinate system.

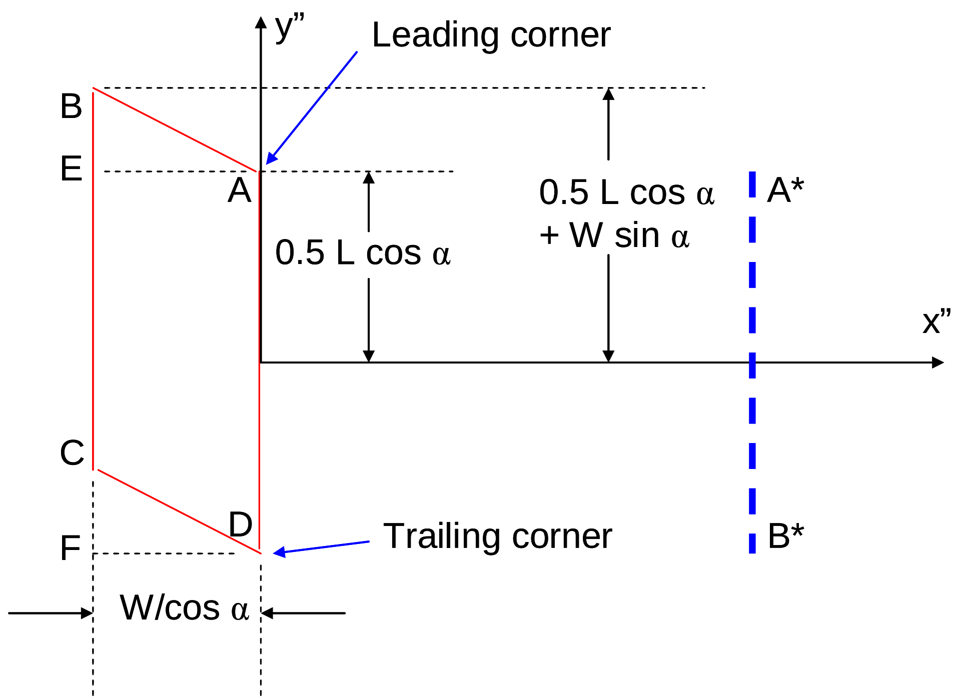

Figure F-4. Source after transformation in x″-y″ coordinate system.

In comparing Figures F-2 and F-4, one can see that the parallelogram in Figure F-4 is approximated by the rectangular source shown in Figure F-2. For this approximation to be valid, it is necessary that

$$\frac{0.5L\ \cos\alpha + W\sin\alpha}{0.5L\ \cos\alpha} = 1 + \frac{W}{L}2\ \tan\alpha = 1 + \varepsilon \approx 1 \qquad \text{(F-7)}$$

Proviso (F-7) implies that A and D are of approximately the same respective ordinates as B and C on the y” axis so that ABCD is approximately rectangular as shown in Figure F-2.

For the second term in Proviso (F-7) to be very small, with tolerance = ε, the following condition must be satisfied.

$$\alpha \ \leq\ \tan^{-1}\left(\frac{L}{W}\frac{\varepsilon}{2}\right) \qquad \text{(F-8)}$$

Proviso (F-8) gives the maximum value of the complementary inclination angle that Proviso (F-7) is not violated as a function of the source aspect ratio (L/W) and tolerance (ε). Examples of limits on the conjugate inclination angle as a function of aspect ratio and tolerance are given in **Table F-1**.

Table F-1. Limits of Complementary Inclination Angle α

Aspect Ratio (L/W)	α (Degrees)	
	ε = 0.01	ε = 0.02
500[a]	68	79
1,000[b]	79	84
10,000[c]	89	89

Notes

[a] A typical example: a mile long 10-ft lane

[b] A typical example: two-mile long 10-ft lane

[c] A typical example: twenty-mile long 10-ft lane

From Table F-1, one can see that the larger the aspect ratio of the source or tolerance, the larger the permissible complementary inclination angle for Proviso (F-7) to be valid.

F.2.4 End Effects

A typical concentration distribution along line A*B* (in Figure F-4) due to a typical rectangular source is given in **Figure F-5**. In the figure, a reference concentration profile without lateral dispersion, with a well-defined profile width based on advection alone (L cos **α**), is shown. Shown along with the reference profile is a typical corresponding plume with lateral dispersion.

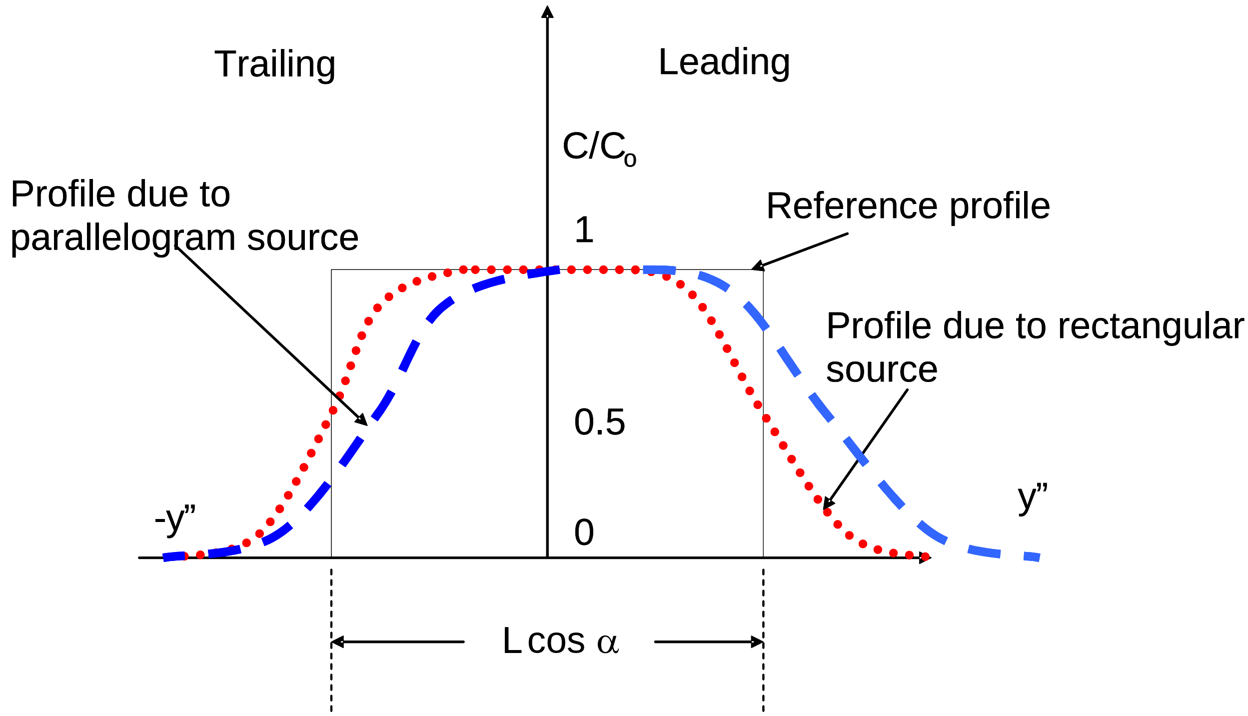

Figure F-5. Concentration profiles along line A*B* (in Figure F-4) due to rectangular source and parallelogram source. The black solid line represents a reference profile without lateral dispersion.

In the previous subsection, it has been shown that if the complementary inclination criterion is violated, the approximation by a rectangular source may incur error because the actual geometry of the transformed source is that of a parallelogram. Plotted in Figure F-5 is a typical concentration profile along Line A*B* due to a parallelogram source. In the figure, it can be seen that the mass is shifted laterally towards the positive y″. The reason for this shift can be inferred from Figure F-4. In the figure, it can be seen that in order to approximate parallelogram ABCD by rectangle AEFD, the mass in triangle ABE has to be shifted to triangle CDF. For this reason, the solution based on the rectangular source may tend to overestimate concentration in the vicinity of the plume emanating from the leading corner (see Figures F-3 and F-4) and underestimate concentration in the vicinity of the plume emanating from the trailing corner (see Figures F-3 and F-4). It should be noted also that, because of the geometry of the source near the parallelogram's top and bottom apices (B and D), the profile of the parallelogram source shows more apparent lateral dispersion.

To overcome the problem of end effects, a recommendation is given in **Figure F-6**. In the figure, it can be seen that source is artificially extended from either end by a length of W tan **α**. This extension makes the transport solution conservative as it will tend to overestimate concentration in the area of the plume that emanates from the leading corner of the source.

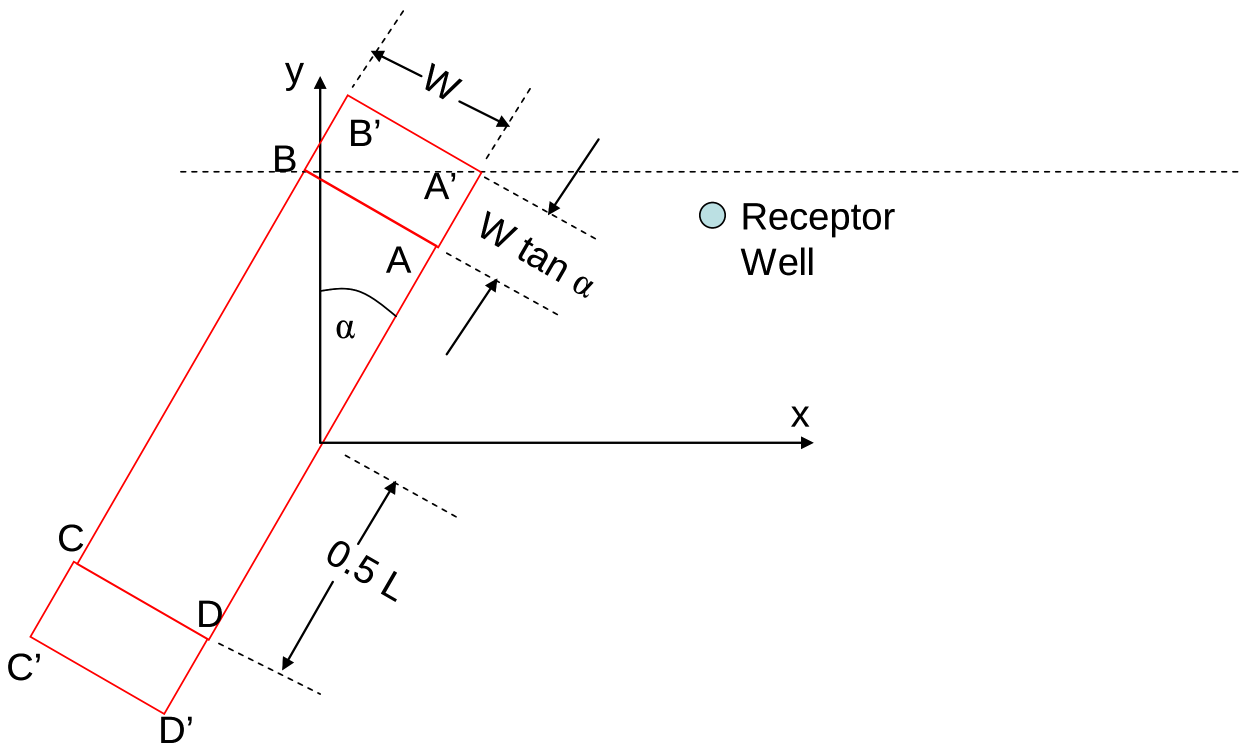

Figure F-6. Artificial extension of the source length to overcome the end effects.

