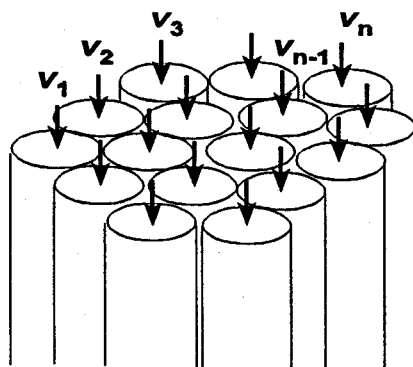


*The CXTFIT Code for Estimating Transport  
Parameters from Laboratory or Field  
Tracer Experiments*

Version 2.1



Research Report No. 137

April 1999

U. S. SALINITY LABORATORY  
AGRICULTURAL RESEARCH SERVICE  
U. S. DEPARTMENT OF AGRICULTURE  
RIVERSIDE, CALIFORNIA

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## DISCLAIMER

This report documents version 2.1 of CXTFIT (updated in November, 1998), a computer program for estimating solute transport parameters from observed concentrations (the inverse problem) or for predicting solute concentrations (the direct problem) using the convection-dispersion equation as the transport model. CXTFIT 2.1 is a public domain code, and as such may be used and copied freely. The code has been verified against a large number of test cases. However, no warranty is given that the program is completely error-free. If you do encounter problems with the code, find errors, or have suggestions for improvement, please contact one of the authors<sup>1</sup> at

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## ABSTRACT

N. Toride, F. J. Leij, and M. Th. van Genuchten. The CXTFIT Code for Estimating Transport Parameters from Laboratory or Field Tracer Experiments, Version 2.1 , Research Report No. 137, U. S. Salinity Laboratory, USDA, ARS, Riverside, CA.

The successful prediction of the fate and transport of solutes in the subsurface hinges on the availability of accurate transport parameters. We modified and updated the CXTFIT code of *Parker and van Genuchten* [1984b] for estimating solute transport parameters using a nonlinear least-squares parameter optimization method. The program may be used to solve the inverse problem by fitting mathematical solutions of theoretical transport models, based upon the convection-dispersion equation (CDE), to experimental results. This approach allows parameters in the transport models to be quantified. The program may also be used to solve the direct or forward problem to determine the concentration as a function of time and/or position. Three different one-dimensional transport models are included: (i) the conventional CDE; (ii) the chemical and physical nonequilibrium CDE; and (iii) a stochastic stream tube model based upon the local-scale CDE with equilibrium or nonequilibrium adsorption. The two independent stochastic parameters in the stream-tube model are the pore-water velocity,  $v$ , and either the dispersion coefficient,  $D$ , the distribution coefficient,  $K_d$ , or the nonequilibrium rate parameter,  $\alpha$ . These pairs of stochastic parameters were described with a bivariate lognormal probability density function (pdf). Examples are given on how transport parameters may be determined from laboratory or field tracer experiments for several types of initial and boundary conditions, as well as different zero-order production profiles. A detailed description is provided of the computer program, including the subroutines used to evaluate the analytical solutions for optimizing model parameters. Input and output files for all major problems are included in this manual.

**Keywords:** Solute transport, parameter estimation, convection-dispersion equation, analytical solutions, nonequilibrium transport, stochastic transport, stream tube model.



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## LIST OF SYMBOLS

$a$	constant in Goldstein's $J$ -function (Table 3.4)
$A$	area of a field [ $L^2$ ]
$A_k$	auxiliary functions for the nonequilibrium BVP (eqs. 3.21-3.24, $k = 1, 2$ )
$b$	constant in Goldstein's $J$ -function (Table 3.4)
$c$	volume-averaged or resident concentration of the liquid phase [ $ML^{-3}$ ]
$c_o$	characteristic concentration for dimensionless parameters used in Tables 2.1 and 3.1 [ $ML^{-3}$ ]
$c_o(t)$	time-dependent input concentration (eq. 4.6) [ $ML^{-3}$ ]
$c_i(x)$	position-dependent initial concentration (eq. 4.5) [ $ML^{-3}$ ]
$C_k^B$	dimensionless concentration of phase $k$ for the BVP ( $k = 1, 2$ )
$C_f$	dimensionless flux-averaged concentration (eq. 2.13)
$C$ or $C_r$	dimensionless resident concentration
$C_i(Z)$	dimensionless initial concentration (eq. 2.8)
$C_k^I$	dimensionless concentration of phase $k$ for the IVP ( $k = 1, 2$ )
$C_T$	dimensionless total resident concentration (eqs. 2.12 or 3.12)
$C_o(T)$	dimensionless time dependent input concentration (eq. 2.9)
$C_k^P$	dimensionless concentration of phase $k$ for the PVP ( $k = 1, 2$ )
CV	coefficient of variation (eq. 4.12)
$D$	dispersion coefficient [ $L^2T^{-1}$ ]
$D_m$	dispersion coefficient of the mobile liquid phase [ $L^2T^{-1}$ ]
$\text{erfc}(t)$	complementary error function; $\text{erfc}(t) = \frac{2}{\sqrt{\pi}} \int_0^t e^{-u^2} du$
$f$	fraction of exchange sites assumed to be at equilibrium for the two-site model (eq. 3.1); fraction of adsorption sites that equilibrates with the mobile liquid phase for the two-region model (eq. 3.3)
$f(\eta)$	probability density function (pdf) for $\eta$ (either $D$ , $K_d$ , or $\alpha$ ) defined by eq. 4.15
$f(v, \eta)$	joint probability density function (pdf) for $v$ and $\eta$ as defined by eq. 4.8
$f(Z, T)$	travel time probability density function for the nonequilibrium CDE defined by eq. 3.15
$f_i$	input concentrations for the BVP (eq. 2.19; $i = 1, 2, \dots, n$ )
$G_i^E$	auxiliary functions for equilibrium transport (Table 2.3, $i = 1, 2$ )
$G_1^N$	auxiliary functions for nonequilibrium transport (Table 3.3)
$H_i(\tau, T)$	auxiliary expressions with Bessel functions for nonequilibrium transport (Table 3.4; $i = 0, 1$ )
$I_0, I_1$	modified Bessel function of orders zero and one, respectively

$J$	Goldstein's $J$ -function (Table 3.4)
$J_w$	volumetric water flux density [ $LT^{-1}$ ]
$K_d$	distribution coefficient for linear adsorption [ $M^{-1}L^3$ ]
$L$	characteristic length (Tables 2.1 and 3.1) [ $L$ ]
$m_B$	amount of mass added to unit area of solution phase (eq. 2.16b or 4.22) [ $ML^{-2}$ ]
$m_I$	amount of mass present per unit soil area for a Dirac initial distribution (eq. 2.24b or 4.23) [ $ML^{-2}$ ]
$M_B$	dimensionless amount of applied solute for a Dirac input (eq. 2.16a or 3.16)
$M_I$	dimensionless amount of solute present per unit soil area for a Dirac initial distribution (eq. 2.24a or 3.33)
$p$	variable in nonequilibrium solution for exponential input function (eq. 3.30a)
$P$	Peclet number (Tables 2.1 and 3.1) [-]
$q$	variable in nonequilibrium solution for exponential input function (eq. 3.30b)
$R$	retardation factor (eq. 2.4, Tables 2.1 and 3.1) [-]
$s$	concentration of the adsorbed phase [ $MM^{-1}$ ]
$t$	time [ $T$ ]
$T$	dimensionless time (Tables 2.1 and 3.1)
$T_i$	dimensionless times for multiple pulse input (eq. 2.19; $i = 1, 2, \dots, n$ )
$U_i$	initial concentrations for the IVP (eq. 2.26; $i = 1, 2, \dots, n$ )
$v$	average pore-water velocity [ $LT^{-1}$ ]
Var[...]	variance (eqs. 4.20 or 4.21)
$x$	distance [ $L$ ]
$Y_v, Y_\eta$	variables in lognormal distribution (eq. 4.10)
$Z$	dimensionless distance (Tables 2.1 and 3.1)
$Z_i$	dimensionless distances for stepwise initial or production distribution (eq. 2.26 or 2.31; $i = 1, 2, \dots, n$ )
$Z_{k,i}$	dimensionless distances for stepwise production distribution in phase $k$ during nonequilibrium transport (eq. 3.36; $k = 1, 2$ ; $i = 1, 2, \dots, n$ )

## Greek

$\alpha$	first-order kinetic rate coefficient (eq. 3.1-3.4) [ $T^{-1}$ ]
$\beta$	dimensionless variable for partitioning in nonequilibrium transport models (Table 3.1)
$\gamma$	zero-order production term (eq. 2.6) [ $ML^{-3}T^{-1}$ ]
$\gamma^E$	dimensionless zero-order production terms for equilibrium transport (Table 2.1)
$\gamma_i$	dimensionless production constants for the PVP (eq. 2.31; $i = 1, 2, \dots, n$ )
$\gamma_k$	dimensionless zero-order production terms for nonequilibrium transport (Table 3.1)
$\gamma_{k,i}$	dimensionless production constants for the PVP in phase $k$ (eq. 3.45; $k = 1, 2$ ; $i = 1, 2, \dots, n$ )
$\gamma_\ell$	zero-order production term for the liquid phase (eqs. 3.1 and 4.1; Table 3.1) [ $ML^{-3}T^{-1}$ ]
$\gamma_{\ell,m}, \gamma_{\ell,im}$	zero-order production term for the mobile and immobile liquid phases, respectively (Table 3.1) [ $ML^{-3}T^{-1}$ ]
$\gamma_s$	zero-order production term for the adsorbed phase (eq. 4.2) [ $MM^{-1}T^{-1}$ ]
$\gamma_{s,e}$	zero-order production term for the equilibrium adsorbed phase (eq. 3.1) [ $MM^{-1}T^{-1}$ ]
$\gamma_{s,k}$	zero-order production term for the kinetically adsorbed phase (eq. 3.2) [ $MM^{-1}T^{-1}$ ]
$\gamma_{s,m}$	zero-order production term for the mobile adsorbed phase (eq. 3.3) [ $ML^{-3}T^{-1}$ ]
$\gamma_{s,m}, \gamma_{s,im}$	zero-order production term for the immobile adsorbed phase (eq. 3.4) [ $ML^{-3}T^{-1}$ ]
$\Gamma(n)$	Gamma function; $\Gamma(n) = \int_0^\infty u^{n-1} e^{-u} du$
$\Gamma_i^E$	auxiliary functions for equilibrium transport (Table 2.2; $i = 1, 2$ )
$\Gamma_i^N$	auxiliary functions for nonequilibrium transport (Table 3.2; $i = 1, 2$ )
$\delta$	Dirac delta function (eq. 2.16 or 2.24)
$\theta$	volumetric water content (eq. 2.1) [ $L^3L^{-3}$ ]
$\theta_m, \theta_{im}$	volumetric water contents of mobile and immobile liquid phases (eq. 3.3 and 3.4; $\theta = \theta_m + \theta_{im}$ ) [ $L^3L^{-3}$ ]
$\lambda$	dispersivity eq. 4.25 [ $L$ ]
$\lambda^B$	dimensionless constant for exponential input (eqs. 2.21 and 3.25)
$\lambda^I$	dimensionless constant for exponential initial distribution (eqs. 2.28 and 3.39)
$\lambda^P$	dimensionless constant for exponential production profile (eq. 2.35)
$\lambda_k^P$	dimensionless constant for exponential production profile in phase $k$ (eq. 3.49; $k = 1, 2$ )
$\mu_v, \mu_\eta$	mean of logtransformed $v$ and $\eta$ ( $D$ , $K_d$ or $\alpha$ ), respectively
$\mu$	first-order decay coefficient (eq. 2.5) [ $T^{-1}$ ]
$\mu^E$	dimensionless first-order decay coefficient for equilibrium transport (Table 2.1)
$\mu_k$	dimensionless first-order decay coefficient for phase $k$ (Table 3.1; $k = 1, 2$ )
$\mu_{\ell,m}, \mu_{\ell,im}$	first-order decay coefficients for the mobile and immobile liquid phases, respectively (eqs. 3.3 and 3.4) [ $T^{-1}$ ]



$\mu_\ell$	first-order decay coefficient for the liquid phase (eq. 3.1) [ $T^{-1}$ ]
$\mu_s$	first-order decay coefficient for the adsorbed phase (eq. 4.2) [ $T^{-1}$ ]
$\mu_{s,m}, \mu_{s,im}$	first-order decay coefficients for the mobile and immobile adsorbed phases, respectively (eqs. 3.3 and 3.4) [ $T^{-1}$ ]
$\mu_{s,e}, \mu_{s,k}$	first-order decay coefficient for phase with equilibrium and kinetic adsorption, respectively (eqs. 3.1 and 3.2) [ $T^{-1}$ ]
$\rho_b$	bulk density (2.1) [ $ML^{-3}$ ]
$\rho_{v\eta}$	correlation coefficient between $Y_v$ and $Y_\eta$ (eq. 4.11; $\eta = D, K_d$ , or $\alpha$ )
$\sigma_v, \sigma_\eta$	standard deviation of the logtransform of $v$ and $\eta$ , respectively (eq. 4.9; $\eta = D, K_d$ , or $\alpha$ )
$\phi_m$	fraction of mobile water (Table 3.5) [-]
$\Phi_k$	auxiliary functions in solution for nonequilibrium transport involving an exponential input (eqs. 3.28 and 3.29; $k = 1, 2$ )
$\psi_i^E$	auxiliary functions for equilibrium transport (Table 2.2; $i = 1, 2$ )
$\psi_i^N$	auxiliary functions for nonequilibrium transport (Table 3.2; $i = 1, 2$ )
$\omega$	dimensionless mass transfer coefficient (Table 3.1)

### Subscripts

$D$	stochastic dispersion coefficient
$e$	equilibrium
$f$	flux-averaged
$im$	immobile phase
$k$	kinetic
$Kd$	stochastic distribution coefficient
$\ell$	liquid phase
$m$	mobile phase
$r$	resident (volume averaged)
$s$	adsorbed phase
$T$	total (resident)
$v$	stochastic pore-water velocity
$\alpha$	stochastic first-order kinetic rate coefficient
$\eta$	stochastic transport parameter ( $D, K_d$ , or $\alpha$ )
1	phase 1 (equilibrium phase)
2	phase 2 (nonequilibrium phase)

### **Superscripts**

<i>B</i>	boundary value problem
<i>E</i>	equilibrium
<i>I</i>	initial value problem
<i>N</i>	nonequilibrium
<i>P</i>	production value problem

### **Special Symbols**

$\langle \dots \rangle$	ensemble average (eq. 4.11)
$\hat{\phantom{x}}$	field-scale concentration defined by (eq. 4.16)

### **Abbreviations**

CDE	convection-dispersion equation
BTC	breakthrough curve
BVP	boundary value problem
EC	electrical conductivity
IVP	initial value problem
pdf	probability density function
PVP	production value problem
TDR	time-domain reflectometry



# 1. INTRODUCTION

The fate and movement of dissolved substances in soils and groundwater has generated considerable interest out of concern for the quality of the subsurface environment. The behavior of solutes over relatively long spatial and temporal scales has to be assessed with the help of theoretical models since it is usually not feasible to carry out experimental studies over sufficiently long distances and/or time periods. Mathematical models are often used to predict solute concentrations before management strategies are implemented. Advances in software and hardware now permit the simulation of subsurface transport using sophisticated mathematical models. Unfortunately, it is generally difficult to obtain reliable values for transport parameters such as the pore-water velocity, the retardation factor, the dispersion coefficient, and degradation or production parameters.

The program CXTFIT 2.1 may be used to estimate parameters in several models for transport during steady one-dimensional flow by fitting the parameters to observed laboratory or field data obtained from solute displacement experiments. The inverse problem is solved by minimizing an objective function, which consists of the sum of the squared differences between observed and fitted concentrations. The objective function is minimized using a nonlinear least-squares inversion method according to *Marquardt* [1963]. In addition, CXTFIT 2.1 may also be used for the direct problem to predict solute distributions versus time and/or space for specified model parameters.

CXTFIT 2.1 is an extension and update of an earlier version program published more than ten years ago by *Parker and van Genuchten* [1984b]. The new CXTFIT, version 2.1, again uses the convection-dispersion equation, but with a greater number of analytical solutions to various initial, boundary, and production value problems. The nonequilibrium transport models now contains also terms for zero-order production and first-order decay. Considerably more attention is being paid to the use of stream tube models for simulating transport in heterogenous fields, thus reflecting the growing popularity of stochastic approaches for modeling field-scale solute transport. A bivariate lognormal probability density function is used to quantify stochastic flow and either stochastic dispersion, adsorption, or nonequilibrium solute transfer. Solute concentrations across the field can be in the resident mode or in two different types of flux-averaged modes.

This report serves to document the CXTFIT 2.1 computer program. Equilibrium transport according to the convection-dispersion equation (CDE) is reviewed in Chapter 2. The mathematical

problem is first stated, and solutions for the initial value problem (IVP), the boundary value problem (BVP), and the production value problem (PVP) are listed. The program may be used to estimate the pore-water velocity ( $v$ ), the dispersion coefficient ( $D$ ), the retardation factor ( $R$ ), the first-order degradation coefficient ( $\mu$ ), and/or the zero-order production coefficient ( $\gamma$ ) from observed concentration distributions versus time and/or distance. Nonequilibrium transport is discussed in Chapter 3 in terms of alternative physical and chemical nonequilibrium models. Solutions of the (bimodal) dimensionless nonequilibrium transport equation are presented for the same cases as for equilibrium transport. In addition to  $v$ ,  $D$ ,  $R$ ,  $\mu$ , and  $\gamma$ , the coefficient of partitioning between the equilibrium and nonequilibrium phases ( $\beta$ ) and the mass transfer coefficient ( $\omega$ ) for transfer between the two phases can now be fitted as well. Chapter 4 describes the stream tube model as a relatively simple conceptualization of solute transport in heterogeneous fields. Transport in each stream tube (the local scale) is described with the CDE as an initial or a boundary value problem. Pairs of stochastic parameters, one always being  $v$ , are used in solutions of the CDE. Transport at the field scale is subsequently modeled by averaging the local concentrations.

Chapter 5 provides details about the numerical evaluation of some of the analytical functions, including the numerical integration procedures. This chapter also gives an outline of the parameter estimation procedure. Chapter 6 serves as user's guide for the program. This chapter lists all available transport models and gives instructions on how to solve the inverse problem. All possible variables in the input file are documented in terms of separate blocks. The blocks pertain to model selection, solution of the inverse problem, definition of transport parameters, stipulation of boundary, initial, as well as production conditions, and specification of times and positions for which the direct problem is to be solved. Examples of input and output files are also provided. The examples are those given on the diskette accompanying this manual. Finally, Chapter 7 illustrates the use of CXTFIT 2.1 for several forward and inverse problems.

