3.0 What Is The EPACMTP Model?

EPACMTP is a subsurface fate and transport model used by EPA to evaluate migration of waste constituents through the ground-water pathway from land disposal units to wells and establish protective levels in waste.

EPACMTP consists of four major components:

- A source module that simulates the rate and concentration of leachate exiting from beneath a WMU and entering the unsaturated zone;
- An unsaturated zone module which simulates 1-D vertical flow of water and dissolved constituent transport in the unsaturated zone;
- A saturated zone model which simulates ground-water flow and dissolved constituent transport in the saturated zone; and
- A Monte Carlo module for randomly selecting input values to account for the effect of variations in model parameters on predicted ground-water well concentrations, and determining the probability distribution of predicted ground-water concentrations.

Figure 3.1 depicts a cross-sectional view of the subsurface system simulated by EPACMTP. 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. EPACMTP simulates one-dimensional (1-D), vertically downward flow and transport of constituents in the unsaturated zone beneath a waste disposal unit as well as ground-water flow and three-dimensional (3-D) constituent transport in the underlying saturated zone. The unsaturated zone and saturated zone modules are computationally linked through continuity of flow and constituent concentration across the water table directly underneath the WMU. The model accounts for the following processes affecting constituent fate and transport: 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 primary input to the model is the rate of constituent release (leaching) from a WMU along with WMU design and site hydrogeological characteristics. The output from EPACMTP is a prediction of the constituent concentration arriving at a downgradient well. This can be either a steady-state concentration value, corresponding to a continuous source scenario, or a time-dependent concentration, corresponding to a finite source scenario. In the latter case, the model 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).

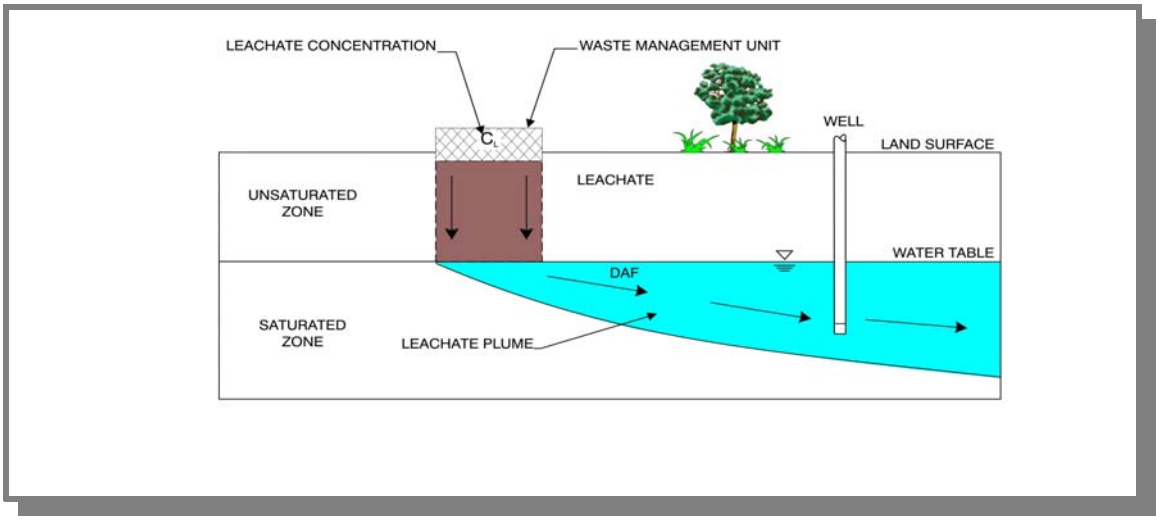

Figure 3.1 Conceptual Cross-Section View of the Subsurface System Simulated by EPACMTP.