F.2.5 Special Case with Complementary Angle of Inclination = 90°

In the case that the complementary angle of inclination is 90°, it is recommended that the length L be treated as the width W and vice versa as shown in **Figure F-7**.

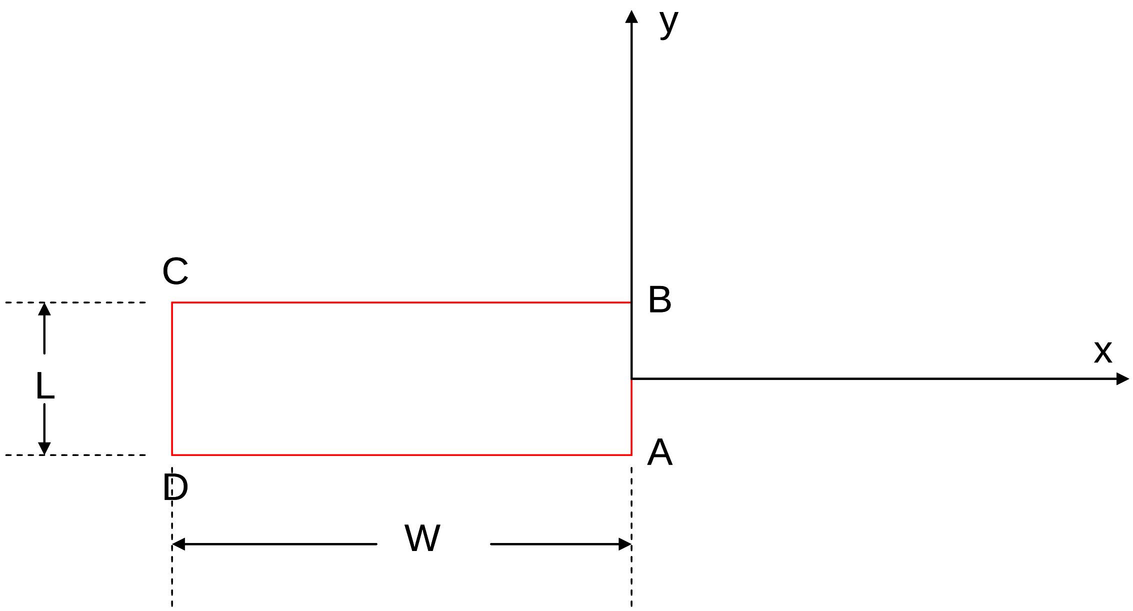

Figure F-7. Special case with conjugate angle of inclination (α) = 90 degrees.

F.3 Summary

Based on the derivation shown in **Section F-2**, the following can be stated:

- The transport equation remains unchanged in form after two successive transformations from x-y-z to x′-y′-z′ to x″-y″-z″ coordinate systems. The resulting equation in the x″-y″-z″ system is identical to the one in the original x-y-z system.
- End effects are minimal if Proviso (F-8) is not violated.
- End effects may be circumvented by extending the source artificially from either end by a length of W tan **α**, W being the width of the source and **α,** the complementary angle of inclination.
- In a special case where **α** = 90°, it is recommended that the length L be treated as the width W and vice versa.

F.4 References

U.S. EPA (Environmental Protection Agency). 2003a. *EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP): Technical Background Document*. U.S. EPA, Office of Solid Waste, EPA530-R-03-002, April.

U.S. EPA (Environmental Protection Agency). 2003b. *EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP): Parameter/Data Background Document*. U.S. EPA, Office of Solid Waste, EPA530-R-03-003, April.

U.S. EPA (Environmental Protection Agency). 2003c. *EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP): Draft Addendum to the Technical Background Document*. USEPA, Office of Solid Waste. September.

U.S. EPA (Environmental Protection Agency). 2003d. *EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP): Draft Addendum to the Parameter/Data Background Document*. U.S. EPA, Office of Solid Waste. April.

Appendix G: Verification of the Roadway Module in IWEM

G.1 Introduction

This appendix describes the verification performed on the roadway module. The verification was conducted using the roadway module in IWEM 3.0. IWEM 3.0 is a descendent of IWEM 2.0, which was revised to enhance the functionality and usability of the module. The enhancement allow for a more rigorous treatment of leaching through the roadway cross-section by accounting surface runoff and flow through ditches and drains; these processes were omitted in IWEM 2.0.

G.1.1 Background

A typical highway is depicted in **Figure G-1**. It was assumed that only a segment of the highway shown in the figure is constructed with industrial materials. For the sake of simplicity, it was assumed that the segment is sublinear and can be approximated by a straight line. In the event that the segment is long and meandering, it must be subdivided into several sublinear segments so that each sublinear segment can be represented by a straight line.

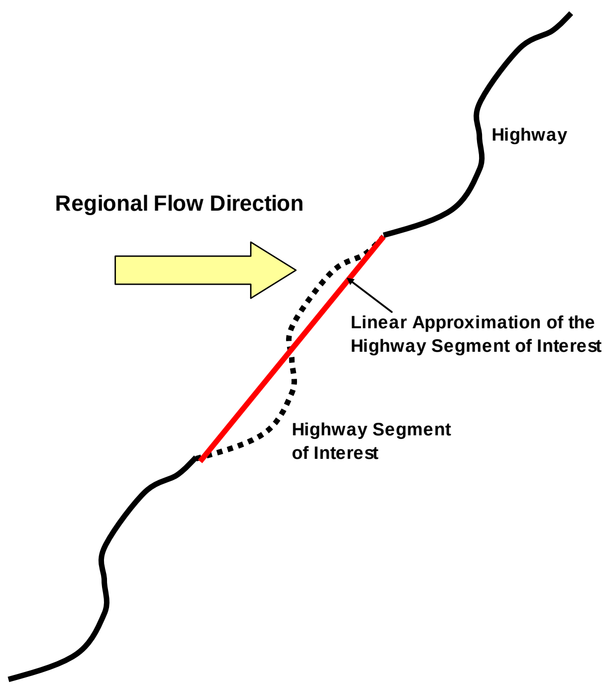

Figure G-1. A Typical Highway with a Recycled-Material Segment

Figure G-2 shows a typical cross section of a highway, indicating that a highway may comprise several components (e.g., travel lane, shoulder, and ditch). Each component was idealized as a column, referred to henceforth as the “highway-source column.” In the vertical direction, as shown in **Figure G-3**, each highway-source column included materials starting vertically upward from a reference datum (which could be the top of subgrade) to the surface of a pavement or a road shoulder or an embankment or a ditch. As shown in Figure G-3, each highway-source column was underlain by a corresponding vadose-zone column.

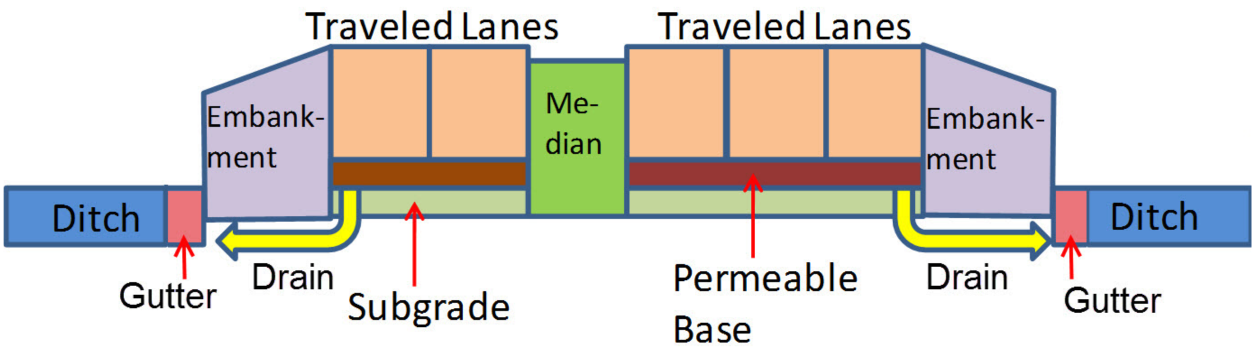

Figure G-2. A typical cross section of a roadway.

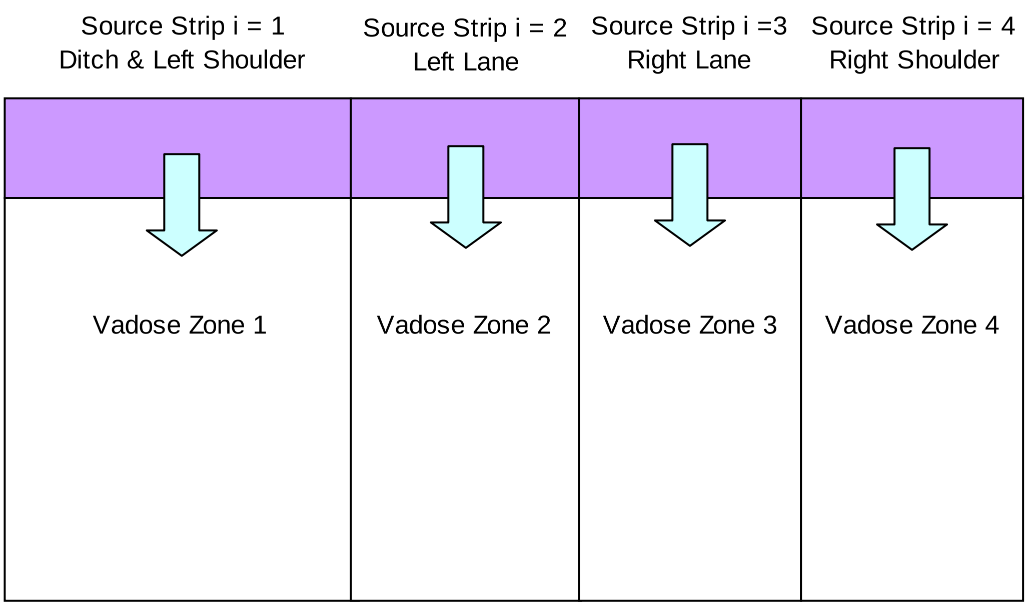

Figure G-2. Modules in IWEM Corresponding to Multiple Highway-Source Strips

A highway-source column was assumed to be uniform in terms of parameters and properties along the length of interest. Therefore, a highway-source column becomes a highway-source strip in three dimensions. **Figure G-4** shows an example of a highway cross section comprising three highway-source strips representing, respectively, a median, a travel lane, and a ditch. Note that a typical highway may consist of at least five highway-source strips: left shoulder, left travel lane, median, right travel lane, and right shoulder. An example of only three highway-source strips is used here as a basis for further discussion. Each highway-source strip may consist of several layers, depending on how a given highway was constructed. A travel lane way strip may be composed of a pavement layer (pPortland-cement concrete or asphalt concrete), a base-course layer, a subbase layer, and a subgrade layer. A median may comprise a base layer, a subbase layer, and a subgrade layer. An unpaved road shoulder may have only one a layer: a subgrade layer. With this type of conceptualization, one can see that each highway-source strip was equivalent to the existing landfill source module that is available within EPACMTP. However, the existing landfill module could accommodate only sources with square footprint and one layer.