## 2. DETERMINISTIC EQUILIBRIUM CDE

### 2.1. Transport Model

The convection-dispersion equation (CDE) for one-dimensional transport of reactive solutes, subject to adsorption, first-order degradation, and zero-order production, in a homogeneous soil, is written as

$$\frac{\partial}{\partial t}(\theta c_r + \rho_b s) = \frac{\partial}{\partial x} \left( \theta D \frac{\partial c_r}{\partial x} - J_w c \right) - \theta \mu_l c_r - \rho_b \mu_s s + \theta \gamma_l(x) + \rho_b \gamma_s(x) \quad (2.1)$$

where  $c_r$  is the volume-averaged or resident concentration of the liquid phase ( $\text{ML}^{-3}$ ),  $s$  is the concentration of the adsorbed phase ( $\text{MM}^{-1}$ ),  $D$  is the dispersion coefficient ( $\text{L}^2\text{T}^{-1}$ ),  $\theta$  is the volumetric water content ( $\text{L}^3\text{L}^{-3}$ ),  $J_w$  is the volumetric water flux density ( $\text{LT}^{-1}$ ),  $\rho_b$  is the soil bulk density ( $\text{ML}^{-3}$ ),  $\mu_l$  and  $\mu_s$  are first-order decay coefficients for degradation of the solute in the liquid and adsorbed phases, respectively ( $\text{T}^{-1}$ );  $\gamma_l$  ( $\text{ML}^{-3}\text{T}^{-1}$ ) and  $\gamma_s$  ( $\text{MM}^{-1}\text{T}^{-1}$ ) are zero-order production terms for the liquid and adsorbed phases, respectively;  $x$  is distance (L), and  $t$  is time (T). We assume that  $\mu$  cannot be negative. Note that the production functions are given as a function of distance.

Solute adsorption by the solid phase is described with a linear isotherm as

$$s = K_d c_r \quad (2.2)$$

where  $K_d$  is an empirical distribution constant ( $\text{M}^{-1}\text{L}^3$ ). Using (2.2) and assuming steady-state flow in a homogeneous soil, (2.1) may be rewritten as

$$R \frac{\partial c_r}{\partial t} = D \frac{\partial^2 c_r}{\partial x^2} - v \frac{\partial c_r}{\partial x} - \mu c_r + \gamma(x) \quad (2.3)$$

where  $v$  ( $= J_w / \theta$ ) is the average pore-water velocity,  $R$  is the retardation factor given by

$$R = 1 + \frac{\rho_b K_d}{\theta} \quad (2.4)$$

and  $\mu$  and  $\gamma$  are combined first- and zero-order rate coefficients:

$$\mu = \mu_l + \frac{\rho_b K_d \mu_s}{\theta} \quad (2.5)$$

$$\gamma(x) = \gamma_l(x) + \frac{\rho_b \gamma_s(x)}{\theta} \quad (2.6)$$

Note that when the first-order degradation coefficients in the liquid ( $\mu_l$ ) and adsorbed ( $\mu_s$ ) phases are identical, (2.5) reduces to  $\mu = \mu R$  (Section 4.1).

Table 2.1 lists the dimensionless parameters that allow (2.3) to be written in reduced form as

$$R \frac{\partial C_r}{\partial T} = \frac{1}{P} \frac{\partial^2 C_r}{\partial Z^2} - \frac{\partial C_r}{\partial Z} - \mu^E C_r + \gamma^E(Z) \quad (2.7)$$

where  $C_r$  is the reduced volume-averaged solute concentration,  $P$  is the Peclet number,  $\mu^E$  is a first-order decay coefficient ( $= L\mu/v$ ),  $\gamma^E$  is a zero-order production coefficient for equilibrium transport ( $= L\gamma/vc_o$ ), and  $Z$  and  $T$  are the dimensionless space and time variables, respectively.

Table 2.1. Dimensionless Parameters for the Equilibrium CDE†

Parameters	$T$	$Z$	$P$	$R$	$C$	$\mu^E$	$\gamma^E$
Expressions	$\frac{vt}{L}$	$\frac{x}{L}$	$\frac{vL}{D}$	$1 + \frac{\rho_b K_d}{\theta}$	$\frac{c}{c_o}$	$\frac{L(\theta\mu_l + \rho_b K_d \mu_s)}{\theta v}$	$\frac{L(\theta\gamma_l + \rho_b \gamma_s)}{\theta v c_o}$

†  $c_o$  and  $L$  represent a characteristic concentration and length, respectively.

## 2.2. Analytical Solutions

Solutions of the CDE will be presented in terms of the above dimensionless parameters. Dimensional solutions can be easily obtained by substituting the parameters listed in Table 2.1 back into the dimensionless solutions.

### Resident Concentration

Analytical solutions of (2.7) are included in CXTFIT 2.1 for relatively simple initial and boundary conditions. The general initial condition is given by

$$C_r(Z, 0) = C_i(Z) \quad (2.8)$$

where  $C_i$  is the initial concentration as a function of  $Z$ . Either a first- or a third-type condition is used for the inlet boundary, i.e.,

$$C_r(0, T) = C_o(T) \quad (2.9a)$$

or

$$C_r(0, T) - \frac{1}{P} \frac{\partial C_r(0, T)}{\partial Z} = C_o(T) \quad (2.9b)$$

where  $C_o$  is the input concentration as a function of  $T$ . The third-type boundary condition (2.9b) in terms of dimensional parameters is given as

$$v c_r(0, t) - D \frac{\partial c_r(0, t)}{\partial x} = v c_o(t) \quad (2.10)$$

where  $c_o(t)$  represents a dimensional concentration that depends on real time,  $t$ . We will present solutions for both first- and third-type inlet conditions. Note that a third-type inlet condition is to be preferred for most transport scenarios since it conserves mass if we ignore dispersion outside the soil [van Genuchten and Parker, 1984; Parker and van Genuchten, 1984a; van Genuchten and Parker, 1994].

The outlet condition for an effectively semi-infinite system is given by

$$\frac{\partial C_r}{\partial Z}(\infty, T) = 0 \quad (2.11a)$$

Although no "correct" outlet condition can probably be formulated for finite systems [Parlange *et al.*, 1992], a zero concentration gradient is often used for a finite system of length  $L$ :

$$\frac{\partial C_r}{\partial Z}(1, T) = 0 \quad (2.11b)$$

This condition is based on the assumption that the concentration is macroscopically continuous at the outlet and that no dispersion occurs outside the soil [Danckwerts, 1953; Wehner and Wilhelm, 1956]. Solutions for an infinite outlet condition can be applied to the finite region  $0 \leq x \leq L$  by making the assumption that upstream solute concentrations are not affected by the outlet boundary [Parker and van Genuchten, 1984a]. All solutions in this report are based on the infinite outlet condition (2.11a).

In addition to the resident solution concentration, we define the total resident concentration as the amount of solute per unit volume of soil solution:

$$C_T = R C_r \quad (2.12)$$



### ***Flux-Averaged Concentration***

The injection and detection modes for several solute displacement experiments may require the use of flux-averaged or flowing concentrations in the mathematical model [Kreft and Zuber, 1978; Parker and van Genuchten, 1984a]. Flux-averaged concentrations are defined as the ratio of the solute and water fluxes; they occur, for example, if a solute breakthrough curve is determined from effluent samples. The specification of the type of concentration is discussed in Chapter 7.

For transport according to the CDE, the flux-averaged concentration can be obtained from the resident concentration using the transformation:

$$C_f = C_r - \frac{1}{P} \frac{\partial C_r}{\partial Z} \quad (2.13)$$

where the subscript  $f$  refers to a flux-averaged concentration. Expressions for  $C_f$  are easily derived by substituting the solution for  $C_r$  for a third-type inlet condition into (2.13). We may drop the subscript of  $C$  if the difference between the two concentration modes is immaterial or if it is clear that we refer to a resident concentration.

### ***Superposition***

Since the governing equations and the initial and boundary conditions are linear in  $C$ , the superposition principle — as explained, for example, in Farlow [1982] — may be used to express the analytical solution as the sum of three independent subproblems involving a boundary value problem (BVP), an initial value problem (IVP), and a production value problem (PVP). The overall solution can then be written as

$$C(Z,T) = C^B(Z,T) + C^I(Z,T) + C^P(Z,T) \quad (2.14)$$

where the superscripts  $B$ ,  $I$  and  $P$  denote the boundary, initial, and production value problems, respectively. We first present the general solution to each subproblem, subsequently we give several specific solutions.

### 2.2.1. Boundary Value Problem (BVP)

#### General Solution

The general solution of the BVP is given by

$$C^B(Z, T) = \int_0^T C_o(T - \tau) \Gamma_1^E(Z, \tau) d\tau \quad (2.15)$$

where the auxiliary function  $\Gamma_1^E$  is defined in Table 2.2. Note that  $\Gamma_1^E$  is identical for  $C_f$  and  $C_r$  if a first-type inlet condition is used. General expression (2.15) will be used to obtain specific solutions for an input concentration,  $C_o(T)$ , given by Dirac delta, multiple pulse, and exponential functions.

#### Specific Solution

**1. Dirac Delta Input.** For instantaneous solute application,  $C_o(T)$  may be written as

$$C_o(T) = M_B \delta(T) \quad (2.16a)$$

where  $\delta(T)$  is the Dirac delta (unit impulse) function, and  $M_B$  is a dimensionless amount of applied solute. A dimensional Dirac delta input may be given by

$$c_o(t) = \frac{m_B}{v} \delta(t) \quad (2.16b)$$

where  $\delta(t)$  is a Dirac function with respect to  $t$  ( $T^{-1}$ ), and  $m_B$  is the total amount of mass added to a unit area of the soil liquid phase ( $ML^{-2}$ ). The dimensional and dimensionless Dirac inlet conditions are related as  $\delta(T) = L\delta(t)/v$ , with  $M_B = m_B/(Lc_o)$ . The following properties of the Dirac delta function were used to evaluate the general solution:

$$\int_0^\infty \delta(t) dt = 1 \quad (2.17a)$$

and, for any continuous function  $G(t)$ ,

$$\int_0^\infty \delta(t) G(t) dt = G(0) \quad (2.17b)$$

$$\int_0^\infty \delta(t - a) G(t) dt = G(a) \quad (2.17c)$$

Substitution of (2.16a) into (2.15) leads to

$$C^B(Z, T) = M_B \Gamma_1^E(Z, T) \quad (2.18)$$

This solution is sometimes referred to as the travel time probability density function (pdf) for the equilibrium CDE [Jury and Roth, 1990].

**2. Multiple Pulse Input Conditions.** The input concentration for a series of successive applications of rectangular (constant) solute pulses, as illustrated in Figure 2.1, can be expressed as

$$C_o(T) = f_i \quad T_i \leq T < T_{i+1} \quad (2.19)$$

( $i=1, 2, \dots, n$ ;  $T_1=0$  and  $T_{n+1} \rightarrow \infty$ )

where  $f_i$  ( $i = 1, 2, \dots, n$ ) is constant. The analytical solution for this case may be written as the following sum of the solutions for the individual pulses:

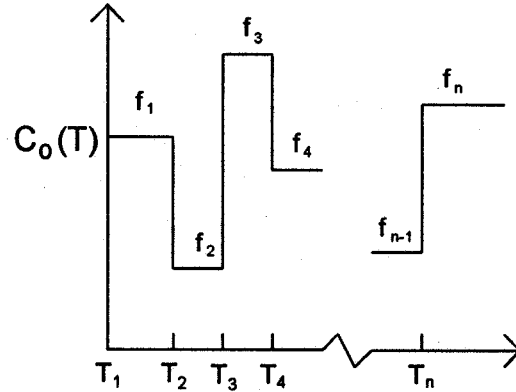


Figure 2.1. Multiple pulse input.

$$C^B(Z, T) = \sum_{j=1}^i (f_j - f_{j-1}) G_1^E(Z, T - T_j; \mu^E) \quad (i = 1, 2, \dots, n; f_0 = 0) \quad (2.20)$$

where  $G_1^E(Z, T; \mu^E)$  is listed in Table 2.3. Note that the formulations for  $G_1^E(Z, T; \mu^E)$  for  $\mu^E = 0$  and  $\mu^E \neq 0$  are different [van Genuchten and Alves, 1982].

**3. Exponential Input Function.** The exponential input concentration function is given by

$$C_o(T) = f_1 + f_2 \exp(-\lambda^B T) \quad (2.21)$$

where  $f_1, f_2$ , and  $\lambda^B$  are constants. Substitution of (2.21) into (2.15), and integration, yields

$$C^B(Z, T) = f_1 G_1^E(Z, T; \mu^E) + f_2 \exp(-\lambda^B T) G_1^E(Z, T; \mu^E - R\lambda^B) \quad (2.22)$$

where  $G_1^E(Z, T; \Omega)$  is again given in Table 2.3. In this solution, a distinction needs to be made between  $\Omega = 0$  (i.e.,  $\mu^E = R\lambda^B$ ) and  $\Omega \neq 0$ . Furthermore, when  $\lambda^B > (\mu^E + P/4)/R$ , it is necessary to evaluate the general expression for  $G_1^E(Z, T)$  numerically since the parameter  $u$  in Table 2.3 becomes complex. CXTFIT 2.1 internally selects the appropriate expression for  $G_1^E(Z, T)$ .

### 2.2.2. Initial Value Problem (IVP)

#### General Solution

The general solution of the IVP is given by

$$C^I(Z, T) = \int_0^{\infty} C_i(\eta) \Gamma_2^E(Z, \eta, T) d\eta \quad (2.23)$$

where  $\Gamma_2^E(Z, \eta, \tau)$  is listed in Table 2.2. Specific solutions of the IVP are obtained for the same type of  $C_i(Z)$  functions as for  $C_o(T)$  in the BVP as discussed in the previous section, i.e., Dirac delta, stepwise, and exponential initial distributions.

#### Specific Solution

1. **Dirac Delta Initial Distribution.** When all of the solute is initially located at position  $Z = Z_1$ , the initial concentration distribution  $C_i(Z)$  may be written as

$$C_i(Z) = M_I \delta(Z - Z_1) \quad (2.24a)$$

where  $\delta(Z)$  is the Dirac delta function, and  $M_I$  is a relative amount of solute in the liquid phase. For a dimensional distance,  $x$ , the Dirac initial condition may be given by

$$c_i(x) = \frac{m_I}{\theta} \delta(x - x_1) \quad (2.24b)$$

where  $\delta(x)$  is the Dirac function with respect to  $x$  [ $L^{-1}$ ], and  $m_I$  is the amount of mass initially present in the liquid phase per unit area of soil [ $ML^{-2}$ ] at  $x = x_1$ . The total amount of mass per unit soil area is given by  $m_I R$ . Dimensional and dimensionless initial conditions are related according to  $\delta(Z) = L\delta(x)$  with  $M_I = m_I/(\theta L c_o)$ . Substitution of (2.24a) into (2.23) yields

$$C^I(Z, T) = M_I \Gamma_2^E(Z, Z_1, T) \quad (2.25)$$

Notice that for a third-type inlet condition, the resident concentration according to (2.25) for  $Z_1 = 0$  in (2.24a) — i.e., solutes reside initially at the soil surface — is identical to solution (2.18) for the BVP with a Dirac input since  $\Gamma_1^E(Z, T) = \Gamma_2^E(Z, Z_1=0, T)$  in Table 2.2.

**2. Stepwise Initial Distribution.** A stepwise initial concentration distribution, consisting of  $n$  step functions, may be written in the form where

$$C_i(Z) = U_i \quad Z_i \leq Z < Z_{i+1} \quad (2.26)$$

( $i=1,2,\dots,n$ ;  $Z_1=0$  and  $Z_{n+1} \rightarrow \infty$ )

$U_i$  is a constant. Figure 2.2 shows an example of such a stepwise initial concentration distribution. The analytical solution can again be written as the sum of solutions of the IVP for a single pulse:

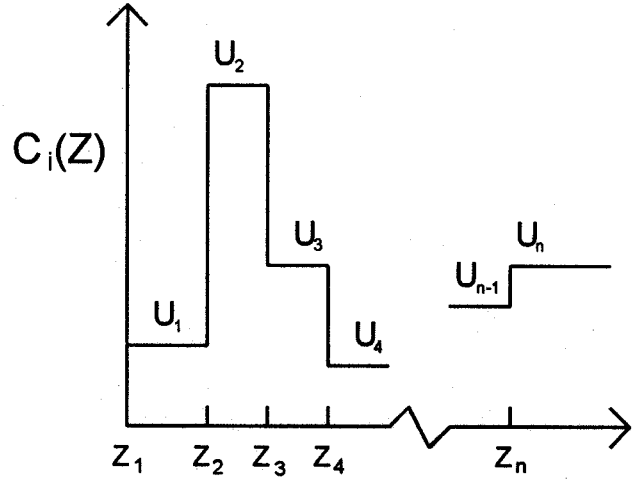


Figure 2.2. Stepwise initial distribution.

$$C^I(Z,T) = \sum_{i=1}^n (U_i - U_{i-1}) \psi_1^E(Z,T;Z_i) \quad (i=1,2,\dots,n; U_0=0) \quad (2.27)$$

where  $\psi_1^E$  is listed in Table 2.2 [cf. A5 and A6 of *van Genuchten and Alves*, 1982]. For a uniform initial concentration (i.e.,  $n=1$ ;  $C_i=U_1$  for  $0 \leq Z < \infty$ ), the expression for  $C_f$  is identical to that of  $C_r$  for a first-type inlet condition [*Parker and van Genuchten*, 1984b; *Toride et al.*, 1993a, 1993b].

**3. Exponential Initial Distribution.** The IVP can also be solved for an initial condition that changes exponentially with distance:

$$C_i(Z) = U_1 + U_2 \exp(-\lambda^I Z) \quad (2.28)$$

where  $U_1$ ,  $U_2$ , and  $\lambda^I$  are constants. The specific solution for this condition is given by [cf. A7 and A8 of *van Genuchten and Alves*, 1982]:

$$C^I(Z,T) = U_1 \psi_1^E(Z,T;0) + U_2 \psi_2^E(Z,T;\lambda^I) \quad (2.29)$$

where  $\psi_1^E$  and  $\psi_2^E$  are listed in Table 2.2.

### 2.2.3. Production Value Problem (PVP)

#### General Solution

The solution for a depth-dependent production,  $\gamma(Z)$ , is [Lindstrom and Boersma, 1989]:

$$C^P(Z, T) = \frac{1}{R} \int_0^T \int_0^\infty \gamma^E(\eta) \Gamma_2^E(Z, \eta, \tau) d\eta d\tau \quad (2.30)$$

where  $\Gamma_2^E$  is listed in Table 2.2. This solution is quite similar as (2.23) for the IVP. Specific solutions of the PVP for stepwise and exponential profiles can be obtained by integrating with respect to time.