The relationship between the constituent concentration leaching from a LF WMU and the resulting ground-water exposure at a well located down-gradient from the WMU is depicted in Figure 3.2. Figure 3.2a shows how the leachate concentration emanating from the LF unit gradually diminishes over time as a result of depletion of the waste mass remaining in the unit. As seen in Figure 3.2b, the constituent does not arrive at the at the well until some time after the leaching begins, but eventually the ground-water concentration will reach a peak value, and then begin to diminish because the leaching from the waste unit 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 concentration over a specified time period, as depicted by the horizontal dashed line in Figure 3.2b.

The following sections describe the four main components, or modules, of EPACMTP and the role of each in simulating constituent fate and transport.

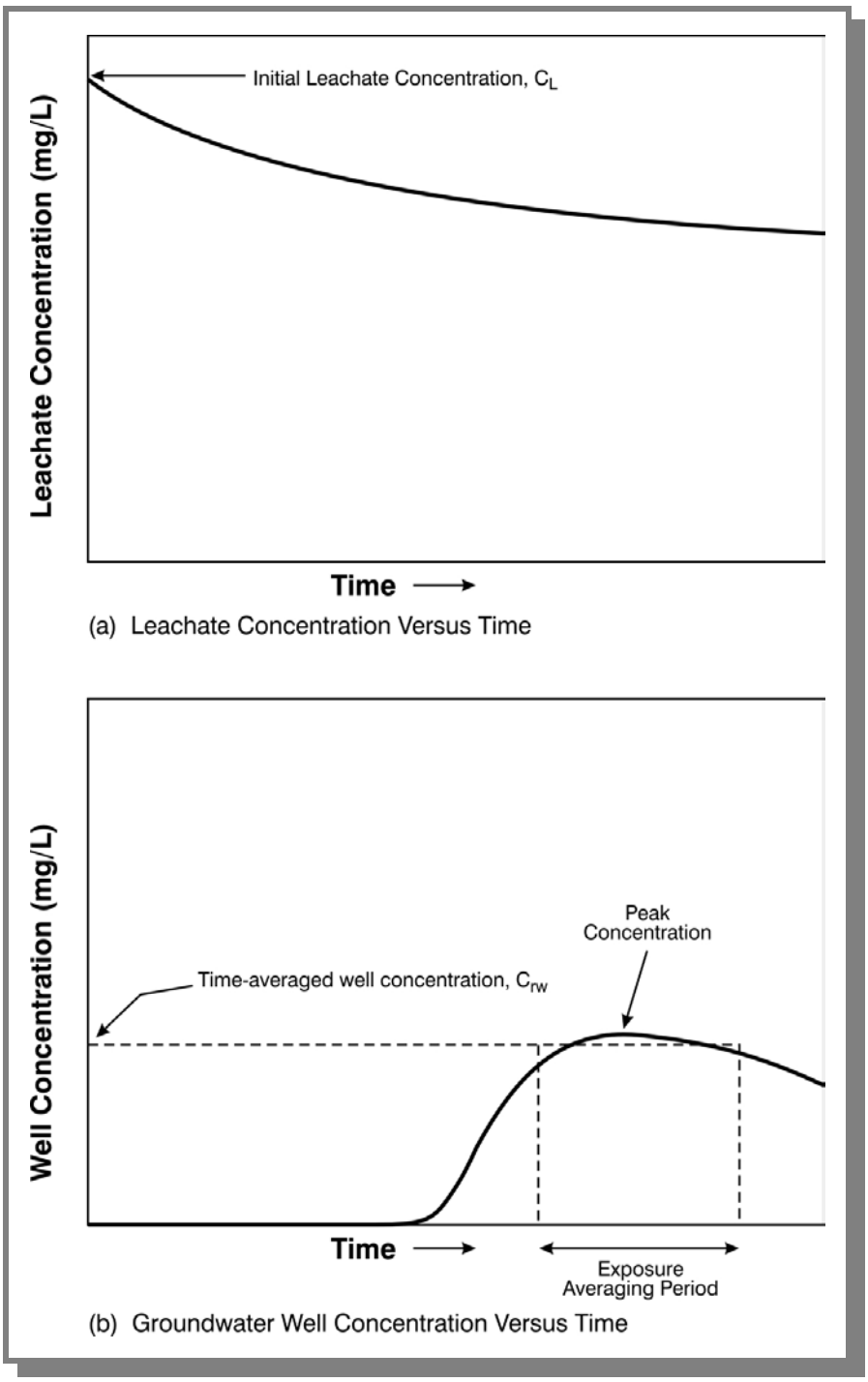

Figure 3.2 Conceptual Relationship Between Leachate Concentration (a) and Ground-Water Exposure Concentration (b).

3.1 WMU Source Module

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 SI units.

3.1.1 How EPACMTP Determines Releases From a Source

The purposes of the WMU source module in EPACMTP is to provide a leachate flux and concentration to the unsaturated zone. The source module is a function of both the design and operational characteristics of the WMU and the waste stream characteristics (quantity and concentrations) and is defined in terms of four primary parameters:

1) Area of the waste unit;
2) Leachate flux rate emanating from the waste unit (infiltration rate);
3) Constituent-specific leachate concentration; and