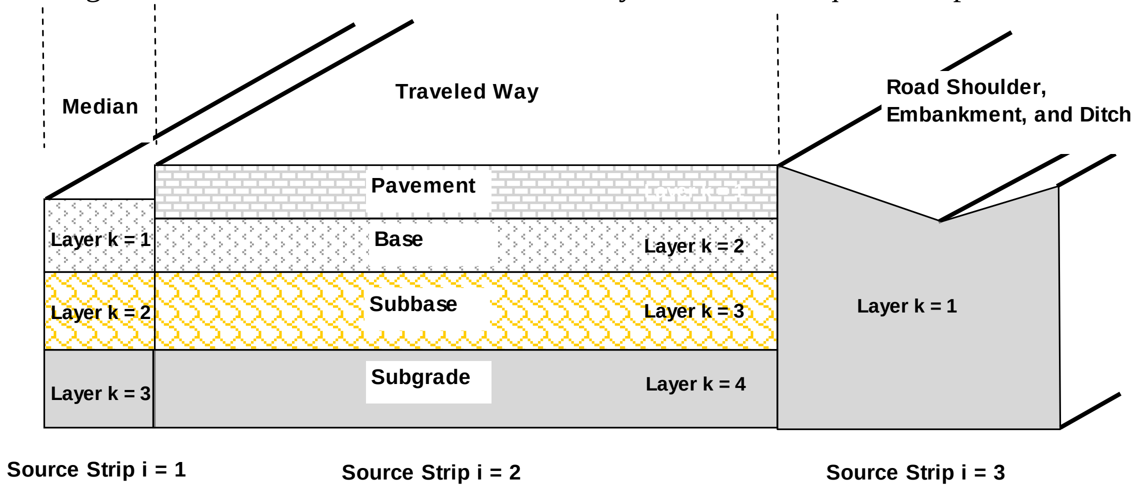

Figure G-3. An Example of Layering in Highway-Source Strips

Furthermore, given a highway's general settings, it is possible that the highway axis may not be normal to the regional flow direction. **Figure G-5** shows an idealized (straight line) highway segment with several laterally contiguous rectangular highway-source strips oriented at an angle α with respect to the normal of the regional flow direction. The existing aquifer transport module could handle only the case with $\alpha = 0°$, in which the flow direction is normal to the highway axis.

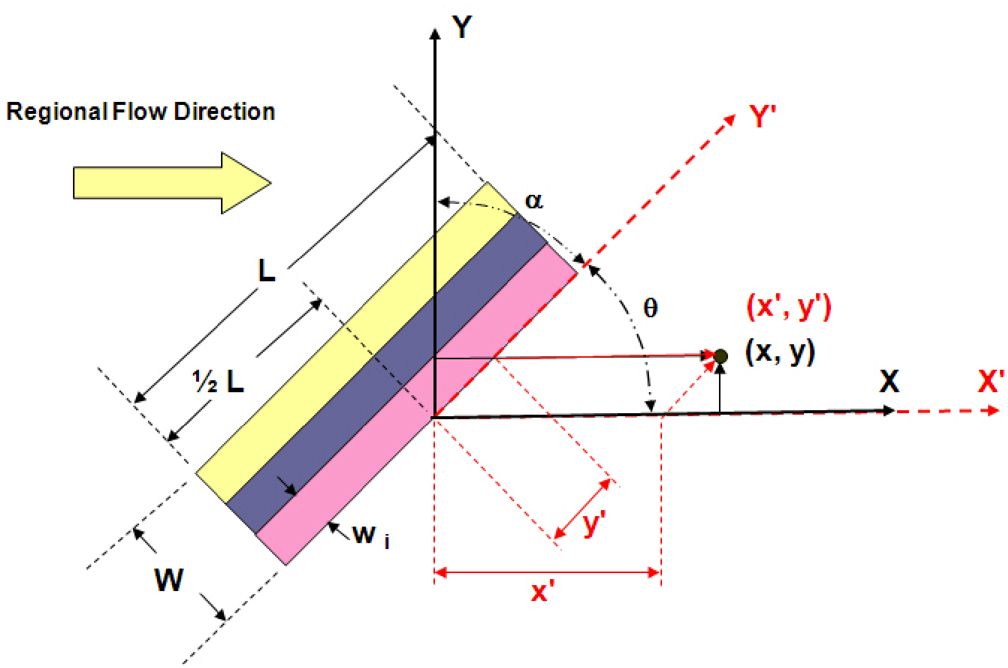

Figure G-5. Non-Orthogonal Source

G.1.2 Verification Objectives

In order to improve the highway source term, the following enhancements were implemented to the IWEM 3.0..

- **Non-aligned flow direction.** It is no longer necessary for the regional flow direction to coincide with the normal of the highway axis.
- **Multiple-layer and multiple-strip source.** The source module can now comprise multiple layers and multiple strips.

The main objective of the verification was to ensure that the above two new features have been correctly incorporated into the IWEM software. In addition, the non-aligned flow direction feature involves an approximate transformation of the transport equation. The objective of the verification was also to ascertain the degree of accuracy of the transformation.

G.1.3 Verification Approach

The verification was carried out by comparing the results obtained from a number of verification scenarios using the IWEM software and U.S. Geological Survey (USGS) MODHMS (HGL, 2006). MODHMS can solve the flow-and-transport equations without the approximate transformation used in the non-aligned flow direction feature (RTI and HGL, 2006). The transport-equation solutions provided by the MODHMS code were considered accurate and treated as a standard with which the IWEM software was compared.

MODHMS is an enhanced version of the USGS MODFLOW modular three-dimensional groundwater flow code (McDonald and Harbaugh, 1988). The MODHMS code has been selected for the following reasons:

- It can handle variably saturated flow and transport.
- It has been extensive verified and documented.
- It has been implemented by a number of government agencies in different settings.

The verification scenarios are described in **Section G.2**. Verification results are presented in **Section G.3**.

G.2 Verification Scenario Description

Contaminant transport simulations using the new IWEM source module and MODHMS under the following three verification scenarios were performed:

1. Transport with a single-strip single-layer source;
2. Transport with a single-strip and multiple-layer source; and
3. Transport with a multiple-strip and single-layer source.

In all cases, it was assumed that the vadose zone did not exist so that the infiltration with contaminant entered the water table immediately after leaving the bottom of the roadway source. This assumption makes the leachate influx at the top of the water table to be well defined, thereby allowing the influx conditions for the MODHMS model and the IWEM saturated zone module to be identical. The vadose-zone module in EPACMTP (U.S. EPA, 2003) was not part of the verification exercise because it is not impacted by the non-aligned flow direction feature and it has been previously verified as part of the EPACMTP code. In all cases, it was assumed that neither adsorption nor degradation occurred in the groundwater. The regional groundwater gradient in the MODHMS-based model was imposed by constant heads along the boundaries.

The above three scenarios are described in the following subsections. Results are given in **Section G-3**.

G.2.1 Verification Scenario 1: Single-Strip and Single-Layer Roadway Source with Flow at Different Angles to the Axis of the Roadway

Verification Scenario 1 represents a single-strip and single-layer highway source with flow at two different angles to the axis of the roadway:

(a) Orthogonal: Flow orthogonal to the roadway ($\alpha = 0°$, $\theta = 90°$); and

(b) Sub-Orthogonal: Flow at 45E to the roadway ($\alpha = 45°$, $\theta = 45°$).

The above two scenarios are diagrammatically summarized in **Figure G-6**. A continuous infiltration source with a constant concentration (C_0 = 1 mg/L) was assumed. For each case, MODHMS and IWEM models were constructed.

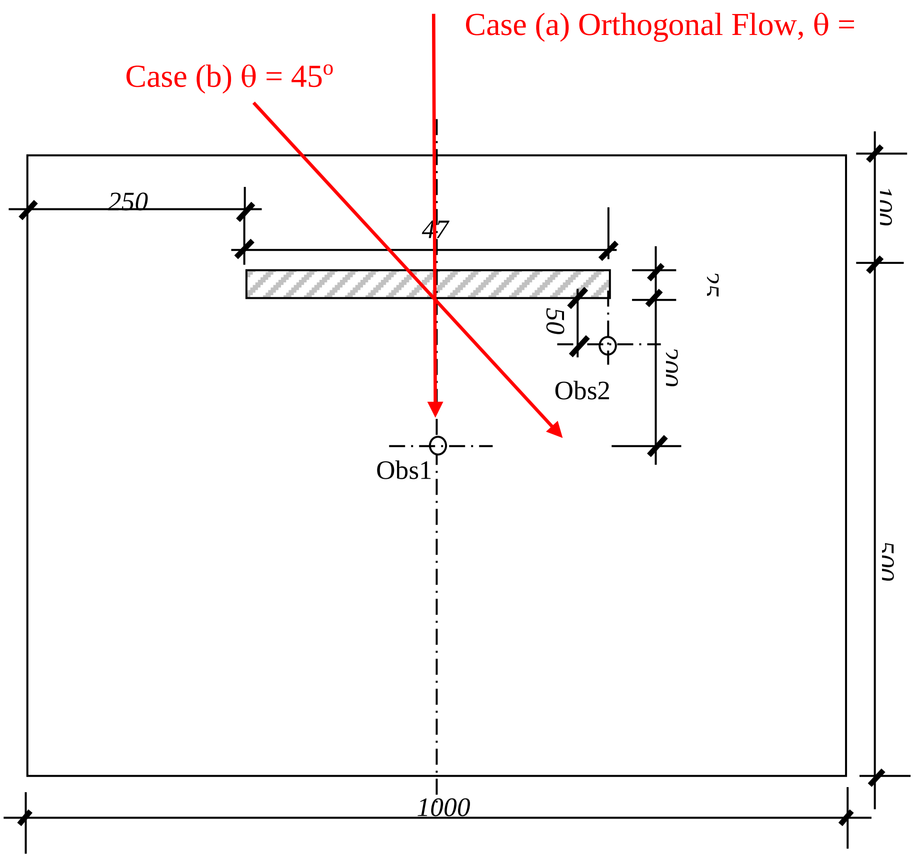

Figure G-6. Flow Angles

It has been shown that the conjugate inclination angle must satisfy the following proviso:

$$\alpha \leq \tan^{-1}\left(\frac{L}{W}\frac{\varepsilon}{2} \right) \quad \text{(G-1)}$$

Proviso (G-1) gives the maximum value of the conjugate inclination angle as a function of the source aspect ratio (L/W) and tolerance (unitless) that the approximation of the source as a rectangle in the x″-y″ coordinate system remains valid.