#### Specific Solution

**1. Stepwise Production Profile.** Solute production having a distribution of  $n$  distinct steps is given as

$$\gamma^E(Z) = \gamma_i \quad Z_i \leq Z < Z_{i+1} \quad (i = 1, 2, \dots, n; Z_1 = 0 \text{ and } Z_{n+1} \rightarrow \infty) \quad (2.31)$$

where  $\gamma_i$  is a constant. Inserting (2.31) into (2.30) and integrating with respect to  $\eta$  yields

$$C^P(Z, T) = \frac{1}{R} \int_0^T \sum_{i=1}^n (\gamma_i - \gamma_{i-1}) \psi_1^E(Z, \tau; Z_i) d\tau \quad (i=1, 2, \dots, n; \gamma_0 = 0) \quad (2.32)$$

where the expression for  $\psi_1^E$  is given in Table 2.2. For uniform solute production throughout the soil profile ( $n = 1$ ), (2.32) reduces to

$$C^P(Z, T) = \frac{\gamma_1}{R} \int_0^T \psi_1^E(Z, \tau; Z_1 = 0) d\tau \quad (2.33)$$

This expression can be readily integrated by parts. If  $\mu^E \neq 0$ , the concentration as a result of uniform solute production becomes [cf. A5 and A6 of van Gemuchten and Alves, 1982]:

$$C^P(Z, T) = \frac{\gamma_1}{\mu^E} \left[ 1 - \psi_1^E(Z, T; 0) - G_1^E(Z, T; \mu^E) \right] \quad (2.34)$$

where  $\psi_1^E$  and  $G_1^E(Z, T)$  are given in Tables 2.2 and 2.3, respectively. For  $\mu^E = 0$ , the solution is [cf. B5 and B6 of van Gemuchten and Alves, 1982]:

$$C^P(Z, T) = \gamma_1 G_2^E(Z, T) / R \quad (2.35)$$

where  $G_2^E(Z, T)$  is given in Table 2.3.

**2. Exponential Production Profile.** Solute production can be expressed as an exponential function in a manner similar as for the IVP:

$$\gamma^E(Z) = \gamma_1 + \gamma_2 \exp(-\lambda^P Z) \quad (2.36)$$

where  $\gamma_1$ ,  $\gamma_2$ , and  $\lambda^P$  are constants. The solution is now given by

$$C^P(Z, T) = \frac{1}{R} \int_0^T \gamma_1 \psi_1^E(Z, \tau; 0) + \gamma_2 \psi_2^E(Z, \tau; \lambda^P) d\tau$$

$$= \begin{cases} \frac{\gamma_1}{\mu^E} \left[ 1 - \psi_1^E(Z, T; 0) - G_1^E(Z, T; \mu^E) \right] & (\mu^E > 0) \\ + \frac{\gamma_2}{R} \int_0^T \psi_2^E(Z, \tau; \lambda^P) d\tau & \\ \frac{\gamma_1}{R} G_2^E(Z, T) + \frac{\gamma_2}{R} \int_0^T \psi_2^E(Z, \tau; \lambda^P) d\tau & (\mu^E = 0) \end{cases} \quad (2.37)$$

where  $\psi_1^E$  and  $\psi_2^E$  are given in Table 2.2, while  $G_1^E(Z, T, \Omega)$  and  $G_2^E(Z, T)$  are defined in Table 2.3.

Table 2.2. Expressions for  $\Gamma^E$  and  $\psi^E$  in the Solutions for the Resident and Flux-Averaged Concentrations of the Equilibrium CDE

Function	Resident Concentration, $C_r$		Flux-averaged Concentration, $C_f$
	First-Type	Third-Type	
$\Gamma_1^E(Z, \tau)$	$\exp\left(-\frac{\mu^E \tau}{R}\right) \sqrt{\frac{RPZ^2}{4\pi\tau^3}} \exp\left[-\frac{P(RZ-\tau)^2}{4R\tau}\right]$	$\exp\left(-\frac{\mu^E \tau}{R}\right) \left\{ \sqrt{\frac{P}{\pi R\tau}} \exp\left[-\frac{P(RZ-\tau)^2}{4R\tau}\right] - \frac{P}{2R} \exp(PZ) \operatorname{erfc}\left(\frac{RZ+\tau}{\sqrt{4R\tau/P}}\right) \right\}$	$\exp\left(-\frac{\mu^E \tau}{R}\right) \sqrt{\frac{RPZ}{4\pi\tau^3}} \exp\left[-\frac{P(RZ-\tau)^2}{4R\tau}\right]$
$\Gamma_2^E(Z, \eta, \tau)$	$\exp\left(-\frac{\mu^E \tau}{R}\right) \sqrt{\frac{RP}{4\pi\tau}} \left\{ \exp\left[-\frac{P[R(\eta-Z)+\tau]^2}{4R\tau}\right] - \exp(PZ) \exp\left[-\frac{P[R(\eta+Z)+\tau]^2}{4R\tau}\right] \right\}$	$\exp\left(-\frac{\mu^E \tau}{R}\right) \left\{ \sqrt{\frac{RP}{4\pi\tau}} \exp\left[-\frac{P[R(\eta-Z)+\tau]^2}{4R\tau}\right] + \sqrt{\frac{RP}{4\pi\tau}} \exp(PZ) \exp\left[-\frac{P[R(\eta+Z)+\tau]^2}{4R\tau}\right] - \frac{P}{2} \exp(PZ) \operatorname{erfc}\left[\frac{R(\eta+Z)+\tau}{\sqrt{4R\tau/P}}\right] \right\}$	$\exp\left(-\frac{\mu^E \tau}{R}\right) \sqrt{\frac{RP}{4\pi\tau}} \times \left\{ \left[1 - \frac{R(\eta-Z)+\tau}{2\tau}\right] \exp\left[-\frac{P[R(\eta-Z)+\tau]^2}{4R\tau}\right] - \left[1 - \frac{R(\eta+Z)+\tau}{2\tau}\right] \exp(PZ) \exp\left[-\frac{P[R(\eta+Z)+\tau]^2}{4R\tau}\right] \right\}$
$\psi_1^E(Z, \tau, Z_i)$	$\exp\left(-\frac{\mu^E \tau}{R}\right) \left\{ 1 - \frac{1}{2} \operatorname{erfc}\left[\frac{R(Z-Z_i)-\tau}{\sqrt{4R\tau/P}}\right] - \frac{1}{2} \exp(PZ) \operatorname{erfc}\left[\frac{R(Z+Z_i)+\tau}{\sqrt{4R\tau/P}}\right] \right\}$	$\exp\left(-\frac{\mu^E \tau}{R}\right) \left\{ 1 - \frac{1}{2} \operatorname{erfc}\left[\frac{R(Z-Z_i)-\tau}{\sqrt{4R\tau/P}}\right] - \sqrt{\frac{P\tau}{\pi R}} \exp\left[PZ - \frac{P[R(Z+Z_i)+\tau]^2}{4R\tau}\right] + \frac{1}{2} \left[1 + P(Z+Z_i) + \frac{P\tau}{R}\right] \exp(PZ) \operatorname{erfc}\left[\frac{R(Z+Z_i)+\tau}{\sqrt{4R\tau/P}}\right] \right\}$	$\frac{1}{2} \exp\left(-\frac{\mu^E \tau}{R}\right) \left\{ 2 - \operatorname{erfc}\left[\frac{R(Z-Z_i)-\tau}{\sqrt{4R\tau/P}}\right] - \exp(PZ) \times \operatorname{erfc}\left[\frac{R(Z+Z_i)+\tau}{\sqrt{4R\tau/P}}\right] - \sqrt{\frac{R}{\pi P\tau}} \exp\left[-\frac{P[R(Z-Z_i)-\tau]^2}{R\tau}\right] + \sqrt{\frac{R}{\pi P\tau}} \exp(PZ) \exp\left[-\frac{P[R(Z+Z_i)+\tau]^2}{4R\tau}\right] \right\}$
$\psi_2^E(Z, \tau, \lambda)$	$\frac{1}{2} \exp\left(-\frac{\mu^E \tau}{R} + \frac{\lambda^2 \tau}{RP} + \frac{\lambda \tau}{R} - \lambda Z\right) \times \left\{ 2 - \operatorname{erfc}\left[\frac{RZ - (1+2\lambda/P)\tau}{\sqrt{4R\tau/P}}\right] + \exp(PZ+2\lambda Z) \operatorname{erfc}\left[\frac{RZ + (1+2\lambda/P)\tau}{\sqrt{4R\tau/P}}\right] \right\}$	$\exp\left(-\frac{\mu^E \tau}{R} + \frac{\lambda^2 \tau}{RP} + \frac{\lambda \tau}{R} - \lambda Z\right) \left\{ 1 - \frac{1}{2} \operatorname{erfc}\left[\frac{RZ - (1+2\lambda/P)\tau}{\sqrt{4R\tau/P}}\right] + \frac{1}{2} \left(1 + \frac{P}{\lambda}\right) \exp(PZ+2\lambda Z) \operatorname{erfc}\left[\frac{RZ + (1+2\lambda/P)\tau}{\sqrt{4R\tau/P}}\right] - \frac{P}{2\lambda} \exp\left(-\frac{\mu^E \tau}{R} + PZ\right) \operatorname{erfc}\left[\frac{RZ+\tau}{\sqrt{4R\tau/P}}\right] \right\}$	$\frac{1}{2} \left(1 + \frac{\lambda}{P}\right) \exp\left(-\frac{\mu^E \tau}{R} + \frac{\lambda^2 \tau}{RP} + \frac{\lambda \tau}{R} - \lambda Z\right) \times \left\{ 2 - \operatorname{erfc}\left[\frac{RZ - (1+2\lambda/P)\tau}{\sqrt{4R\tau/P}}\right] + \exp(PZ+2\lambda Z) \operatorname{erfc}\left[\frac{RZ + (1+2\lambda/P)\tau}{\sqrt{4R\tau/P}}\right] \right\}$



Table 2.3. Expressions for  $G^E(Z, T)$  in the Solutions for the Resident and Flux-Averaged Concentrations

$G^E$	$C_r$ $C_f$ First-Type	$C_r$ Third-Type
General $G_1^E(Z, T; \Omega)^\dagger$	$\int_0^T \exp\left(-\frac{\Omega\tau}{R}\right) \frac{Z}{\tau} \sqrt{\frac{RP}{4\pi\tau}} \exp\left[-\frac{P(RZ-\tau)^2}{4R\tau}\right] d\tau$	$\int_0^T \exp\left(-\frac{\Omega\tau}{R}\right) \left\{ \sqrt{\frac{P}{\pi R\tau}} \exp\left[-\frac{P(RZ-\tau)^2}{4R\tau}\right] - \frac{P}{2R} \exp(PZ) \operatorname{erfc}\left(\frac{RZ+\tau}{\sqrt{4R\tau/P}}\right) \right\} d\tau$
for $\Omega = 0$ $G_1^E(Z, T; 0)$	$\frac{1}{2} \operatorname{erfc}\left(\frac{RZ-T}{\sqrt{4RT/P}}\right) + \frac{1}{2} \exp(PZ) \operatorname{erfc}\left(\frac{RZ+T}{\sqrt{4RT/P}}\right)$	$\frac{1}{2} \operatorname{erfc}\left(\frac{RZ-T}{\sqrt{4RT/P}}\right) + \sqrt{\frac{P}{\pi R}} \exp\left[-\frac{P(RZ-T)^2}{4RT}\right] - \frac{1}{2} \left(1 + PZ + \frac{PT}{R}\right) \exp(PZ) \operatorname{erfc}\left(\frac{RZ+T}{\sqrt{4RT/P}}\right)$
for $\Omega \neq 0$ ( $\Omega > -P/4$ ) $G_1^E(Z, T; \Omega)$	$\frac{1}{2} \exp\left[\frac{P(1-u)Z}{2}\right] \operatorname{erfc}\left(\frac{RZ-uT}{\sqrt{4RT/P}}\right) + \frac{1}{2} \exp\left[\frac{P(1+u)Z}{2}\right] \operatorname{erfc}\left(\frac{RZ+uT}{\sqrt{4RT/P}}\right)$	$\frac{1}{1+u} \exp\left[\frac{P(1-u)Z}{2}\right] \operatorname{erfc}\left(\frac{RZ-uT}{\sqrt{4RT/P}}\right) + \frac{1}{1-u} \exp\left[\frac{P(1+u)Z}{2}\right] \operatorname{erfc}\left(\frac{RZ+uT}{\sqrt{4RT/P}}\right) - \frac{2}{1-u^2} \exp\left[PZ + \frac{P(1-u^2)T}{4R}\right] \operatorname{erfc}\left(\frac{RZ+T}{\sqrt{4RT/P}}\right)$
	with $u = \sqrt{1 + \frac{4\Omega}{P}}$	
$G_2^E(Z, T)$	$T + \frac{RZ-T}{2} \operatorname{erfc}\left(\frac{RZ-T}{\sqrt{4RT/P}}\right) - \frac{RZ+T}{2} \exp(PZ) \operatorname{erfc}\left(\frac{RZ+T}{\sqrt{4RT/P}}\right)$	$T + \frac{1}{2} \left(RZ - T + \frac{R}{P}\right) \operatorname{erfc}\left(\frac{RZ-T}{\sqrt{4RT/P}}\right) - \sqrt{\frac{PT}{4\pi R}} \left(RZ + T + \frac{2R}{P}\right) \exp\left[-\frac{P(RZ-T)^2}{4RT}\right] + \left[\frac{T}{2} - \frac{R}{2P} + \frac{P(RZ+T)^2}{4R}\right] \exp(PZ) \operatorname{erfc}\left(\frac{RZ+T}{\sqrt{4RT/P}}\right)$

$^\dagger$  The integrals in  $G_1^E(Z, T; \Omega)$  are evaluated numerically for  $\Omega > -P/4$ .

### 3. DETERMINISTIC NONEQUILIBRIUM CDE

#### 3.1. Transport Model

Solute transport in the subsurface is affected by a variety of chemical and physical nonequilibrium processes [Nielsen *et al.*, 1986; Aharoni and Sparks, 1991]. Chemical nonequilibrium may occur as a result of kinetic adsorption while physical nonequilibrium is caused by a heterogeneous flow regime. Chemical nonequilibrium models consider adsorption on some (or none) of the adsorption sites to be instantaneous, while adsorption on the remaining sites is governed by first-order kinetics [Selim *et al.*, 1976; Cameron and Klute, 1977]. In contrast, physical nonequilibrium is often modeled by using a two-region (dual-porosity) type formulation. The medium contains two distinct mobile (flowing) and immobile (stagnant) liquid regions [Coats and Smith, 1964; van Genuchten and Wierenga, 1976]; mass transfer between the two regions is modeled as a first-order process.

Although the chemical and physical nonequilibrium CDE are based on different concepts, they can be put into the same dimensionless form for conditions of linear adsorption and steady-state water flow [Nkedi-Kizza *et al.*, 1984; van Genuchten and Wagenet, 1989]. We will first present the formulations of the two-site and two-region models, followed by both general and specific solutions of the nonequilibrium CDE (cf. Chapter 2).

##### 3.1.1. Two-Site Nonequilibrium Transport

The two-site nonequilibrium model makes a distinction between type-1 (equilibrium) and type-2 (first-order kinetic) adsorption sites [van Genuchten and Wagenet, 1989]. For steady-state flow in a homogeneous soil, transport of a linearly adsorbed solute is given by

$$\left(1 + \frac{f\rho_b K_d}{\theta}\right) \frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} - v \frac{\partial c}{\partial x} - \frac{\alpha \rho_b}{\theta} [(1-f)K_d c - s_k] - \mu_l c - \frac{f\rho_b K_d \mu_{s,e} c}{\theta} + \gamma_l(x) + \frac{f\rho_b \gamma_{s,e}(x)}{\theta} \quad (3.1)$$

$$\frac{\partial s_k}{\partial t} = \alpha [(1-f)K_d c - s_k] - \mu_{s,k} s_k + (1-f)\gamma_{s,k}(x) \quad (3.2)$$

where  $\alpha$  is a first-order kinetic rate coefficient ( $T^{-1}$ ),  $f$  is the fraction of exchange sites that are always

at equilibrium, and the subscripts  $e$  and  $k$  refer to equilibrium and kinetic adsorption sites, respectively. Equations (3.1) and (3.2) use the customary first-order rate expression for describing kinetic adsorption on type-2 sites. The two-site adsorption model reduces to the one-site fully kinetic adsorption model if  $f = 0$  (only type-2 sites are present). The one-site model is used in Section 4.2 in the stream-tube formulation for field transport.

### 3.1.2. Two-Region Nonequilibrium Transport

The two-region transport model assumes that the liquid phase can be partitioned into mobile (flowing) and immobile (stagnant) regions. Solute exchange between the two liquid regions is modeled as a first-order process. The two-region solute transport model is given by [see also *van Genuchten and Wagenet, 1989*]:

$$(\theta_m + f\rho_b K_d) \frac{\partial c_m}{\partial t} = \theta_m D_m \frac{\partial^2 c_m}{\partial x^2} - J_w \frac{\partial c_m}{\partial x} - \alpha(c_m - c_{im}) - (\theta_m \mu_{\ell,m} + f\rho_b K_d \mu_{s,m}) c_m + \theta_m \gamma_{\ell,m}(x) + f\rho_b \gamma_{s,m}(x) \quad (3.3)$$

$$[\theta_{im} + (1-f)\rho_b K_d] \frac{\partial c_{im}}{\partial t} = \alpha(c_m - c_{im}) - [\theta_{im} \mu_{\ell,im} + (1-f)\rho_b K_d \mu_{s,im}] c_{im} + \theta_{im} \gamma_{\ell,im}(x) + (1-f)\rho_b \gamma_{s,im}(x) \quad (3.4)$$

where the subscripts  $m$  and  $im$  refer to the mobile and immobile liquid regions, respectively,  $J_w = v\theta = v_m \theta_m$  is the volumetric water flux density ( $LT^{-1}$ ),  $f$  represents the fraction of adsorption sites that equilibrates with the mobile liquid phase, and  $\alpha$  is again a first-order mass transfer coefficient ( $T^{-1}$ ) governing the rate of solute exchange between the mobile and immobile liquid regions. Note that  $\theta$  is equal to  $\theta_m + \theta_{im}$ .