4) 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 well and the top of the unsaturated zone column, through which leachate passes. The WMU source module determines 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 result of these processes are used as inputs to the model. For instance, in developing the IWEM Tier 1 and Tier 2 evaluations for LFs, WPs, and LAUs, we used the Hydrologic Evaluation of LF Performance (HELP) model (Schroeder et al, 1994) to determine infiltration rates for unlined and single lined units outside of EPACMTP, and used these infiltration rates as inputs to EPACMTP. 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 (TCLP) or Synthetic Precipitation Leaching Procedure (SPLP) test; the resulting leachate concentration is then used as an EPACMTP input.

EPACMTP models the leaching process in one of two ways: 1) as a depleting source; or 2) as a pulse source. In the depleting source scenario, the WMU is considered permanent and leaching continues until all waste that is originally present has been depleted. In the pulse source scenario, leaching occurs at a constant leachate concentration for a fixed period of time, after which leaching stops[3]. EPACMTP uses the pulse source scenario to model temporary WMUs; usually the leaching period represents the operational life of the unit. Under this scenario, we assume clean closure conditions and the leaching stops when the unit is closed.

Figure 3.3 graphically presents the leachate concentration under the depleting source scenario and the pulse source scenario. 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, 2002a) provides a detailed discussion of the depleting source scenario. In the pulse source scenario, the user must provide the value of 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.

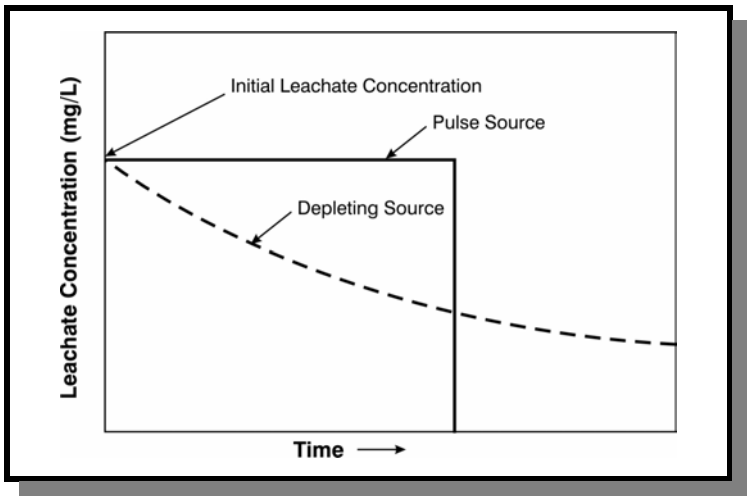

Figure 3.3 Leachate Concentration Versus Time for Pulse Source and Depleting Source Conditions.