Based on the aspect ratio value of 19 (47.5 ft/ 2.5 ft, Figure G-6), maximum permissible conjugate inclination angle values as a function of tolerance are given below

ε	α (Degrees)
0.05	25
0.1	45

According to the table above, for the tolerance value = 0.1 (which is considered relatively large), the conjugate inclination angle is maximum permissible based on Proviso (G.1) is 45°.

Simulation results from these models are summarized in **Section G.3**.

G.2.2 Verification Scenario 2: Single-Strip and Multiple-Layer Roadway Source with Flow at Different Angles to the Axis of the Roadway

Verification Scenario 2 consists of a three-layer single-strip roadway source. The hydrogeological properties of the sources were assumed to be identical. The only differences among the sources were the thickness and initial concentration. As shown in **Figure G-7**, the thicknesses of the top layer to the bottom layer are 1 foot, 1 foot, and 2 feet, respectively. Only the middle layer contains a contaminant at an initial concentration of 1 unit mass/unit volume. The other two layers are contaminant-free. This configuration of the source layers results in a square concentration pulse at the bottom of the bottommost layer, as shown in Figure G-7. Note that the infiltration contains no mass when entering the top layer. It was also assumed that no adsorption occurred in any of the three layers. The shape of the pulse in Figure G-7 is based on the pulse formulation given in (RTI and HGL, 2006). In Figure G-7, one can see that the pulse first appears at 300 days because it takes 300 days for the mass from the middle layer to traverse the bottom layer before it emerges as leachate. The length of the pulse is 100 days.

The simulation of the MODHMS model was divided into three stress periods to account for the square pulse. In all stress periods, the infiltration was kept constant at 0.01-ft/day. As shown in Figure G-7, the first stress period is 300 days and contaminant free (concentration = 0). The second stress period is 100 days with constant leachate concentration (1 mg/L). The last stress period is 36,500 days with leachate concentration = 0. Two test cases were simulated under this scenario: (a) the orthogonal flow case; and (b) the sub-orthogonal flow case (45° inclination). These two cases correspond to Cases (a) and (b), respectively, in **Section G.2.1**. Simulation results are summarized in **Section G.3**.

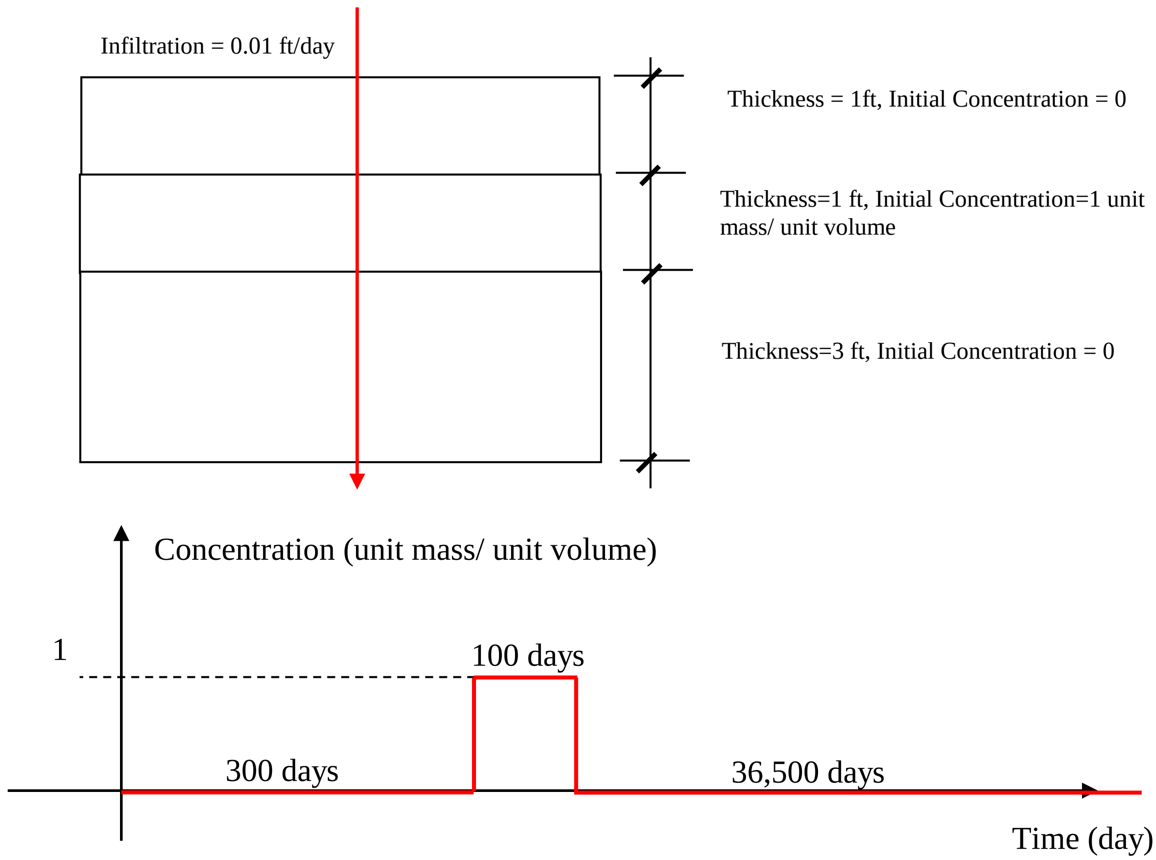

Figure G-7. Single-strip, Multiple-layer Source.

G.2.3 Verification Scenario 3: Multiple-Strip and Single-Layer Roadway Source with Flow at Different Angles to the Axis of the Roadway

Verification Scenario 3 consists of a single-layer three-strip roadway source. The strips have identical dimensions of 500-ft by 25-ft, and are placed side-by-side as shown in **Figure G-8**. An upgradient and a downgradient strips were added to the original strip in Verification Cases 1 and 2. The infiltration rate was assumed to be 0.01-ft/day for all three strips, but the initial concentrations of individual strips were different. The strip closest to the upstream boundary was assigned with the highest concentration of 1unit mass/unit volume. The second strip had a concentration of 0.5 mg/L. The downstream-most strip had the lowest concentration of 0.1 mg/L.

Two test cases were simulated under this scenario: (a) the orthogonal flow case and (b) the sub-orthogonal flow case (45° inclination). These two cases correspond to Cases (a) and (b), respectively, in **Section G.2.1**. Simulation results are summarized in **Section G.3**.

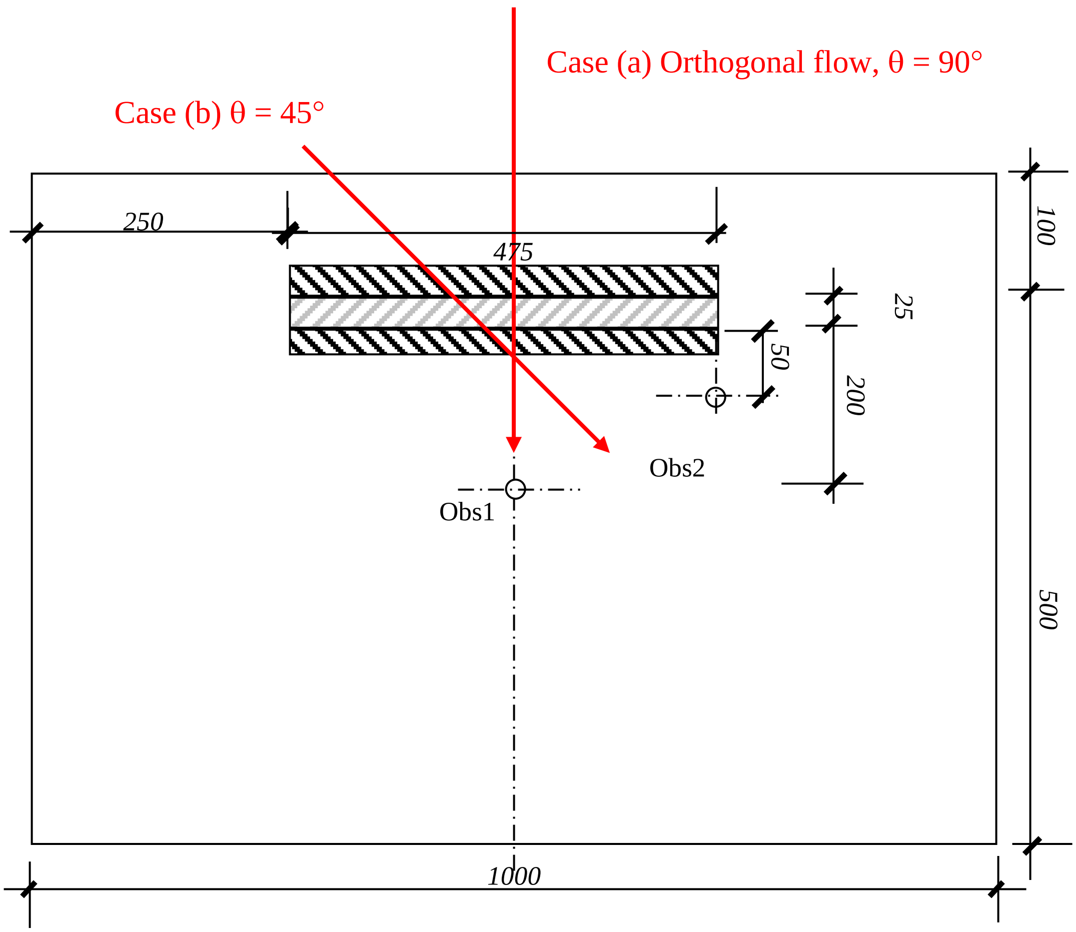

Figure G-8. Multiple-strip, Single-layer Source Scenario

G.2.4 Verification Scenario 4: Multiple-Strip Roadway Source with Drainage Systems and Ditches