### 3.1.3. Dimensionless Transport Equations

If we employ the dimensionless parameters listed in Table 3.1, the two-site and two-region models reduce to the same dimensionless form [see also *Nkedi-Kizza et al.*, 1984]:

$$\beta R \frac{\partial C_1}{\partial T} = \frac{1}{P} \frac{\partial^2 C_1}{\partial Z^2} - \frac{\partial C_1}{\partial Z} - \omega(C_1 - C_2) - \mu_1 C_1 + \gamma_1(Z) \quad (3.5)$$

$$(1 - \beta)R \frac{\partial C_2}{\partial T} = \omega(C_1 - C_2) - \mu_2 C_2 + \gamma_2(Z) \quad (3.6)$$

where the subscripts 1 and 2 refer to equilibrium and nonequilibrium sites, respectively;  $\beta$  is a partitioning coefficient, and  $\omega$  is a dimensionless mass transfer coefficient. Table 3.1 defines the various dimensionless parameters for the one-site ( $f=0$ ) and two-site adsorption models, as well as for the two-region model. We further assume that  $\omega$  and  $\mu$  cannot be negative. Note that  $P$  is defined as  $D = \theta_m D_m / \theta$  for the two-region model (Table 3.1). In CXTFIT 2.1,  $\nu (= \theta_m \nu_m / \theta)$  and  $D$  are used as input parameters instead of  $\nu_m$  and  $D_m$ . Also note that  $\beta$  for the two-region model represents the fraction of mobile water,  $\phi_m (= \theta_m / \theta)$  if the solute is nonreactive.

## 3.2. Analytical Solutions

Similar mathematical conditions as for the equilibrium model can be formulated also for the nonequilibrium problem [*Toride et al.*, 1993a]. If the same initial condition is used for the equilibrium and nonequilibrium phase, we can write the general initial condition for the dimensionless nonequilibrium transport model as

$$C_1(Z, 0) = C_2(Z, 0) = C_i(Z) \quad (3.7)$$

The condition at the inlet is again given by either a first- or a third-type condition, i.e.,

$$C_1(0, T) = C_o(T) \quad (3.8a)$$

or

$$C_1(0, T) - \frac{1}{P} \frac{\partial C_1(0, T)}{\partial Z} = C_o(T) \quad (3.8b)$$

while the invoked outlet condition is

$$\frac{\partial C_1}{\partial Z}(\infty, T) = 0 \quad (3.9)$$

Table 3.1. Dimensionless Parameters for the Nonequilibrium CDE†

Parameter	Model		
	One-Site‡	Two-Site	Two-Region*
$T$	$\frac{vt}{L}$	$\frac{vt}{L}$	$\frac{vt}{L}$
$Z$	$\frac{x}{L}$	$\frac{x}{L}$	$\frac{x}{L}$
$P$	$\frac{vL}{D}$	$\frac{vL}{D}$	$\frac{v_m L}{D_m} = \frac{vL}{D}$
$R$	$1 + \frac{\rho_b K_d}{\theta}$	$1 + \frac{\rho_b K_d}{\theta}$	$1 + \frac{\rho_b K_d}{\theta}$
$\beta$	$\frac{1}{R}$	$\frac{\theta + f\rho_b K_d}{\theta + \rho_b K_d}$	$\frac{\theta_m + f\rho_b K_d}{\theta + \rho_b K_d}$
$\omega$	$\frac{\alpha(R-1)L}{v}$	$\frac{\alpha(1-\beta)RL}{v}$	$\frac{\alpha L}{\theta v}$
$C_1$	$\frac{c}{c_o}$	$\frac{c}{c_o}$	$\frac{c_m}{c_o}$
$C_2$	$\frac{s_k}{K_d c_o}$	$\frac{s_k}{(1-f)K_d c_o}$	$\frac{c_{im}}{c_o}$
$\mu_1$	$\frac{L\mu_\ell}{v}$	$\frac{L(\theta\mu_\ell + f\rho_b K_d \mu_{s,e})}{\theta v}$	$\frac{L(\theta_m \mu_{\ell,m} + f\rho_b K_d \mu_{s,m})}{\theta v}$
$\mu_2$	$\frac{L(R-1)\mu_s}{v}$	$\frac{L(1-f)\rho_b K_d \mu_{s,k}}{\theta v}$	$\frac{L(\theta_{im} \mu_{\ell,im} + (1-f)\rho_b K_d \mu_{s,im})}{\theta v}$
$\gamma_1$	$\frac{L\gamma_\ell}{vc_o}$	$\frac{L(\theta\gamma_\ell + f\rho_b \gamma_{s,e})}{\theta vc_o}$	$\frac{L(\theta_m \gamma_{\ell,m} + f\rho_b \gamma_{s,m})}{\theta vc_o}$
$\gamma_2$	$\frac{L\rho_b \gamma_{s,k}}{\theta vc_o}$	$\frac{L(1-f)\rho_b \gamma_{s,k}}{\theta vc_o}$	$\frac{L(\theta_{im} \gamma_{\ell,im} + (1-f)\rho_b \gamma_{s,im})}{\theta vc_o}$

†  $c_o$  and  $L$  represent a characteristic concentration and length, respectively.‡ The one-site model is obtained by setting  $f=0$  in the two-site model.\*  $D = \theta_m D_m / \theta$

Because of the linearity of the problem in terms of  $C$ , the solution can again be obtained as the sum of independent solutions for a boundary value problem (BVP), an initial value problem (IVP), and a production value problem (PVP), hence:

$$C_1(Z,T) = C_1^B(Z,T) + C_1^I(Z,T) + C_1^P(Z,T) \quad (3.10)$$

$$C_2(Z,T) = C_2^B(Z,T) + C_2^I(Z,T) + C_2^P(Z,T) \quad (3.11)$$

Analytical solutions of (3.5) and (3.6) subject to (3.7) through (3.9) can be derived using Laplace transforms [Lindstrom and Narasimhan, 1973; Lindstrom and Stone, 1974; Lindstrom, 1976]. Details of the solution process are outlined by Toride *et al.* [1993a], and will not be reported here.

We will follow the same approach as in Chapter 2 by first presenting the general solution and subsequently giving several specific solutions. Expressions for the resident concentration, obtained for both a first- and a third-type inlet condition, and the flux-averaged concentration are provided. Solutions for the nonequilibrium CDE can be readily reduced to those for the equilibrium CDE by first assuming  $\omega = 0$  and subsequently setting  $\beta = 1$  [Toride *et al.*, 1993a]. The nonequilibrium solutions are given in terms of auxiliary expressions listed in Tables 3.2 and 3.3; these functions are similar to those in Tables 2.2 and 2.3 except for the nonequilibrium parameter  $\beta$ .

Effluent concentrations obtained from column displacement experiments are usually viewed to represent flux-averaged equilibrium concentrations,  $C_{1,f}$ . Resident concentrations, on the other hand, are typically obtained from core samples. Current measurement techniques are inadequate for distinguishing the equilibrium and nonequilibrium phases of the resident concentration (this is particularly true for the two-region model where a further partitioning of the liquid phase is needed). Usually the total resident concentration,  $C_T$ , is measured:

$$C_T = \beta RC_{1,r} + (1-\beta)RC_{2,r} \quad (3.12)$$

i.e., the total amount of solute in phases 1 and 2 per unit volume of soil solution at a given point in time and space [Parker and Valocchi, 1986].

### 3.2.1. Boundary Value Problem (BVP)

#### General solution

Concentrations as a result of an arbitrary input function,  $C_o(T)$ , can be expressed as

$$C_1^B(Z, T) = \int_0^T C_o(T - \tau) f(Z, \tau) d\tau \quad (3.13)$$

$$C_2^B(Z, T) = \frac{\omega}{(1-\beta)R} \int_0^T C_1^B(Z, \tau) \exp\left[-\frac{(\omega + \mu_2)(T - \tau)}{(1-\beta)R}\right] d\tau \quad (3.14)$$

where

$$f(Z, T) = \Gamma_1^N(Z, T) \exp\left(-\frac{\omega T}{\beta R}\right) + \frac{\omega}{R} \int_0^T \sqrt{\frac{\tau}{\beta(1-\beta)(T-\tau)}} \Gamma_1^N(Z, \tau) H_1(\tau, T) d\tau \quad (3.15)$$

with  $\Gamma_1^N(Z, \tau)$  given in Table 3.2 and where the superscript refers to the nonequilibrium solution. Furthermore,  $H_1(\tau, T)$  is given in Table 3.4 with  $I_1$  as the modified Bessel function of order one. Below we give specific solutions for cases where  $C_o(T)$  in (3.8) is described by a Dirac delta, a multiple pulse, and an exponential function.

#### Specific Solution

1. **Dirac Delta Input Function.** The inlet condition for a Dirac delta function is (cf. (2.16a)):

$$C_o(T) = M_B \delta(T) \quad (3.16)$$

Substitution of (3.16) into the general solutions leads to the following specific solutions:

$$C_1^B(Z, T) = M_B f(Z, T) \quad (3.17)$$

$$C_2(Z, T) = \frac{M_B \omega}{(1-\beta)R} \int_0^T \Gamma_1^N(Z, \tau) H_0(\tau, T) d\tau \quad (3.18)$$

where the nonequilibrium travel time pdf,  $f(Z, T)$ , is given by (3.15),  $\Gamma_1^N(Z, \tau)$  can be found in Table 3.2, and  $H_0(\tau, T)$  is given in Table 3.4 with  $I_0$  as the modified Bessel function of order zero.

**2. Multiple Pulse Input Conditions.** The input concentration for a series of successive applications of rectangular solute pulses, as illustrated in Figure 2.1, is

$$C_o(T) = f_i \quad T_i \leq T < T_{i+1} \quad (i=1,2,\dots,n; T_1=0 \text{ and } T_{n+1} \rightarrow \infty) \quad (3.19)$$

where  $f_i$  denotes again an arbitrary constant. The superposition principle allows the solution to be written as the sum of the equilibrium ( $k=1$ ) and nonequilibrium ( $k=2$ ) concentrations resulting from a single pulse input as published by, for example, *Lindstrom and Stone* [1974]:

$$C_k^B(Z,T) = \sum_{j=1}^i (f_j - f_{j-1}) A_k(Z, T - T_j) \quad (i=1,2,\dots,n, k=1,2; f_0=0) \quad (3.20)$$

with

$$A_1(Z,T) = \int_0^T \Gamma_1^N(Z,\tau) \exp\left[-\frac{\omega \mu_2 \tau}{(\omega + \mu_2) \beta R}\right] J(a,b) d\tau \quad (3.21)$$

$$A_2(Z,T) = \frac{\omega}{\omega + \mu_2} \int_0^T \Gamma_1^N(Z,\tau) \exp\left[-\frac{\omega \mu_2 \tau}{(\omega + \mu_2) \beta R}\right] [1 - J(b,a)] d\tau \quad (3.22)$$

where Goldstein's  $J$ -function,  $J(a,b)$ , and  $a$  and  $b$  are given in Table 3.4.

The following alternative expression can be obtained for  $A_k(Z,T)$  by partial integration of (3.21) [see *De Smedt and Wierenga*, 1979; *Toride et al.*, 1993a]:

$$\begin{aligned} A_1(Z,T) = & G_1^N\left(Z,T; \mu_1 + \frac{\omega \mu_2}{\omega + \mu_2}\right) \exp\left[-\frac{\omega^2 T}{(\omega + \mu_2) \beta R}\right] \\ & + \frac{\omega}{R} \int_0^T G_1^N\left(Z,\tau; \mu_1 + \frac{\omega \mu_2}{\omega + \mu_2}\right) \exp[-a-b] \\ & \cdot \left[ \frac{\omega}{(\omega + \mu_2) \beta} I_0[2\sqrt{ab}] + \sqrt{\frac{\tau}{\beta(1-\beta)-\tau}} I_1[2\sqrt{ab}] \right] d\tau \end{aligned} \quad (3.23)$$

$$\begin{aligned} A_2(Z,T) = & \frac{\omega}{(1-\beta)R} \int_0^T G_1^N\left(Z,\tau; \mu_1 + \frac{\omega \mu_2}{\omega + \mu_1}\right) \exp[-a-b] \\ & \cdot \left[ I_0[2\sqrt{ab}] + \frac{\omega}{\omega + \mu_2} \sqrt{\frac{(1-\beta)(T-\tau)}{\beta \tau}} I_1[2\sqrt{ab}] \right] d\tau \end{aligned} \quad (3.24)$$



where  $G_1^N(Z, T; \Omega)$  is given in Table 3.3. CXTFIT always assumes that  $\mu_1 + \omega\mu_2/(\omega + \mu_2) \geq 0$ , which is consistent with earlier assumptions that  $\mu_1$  and  $\mu_2 \geq 0$ . Differentiating the solutions for a single step input (i.e.,  $A_1(Z, T)$  and  $A_2(Z, T)$ ) with respect to  $T$  yields the travel time pdf (cf. (3.17) and (3.18)) [De Smedt and Wierenga, 1979].

**3. Exponential Input Function.** The exponential input function is given by

$$C_o(T) = f_1 + f_2 \exp(-\lambda^B T) \quad (3.25)$$

where  $f_1, f_2$ , and  $\lambda^B$  are constants. As described by Leij *et al.* [1993], an approximate solution for this exponential input can be derived by using the series expansion of the zero-order modified Bessel function [9.6.12 of Abramowitz and Stegun, 1970]:

$$C_1^B(Z, T) = f_1 A_1(Z, T) + f_2 \exp(-\lambda^B T) G_1^N \left( Z, T; \mu_1 + \omega + \frac{\beta R p q}{\lambda^B - q} - \beta R \lambda^B \right) - f_2 \exp(-q T) \int_0^T \Gamma_1^N(Z, \tau) \exp \left[ -\frac{\tau}{\beta R} (\omega - \beta R q) \right] \Phi_1(\tau) d\tau \quad (3.26)$$

$$C_2^B(Z, T) = f_1 A_2(Z, T) + \frac{\omega f_2}{(1 - \beta)R} \left\{ \frac{\exp(-q T)}{\lambda^B - q} G_1^N \left( Z, T; \mu_1 + \omega + \frac{\beta R p q}{\lambda^B - q} - \beta R q \right) - \frac{\exp(-\lambda^B T)}{\lambda^B - q} G_1^N \left( Z, T; \mu_1 + \omega + \frac{\beta R p q}{\lambda^B - q} - \beta R \lambda^B \right) - f_2 \exp(-q T) \int_0^T \Gamma_1^N(Z, \tau) \exp \left[ -\frac{\tau}{\beta R} (\omega - \beta R q) \right] \Phi_2(\tau) d\tau \right\} \quad (3.27)$$

with

$$\Phi_1(\tau) = \sum_{n=1}^{\infty} \frac{(p q \tau)^n}{n!} \left[ \sum_{k=1}^n \left( \frac{-1}{\lambda^B - q} \right)^k \frac{(T - \tau)^{n-k}}{(n-k)!} \right] \quad (3.28)$$

$$\Phi_2(\tau) = \sum_{n=1}^{\infty} \frac{(p q \tau)^n}{n!} \left[ \sum_{k=1}^n \left( \frac{-1}{\lambda^B - q} \right)^k \frac{(T - \tau)^{n-k+1}}{(n-k+1)(n-k)!} \right] \quad (3.29)$$

and

$$p = \frac{a}{\tau} = \frac{\omega^2}{(\omega + \mu_2)\beta R}, \quad q = \frac{b}{T - \tau} = \frac{\omega + \mu_2}{(1 - \beta)R} \quad (3.30a,b)$$

The auxiliary functions  $A_1(Z, T)$  and  $A_2(Z, T)$  are given by (3.21) and (3.22), respectively. In analogy to the equilibrium solution of the BVP for an exponential input (cf. (2.22)), the parameter  $u$  in  $G_1^N(Z, T)$  can be complex for large  $\lambda^B$ . A convergent solution is usually obtained for a maximum  $n$  value of 25. The solution is less appropriate for relatively large values of the product  $pq$  and/or  $T$ .

### 3.2.2. Initial Value Problem (IVP)

#### General Solution

The general solution of the IVP is

$$C_1^I(Z, T) = \exp\left(-\frac{\omega T}{\beta R}\right) \int_0^\infty C_i(\eta) \Gamma_2^N(Z, \eta, T) d\eta \\ + \frac{\omega}{\beta R} \int_0^T \left( H_0(\tau, T) + \sqrt{\frac{\beta \tau}{(1 - \beta)(T - \tau)}} H_1(\tau, T) \right) \int_0^\infty C_i(\eta) \Gamma_2^N(Z, \eta, \tau) d\eta d\tau \quad (3.31)$$

$$C_2^I(Z, T) = C_i(Z) \exp\left[-\frac{(\omega + \mu_2)T}{(1 - \beta)R}\right] \\ + \frac{\omega}{(1 - \beta)R} \int_0^T \left( H_0(\tau, T) + \sqrt{\frac{(1 - \beta)(T - \tau)}{\beta \tau}} H_1(\tau, T) \right) \int_0^\infty C_i(\eta) \Gamma_2^N(Z, \eta, \tau) d\eta d\tau \quad (3.32)$$

where  $\Gamma_2^N(Z, \eta, \tau)$  is listed in Table 3.2, and  $H_0(\tau, T)$  and  $H_1(\tau, T)$  are given in Table 3.4. Specific solutions will again be presented for a Dirac delta, stepwise and an exponential initial distribution. These solutions are obtained by substituting the initial profile  $C_i(Z)$  into (3.31) and (3.32), followed by integration with respect to  $\eta$  (cf. Section 2.2.2).

#### Specific Solution

**1. Dirac Delta Initial Distribution.** If solutes are initially located at  $Z = Z_1$ , the initial concentration  $C_i(Z)$  is written as

$$C_i(Z) = M_i \delta(Z - Z_1) \quad (3.33)$$

where  $\delta(Z)$  is a Dirac delta function, and  $M_i$  is the dimensionless amount of solutes initially placed at  $Z = Z_1$ . The corresponding dimensional initial condition is given by (2.24b). After substituting (3.33) into (3.31) and (3.32), the dimensionless concentrations of phases 1 and 2 become

$$C_1^I(Z, T) = \exp\left(-\frac{\omega T}{\beta R}\right) \Gamma_2^N(Z, Z_1, T) + \frac{\omega}{\beta R} \int_0^T \left( H_0(\tau, T) + \sqrt{\frac{\beta \tau}{(1-\beta)(T-\tau)}} H_1(\tau, T) \right) \Gamma_2^N(Z, Z_1, \tau) d\tau \quad (3.34)$$

$$C_2^I(Z, T) = C_i(Z) \exp\left[-\frac{(\omega + \mu_2)T}{(1-\beta)R}\right] + \frac{\omega}{(1-\beta)R} \int_0^T \left( H_0(\tau, T) + \sqrt{\frac{(1-\beta)(T-\tau)}{\beta \tau}} H_1(\tau, T) \right) \Gamma_2^N(Z, Z_1, \tau) d\tau \quad (3.35)$$

In contrast with the equilibrium CDE, the above solution for a Dirac initial condition at  $Z_1 = 0$  differs from the solution for the Dirac input (i.e., (3.17) and (3.18)).