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

3.1.2 How EPACMTP Determines Infiltration Rate for Surface Impoundments

Because the infiltration rate from SIs 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 SI infiltration rates as a function of impoundment depth and other SI parameters. In particular, the SI module calculates the infiltration rate through a zone of reduced permeability materials (which may or may not included engineered liners) at the base of the impoundment. The various reduced permeability layers represented in the SI infiltration module are depicted graphically in Figure 3.4.

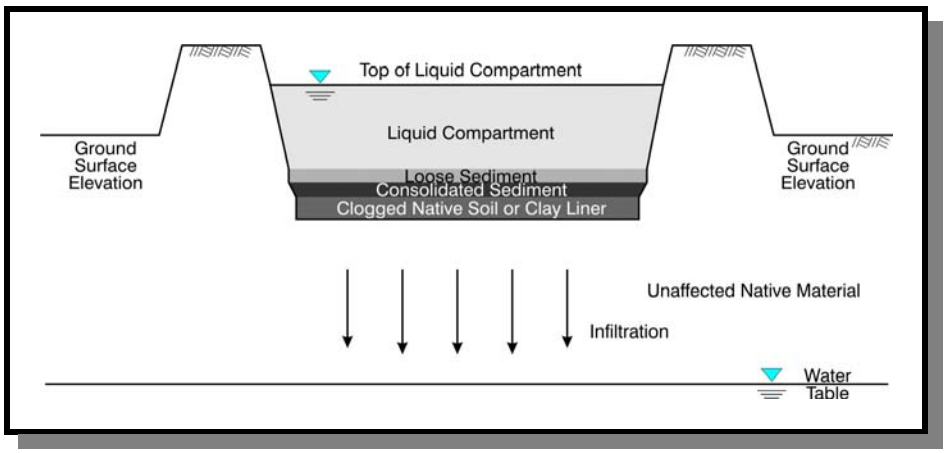

Figure 3.4 Surface Impoundment Infiltration Module.

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 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 meters, and the hydraulic conductivity of this clogged layer is assigned a value of 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 3.4. If EPACMTP is used to model a lined SI, the thickness and hydraulic conductivity of the clay liner are model inputs. The EPACMTP SI module calculates the steady state infiltration rate through the multi-layer system of sediment-clogged native soil/clay liner-native soil by applying the 1-D Richards equation (Jury et al., 1991) with a constant head boundary condition, given by the SI ponding depth. EPACMTP uses the Richards equation to accommodate partially saturated conditions which 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, 2002a).

3.2 EPACMTP Unsaturated Zone Module

EPACMTP models water flow and solute transport in the unsaturated zone between the base of the WMU and the water table as a 1-D, vertically downward process. As shown in Figure 3.1, constituents migrate downward from the WMU through the unsaturated zone to the water table. EPACMTP assumes the flow rate is steady-state, that is, it does not change in time. The soil underneath the WMU 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 WMU. Inputs to the unsaturated zone module are the rate of water and constituent leaching from the disposal facility, as well as soil hydraulic properties. EPACMTP solves the governing 1-D steady-state Richards flow equation (Jury et al., 1991) using a semi-numerical technique described in the *EPACMTP Technical Background Document* (U.S. EPA, 2002a).

Constituent transport in the unsaturated zone is assumed to occur by advection and dispersion[4]. The unsaturated zone is assumed to be initially constituent-free and constituents migrate vertically downward from the WMU. EPACMTP can simulate both steady-state and transient 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:

[4] 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.

$$\frac{\partial}{\partial z}\left(D\frac{\partial c}{\partial z}\right) - V\frac{\partial c}{\partial z} - \theta\lambda c = \theta R\frac{\partial c}{\partial t} + Q \qquad (3.1)$$

here

z = Soil depth coordinate (L),
t = Time (T),
c = Constituent concentration (M/L^3),
D = Dispersion coefficient, (L^2/T),
V = Darcy velocity (L/T),
R = Retardation factor (dimensionless),
λ = First-order decay constant (1/T),
θ = Volumetric water content (dimensionless), and
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 kilograms per cubic meter (kg/m^3).