Figure G-9 depicts the settings of Verification Scenario 4 in which the flow is perpendicular to the highway axis. The size of the model domain, as shown in Figure G-9a, is 1,200 ft by 1,600 ft. Flow and transport properties in the model domain are homogeneous with a hydraulic conductivity of 10 ft/day and an effective porosity of 0.3. A hydraulic gradient of 0.0075 along the direction perpendicular to the highway axis was assigned across the model domain. A 400 ft by 90 ft strip source is located 110 ft from the up-stream boundary and 600 ft from the upper boundary. The 90 ft wide source is composed of two 10 ft wide roadside ditches and seven strips with the following widths: 10, 10, 20, 10, 20, 10, and 10 ft. An infiltration rate of $7.3\text{x}10^{-3}$ ft/day was imposed on the seven roadway-source strips. Two infiltration rates of 1.6634 and 1.9644 ft/day were applied to the left-hand-side and right-hand-side ditches, respectively. As shown in Figure G-9a, four observation wells (Obs1 to Obs4) are located down-gradient from the source. Obs1 is 100 ft from the down-gradient edge of the source and on the centerline of the domain. Obs2 is 100 ft from the down-gradient edge of the source and 180 ft from the centerline of the domain. Obs3 is 800 ft from the down-gradient edge of the source and 180 ft from the centerline of the domain. Obs4 is 800 ft from the down-gradient edge of the source and on the centerline of the domain. All four observation wells are screened in the top layer. The longitudinal and transverse dispersivities of 100 and 10 ft, respectively, were used in the simulation. A uniform saturated thickness of 100 ft exists throughout the model domain. In the vertical direction, the entire saturated thickness was represented by ten uniform layers. In the horizontal direction, the domain was discretized into uniform 25 ft by 25 ft grid cells. The source was discretized into four grid intervals along the flow direction (20 ft, 25 ft, 25 ft, and 20 ft) and 16 uniform grid intervals (25 ft) perpendicular to the flow direction. Based on the current configuration, the aspect ratio of the source is equal to 400 ft/ 90 ft or 4.4.

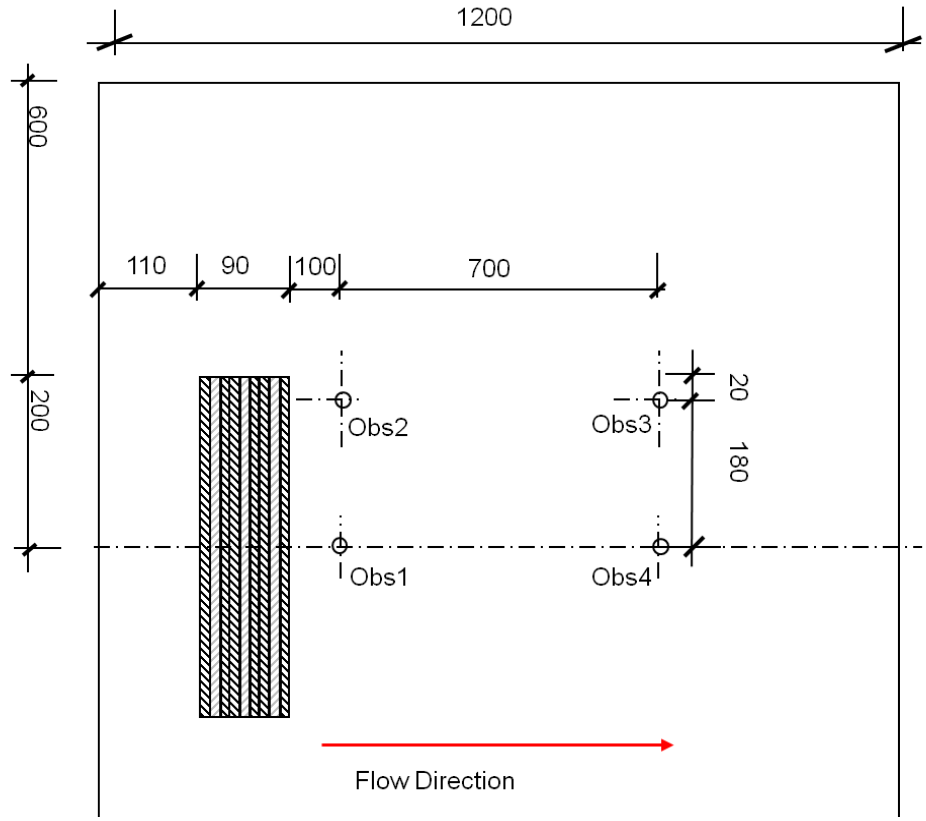

Figure G-9. Multiple-strip (7 strips) with Drainage Systems and Ditches Scenario

Figure G-10 shows the roadway cross section comprising two ditches and seven roadway-source strips: one left embankment; two left travel lane; one median; two right travel lane; and one right embankment. Two symmetrical drainage systems with a permeable base and an edge drain leading to a ditch were adopted for both sides of the roadway in this example. Each travel lane strip is composed of two pavement layers, one permeable base layer, and one subgrade layer. Each permeable base layer diverts part of infiltration water to a receiving ditch. The median comprises two layers: a base layer and a subgrade layer. The dimensions are shown in Figure G-9b.

Contaminant pulses entering the vadose zone are based on the parameters given in **Table G-1** and are shown in **Figure G-11**. All the pulses were verified manually. The pulses exiting the base of the pavement systems from different strips are shown in the figure.

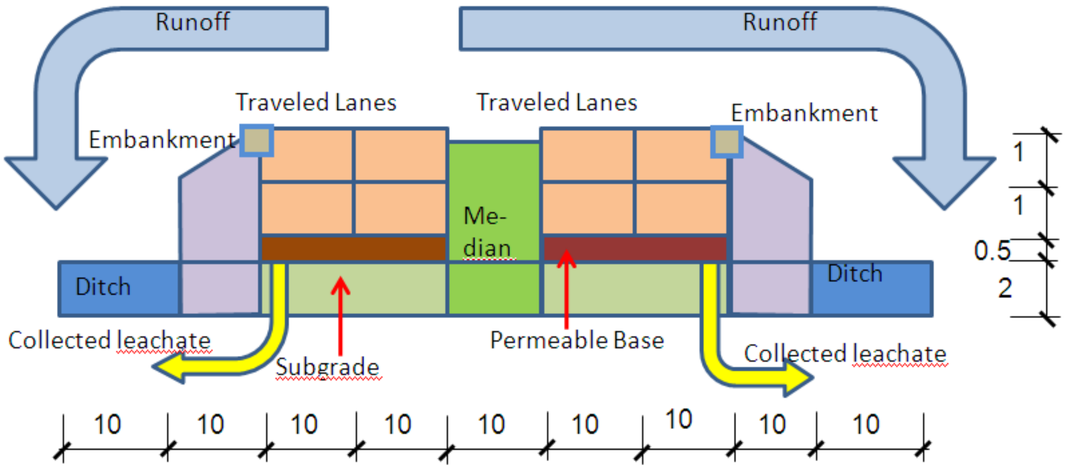

Figure G-10. Cross section of roadway segment in Case 4 with two symmetric drainage systems.

Table G-1 Parameter Values for IWEM Roadway Source Module Example

Parameter	Description	Remarks
Source Geometry		
θ	Angle of inclination (see Figure 1.5, Chapter 1)	90
$d_{k,i}$	Thickness of layer *k* of the pavement structure in roadway-source strip *i* (see Figure 1.4, Chapter 1, and Figure G-10, this appendix)	$d_{k,i}$=1 ft (0.3 m) for the top 2 layers above permeable base; $d_{k,i}$=2.5 ft (0.75 m) for roadway-source strip without permeable base.
w_i	Width of roadway-source strip *i* (see Figure 1.5)	10 ft (3m)
L	Length of given roadway segment (see Figure 1.5)	400 ft (120 m)
nStrips	Number of roadway-source strips	7
nLayers(i)	Number of material layers for roadway-source strip *i*	2 layers in each strip. Note that the Strips 1 and 7 represent embankments, and Strip 4 represents a median. These strips are is not underlain by a permeable base
nSubLayers (left)	Number of the left-hand side subgrade layers	1
nSubLayers (right)	Number of the right-hand side subgrade layers	1
d_{PB}*(left)*	Thickness of the left-hand side permeable base	0.5 ft (0.15 m)
w_{Ditch} *(left)*	Width of the left-hand side ditch	10 ft (3 m)
$d_{SG,i}$ *(left)*	Thickness of the left-hand side subgrade layer *j*	2 ft (0.6 m)
d_{PB}*(right)*	Thickness of the right-hand side permeable base	0.5 ft (0.15 m)
w_{Ditch} *(right)*	Width of the right-hand side ditch	10 ft (3 m)
$d_{SG,i}$ *(right)*	Thickness of the right-hand side subgrade layer *j*	2 ft (0.6 m)

(continued)

Table G-1 Parameter Values for IWEM Roadway Source Module Example

Parameter	Description	Remarks
Source Constituent Information		
$C^0_{L,k,i}$	Initial leachate concentration for layer k in roadway-source strip i	Top layer: Strips 1 to 7 (1, 0, 0, 1, 0, 0, 1 mg/L) Below-top layer: Strips 1 to 7 (1, 1, 1, 1, 1, 1, 1 mg/L)
$C^0_{Total,k,i}$	Initial total constituent concentration for material layer k in roadway-source strip i	Top layer: Strips 1 to 7 (0.05, 0, 0, 0.05, 0, 0, 0.05 mg/kg)[b] Below-top layer: Strips 1 to 7 (0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05 mg/kg)[b]
$C^0_{L,PB}$ (left)	Initial leachate concentration for the left-hand side permeable base	1 mg/L
$C^0_{Total,PB}$ (left)	Initial total constituent concentration for the left-hand side permeable base	0.05 mg/kg
$C^0_{L,SG,j}$ (left)	Initial leachate concentration for the left-hand side subgrade layer j	1 mg/L
$C^0_{Total,SG,j}$(left)	Initial total constituent concentration for the left-hand side subgrade layer j	0.05 mg/kg[2]
$C^0_{L,PB}$ (right)	Initial leachate concentration for the right-hand side permeable base	1 mg/L
$C^0_{Total,PB}$ (right)	Initial total constituent concentration for the right-hand side permeable base	0.05 mg/kg
$C^0_{L,SG,j}$ (right)	Initial leachate concentration for the right -hand side subgrade layer j	1 mg/L
$C^0_{Total,SG,j}$ (right)	Initial total constituent concentration for the right -hand side subgrade layer j	0.05 mg/kg
C_{in} (left)	Contaminant concentration of the left -hand side ditch inflow;	0.05 mg/L
C_{in} (right)	Contaminant concentration of the right -hand side ditch inflow;	0.05 mg/L
C_{Crit}	minimum concentration level in the ditch	0.05 mg/L (Assumed)
Note that the above information must be provided for all constituents		
$\rho^0_{Bulk,k,i}$	Initial bulk density for material layer k in roadway-source strip i	2 g/cm^3 (all layers and strips)
$\rho^0_{Bulk,PB}$ (left)	Initial bulk density in the left-hand side permeable base	2 g/cm^3 (all layers and strips)
$\rho^0_{Bulk,SG,j}$ (left)	Initial bulk density for the left -hand side subgrade layer j	2 g/cm^3 (all layers and strips)
$\rho^0_{Bulk,PB}$ (right)	Initial bulk density in the right-hand side permeable base	2 g/cm^3 (all layers and strips)
$\rho^0_{Bulk,SG,j}$ (right)	Initial bulk density for the right -hand side subgrade layer j	2 g/cm^3 (all layers and strips)
Hydrologic Parameters		
Ii	Infiltration rate for roadway-source strip i	4.62 inches/year(11.7 cm/yr) (Site: Montepelier,VT; From: AC-Low in Table 1.4)