**2. Stepwise Initial Distribution.** The stepwise initial distribution is given by

$$C_i(Z) = U_i \quad Z_i \leq Z < Z_{i+1} \quad (i=1, 2, \dots, n; Z_1 = 0 \text{ and } Z_{n+1} \rightarrow \infty) \quad (3.36)$$

where  $U_i$  denotes an arbitrary constant (cf. Figure 2.2). The solution of the IVP for this case is

$$C_1^I(Z, T) = \exp\left(-\frac{\omega T}{\beta R}\right) \sum_{i=1}^n (U_i - U_{i-1}) \psi_1^N(Z, T; Z_i) + \frac{\omega}{\beta R} \int_0^T \left( H_0(\tau, T) + \sqrt{\frac{\beta \tau}{(1-\beta)(T-\tau)}} H_1(\tau, T) \right) \sum_{i=1}^n (U_i - U_{i-1}) \psi_1^N(Z, \tau; Z_i) d\tau \quad (3.37)$$

$$C_2^I(Z, T) = C_i(Z) \exp\left[-\frac{(\omega + \mu_2)T}{(1-\beta)R}\right] + \frac{\omega}{(1-\beta)R} \int_0^T \left( H_0(\tau, T) + \sqrt{\frac{(1-\beta)(T-\tau)}{\beta \tau}} H_1(\tau, T) \right) \sum_{i=1}^n (U_i - U_{i-1}) \psi_1^N(Z, \tau; Z_i) d\tau \quad (3.38)$$

(i=1, 2, ..., n,  $U_0 = 0$ )

where  $\psi_1^N$  is listed in Table 3.2.

**3. Exponential Initial Distribution.** The exponential initial condition is given by

$$C_i(Z) = U_1 + U_2 \exp(-\lambda^I Z) \quad (3.39)$$

where  $U_1$ ,  $U_2$ , and  $\lambda^I$  are constants. The specific solutions for this condition are

$$C_1^I(Z, T) = \exp\left(-\frac{\omega T}{\beta R}\right) \left[ U_1 \psi_1^N(Z, T; 0) + U_2 \psi_2^N(Z, T; \lambda^I) \right] + \frac{\omega}{\beta R} \int_0^T \left( H_0(\tau, T) + \sqrt{\frac{\beta \tau}{(1-\beta)(T-\tau)}} H_1(\tau, T) \right) \left[ U_1 \psi_1^N(Z, \tau; 0) + U_2 \psi_2^N(Z, \tau; \lambda^I) \right] d\tau \quad (3.40)$$

$$C_2^I(Z, T) = C_i(Z) \exp\left[-\frac{(\omega + \mu_2)T}{(1-\beta)R}\right] + \frac{\omega}{(1-\beta)R} \int_0^T \left( H_0(\tau, T) + \sqrt{\frac{(1-\beta)(T-\tau)}{\beta \tau}} H_1(\tau, T) \right) \left[ U_1 \psi_1^N(Z, \tau; 0) + U_2 \psi_2^N(Z, \tau; \lambda^I) \right] d\tau \quad (3.41)$$

where  $\psi_1^N$  and  $\psi_2^N$  are listed in Table 3.2, and  $H_0(\tau, T)$  and  $H_1(\tau, T)$  are given in Table 3.4.

### 3.2.3. Production Value Problem (PVP)

#### General Solution

As outlined in the Appendix of *Toride et al.* [1993a], the general solution for the equilibrium concentration in case of production profiles  $\gamma_1(Z)$  and  $\gamma_2(Z)$  can be written as

$$C_1^P(Z, T) = \frac{1}{\beta R} \int_0^T \exp\left[-\frac{\omega \mu_2 \tau}{(\omega + \mu_2)\beta R}\right] J(a, b) \int_0^\infty \left( \gamma_1(\eta) + \frac{\omega}{\omega + \mu_2} \gamma_2(\eta) \right) \cdot \Gamma_2^N(Z, \eta, \tau) d\eta d\tau - \frac{1}{\beta R} \int_0^T H_0(\tau, T) \int_0^\infty \frac{\omega}{\omega + \mu_2} \gamma_2(\eta) \Gamma_2^N(Z, \eta, \tau) d\eta d\tau \quad (3.42)$$

Two cases need to be distinguished for the solution of phase 2, viz.  $\omega + \mu_2 > 0$  and  $\omega = \mu_2 = 0$ . For the special case that  $\omega = \mu_2 = 0$ , we have the simple solution

$$C_2^P(Z, T) = \frac{\gamma_2(Z) T}{(1-\beta)R} \quad (3.43)$$

whereas for  $\omega + \mu_2 > 0$  the nonequilibrium (phase 2) concentration is given by

$$C_2^P(Z, T) = \frac{\gamma_2(Z)}{\omega + \mu_2} \left\{ 1 - \exp \left[ -\frac{(\omega + \mu_2)T}{(1-\beta)R} \right] \right\} + \frac{\omega}{\beta R(\omega + \mu_2)} \int_0^T \exp \left[ -\frac{\omega \mu_2 \tau}{(\omega + \mu_2)\beta R} \right] \cdot [1 - J(b, a)] \int_0^\infty \left( \gamma_1(\eta) + \frac{\omega}{\omega + \mu_2} \gamma_2(\eta) \right) \Gamma_2^N(Z, \eta, \tau) d\eta d\tau - \frac{1}{\beta R} \int_0^T \sqrt{\frac{\beta(T-\tau)}{(1-\beta)\tau}} H_1(\tau, T) \int_0^\infty \frac{\omega}{\omega + \mu_2} \gamma_2(\eta) \Gamma_2^N(Z, \eta, \tau) d\eta d\tau \quad (3.44)$$

where  $\Gamma_2^N$ , which is the same as for the IVP, is listed in Table 3.2 and  $H_0(\tau, T)$ ,  $H_1(\tau, T)$ , and  $J(a, b)$  is again given in Table 3.4. Specific solutions for stepwise and exponential distributions for the production profiles,  $\gamma_1(Z)$  and  $\gamma_2(Z)$ , are given below for  $\omega + \mu_2 > 0$ . In case  $\omega + \mu_2 = 0$ , the concentration for phase 1 can be readily obtained from (3.42) (cf. (2.30)), whereas a specific solution for phase 2 can be obtained by substituting the production profile into (3.44).

### Specific Solution

**1. Stepwise Production Profile.** The production distribution for  $n$  distinct steps is given as

$$\gamma_1(Z) = \gamma_{1,i} \quad Z_{1,i} \leq Z < Z_{1,i+1} \quad (i=1, 2, \dots, n; Z_{1,1}=0 \text{ and } Z_{1,n+1} \rightarrow \infty) \quad (3.45)$$

$$\gamma_2(Z) = \gamma_{2,j} \quad Z_{2,j} \leq Z < Z_{2,j+1} \quad (j=1, 2, \dots, m; Z_{2,1}=0 \text{ and } Z_{2,m+1} \rightarrow \infty) \quad (3.46)$$

where  $\gamma_{1,i}$ ,  $\gamma_{2,j}$ ,  $Z_{1,i}$ , and  $Z_{2,j}$  are constants. For a single step ( $n=1, m=1$ ), the production is uniform throughout the soil profile. Inserting (3.45) and (3.46) into the general solution and subsequent integration with respect to  $\eta$  yields

$$C_1^P(Z, T) = \frac{1}{\beta R} \int_0^T \exp \left[ -\frac{\omega \mu_2 \tau}{(\omega + \mu_2)\beta R} \right] J(a, b) \sum_{i=1}^n (\gamma_{1,i} - \gamma_{1,i-1}) \psi_1^N(Z, \tau; Z_{1,i}) d\tau + \frac{\omega}{\beta R(\omega + \mu_2)} \int_0^T \left\{ \exp \left[ -\frac{\omega \mu_2 \tau}{(\omega + \mu_2)\beta R} \right] J(a, b) - H_0(\tau, T) \right\} \cdot \sum_{j=1}^m (\gamma_{2,j} - \gamma_{2,j-1}) \psi_1^N(Z, \tau; Z_{2,j}) d\tau \quad (3.47)$$

$$\begin{aligned}
C_2^P(Z, T) = & \frac{\gamma_2(Z)}{\omega + \mu_2} \left\{ 1 - \exp \left[ - \frac{(\omega + \mu_2)T}{(1 - \beta)R} \right] \right\} \\
& + \frac{\omega}{\beta R(\omega + \mu_2)} \int_0^T \left\{ \exp \left[ - \frac{\omega \mu_2 \tau}{(\omega + \mu_2)\beta R} \right] [1 - J(b, a)] \sum_{i=1}^n (\gamma_{1,i} - \gamma_{1,i-1}) \psi_1^N(Z, \tau; Z_{1,i}) \right. \\
& + \left[ \frac{\omega}{\omega + \mu_2} \exp \left( - \frac{\omega \mu_2 \tau}{(\omega + \mu_2)\beta R} \right) [1 - J(b, a)] - \sqrt{\frac{\beta(T - \tau)}{(1 - \beta)\tau}} H_1(\tau; T) \right] \\
& \cdot \sum_{j=1}^m (\gamma_{2,j} - \gamma_{2,j-1}) \psi_1^N(Z, \tau; Z_{2,j}) \left. \right\} d\tau \quad (i=1, 2, \dots, n, \gamma_{1,0} = \gamma_{2,0} = 0)
\end{aligned} \tag{3.48}$$

where  $\psi_1^N$  is listed in Table 3.2.

**2. Exponential Production Profile.** The depth-dependent production terms are given by:

$$\gamma_k(Z) = \gamma_{k,1} + \gamma_{k,2} \exp(-\lambda_k^P Z) \quad (k=1, 2) \tag{3.49}$$

where  $\gamma_{k,1}$ ,  $\gamma_{k,2}$ , and  $\lambda_k^P$  are constants. The concentrations are now given by

$$\begin{aligned}
C_1^P(Z, T) = & \frac{1}{\beta R} \int_0^T \exp \left[ - \frac{\omega \mu_2 \tau}{(\omega + \mu_2)\beta R} \right] J(a, b) \\
& \cdot [\gamma_{1,1} \psi_1^N(Z, \tau; 0) + \gamma_{1,2} \psi_2^N(Z, \tau; \lambda_1^P)] d\tau \\
& + \frac{\omega}{\beta R(\omega + \mu_2)} \int_0^T \left\{ \exp \left[ - \frac{\omega \mu_2 \tau}{(\omega + \mu_2)\beta R} \right] J(a, b) - H_0(\tau; T) \right\} \\
& \cdot [\gamma_{2,1} \psi_1^N(Z, \tau; 0) + \gamma_{2,2} \psi_2^N(Z, \tau; \lambda_2^P)] d\tau
\end{aligned} \tag{3.50}$$

$$\begin{aligned}
C_2^P(Z, T) = & \frac{\gamma_2(Z)}{\omega + \mu_2} \left\{ 1 - \exp \left[ - \frac{(\omega + \mu_2)T}{(1 - \beta)R} \right] \right\} + \frac{\omega}{\beta R(\omega + \mu_2)} \int_0^T \left\{ \exp \left[ - \frac{\omega \mu_2 \tau}{(\omega + \mu_2)\beta R} \right] \right. \\
& \cdot [1 - J(b, a)] [\gamma_{1,1} \psi_1(Z, \tau; 0) + \gamma_{1,2} \psi_2(Z, \tau; \lambda_1^P)] \\
& + \left[ \frac{\omega}{\omega + \mu_2} \exp \left( - \frac{\omega \mu_2 \tau}{(\omega + \mu_2)\beta R} \right) [1 - J(b, a)] - \sqrt{\frac{\beta(T - \tau)}{(1 - \beta)\tau}} H_1(\tau; T) \right] \\
& \cdot [\gamma_{2,1} \psi_1(Z, \tau; 0) + \gamma_{2,2} \psi_2(Z, \tau; \lambda_2^P)] \left. \right\} d\tau
\end{aligned} \tag{3.51}$$

Table 3.2. Expressions for  $\Gamma^W$  and  $\psi^N$  in the Solutions for the Resident and Flux-Averaged Concentrations of the Nonequilibrium CDE

Function	Resident Concentration, $C_r$		Flux-averaged Concentration, $C_f$
	First-Type	Third-Type	
$\Gamma_1^N(Z, \tau)$	$\exp\left(-\frac{\mu_1 \tau}{\beta R}\right) \frac{Z}{\tau} \sqrt{\frac{\beta R P}{4 \pi \tau}} \exp\left[-\frac{P(\beta R Z - \tau)^2}{4 \beta R \tau}\right]$	$\exp\left(-\frac{\mu_1 \tau}{\beta R}\right) \left\{ \sqrt{\frac{P}{\pi \beta R \tau}} \exp\left[-\frac{P(\beta R Z - \tau)^2}{4 \beta R \tau}\right] - \frac{P}{2 \beta R} \exp(PZ) \operatorname{erfc}\left[\frac{\beta R Z + \tau}{\sqrt{4 \beta R \tau / P}}\right] \right\}$	$\exp\left(-\frac{\mu_1 \tau}{\beta R}\right) \frac{Z}{\tau} \sqrt{\frac{\beta R P}{4 \pi \tau}} \exp\left[-\frac{P(\beta R Z - \tau)^2}{4 \beta R \tau}\right]$
$\Gamma_2^N(Z, \eta, \tau)$	$\exp\left(-\frac{\mu_1 \tau}{\beta R}\right) \sqrt{\frac{\beta R P}{4 \pi \tau}} \left\{ \exp\left[-\frac{P[\beta R(\eta - Z) + \tau]^2}{4 \beta R \tau}\right] - \exp(PZ) \exp\left[-\frac{P[\beta R(\eta + Z) + \tau]^2}{4 \beta R \tau}\right] \right\}$	$\exp\left(-\frac{\mu_1 \tau}{\beta R}\right) \left\{ \sqrt{\frac{\beta R P}{4 \pi \tau}} \exp\left[-\frac{P[\beta R(\eta - Z) + \tau]^2}{4 \beta R \tau}\right] + \sqrt{\frac{\beta R P}{4 \pi \tau}} \exp(PZ) \exp\left[-\frac{P[\beta R(\eta + Z) + \tau]^2}{4 \beta R \tau}\right] - \frac{P}{2} \exp(PZ) \operatorname{erfc}\left[\frac{\beta R(\eta + Z) + \tau}{\sqrt{4 \beta R \tau / P}}\right] \right\}$	$\exp\left(-\frac{\mu_1 \tau}{\beta R}\right) \sqrt{\frac{\beta R P}{4 \pi \tau}} \left\{ \left[1 - \frac{\beta R(\eta - Z) + \tau}{2 \tau}\right] \times \exp\left[-\frac{P[\beta R(\eta - Z) + \tau]^2}{4 \beta R \tau}\right] + \left[\frac{\beta R(\eta + Z) - \tau}{2 \tau}\right] \exp\left[PZ - \frac{P[\beta R(\eta + Z) + \tau]^2}{4 \beta R \tau}\right] \right\}$
$\psi_1^N(Z, \tau, Z_i)$	$\exp\left(-\frac{\mu_1 \tau}{\beta R}\right) \left\{ 1 - \frac{1}{2} \operatorname{erfc}\left[\frac{\beta R(Z - Z_i) - \tau}{\sqrt{4 \beta R \tau / P}}\right] - \frac{1}{2} \exp(PZ) \operatorname{erfc}\left[\frac{\beta R(Z + Z_i) + \tau}{\sqrt{4 \beta R \tau / P}}\right] \right\}$	$\exp\left(-\frac{\mu_1 \tau}{\beta R}\right) \left\{ 1 - \frac{1}{2} \operatorname{erfc}\left[\frac{\beta R(Z - Z_i) - \tau}{\sqrt{4 \beta R \tau / P}}\right] - \sqrt{\frac{P \tau}{\pi \beta R}} \exp\left[PZ - \frac{P[\beta R(Z + Z_i) + \tau]^2}{4 \beta R \tau}\right] + \frac{1}{2} \left[1 + P(Z + Z_i) + \frac{P \tau}{\beta R}\right] \exp(PZ) \operatorname{erfc}\left[\frac{\beta R(Z + Z_i) + \tau}{\sqrt{4 \beta R \tau / P}}\right] \right\}$	$\exp\left(-\frac{\mu_1 \tau}{\beta R}\right) \left\{ 1 - \frac{1}{2} \operatorname{erfc}\left[\frac{\beta R(Z - Z_i) - \tau}{\sqrt{4 \beta R \tau / P}}\right] - \frac{1}{2} \exp(PZ) \operatorname{erfc}\left[\frac{\beta R(Z + Z_i) + \tau}{\sqrt{4 \beta R \tau / P}}\right] + \sqrt{\frac{\beta R}{4 \pi P \tau}} \times \exp\left[PZ - \frac{P[\beta R(Z + Z_i) + \tau]^2}{4 \beta R \tau}\right] - \exp\left(-\frac{P[\beta R(Z - Z_i) - \tau]^2}{4 \beta R \tau}\right) \right\}$
$\psi_2^N(Z, \tau, \lambda)$	$\frac{1}{2} \exp\left(-\frac{\mu_1 \tau}{\beta R} + \frac{\lambda^2 \tau}{\beta R P} + \frac{\lambda \tau}{\beta R} - \lambda Z\right) \times \left\{ 2 - \operatorname{erfc}\left[\frac{\beta R Z - (1 + 2 \lambda / P) \tau}{\sqrt{4 \beta R \tau}}\right] + \exp(PZ + 2 \lambda Z) \operatorname{erfc}\left[\frac{\beta R Z + (1 + 2 \lambda / P) \tau}{\sqrt{4 \beta R \tau}}\right] \right\}$	$\exp\left(-\frac{\mu_1 \tau}{\beta R} + \frac{\lambda^2 \tau}{\beta R P} + \frac{\lambda \tau}{\beta R} - \lambda Z\right) \left\{ 1 - \frac{1}{2} \operatorname{erfc}\left[\frac{\beta R Z - (1 + 2 \lambda / P) \tau}{\sqrt{4 \beta R \tau / P}}\right] + \frac{1}{2} \left(1 + \frac{P}{\lambda}\right) \exp(PZ + 2 \lambda Z) \operatorname{erfc}\left[\frac{\beta R Z + (1 + 2 \lambda / P) \tau}{\sqrt{4 \beta R \tau}}\right] - \frac{P}{2 \lambda} \exp\left(-\frac{\mu_1 \tau}{\beta R} + PZ\right) \operatorname{erfc}\left[\frac{\beta R Z + \tau}{\sqrt{4 \beta R \tau / P}}\right] \right\}$	$\frac{1}{2} \left(1 + \frac{\lambda}{P}\right) \exp\left(-\frac{\mu_1 \tau}{\beta R} + \frac{\lambda^2 \tau}{\beta R P} + \frac{\lambda \tau}{\beta R} - \lambda Z\right) \times \left\{ 2 - \operatorname{erfc}\left[\frac{\beta R Z - (1 + 2 \lambda / P) \tau}{\sqrt{4 \beta R \tau / P}}\right] + \exp(PZ + 2 \lambda Z) \operatorname{erfc}\left[\frac{\beta R Z + (1 + 2 \lambda / P) \tau}{\sqrt{4 \beta R \tau / P}}\right] \right\}$