The dispersion coefficient in the above transport equation accounts for the effects of hydrodynamic dispersion and molecular diffusion and is defined as:

$$D = \alpha V + D_m \qquad (3.2)$$

where

D = Dispersion coefficient (meter squared per year [m^2/yr])
α = Dispersivity (m)
D_m = Molecular diffusion coefficient (m^2/yr)
V = Darcy velocity (m/yr)

The effective molecular diffusion coefficient is calculated using the Millington-Quirk relationship (Jury et al., 1991) as:

$$D_m = D_w \theta^{10/3} / \theta^2 \qquad (3.3)$$

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 accounts for the effects of equilibrium sorption of dissolved constituents onto the solid phase as:

$$R = 1 + (\rho_b k_d) / \theta \quad (3.4)$$

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:

$$k_d = f_{oc} \times K_{oc} \quad (3.5)$$

where:

k_d = Partition coefficient (L^3/kg)
f_{oc} = Fraction organic carbon in the soil (dimensionless)
K_{oc} = Constituent-specific organic carbon partition coefficient (L/kg)

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 4.2.4.3.2).

The parameter λ in the transport equation accounts for first-order transformation processes. Finally, the term Q in the 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.

3.3 Saturated Zone Module

The saturated zone module of EPACMTP is designed to simulate flow and transport in an unconfined aquifer with constant saturated thickness (see Figure 3.1). The model simulates regional flow in a horizontal direction with recharge and infiltration from the overlying unsaturated zone and WMU entering at the water table. 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. EPACMTP accounts for different recharge rates beneath and outside the WMU 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 WMU due to high infiltration rates, and will restrict the allowable infiltration rate to prevent physically unrealistic input parameter combinations (see Section 4.2.6), the actual saturated flow and transport modules in EPACMTP are based on the assumption of a constant saturated thickness, i.e. fixed water table position, and the only direct effect of ground-water mounding is to increase simulated ground-water velocities.

EPACMTP incorporates a number of different mathematical solutions for saturated zone flow and transport. The *EPACMTP Technical Background Document* (U.S. EPA, 2002a) discusses these in detail. Because of the high premium on computational efficiency in the IWEM Tier 2 Monte Carlo tool, we used a pseudo-3-D modeling approach in IWEM. The pseudo-3-D module simulates ground-water flow using a 1-D 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 WMU. In the pseudo-3-D 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-D transport option is based on the concept that when ground-water flow is dominantly 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); 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-D solution option therefore requires about the same effort as a 1-D solution.

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

$$\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial}{\partial x_j}\right) - V_x\frac{\partial c}{\partial x} - \phi\lambda c = \phi R\frac{\partial c}{\partial t} + Q \qquad (3.6)$$

where

i,j	=	Indices to represent different spatial directions; i,j = 1, 2, or 3
x_i	=	Spatial coordinate (L)
t	=	Time (T)
c	=	Constituent concentration (M/L^3)
D_{ij}	=	Dispersion coefficient (L^2/T),
V_x	=	Ground-water flow rate in the x-direction (L/T)
λ	=	First-order transformation coefficient (1/T)
R	=	Retardation coefficient (dimensionless)
ϕ	=	Porosity (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 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 3.6 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-D option of EPACMTP, that ground-water flow is a 1-D process. The other terms in equation 3.6 are defined in the same way as in equation 3.1, 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 3.6 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.:

$$v_x = \frac{V_x}{\phi_e} \tag{3.7}$$

where

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

The total porosity, ϕ, is used in calculating the retardation coefficient, R:

$$R = 1 + \frac{\rho_b k_d}{\phi} \tag{3.8}$$

where

R	=	Retardation coefficient (dimensionless)
ρ_b	=	Saturated zone bulk density (kg/L)
k_d	=	Constituent-specific partition coefficient (L/kg)
ϕ	=	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 4.2.3.3.