(continued)

Table G-1 Parameter Values for IWEM Roadway Source Module Example

Parameter	Description	Remarks
Hydrologic Parameters (continued)		
ROi	Runoff rate per unit area of strip i	23.69 inches/year(60.2 cm/yr) (Site: Montepelier,VT; From: AC-Low in Table 1.4)
EP	Evaporation rate over the ditch	22.25 inches/year (56.5 cm/yr)
P	Precipitation rate over the ditch	36 inches/year (91.4 cm/yr)
RRech	Recharge flux per unit area	9.18 inches/year (23.3 cm/yr)
KDRO (left)	Divertible runoff coefficient for the left-hand side roadway-source strips (dimensionless), varying from 0 to 1	0.5 (Assumed)
KPB (left)	Water flux coefficient for the left-hand side roadway-source strips, varying from 0 to 1.	0.5 (Assumed)
KDRO (right)	Divertible runoff coefficient for the right-hand side roadway-source strips (dimensionless), varying from 0 to 1	0.5 (Assumed)
KPB (right)	Water flux coefficient for the right-hand side roadway-source strips, varying from 0 to 1.	0.5 (Assumed)
n(left)	Manning's coefficient of the left-hand side ditch	0.016[a]
n (right)	Manning's coefficient of the right-hand side ditch	0.016[a]
S (left)	Slope of the left-hand side water surface and stream bed	10^{-8}
S (right)	Slope of the right-hand side water surface and stream bed	10^{-8}
Flow and transport properties for the vadose and saturated zones		
K_{ki}	Hydraulic conductivity for material layer k in roadway-source strip i	Top layer: Strips 1 to 7 (all equals to 3.139 m/yr) Below-top layer: Strips 1 to 7 (0.0017, 3.139, 3.139, 0.0017, 3.139, 3.139, 0.0017 m/d) Note that Strips 1, 4, and 7 of the below-top layer represent subgrade.
KK_{PB} *(left)*	Saturated hydraulic conductivity of the left-hand side permeable base	10^5 ft/d (1.095 x 10^7 m/yr)
K_{SG} *(left)*	Saturated hydraulic conductivity of the left-hand side subgrade layers underlying the permeable base	6.6 x 10^{-5} ft/d (0.0073 m/yr)
K_{Ditch} *(left)*	Vertical hydraulic conductivity of the left-hand side ditch bed	0.01 ft/d (1.095 m/yr) (Silt)
T_{Bed} *(left)*	Thickness of the left-hand side ditch bed	1.5 ft (0.45 m)
HstrLimit (left)	The maximum possible depth of water in the left-hand side ditch	3.28 ft (1m)
KK_{PB} *(right)*	Saturated hydraulic conductivity of the right-hand side permeable base	10^5 ft/d (1.095E07 m/yr)

(continued)

Table G-1 Parameter Values for IWEM Roadway Source Module Example

Parameter	Description	Remarks
K_{SG} *(right)*	Saturated hydraulic conductivity of the right-hand side subgrade layers underlying the permeable base	6.6 x 10^{-5} ft/d (0.0073 m/yr)
K_{Ditch} *(right)*	Vertical hydraulic conductivity of the right-hand side ditch bed	0.01 ft/d (1.095 m/yr) (Silt)
T_{Bed} *(right)*	Thickness of the right-hand side ditch bed	1.5 ft (0.45 m)
HstrLimit (right)	The maximum possible depth of water in the right-hand side ditch(L)	3.28 ft (1m)

[a] Source: http://docs.bentley.com/en/HMSewerCAD/SewerCAD_Help-14-116.html
[b] Fictitiously low values are used to control the pulse length for model verification purposes.

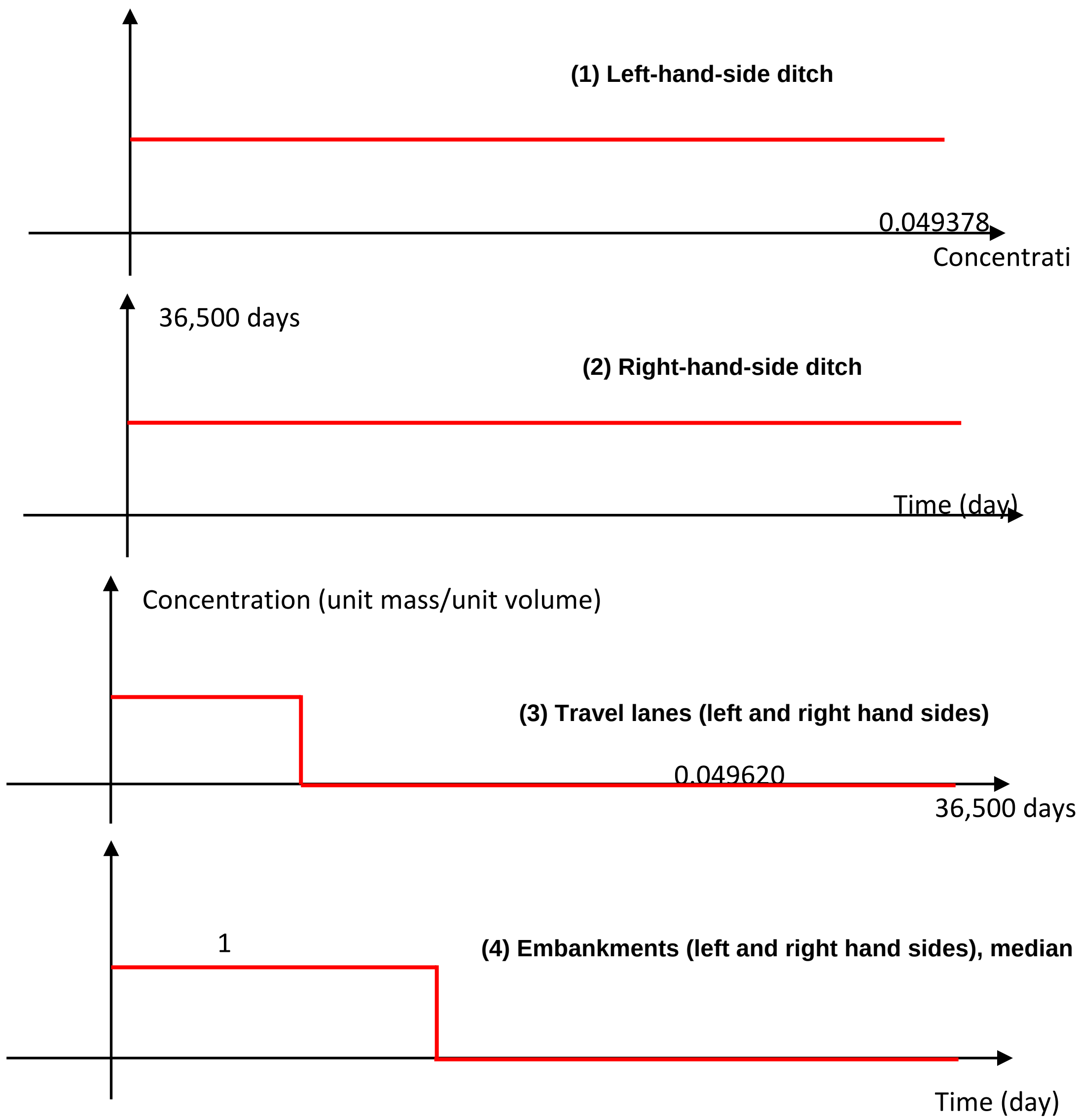

Figure G-11. Contaminant Pulses for Verification Case 4

G.3 Verification Results

G.3.1 Verification Scenario 1: Single-Strip and Single-Layer Roadway Source with Flow at Different Angles to the Axis of the Roadway

Normalized breakthrough curves for the two cases are shown in **Figures G-12** to **G-15**. In each figure, an IWEM-generated and a corresponding MODHMS-generated normalized breakthrough curves are compared. Results are summarized in **Table G-2**.

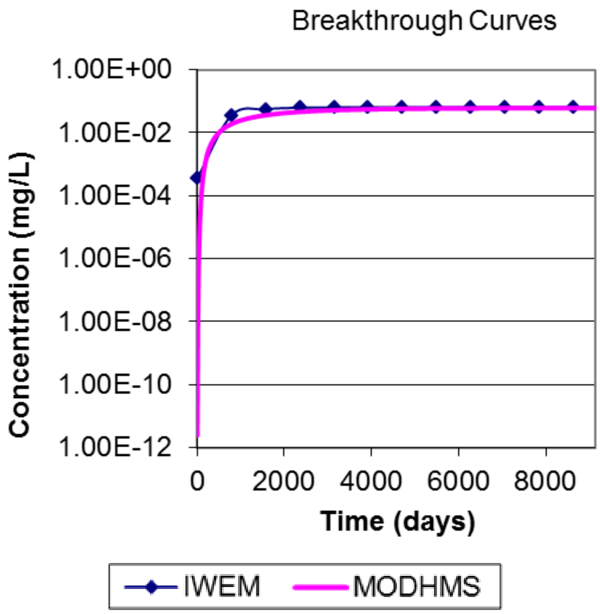

Figure G-12. Concentration at observation location 1 under single-strip, single-layer scenario with orthogonal flow.

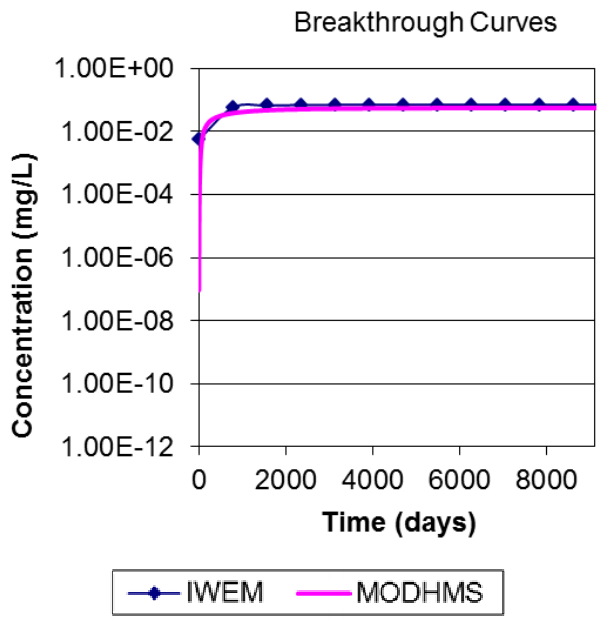

Figure G-13. Concentration at observation location 2 under single-strip, single-layer scenario with orthogonal flow.