Table 3.3. Expressions for  $G^N(Z, T)$  in the Solutions for the Resident and Flux-Averaged Concentrations

$G^N$	$C_r$ First-Type	or	$C_f$	$C_r$ Third-Type
General† $G_1^N(Z, T; \Omega)$	$\int_0^T \exp\left(-\frac{\Omega\tau}{\beta R}\right) \frac{Z}{\tau} \sqrt{\frac{\beta R P}{4\pi\tau}} \exp\left[-\frac{P(\beta R Z - \tau)^2}{4\beta R \tau}\right] d\tau$			$\int_0^T \exp\left(-\frac{\Omega\tau}{\beta R}\right) \left\{ \sqrt{\frac{P}{\pi\beta R \tau}} \exp\left[-\frac{P(\beta R Z - \tau)^2}{4\beta R \tau}\right] - \frac{P}{2\beta R} \exp(PZ) \operatorname{erfc}\left[\frac{\beta R Z + \tau}{\sqrt{4\beta R \tau/P}}\right] \right\} d\tau$
for $\Omega = 0$ $G_1^N(Z, T; 0)$	$\frac{1}{2} \operatorname{erfc}\left[\frac{\beta R Z - T}{\sqrt{4\beta R T/P}}\right] + \frac{1}{2} \exp(PZ) \operatorname{erfc}\left[\frac{\beta R Z + T}{\sqrt{4\beta R T/P}}\right]$			$\frac{1}{2} \operatorname{erfc}\left[\frac{\beta R Z - T}{\sqrt{4\beta R T/P}}\right] + \sqrt{\frac{P}{\pi\beta R}} \exp\left[-\frac{P(\beta R Z - T)^2}{4\beta R T}\right] - \frac{1}{2} \left(1 + PZ + \frac{PT}{\beta R}\right) \exp(PZ) \operatorname{erfc}\left[\frac{\beta R Z + T}{\sqrt{4\beta R T/P}}\right]$
for $\Omega \neq 0$ ( $\Omega > -P/4$ ) $G_1^N(Z, T; \Omega)$	$\frac{1}{2} \exp\left[\frac{P(1-u)Z}{2}\right] \operatorname{erfc}\left[\frac{\beta R Z - uT}{\sqrt{4\beta R T/P}}\right] + \frac{1}{2} \exp\left[\frac{P(1+u)Z}{2}\right] \operatorname{erfc}\left[\frac{\beta R Z + uT}{\sqrt{4\beta R T/P}}\right]$			$\frac{1}{1+u} \exp\left[\frac{P(1-u)Z}{2}\right] \operatorname{erfc}\left[\frac{\beta R Z - uT}{\sqrt{4\beta R T/P}}\right] + \frac{1}{1-u} \exp\left[\frac{P(1+u)Z}{2}\right] \operatorname{erfc}\left[\frac{\beta R Z + uT}{\sqrt{4\beta R T/P}}\right] - \frac{2}{1-u^2} \exp\left[PZ + \frac{P(1-u^2)T}{4\beta R}\right] \operatorname{erfc}\left[\frac{\beta R Z + T}{\sqrt{4\beta R T/P}}\right]$
	with $u = \sqrt{1 + \frac{4\Omega}{P}}$			

† The integral in the general expression of  $G_1^N(Z, T; \Omega)$  is evaluated numerically for  $\Omega > -P/4$ .

Table 3.4. Expressions for  $H(\tau, T)$  and Goldstein's  $J$ -function,  $J(a, b)$

Function	Expression
$H_0(\tau, T)$	$\exp \left[ -\frac{\omega \tau}{\beta R} - \frac{(\omega + \mu_2)(T - \tau)}{(1 - \beta)R} \right] I_0 \left[ \frac{2\omega}{R} \sqrt{\frac{(T - \tau)\tau}{\beta(1 - \beta)}} \right]$
$H_1(\tau, T)$	$\exp \left[ -\frac{\omega \tau}{\beta R} - \frac{(\omega + \mu_2)(T - \tau)}{(1 - \beta)R} \right] I_1 \left[ \frac{2\omega}{R} \sqrt{\frac{(T - \tau)\tau}{\beta(1 - \beta)}} \right]$
$J(a, b)$	$1 - \exp(-b) \int_0^a \exp(-\lambda) I_0[2\sqrt{b\lambda}] d\lambda$ with $a = \frac{\omega^2 \tau}{(\omega + \mu_2)\beta R}$ and $b = \frac{(\omega + \mu_2)(T - \tau)}{(1 - \beta)R}$

### 3.3. Degradation for the Nonequilibrium CDE

Thus far, no assumptions were made regarding the values of the degradation coefficients (i.e.,  $\mu_{s,e}$ ,  $\mu_{s,k}$ ,  $\mu_{l,m}$ ,  $\mu_{l,im}$ ,  $\mu_{s,m}$ ,  $\mu_{s,im}$ ). For many actual transport problems it may not be possible to determine meaningful individual degradation parameters. The number of degradation pathways and associated coefficients can be reduced in several ways.

As outlined by *van Genuchten and Wagenet* [1989], one simplification is to assume that all rate coefficients are the same (e.g., for nuclear decay), i.e.,  $\mu_l = \mu_{s,e} = \mu_{s,k} \equiv \mu$  for the two-site model, or  $\mu_{l,m} = \mu_{l,im} = \mu_{s,m} = \mu_{s,im} \equiv \mu$  for the two-region model. The dimensionless parameters,  $\mu_1$  and  $\mu_2$ , for the two-site and the two-region models (cf. Table 3.1) reduce then to

$$\mu_1 = \beta R \psi, \quad \mu_2 = (1 - \beta) R \psi \quad (3.52a,b)$$

where the dimensionless parameter,  $\psi$ , is defined as

$$\psi = \mu L / v \quad (3.53)$$

An alternative simplification assumes negligible decay in the adsorbed phase. The assumption of exclusive decay in the liquid phase appears realistic for at least some pesticide-soil combinations [Weber and Cole, 1968; Moyer et al., 1972; Ogram et al., 1985]. The dimensionless degradation coefficients for the two-site model are now given by

$$\mu_1 = \psi_l, \quad \mu_2 = 0 \quad (3.54a,b)$$

where  $\psi_l = \mu L / v$ . It may also be possible that degradation occurs only in the adsorbed phase rather than the solution phase; an appropriate  $\psi_s$  is then defined from the corresponding  $\mu_s$ .

Table 3.5 summarizes the expressions for  $\mu_1$  and  $\mu_2$  in terms of  $\psi$  for the most general case as well as for several limiting scenarios. We have furthermore assumed that the degradation coefficients for decay in the liquid or adsorbed phase are the same for both regions in the two-region model when degradation takes place exclusively in the liquid or adsorbed phase.

Table 3.5. Expressions for the Dimensionless Parameters  $\mu_1$  and  $\mu_2$  in (3.5) and (3.6)

	One-site model	Two-site model	Two-region model†
Independent degradations rates in liquid and adsorbed phases	$\mu_1 = \psi_\ell$ $\mu_2 = (R-1)\psi_s$	$\mu_1 = \psi_\ell + (\beta R - 1)\psi_{s,e}$ $\mu_2 = (1-\beta)R\psi_{s,k}$	$\mu_1 = \phi_m\psi_{\ell m} + (\beta R - \phi_m)\psi_{s,m}$ $\mu_2 = \phi_{im}\psi_{\ell im} + [(1-\beta)R - \phi_{im}]\psi_{s,im}$
Identical degradation in liquid and adsorbed phases	$\mu_1 = \psi$ $\mu_2 = (R-1)\psi$	$\mu_1 = \beta R\psi$ $\mu_2 = (1-\beta)R\psi$	$\mu_1 = \beta R\psi$ $\mu_2 = (1-\beta)R\psi$
No degradation in the adsorbed phase	$\mu_1 = \psi_\ell$ $\mu_2 = 0$	$\mu_1 = \psi_\ell$ $\mu_2 = 0$	$\mu_1 = \phi_m\psi_\ell$ $\mu_2 = \phi_{im}\psi_\ell$
No degradation in the liquid phase	$\mu_1 = 0$ $\mu_2 = (R-1)\psi_s$	$\mu_1 = (\beta R - 1)\psi_s$ $\mu_2 = (1-\beta)R\psi_s$	$\mu_1 = (\beta R - \phi_m)\psi_s$ $\mu_2 = [(1-\beta)R - \phi_{im}]\psi_s$

†  $\phi_m = \theta_m/\theta$ ,  $\phi_{im} = \theta_{im}/\theta$

## 4. STREAM TUBE MODEL FOR FIELD-SCALE TRANSPORT

### 4.1. Introduction

Traditional deterministic approaches based upon the convection-dispersion equation (CDE) for chemical transport and the Richards equation for water flow work relatively well for homogeneous soils and packed laboratory soil columns. However, most field soils are far from homogeneous, resulting in sometimes highly nonuniform flow and transport processes. Experimental investigations at the field scale have demonstrated the effects of heterogeneity on solute transport [e.g., *Biggar and Nielsen*, 1976; *Sudicky*, 1986]. A variety of stochastic modeling approaches have been employed to describe nonreactive solute transport in a heterogeneous flow field [e.g., *Dagan*, 1984; *Sposito and Barry*, 1987]. Recently, stochastic methods have also been used to study solute transport subject to equilibrium [*Kabala and Sposito*, 1991] or nonequilibrium adsorption [e.g., *Dagan and Cvetkovic*, 1993; *Bellin et al.*, 1993]. In these investigations, a transport equation in terms of a mean solute concentration across the field is formulated using the covariance functions of local-scale transport parameters. Unfortunately, it is usually not possible to determine a reliable statistical distribution for each parameter.

In a simplified approach to stochastic modeling, the field may be viewed as a series of independent vertical soil columns (cf. Figure 4.1). These columns are generally referred to as "stream tubes" [*Dagan*, 1993; *Jury and Roth*, 1990]. Local-scale transport in each stream tube is described deterministically assuming a convective or convective-dispersive model. Transport at the field scale may be modeled by viewing selected parameters in the convective or convective-dispersive model for each tube as realizations of a stochastic process. The mean solute concentration for an entire field is given by the ensemble average of the local concentrations in all stream tubes. At the field scale, the one-dimensional CDE (perfect mixing perpendicular to the flow direction) and the stream tube model (no mixing between tubes) constitute the limiting cases for solute transport [*Jury and Flühler*, 1992].

There are several ways in which the stream tube model has been used to quantify solute transport in heterogeneous soils. *Dagan and Bresler* [1979] and *Bresler and Dagan* [1979] described the downward movement of nonreactive solutes at the field scale assuming a lognormal distribution for

the saturated hydraulic conductivity. *Jury* [1982] used a so called convective lognormal transfer function model (CLT), which neglects local-scale dispersion. *Van der Zee and van Riemsdijk* [1986, 1987] applied the stream tube model to reactive solutes, while *Destouni and Cvetkovic* [1991] introduced physical and chemical nonequilibrium in the local-scale transport model.

CXTFIT 2.1 allows the use of the stream tube model for a variety of transport scenarios. The analytical solutions of the equilibrium and nonequilibrium CDE as described in Chapters 2 and 3, will be used to model local-scale transport. Stochastic variables are the pore water velocity,  $v$ , in combination with either the dispersion coefficient,  $D$ , the distribution coefficient for linear adsorption,  $K_d$ , or the first-order rate coefficient for nonequilibrium adsorption,  $\alpha$ . These three different pairs of random parameters are described with a bivariate lognormal joint probability density function (pdf). Further details can be found in *Toride and Leij* [1996a]. The implications of describing the transport problem as an initial or as a boundary problem for the stream tube model were discussed by *Jury and Scotter* [1994] and *Toride and Leij* [1996b].

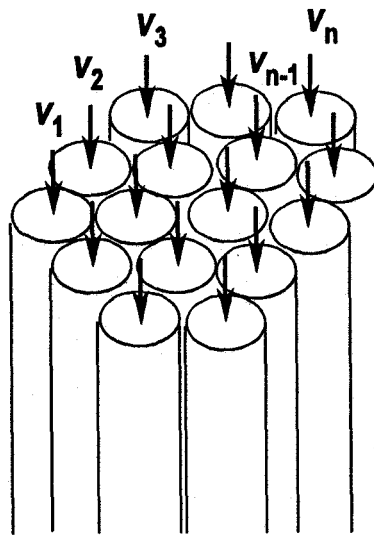


Fig. 4.1. Schematic illustration of the stream tube model.

## 4.2. Local-Scale Transport

We will describe solute transport at the local scale with the one-dimensional one-site chemical nonequilibrium CDE by setting  $f$  to zero in (3.1) and (3.2):

$$\frac{\partial c_r}{\partial t} = D \frac{\partial^2 c_r}{\partial x^2} - v \frac{\partial c_r}{\partial x} - \frac{\alpha \rho_b}{\theta} [K_d c_r - s] - \mu_l c_r + \gamma_l(x) \quad (4.1)$$

$$\frac{\partial s}{\partial t} = \alpha [K_d c_r - s] - \mu_s s + \gamma_s(x) \quad (4.2)$$

The subscript  $k$  is now dropped because there are no equilibrium adsorption sites. Furthermore, transport equations are given in dimensional form in this chapter. For equilibrium adsorption ( $\alpha \rightarrow \infty$ ), the nonequilibrium CDE reduces to (cf. (2.3)):

$$R \frac{\partial c_r}{\partial t} = D \frac{\partial^2 c_r}{\partial x^2} - v \frac{\partial c_r}{\partial x} - \mu c_r + \gamma(x) \quad (4.3)$$

where the retardation factor  $R$  was defined as

$$R = 1 + \frac{\rho_b K_d}{\theta} \quad (4.4)$$

and where  $\mu$  and  $\gamma$  are given by (2.5) and (2.6), respectively. We will assume equal degradation rates in the liquid and adsorbed phases, i.e.,  $\mu = \mu R$ .

The equilibrium and nonequilibrium CDEs were solved subject to the following general initial and boundary conditions (cf. Chapters 2 and 3):

$$c_r(x, 0) = c_i(x), \quad s(x, 0) = K_d c_i(x) \quad (4.5a,b)$$

$$v c_r(0, t) - \delta D \frac{\partial c_r(0, t)}{\partial x} = v c_o(t) \quad (4.6)$$

$$\frac{\partial c_r}{\partial x}(\infty, t) = 0 \quad (4.7)$$

in which  $\delta = 0$  for a first-type and  $\delta = 1$  for a third-type inlet condition. A flux-averaged concentration,  $c_f$ , can be obtained from  $c_r$  according to (2.13). The dimensionless solutions of the BVP, IVP, and PVP were previously presented in Chapters 2 and 3.

The solution of the local-scale transport equation depends exclusively on random transport parameters such as  $v$ ,  $D$ , and  $K_d$ , once the independent variables  $t$  and  $x$  have been specified. For example, Figure 4.2a shows the solution,  $c_r$ , for the equilibrium CDE as a function of  $v$  and  $K_d$  at  $t = 5$  d for a 2-d pulse input at  $x = 100$  cm assuming  $D = 20$  cm<sup>2</sup> d<sup>-1</sup> and  $\rho_b/\theta = 4$  g cm<sup>-3</sup> (cf. (2.20)). The concentration is normalized using the input concentration,  $c_o$ . As  $K_d$  increases, the solute moves slower because of increased adsorption; a higher  $v$  is required for the solute to reach  $x = 100$  cm at  $t = 5$  d.

### 4.3 Field-Scale Transport

#### 4.3.1. Bivariate Lognormal Distribution

The pairs of stochastic parameters in the local-scale model for transport in each stream tube are obtained from a bivariate lognormal joint probability density function (pdf). Because of their relatively low coefficient of variation, CV, the same values for  $\theta$  and  $\rho_b$  are used for each stream tube. The joint pdfs of  $v$ , in conjunction with either  $D$ ,  $K_d$ , or  $\alpha$ , are written as  $f(v, D)$ ,  $f(v, K_d)$ , and  $f(v, \alpha)$ , respectively. The general bivariate lognormal joint pdf is defined as [Spiegel, 1992; p.118]:

$$f(v, \eta) = \frac{1}{2\pi\sigma_v\sigma_\eta v\eta\sqrt{1-\rho_{v\eta}^2}} \exp\left(-\frac{Y_v^2 - 2\rho_{v\eta}Y_vY_\eta + Y_\eta^2}{2(1-\rho_{v\eta}^2)}\right) \quad (4.8)$$

with

$$Y_v = \frac{\ln(v) - \mu_v}{\sigma_v}, \quad Y_\eta = \frac{\ln(\eta) - \mu_\eta}{\sigma_\eta} \quad (4.9a,b)$$

$$\rho_{v\eta} = \langle Y_v Y_\eta \rangle = \int_0^\infty \int_0^\infty Y_v Y_\eta f(v, \eta) dv d\eta \quad (4.10)$$

where  $\eta$  denotes  $D$ ,  $K_d$ , or  $\alpha$  (i.e., the second random parameter in addition to  $v$ ),  $\mu$  and  $\sigma$  are the mean and standard deviation of the log-transformed variable, and  $\rho_{v\eta}$  is the correlation coefficient between  $Y_v$  and  $Y_\eta$ .