The dispersion coefficient (D_{ij}) in equation 3.6 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, 2002a). 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.

3.4 Conducting Probabilistic Analyses Using EPACMTP

The final component of EPACMTP is a Monte Carlo module which allows the model to perform probabilistic analyses of constituent fate and transport. 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 well concentrations. In particular, we use Monte Carlo simulation to determine the likelihood, or probability, that the concentration of a constituent at a well, and hence exposure and risk, will be either above or below a certain 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, reflecting both the range of variation that may be encountered at different waste sites, as well as our uncertainty about the specific conditions at each site. Strictly speaking Monte Carlo analysis can accommodate only parameter variability, not uncertainty. Variability describes parameters whose values are not constant, but which we can measure and characterize with relative precision in terms of a frequency distribution. An example is annual rainfall in different parts of the country. Uncertainty pertains to parameters whose values we know only approximately, such as the hydraulic conductivity of an aquifer. In practice, we use probability distributions to describe both variability and uncertainty, and for the purpose of the EPACMTP Monte Carlo module, we treat them as more or less equivalent.

The Monte Carlo module in EPACMTP is described in detail in the *EPACMTP Technical Background Document (U.S. EPA, 2002a), and the EPACMTP Parameters/ Data Background Document (U.S. EPA, 2002b)*. A general overview of the methodology is presented in the following paragraphs. The specific methodology we used to determine LCTVs for IWEM is presented in Section 6 of this document.

Figure 3.5 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 3.5a). The method involves

EPACMTP Monte Carlo Bootstrap Analysis

In a Monte Carlo analysis the output percentile values depend on the number of realizations. For instance, if we perform a Monte Carlo analysis consisting of 10 realizations of randomly selected model input values, the 90th percentile of the model output can be determined by ordering the output values from low to high and then picking the 9th highest value. This 90th percentile value is likely to be different if we perform another Monte Carlo simulation of 10 realizations with randomly selected inputs, and different still if we simulate 1,000 realizations 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)* we conducted a bootstrap analysis 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 DAF was 10. The bootstrap analysis results suggested that, with 10,000 realizations, the expected value of the 90th percentile DAF was 10 with a 95 percent confidence interval of 10 ± 0.7. Decreasing the number of realizations to 5,000 increased the confidence interval to 10 ± 1.0.

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 (Figure 3.5b) is executed 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***. In using a Monte Carlo modeling approach, a higher number of realizations usually leads to a more stable and more accurate result. However, it is generally not possible to determine beforehand how many realizations 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 the appropriate number of realizations for EPACMTP Monte Carlo analyses (see side bar box).

At the conclusion of the Monte Carlo simulation, the realizations are statistically analyzed to yield a cumulative (probability) density function (CDF) of the ground-water exposure concentration (Figure 3.5c). The construction of the CDF 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 3.5, we assumed an EPACMTP input leachate concentration value of 10 mg/L and performed a Monte Carlo simulation of 10,000 realizations. 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 predicted ground-water concentration, it is possible to assign a probability to these high-end events, or conversely determine what is the expected ground-water concentration corresponding to a specific probability of occurrence.