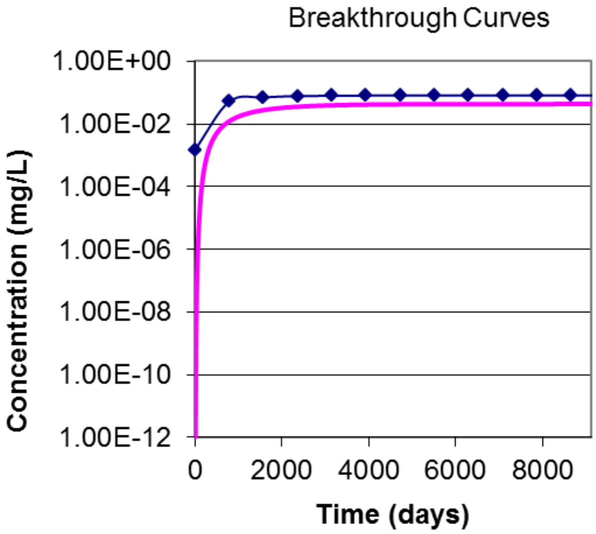

Figure G-14. Concentration at observation location 1 under single-strip, single-layer

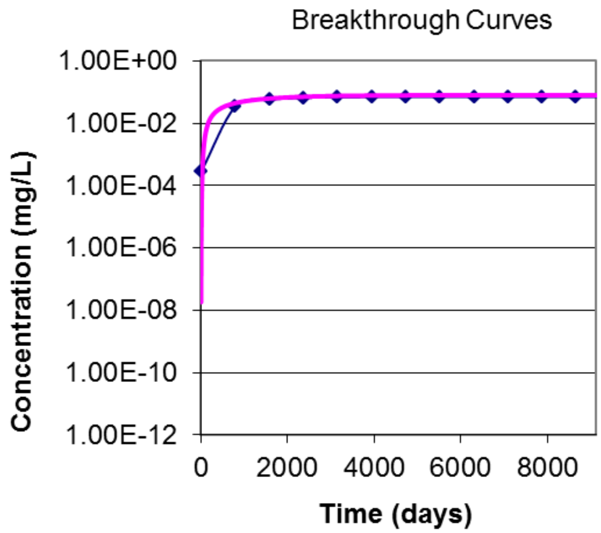

Figure G-15. Concentration at observation location 2 under single-strip, single-layer

scenario with 45º flow. **scenario with 45º flow.**

Table G-2. Summary of Results for Verification Scenario 1

Case	α (°)	θ (°)	In Main Plume (Obs 1)	Edge of/Off Main Plume (Obs 2)
(a) Orthogonal	0	90	**Figure G-11a** Good match overall	**Figure G-11b** Good match overall
(b) Sub-orthogonal	45	45	**Figure G-11c** Good match, IWEM is slightly more conservative	**Figure G-11d** Good match overall

For comparison purposes, the normalized breakthrough curves are divided into two categories: in main plume, and off main or edge of plume. In the former category, the observation location is located well within the swath of paths of fluid particles from the source. The latter refers to the observation location that is near the edge of the particle path swath or just outside the swath. The results summarized in Table G-2 indicate that, for in-main-plume observation wells, the IWEM results generally agree well with the more accurate numerical results. This is true even when the conjugate inclination angle approaches the maximum permissible value of 45°, which is based a relatively large tolerance of 0.1. This observation is thought to be due to the smoothing effect of lateral dispersion near the fringe of the plume originating from near the edge of the source.

The difference between the numerical solution based on the actual source and the IWEM solution based on the approximate source is expected to increasing more evident as α exceeds 45° and approaches 90°.

G.3.2 Verification Scenario 2: Single-Strip and Multiple-Layer Roadway Source with Flow at Different Angles to the Axis of the Roadway

Normalized breakthrough curves for the two cases are shown in **Figures G-16** to **G-19**. In each figure, the IWEM-generated and the corresponding MODHMS-generated normalized breakthrough curves are compared. Results are summarized in **Table G-3**.

In this verification scenario, the multiple-layer IWEM model agrees reasonably well with the more accurate numerical MODHMS-based model. It can be seen that when the distortion is kept within the sub-orthogonal range, the IWEM-generated breakthrough curves agree reasonably well with the MODHMS-generated.

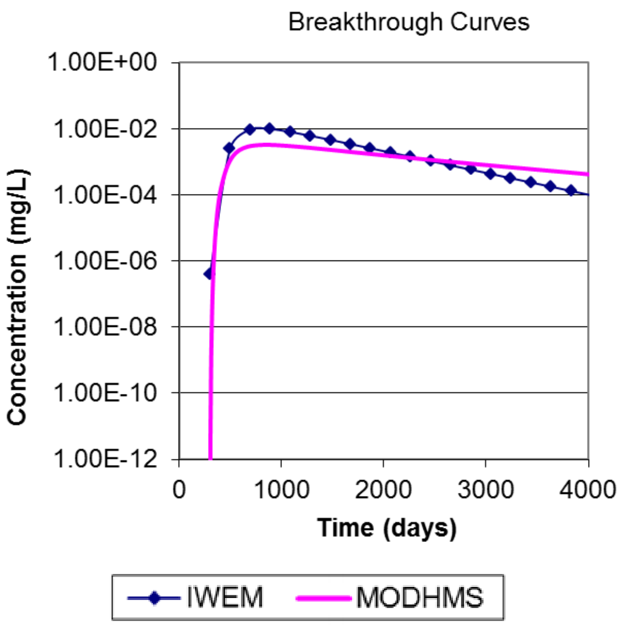

Figure G-16. Concentration at observation location 1 under single-strip, multiple-layer scenario with orthogonal flow.

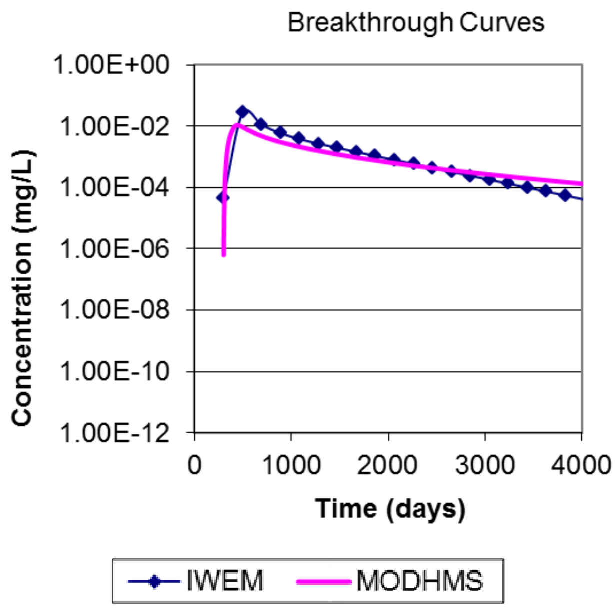

Figure G-17. Concentration at observation location 2 under single-strip, multiple--layer scenario with orthogonal flow.

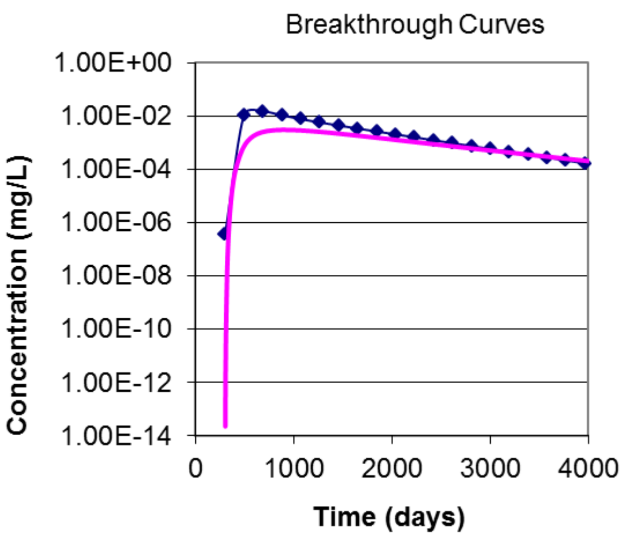

Figure G-18. Concentration at observation location 1 under single-strip, multiple-layer scenario with 45º flow.

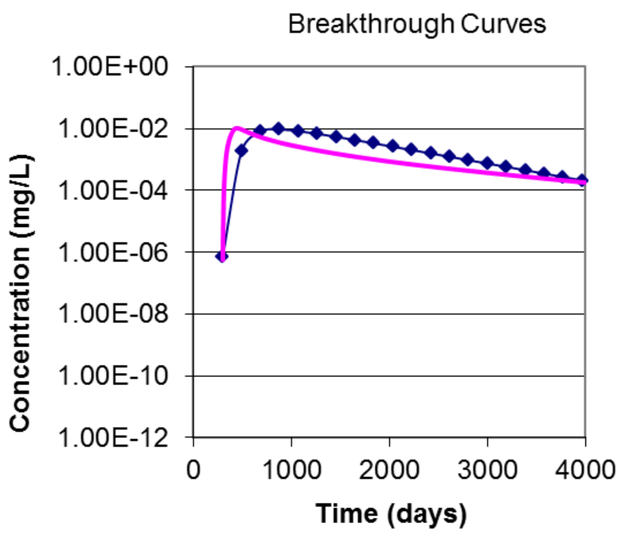

Figure G-19. Concentration at observation location 2 under single-strip, multiple-layer scenario with 45º flow.

Table G-3. Summary of Results for Verification Scenario 2

Case	α (°)	θ (°)	In Main Plume (Obs 1)	Edge of/Off Main Plume (Obs 2)
(a) Orthogonal	0	90	**Figure G-11e** Relatively good match near peak where IWEM is more conservative	**Figure G-11f** Relatively good match near peak where IWEM is more conservative
(b) sub -orthogonal	45	45	**Figure G-11g** Relatively good match near peak where IWEM is more conservative	**Figure G-11h** Relatively good match near peak where IWEM is more conservative

G.3.3 Verification Scenario 3: Multiple-Strip and Single-Layer Roadway Source with Flow at Different Angles to the Axis of the Roadway

Normalized breakthrough curves for the two cases are shown in **Figures G-20 to G-23**. In each figure, the IWEM-generated and the corresponding MODHMS-generated normalized breakthrough curves are compared. Results are summarized in **Table G-4**.