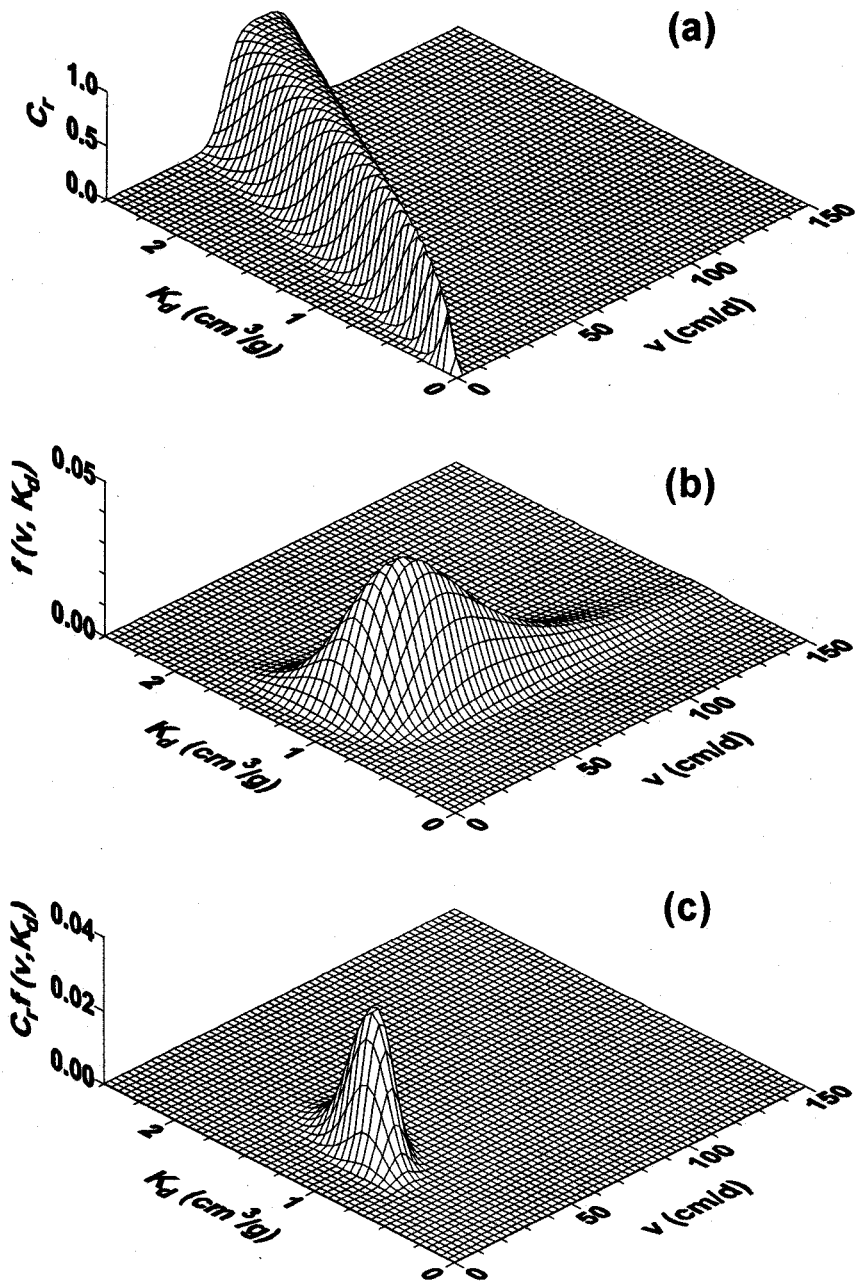


Fig. 4.2. Predicted resident concentrations according to the stream tube model:  
 (a) local-scale  $c_r$  as a function of  $v$  and  $K_d$  at  $x = 100$  cm and  $t = 5$  d;  
 (b) a bivariate lognormal pdf for  $\rho_{vK_d} = -0.5$ ; and  
 (c) expected  $c_r$  at  $x = 100$  cm and  $t = 5$  d.



The ensemble averages of  $v$  and  $\eta$  are given by [Aitchison and Brown, 1963; p. 8]:

$$\langle v \rangle = \exp\left(\mu_v + \frac{1}{2}\sigma_v^2\right), \quad \langle \eta \rangle = \exp\left(\mu_\eta + \frac{1}{2}\sigma_\eta^2\right) \quad (4.11a,b)$$

with the coefficient of variation CV expressed as

$$CV(v) = \sqrt{\exp(\sigma_v^2) - 1}, \quad CV(\eta) = \sqrt{\exp(\sigma_\eta^2) - 1} \quad (4.12a,b)$$

Figure 4.2b presents an example of a bivariate lognormal pdf for  $v$  and  $K_d$  with  $\langle v \rangle = 50 \text{ cm d}^{-1}$ ,  $\sigma_v = 0.2 \text{ cm d}^{-1}$ ,  $\langle K_d \rangle = 1 \text{ cm}^3 \text{ g}^{-1}$ ,  $\sigma_{Kd} = 0.2 \text{ cm}^3 \text{ g}^{-1}$ , and  $\rho_{vKd} = -0.5$ . The distribution for  $v$  is skewed due to the relatively high standard deviation,  $\sigma_v$ , whereas the smaller  $\sigma_{Kd}$  results in a more symmetric distribution for  $K_d$ . The value for  $v$  tends to increase as  $K_d$  decreases.

The joint pdf given by (4.8) can be simplified for some special cases. When two parameters are uncorrelated, i.e.,  $\rho_{v\eta} = 0$ , the joint pdf is the product of two single pdfs:

$$f(v, \eta) = f(v) \cdot f(\eta) \quad (4.13)$$

where the single lognormal distribution is given by

$$f(\eta) = \frac{1}{\sqrt{2\pi}\sigma_\eta\eta} \exp\left(-\frac{[\ln(\eta) - \mu_\eta]^2}{2\sigma_\eta^2}\right) \quad (4.14)$$

A perfect correlation, i.e.,  $\rho_{v\eta} = 1$  or  $-1$ , is the result of a complete dependency of the stochastic variables with  $Y_\eta = Y_v$  and  $Y_\eta = -Y_v$ , respectively. Subsequent use of (4.11) yields

$$\eta(v) = \left(\frac{v}{\langle v \rangle}\right)^{\frac{\rho_{v\eta}\sigma_\eta}{\sigma_v}} \langle \eta \rangle \exp\left(\frac{\rho_{v\eta}\sigma_v\sigma_\eta}{2} - \frac{1}{2}\sigma_\eta^2\right) \quad (4.15)$$

In this case, the distributions of  $v$  and  $\eta$  are given by either  $f(v)$  or  $f(\eta)$ . Figure 4.3 demonstrates the two cases of perfect correlation between  $v$  and  $K_d$  — the same values for the mean and standard deviation are used as in Figure 4.2b. For a perfect negative correlation  $K_d$  decreases as  $v$  increases, and vice versa.

Additional stochastic parameters can be included as long as only two of the parameters are independent. CXTFIT 2.1 can evaluate up to four stochastic parameters in this manner.

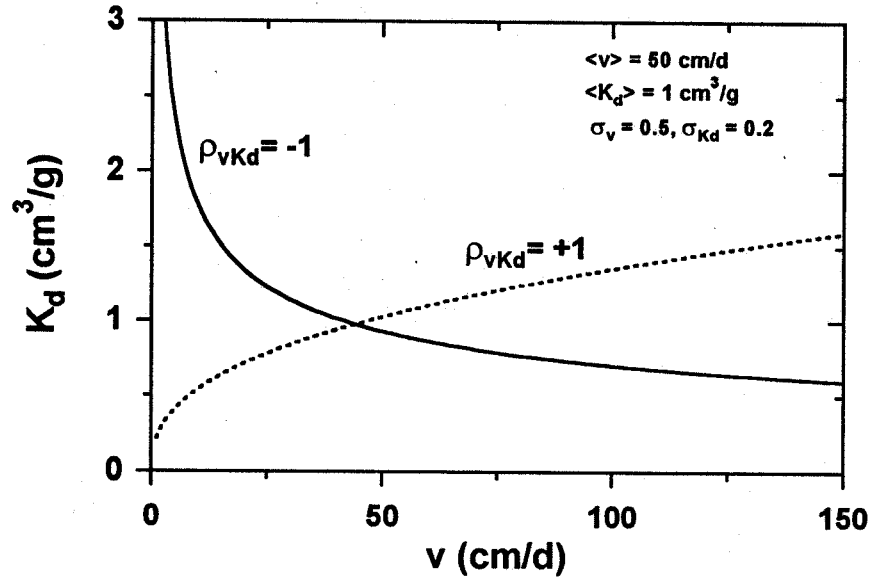


Fig. 4.3. Perfect positive and negative correlation for stochastic  $v$  and  $K_d$ .

#### 4.3.2. Field-Scale Mean Concentration

Field-scale transport may be modeled by averaging the local-scale concentrations over all stream tubes. In case of weak stationarity and ergodicity of the random functions describing the stochastic parameters [cf. *de Marsily*, 1986; *Dagan*, 1989], the spatial average for the entire field is identical to the ensemble average:

$$\langle c(x, t) \rangle = \frac{1}{A} \int_A c(x, t) dA = \int_0^\infty \int_0^\infty c(x, t; v, \eta) f(v, \eta) dv d\eta \quad (4.16)$$

where  $A$  denotes the area of the field. The local concentration can be of the resident or flux-averaged type, in which case the corresponding ensemble averages are  $\langle c_r \rangle$  and  $\langle c_f \rangle$ , respectively. The above assumptions of weak stationarity and ergodicity seem reasonable for our idealized pdfs.

The field-scale resident concentration,  $\hat{c}_r$ , which represents the resident concentration averaged over the entire horizontal plane as determined by a "sufficient" number of samples at a particular depth, is equal to the ensemble average,  $\langle c_r \rangle$ , given by (4.16):

$$\hat{c}_r(x, t) = \langle c_r(x, t) \rangle \quad (4.17)$$

Figure 4.2c shows the product of the individual resident concentrations (Figure 4.2a) and the joint pdf (Figure 4.2b), such a product also appears in the integrand on the right-hand side of (4.16). The peak in Figure 4.2c suggests that stream tubes with  $v \ll 20 \text{ cm d}^{-1}$  and  $K_d \approx 1 \text{ cm}^3 \text{ g}^{-1}$  contribute the most to the field-scale mean concentration for the selected independent variables ( $x = 100 \text{ cm}$  and  $t = 5 \text{ d}$ ). The total volume of the distribution in Figure 4.2c corresponds to the ensemble average  $\langle c_r \rangle$  which is equal to  $\hat{c}_r$ . The field-scale total resident concentration,  $\hat{c}_T$ , for nonequilibrium adsorption is obtained as the total solute amount per unit solution volume:

$$\hat{c}_T = \left\langle c_r + \frac{\rho_b s}{\theta} \right\rangle = \hat{c}_r + \frac{\rho_b}{\theta} \langle s \rangle \quad (4.18)$$

For equilibrium adsorption (i.e.,  $s = K_d c_r$ ), (4.18) can be simplified to  $\hat{c}_T = \langle R c_r \rangle$ . Notice that  $\langle R c_r \rangle \neq \langle R \rangle \langle c_r \rangle$  for a stochastic  $K_d$ .

A field-scale flux-averaged concentration,  $\hat{c}_f$ , can be defined as the ratio of the mean solute and water fluxes in a similar manner as (4.16):

$$\hat{c}_f(x, t) = \langle v c_f \rangle / \langle v \rangle = \frac{1}{\langle v \rangle} \int_0^\infty \int_0^\infty v c_f(x, t; v, \eta) f(v, \eta) dv d\eta \quad (4.19)$$

The solute flux for an entire field is given by  $A \theta \langle v \rangle \hat{c}_f$ . Unlike the resident concentration, the ensemble and field-scale average of this flux-averaged concentration will generally be different (i.e.,  $\hat{c}_f \neq \langle c_f \rangle$ ) since  $\langle v c_f \rangle \neq \langle v \rangle \langle c_f \rangle$ . Because local values for  $v$  are not easily obtained experimentally, estimates for  $\hat{c}_f$  will be difficult to obtain. The pdf for the pore-water velocity,  $f(v)$ , may be estimated from either  $\hat{c}_r$  or  $\langle c_f \rangle$ . Once  $f(v)$  is specified,  $\hat{c}_f$  can be calculated subsequently.

Variations in the local resident or flux-averaged concentration between stream tubes across the horizontal plane (i.e., at a particular depth and time) can be characterized by its variance [Bresler and Dagan, 1981]:

$$\text{Var}[c(x, t)] = \int_0^\infty \int_0^\infty [c(x, t) - \langle c(x, t) \rangle]^2 f(v, \eta) dv d\eta = \langle c^2(x, t) \rangle - \langle c(x, t) \rangle^2 \quad (4.20)$$

where  $c$  may denote either  $c_r$  or  $c_f$ . The variance corresponding to the field-scale flux-averaged concentration,  $\hat{c}_f$ , is expressed as

$$\begin{aligned} \text{Var} \left[ \frac{vc_f(x,t)}{\langle v \rangle} \right] &= \frac{1}{\langle v \rangle^2} \int_0^\infty \int_0^\infty [vc_f(x,t) - \langle vc_f(x,t) \rangle]^2 f(v, \eta) dv d\eta \\ &= \left[ \langle v^2 c_f^2(x,t) \rangle - \langle vc_f(x,t) \rangle^2 \right] / \langle v \rangle^2 \end{aligned} \quad (4.21)$$

The variance for the adsorbed phase concentration  $s$  across the horizontal plane may be defined in a similar manner as (4.20) and (4.21).

#### 4.4. Solute Application for the Stream Tube Model

A correct mathematical description of how the solute is applied at the surface is necessary for effective use of the stream tube model. We will present several possible formulations for the solute application depending upon whether each stream tube contains the same amount of solute, or the amount of solute in each stream tube is proportional to the local-scale pore-water velocity,  $v$ . Only a third-type inlet condition ( $\delta=1$  in (4.6)) will be considered; similar results can be obtained for a first-type inlet condition.

##### *Dirac-Type Application*

The instantaneous application of solute to the surface of an initially solute-free soil profile, may be described as a boundary value problem (BVP) with  $c_i = 0$  and  $c_o(t)$ :

$$c_o(t) = \frac{m_B}{v} \delta(t) \quad (4.22)$$

where  $\delta(t)$  is the Dirac delta function [ $d^{-1}$ ] and  $m_B$  is the amount of mass added to a unit area of the liquid phase in a stream tube [ $g \text{ cm}^{-2}$ ] (see also (2.16b)). The amount of mass added to a unit area of soil is given by  $\theta m_B$  where  $\theta$  is the volumetric water content. When the solute is applied uniformly across the field during a fixed and short period of time, the amount of mass,  $m_B$ , added to each stream tube will be equal to  $v \langle m_B \rangle / \langle v \rangle$ , where  $\langle m_B \rangle$  is the mean of  $m_B$  for all tubes (see input parameter MASSST in Table 6.7).

The above scenario can also be described as an initial value problem (IVP) in which solutes are initially distributed uniformly across the soil surface, and solute-free water ( $c_o(t) = 0$ ) is applied to the soil surface. The initial distribution is now described as

$$c_i(t) = \frac{m_I}{\theta} \delta(x) \quad (4.23)$$

where  $\delta(x)$  is the Dirac delta function [ $\text{cm}^{-1}$ ], describing the initial solute spike at  $x = 0$ , and  $m_I$  is the amount of mass present per unit cross sectional soil area [ $\text{g cm}^{-2}$ ] (see also (2.24b)). The same amount of solute,  $m_I$ , is present in all stream-tubes regardless of  $v$ .

Figure 4.4 illustrates the solute distribution between tubes for the BVP according to (4.22) and the IVP according to (4.23). Figure 4.5 demonstrates the effect of the two different solute applications on  $\hat{c}_r$  predicted as a function of depth at  $t = 1$  d (the concentrations are normalized by assuming  $m_B/v = 1$ ). The same amount of nonreactive chemical ( $R = 1$ ,  $\langle m_B \rangle = m_I/\theta$ ) is recovered in the soil profile, either applied at  $x = 0$  for the BVP or present at  $t = 0$  for the IVP. Additional parameters are:  $\langle v \rangle = 50 \text{ cm d}^{-1}$ ,  $\langle D \rangle = 20 \text{ cm}^2 \text{ d}^{-1}$ , and  $\sigma_v = \sigma_D = 0.5$ . Figure 4.5 shows that more solute remains near the surface for the IVP, while the BVP predicts somewhat faster downward movement since a larger fraction of solutes resides in stream tubes with a higher velocity as a result of the velocity dependent application. Although this example pertains to a Dirac delta function, similar differences between the boundary and initial value problems occur for other influent and initial solute concentration profiles.

The BVP will give identical results as the IVP if  $m_B$  is the same for each tube, regardless of the local  $v$ , as long as solute adsorption is instantaneous. The solutions for the BVP according to (4.22) and the IVP according to (4.23) are identical for the equilibrium CDE when  $m_B = m_I/\theta$  (cf. (2.17) and (2.24)). However, this equality does not hold for nonequilibrium adsorption. The solutions of the nonequilibrium CDE for the BVP and IVP are different because of the kinetic desorption process (cf. (3.17) and (3.34)). We finally note that for the equilibrium CDE, the ensemble average of the flux-averaged concentration,  $\langle c_f \rangle$ , for the BVP with variable  $m_B$  according to (4.22), is identical to the field-scale flux-averaged concentration,  $\hat{c}_f$ , for the IVP according to (4.23).

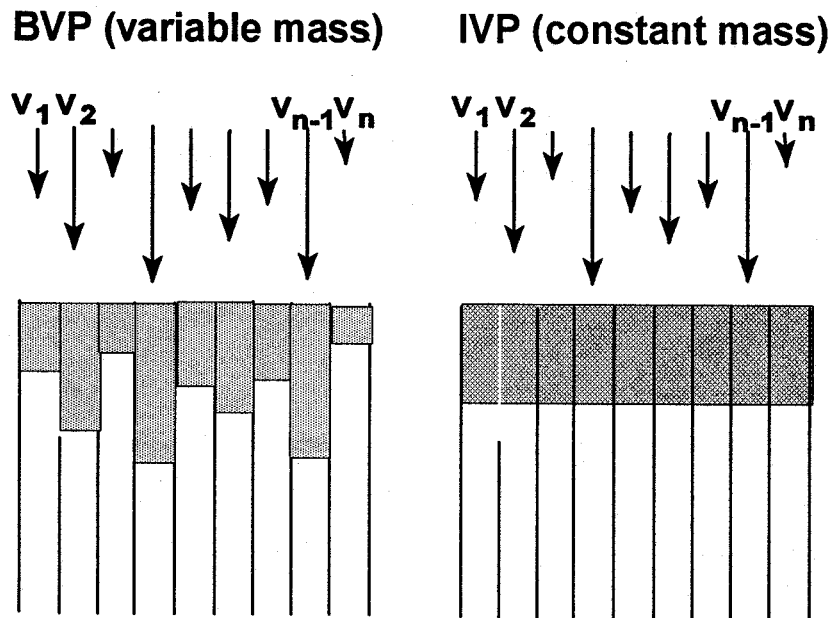


Fig. 4.4. Illustration of the solute distribution in stream tubes for variable and constant mass solute applications based on the BVP and IVP.

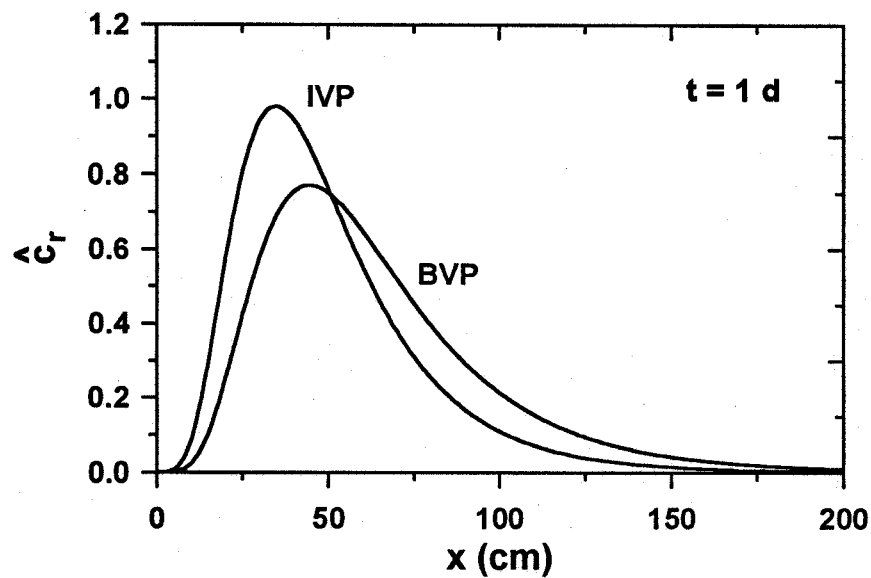


Fig. 4.5. Field-scale resident concentrations ( $\hat{c}_r$ ) versus depth as the result of instantaneous solute application to the surface described as a BVP or an IVP.