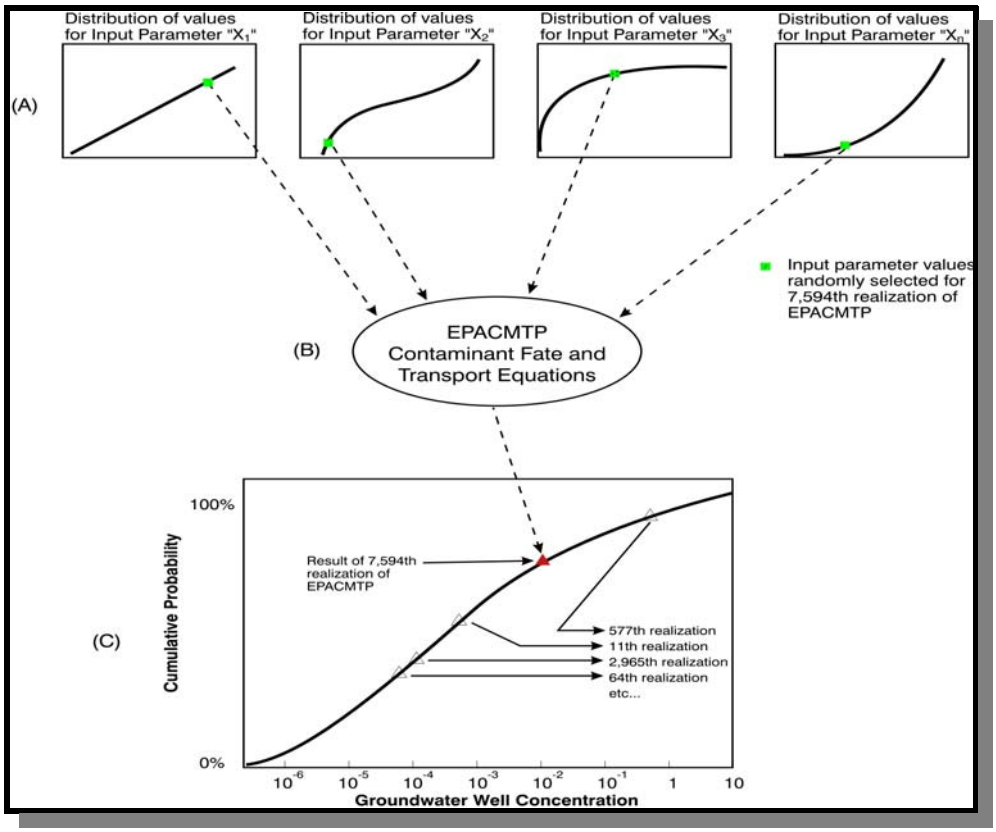

Figure 3.5 Graphical Representation of the EPACMTP Monte Carlo Process.

3.5 EPACMTP Assumptions and Limitations

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 and limitations of EPACMTP that EPA made in developing the model to balance these competing requirements. EPACMTP

may not be suitable for all sites, and the user should understand the capabilities and limitations of the model to ensure it is used appropriately.

Source Module

The EPACMTP source module provides a relatively simple representation of different types of WMU's. WMU's 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 SIs, EPACMTP assumes that the leachate concentration is the same as the constituent concentration in the waste water in the SI. 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 and release of leachate to vary over time.

Unsaturated Zone and Saturated Zone Modules

Uniform Soil and Aquifer Assumption

EPACMTP simulates the unsaturated zone and saturated zone as separate domains that are connected at the water table. Both the unsaturated zone and saturated zone 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.

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 in time or areally. 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 and lakes or ponds and man-made recharge sources near the WMU.

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. The implication is that the saturated zone can be modeled as having a uniform thickness, with mounding underneath the WMU 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 WMU, 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.

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 very 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 large contrast in permeability. 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. 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 soil or aquifer.

For metals, EPACMTP uses a set of effective sorption isotherms which were developed by EPA by running the MINTEQA2 geochemical speciation model 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 metals 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 in Tier 2 evaluations.

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 Tier 2 evaluations. 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.

Monte Carlo Module

The Monte Carlo module of EPACMTP allows you to take into account the effect of parameter variability on predicted 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 that results from processes that are not included in EPACMTP, or are modeled in EPACMTP in a simplified manner. 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 does not account for the uncertainty that results from treating each site as uniform and ignoring aquifer heterogeneity.