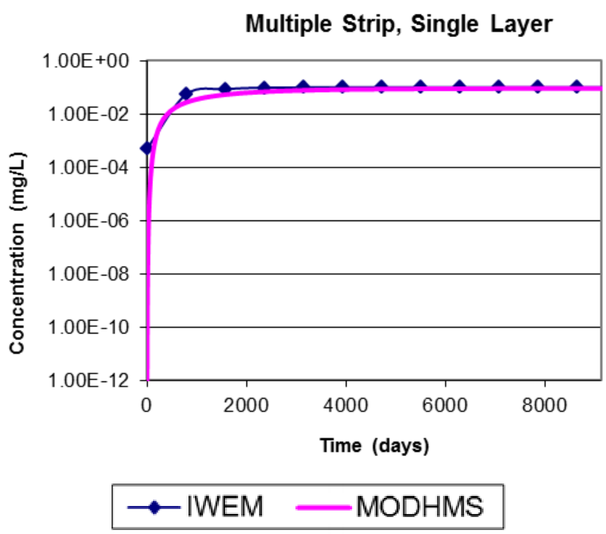

Figure G-20. Concentration at observation location 1 under multiple-strip, single-layer scenario with orthogonal flow.

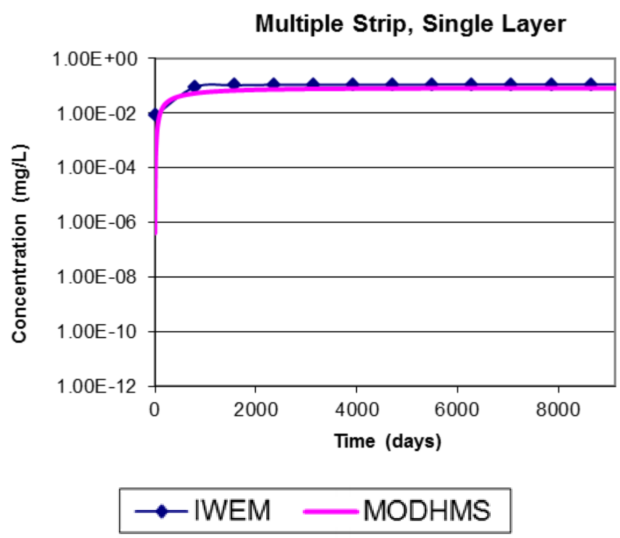

Figure G-21. Concentration at observation location 2 under multiple-strip, single-layer scenario with orthogonal flow.

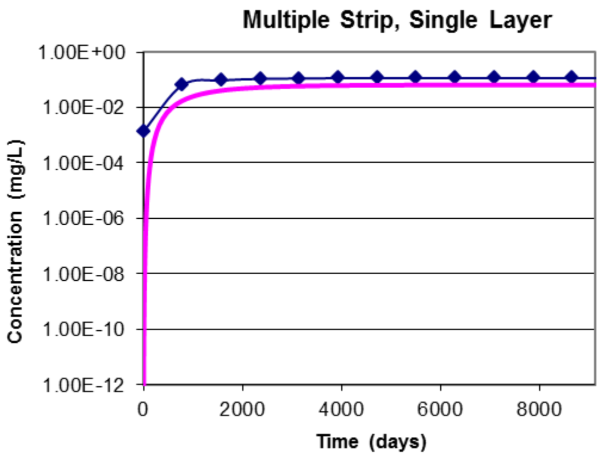

Figure G-22. Concentration at observation location 1 under multiple-strip, single-layer scenario with 45º flow.

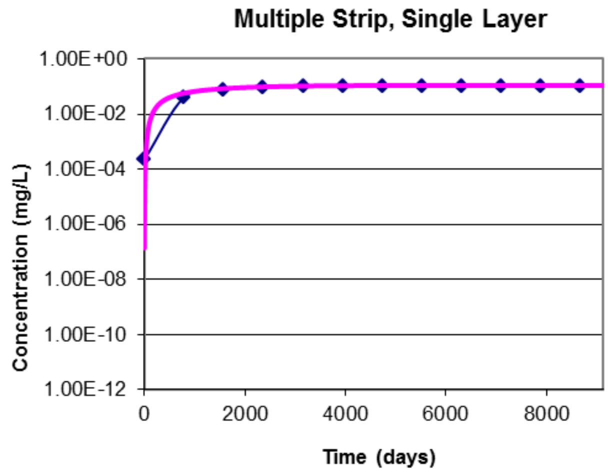

Figure G-23. Concentration at observation location 2 under multiple-strip, single-layer scenario with 45º flow.

Table G-4. Summary of Results for Verification Scenario 3

Case	α (E)	2 (E)	In Main Plume (Obs 1)	Edge of/Off Main Plume (Obs 2)
(a) Orthogonal	0	90	**Figure G-11i** Good match overall	**Figure G-11j** Good match overall
(b) sub –orthogonal	45	45	**Figure G-11k** Good match overall, IWEM is slightly more conservative	**Figure G-11l** Good match overall

In this verification scenario, the multiple-strip IWEM model agrees reasonably well with the more accurate numerical MODHMS-based model. It can be seen that when the distortion is kept within the sub-orthogonal range, the IWEM-generated breakthrough curves agree reasonably well with the MODHMS-generated.

G.3.4 Verification Scenario 4: Multiple-Strip Roadway Source with Drainage Systems and Ditches

Normalized breakthrough curves for this case are shown in **Figures G-24** to **G-27**. In each figure, the IWEM-generated and the corresponding MODHMS-generated normalized breakthrough curves are compared. In this verification scenario, the IWEM-based multiple-strip model agrees reasonably well with the more accurate numerical MODHMS-based model. However, the IWEM-based model tends to be more conservative than the MODHMS-based model.

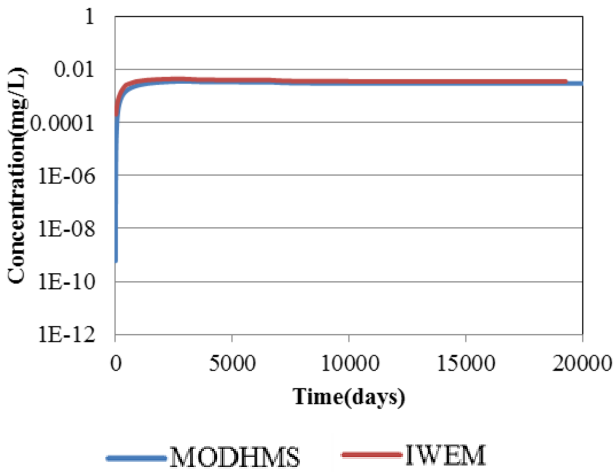

Figure G-24. Concentration at observation location 1.

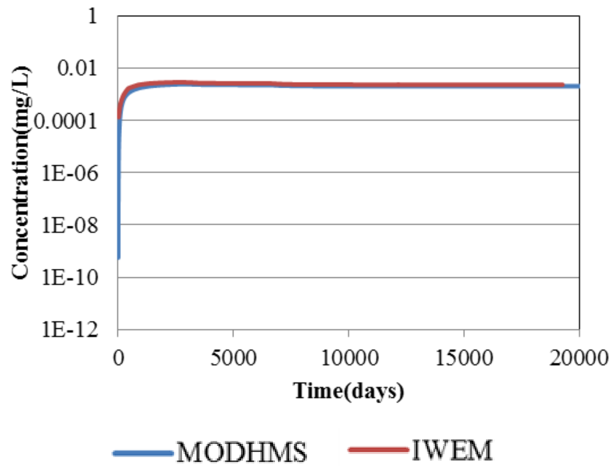

Figure G-25. Concentration at observation location 2.

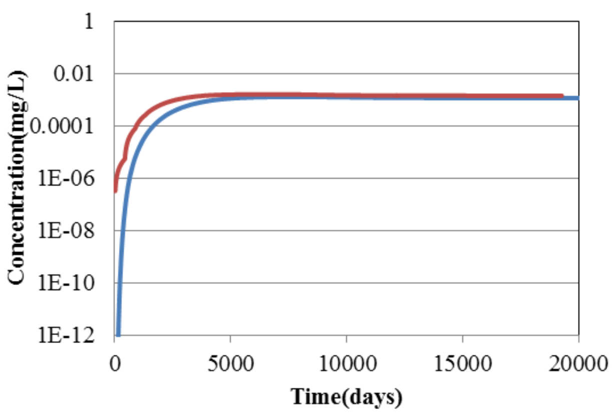

Figure G-26. Concentration at observation location 3.

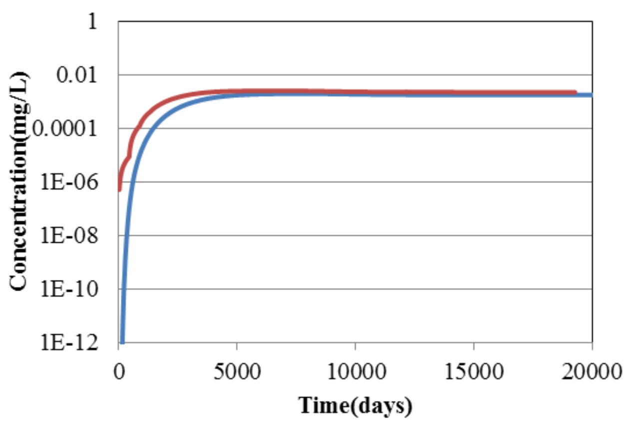

Figure G-27. Concentration at observation location 4.

G.4 Summary

The results reported in this appendix show that, in general, effects due to distortion (the use of non-orthogonal reference frame) is not significant if the conjugate angle of inclination is smaller than the theoretical maximum permissible value. The maximum permissible value is defined by the length and the width of the source, as well as a user-defined tolerance value. For the verification case, the maximum permissible angle based on the tolerance value of 0.1 is 45°. In many cases, the IWEM solutions tend to be slightly more conservative than the fully numerical counterpart (MODHMS). As the deviation from conjugate angle of inclination exceeds the maximum permissible value to sub-parallelism (2 approaches but is smaller than 90°), the difference between the IWEM and MODHMS solutions is expected to become increasingly more evident.

In order to ensure reasonably conservative estimates of the contaminant concentrations at receptor wells, in the event that *maximum permissible conjugate inclination angle* # α < 90° or α = 90°, the reader is referred to **Appendix F**.

G.5 References

McDonald, M.G., and A.W. Harbaugh, 1988. A modular three-dimensional finite difference groundwater flow model: U.S. Geological Survey Techniques of Water-Resources Investigations Book 6, chapter A1.

HGL (HydroGeoLogic). 2006. *MODHMS V 3: Documentation and Users Guide*.

RTI International and HGL (HydroGeoLogic). 2006. *IWEM with Highway Source Module IWEM Version 2.0*. Memorandum submitted to U.S. EPA, Office of Solid Waste, Washington, DC, October, 2006.

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