### ***Pulse-Type Application***

Following *Parker and van Genuchten* [1984b], we study the BVP involving a finite pulse input for the case of either a constant or variable application time for each tube. Consider a pulse-type solute application of concentration  $f_1$  and application time  $t_2$  (cf. Figure 2.1). If  $t_2$  is constant for all stream tubes, the amount of solute in each tube,  $m_B = f_1 t_2 v$ , is directly proportional to the random velocity,  $v$ . The field-averaged mean,  $\langle m_B \rangle$ , is given by  $f_1 t_2 \langle v \rangle$ . However, the same amount of mass,  $m_B$ , can be delivered to each tube by setting the application time inversely proportional to the velocity, i.e.,  $t_2 = m_B / (f_1 v)$ . This scenario, where both  $v$  and  $t_2$  are random, may occur when solid chemicals are added uniformly across the field and leached subsequently by continuously applying solute-free water. The input concentration,  $f_1$ , is regarded as approximately constant since this concentration may be governed by the solubility of the chemical. Figure 4.6 schematically illustrates the solute distribution between tubes for a pulse input of constant and variable duration.

Figure 4.7 presents field-scale resident concentrations ( $\hat{c}_r$ ) versus depth at  $t = 3$  d as a result of a pulse-type solute application with a constant ( $t_2 = 1$  d) and variable ( $\langle t_2 \rangle = 1$  d) solute application time. The same amount of solute is applied to the entire field. The transport parameters for this example are the same as those used for Figure 4.5. Again, more solute remains near the surface for the constant mass injection. Since the amount of solute in stream tubes with a higher  $v$  is larger for the constant duration scenario, solute moves down faster in this case compared to the case of a variable solute application time.

We emphasize that the previous examples involving Dirac- and pulse-type applications are somewhat hypothetical since the stream tube model does not permit mixing between stream tubes. Redistribution between stream tubes is likely to establish an intermediate situation where the mass in each stream tube is not constant, but where differences between tubes are also not as large as for the constant duration case because of horizontal mixing. Some horizontal mixing will likely also occur at the surface.

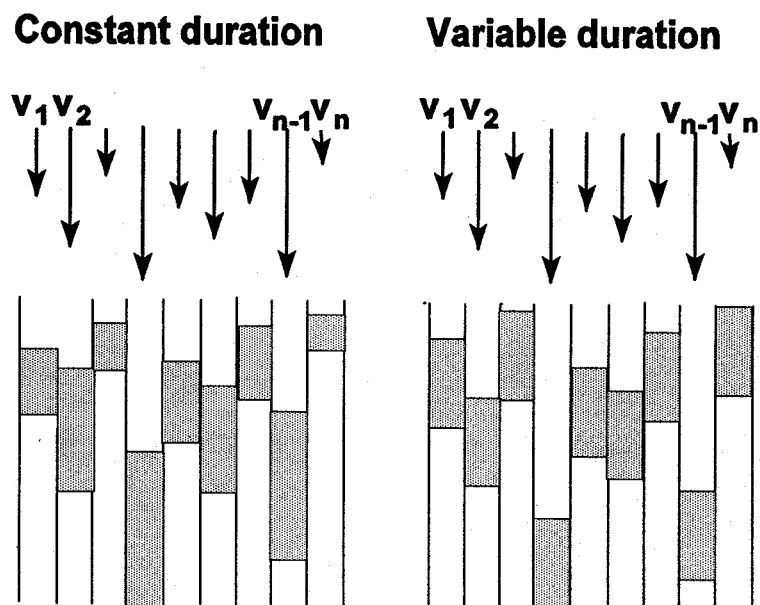


Fig. 4.6. Illustration of the solute distribution in stream tubes after a pulse application of constant and variable duration.

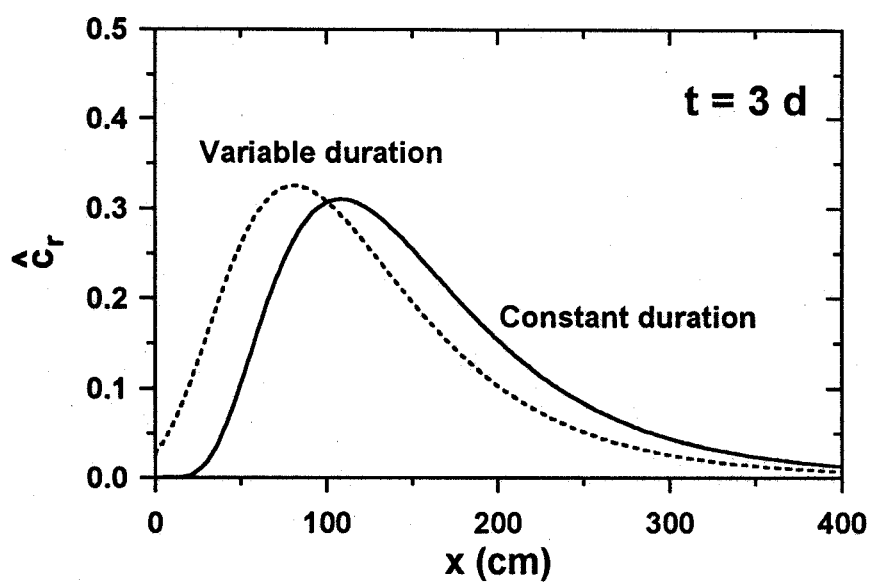


Fig. 4.7. Field-scale resident concentrations ( $\bar{c}_r$ ) versus depth as a result of a pulse-type solute application of constant and variable duration.



## 4.5. Stream Tube Models in CXTFIT 2.1

CXTFIT 2.1 allows the use of the stream tube model using several analytical solutions of the CDE for local-scale transport, and with stochastic parameters described by the bivariate lognormal pdf given by (4.9). Three different pdfs can be used, viz.  $f(v, D)$ ,  $f(v, K_d)$ , and  $f(v, \alpha)$ . Two additional stochastic parameters can be included provided that they are perfectly correlated with  $v$  (cf. (4.15)).

If  $v$  and  $D$  are stochastic, a positive correlation between them might be plausible as suggested by the widely used relationship for the dispersivity,  $\lambda = D/v$ . Substitution of  $\eta = D$  into (4.15) for a perfect positive correlation,  $\rho_{vD} = 1$ , leads to

$$D(v) = \left( \frac{v}{\langle v \rangle} \right)^{\frac{\sigma_D}{\sigma_v}} \langle D \rangle \exp \left( \frac{1}{2} \sigma_v \sigma_D - \frac{1}{2} \sigma_D^2 \right) \quad (4.24)$$

In case  $\sigma_v = \sigma_D$ , the relationship between  $v$  and  $D$  can be simplified to

$$D(v) = \langle D \rangle v / \langle v \rangle \quad (4.25)$$

This equation implies a constant dispersivity  $\lambda = \langle D \rangle / \langle v \rangle$  for all stream tubes (cf. Eq.(60) of *Parker and van Genuchten* [1984b]).

A negative correlation between  $v$  and  $K_d$  may also be plausible since coarse-textured soils generally have a relatively high conductivity — and hence a high  $v$  — and a small  $K_d$  — and therefore a small  $R$  — whereas the opposite is true for fine-textured soils. When  $\rho_{vK_d} = -1$ , the expression for  $K_d$  becomes (cf. (4.15)):

$$K_d(v) = \left( \frac{v}{\langle v \rangle} \right)^{-\frac{\sigma_{Kd}}{\sigma_v}} \langle K_d \rangle \exp \left( -\frac{1}{2} \sigma_v \sigma_{Kd} - \frac{1}{2} \sigma_{Kd}^2 \right) \quad (4.26)$$

If, in addition, we assume that  $\sigma_v = \sigma_{Kd}$  this expression may be written as

$$K_d(v) = \langle v \rangle \langle K_d \rangle \exp(-\sigma_v^2) / v \quad (4.27)$$

An overview of the five stream tube models in CXTFIT 2.1 will be given later in Table 6.1. The boundary (BVP), initial (IVP), and production (PVP) value problems in terms of the field-scale stream tube model follow directly from the local-scale solution.

## 5. NUMERICAL EVALUATION

The FORTRAN program CXTFIT 2.1 was written to evaluate the one-dimensional analytical solutions that were discussed in Chapters 2 through 4. In this chapter we will provide background information on numerical procedures followed to solve the direct and inverse problems. First, the main program units of CXTFIT 2.1 are briefly reviewed. The numerical evaluation of the integrals and various special functions in the analytical solutions are discussed subsequently. The previous version of CXTFIT published by *Parker and van Genuchten* [1984b] was widely used to fit mathematical solutions to experimental results in order to estimate transport parameters. We have outlined the estimation procedure, which is based on the Levenberg-Marquardt algorithm.

We note that all the information needed to use the program is given in Chapter 6. Detailed instructions for the preparation of the input file are presented in Section 6.2, while significant variables and arrays in CXTFIT 2.1 are listed in the Appendix. This Chapter 5 should be of special interest to readers who experience unexpected results due to errors in the evaluation of mathematical functions, or when trying to solve inverse problems.

### 5.1. Description of Program Units

CXTFIT 2.1 consists of a main program, 22 subroutines, and 27 functions. These subprograms are stored in nine source files. The executable program CXTFIT2 is obtained after compiling and linking. Table 5.1 presents a list of the source files and associated subprograms.

#### **CXTFIT2.FOR**

The program unit **Main** controls the input, output, and parameter optimization procedures. The subroutine **MATINV** performs matrix inversion for the least-squares analysis.

#### **DATA.FOR**

Subroutine **DATAIN** reads data from the input file specified by the user. The data is verified with subroutine **CHECK**, which gives error messages for unacceptable input. The subroutine **DATAOUT** writes user-provided input data to the output file.

Table 5.1. Source files in CXTFIT 2.1

Source file	Subroutine and Function
CXTFIT2.FOR	Main, MATINV
DATA.FOR	DATAIN, CHECK, DATAOUT
MODEL.FOR	MODEL, DIRECT
DETCDE.FOR	DETCDE, BOUND, INITIAL, PRODUC
STOCDE.FOR	STOCDE, CONPROV, CONPROY, LIMIT, XLNPROB, BLNPROB
FUNC1.FOR	CTTRAN, CBJ, CBAL, CBEXP, CBIN1, CBIN2, CIVP, C1PRO, C2PRO, CC0, CC1, CC2, CC3, CC4, CC5, PROD0
FUNC2.FOR	DBEXP, EXF, EXPBI0, EXPBI1, PHI1, PHI2, GOLD,
INTEGRAL.FOR	ROMB, ROMB2, CHEBY, CHEBY2, CHEBYCON, CHEBYLOG, CHEBYLOG2
USER.FOR	CONST1, CONST2, CINPUT

**MODEL.FOR**

Subroutine **MODEL** performs coefficient assignments and routes the execution to an appropriate subroutine for evaluation of a particular model. Subroutine **DIRECT** calculates the concentration for specific times and depths (i.e., the solution of the direct problem).

**DETCDE.FOR**

Subroutine **DETCDE** models deterministic transport according to the equilibrium and nonequilibrium CDE by adding the solutions for the BVP, IVP, and PVP. Subroutines **BOUND**, **INITIAL**, and **PRODUC** are used to calculate the specific solutions for the BVP, IVP, and PVP, respectively.

**STOCDE.FOR**

This file calculates concentrations and variances for stochastic transport. Subroutine **STOCDE** routes the execution. Function **CONPROV** is used for integration with respect to  $v$ , while the function **CONPROY** evaluates the integrand for other stochastic parameters. Subroutine **LIMIT** modifies the integration boundaries for the field-scale mean concentrations using the Newton-

Raphson method. Subroutines **XLNPROB** and **BLNPROB** quantify the single and bivariate lognormal distributions, respectively.

### ***FUNC1.FOR***

This file evaluates many of the functions used in the analytical solutions for the equilibrium and nonequilibrium CDE. The integrands in the nonequilibrium CDE are determined by the functions: **CTTRAN** for (3.17) and (3.18), **CBJ** for (3.21) and (3.22), **CBAL** for (3.23) and (3.24), **CBEXP** for (3.26) and (3.27), **CBIN1** for (3.13), **CBIN2** for (3.14), **CIVP** for the IVP (i.e., (3.34), (3.35), (3.37), (3.38), (3.40), and (3.41)), **C1PRO** for (3.47) and (3.50), and **C2PRO** for (3.48) and (3.51). The functions listed in Tables 2.2, 2.3, 3.2, and 3.3 are evaluated as follows: **CC0** for  $\Gamma_1^E$  or  $\Gamma_1^N$ , **CC1** for  $G_1^E$  or  $G_1^N$  for  $\Omega = 0$ , **CC2** for  $\psi_1^E$  or  $\psi_1^N$ , **CC3** for  $\psi_2^E$  or  $\psi_2^N$ , **CC4** for  $G_1^E$  or  $G_1^N$  if  $\Omega \neq 0$ , **CC5** for  $\Gamma_2^E$  or  $\Gamma_2^N$ , and **PROD0** for  $G_2^E$ .

### ***FUNC2.FOR***

The remaining functions in the analytical solutions are evaluated in **FUNC2.FOR**. The function **DBEXP** calculates the exponential function (exp), a (minimum) constraint of -100 is placed on the argument. The function **EXF** evaluates the product of exponential (exp) and complementary error (erfc) functions. **EXPBI0** and **EXPBI1** are used to determine the product of the exponential function (exp) and the modified Bessel functions of order zero ( $I_0$ ) and one ( $I_1$ ), respectively (used in  $H_0$  and  $H_1$  as shown in Table 3.4). Functions **PHI1** and **PHI2** are used for exponential solute input to calculate  $\Phi_1$  in (3.28) and  $\Phi_2$  in (3.29). Goldstein's J-function (Table 3.4) is determined with the function **GOLD**, which appears in the BVP and PVP for the nonequilibrium CDE.

### ***INTEGRAL.FOR***

This file includes subroutines for numerical integration. Subroutines **ROMB** and **ROMB2** perform a Romberg quadrature on a log-transformed interval for the field-scale mean concentration. Subroutines **CHEBY**, **CHEBY2**, and **CHEBYCON** use Gauss-Chebyshev quadrature to determine integrals in the solutions for the nonequilibrium CDE. Similarly, routines **CHEBYLOG** and **CHEBYLOG2** carry out the integration on a log-transformed interval.

## USER.FOR

USER.FOR contains subroutines that allow a user to change settings for the numerical integration or the input function. The default settings have been found to work well in most cases. Subroutine CONST1 includes parameters for the least-squares inversion method and Gauss-Chebyshev quadrature, while CONST2 specifies parameters for Romberg quadrature. The user can specify an arbitrary input function with CINPUT.

## 5.2. Deterministic CDE

The analytical solutions described in Chapters 2 and 3 are evaluated in DETER.FOR. Several functions for evaluating these solutions are stored in FUNC1.FOR and FUNC2.FOR. The expressions for the equilibrium CDE (Table 2.2 and 2.3) are evaluated by setting  $\beta = 1$  in the functions for the nonequilibrium CDE (Table 3.2 and 3.3).

The function EXF(A,B) defines the product of the exponential function (exp) and the complementary error function (erfc) [van Genuchten and Alves, 1982]:

$$EXF(A,B) = \exp(A) \operatorname{erfc}(B) \quad (5.1)$$

where

$$\operatorname{erfc}(B) = \frac{2}{\sqrt{\pi}} \int_B^{\infty} \exp(-\tau^2) d\tau \quad (5.2)$$

Two different approximations are used for EXF(A,B). For  $0 \leq B \leq 3$  [see also (7.1.26) of Abramowitz and Stegun, 1970]

$$\operatorname{erfc}(B) \approx \exp(-B^2) (a_1 \tau + a_2 \tau^2 + a_3 \tau^3 + a_4 \tau^4 + a_5 \tau^5) \quad (5.3)$$

where  $\tau = 1/(1+0.3275911B)$ ,  $a_1 = 0.254896$ ,  $a_2 = -0.2844967$ ,  $a_3 = 1.421414$ ,  $a_4 = -1.453152$ , and  $a_5 = 1.061405$ . For  $B > 3$  [(7.1.14) of Abramowitz and Stegun, 1970]:

$$EXF(A,B) \approx \frac{1}{\sqrt{\pi}} \exp(A-B^2) / (B+0.5/(B+1.0/(B+1.5/(B+2.0/(B+2.5/(B+1.0)))))) \quad (5.4)$$

The following relation is used for negative values of B:

$$EXF(A,B) = 2 \exp(A) - EXF(A, -B) \quad (5.5)$$

The above approximations do not work well if the arguments A and/or B are small. Therefore,

**EXF(A,B)** is set to zero for either of the following two conditions:

$$\begin{array}{cc} |A| > 170 & \text{or} & |A - B^2| > 170 \\ B \leq 0 & & B > 0 \end{array} \quad (5.6)$$

Evaluation of the function  $G(Z, T, \Omega)$  listed in Tables 2.3 and 3.3 depends on the value of  $\Omega$ . Note that for an exponential input involving a large  $\lambda^B$ ,  $\Omega$  in solution (2.21) can be less than  $-P/4$ . In this case the integral in the general expression for  $G(Z, T, \Omega)$  will be evaluated using numerical integration.

The functions  $H_0(\tau, T)$  and  $H_1(\tau, T)$  in the solutions listed in Table 3.4 are evaluated with **EXPBI0** and **EXPBI1**, respectively, using (9.8.1), (9.8.2), (9.8.3), and (9.8.4) of *Abramowitz and Stegun* [1970] with  $Y = X / 3.75$ :

$$\begin{aligned} \text{EXPBI0}(X, Z) &= e^Z I_0(X) \\ &= \begin{cases} e^Z (1.0 + 3.5156229 Y^2 + 3.0899424 Y^4 + 1.2067492 Y^6 \\ \quad + 0.2659732 Y^8 + 0.0360768 Y^{10} + 0.0045813 Y^{12}) & (-3.71 \leq X \leq 3.7) \\ e^{(Z+X)/\sqrt{X}} (0.39894228 + 0.01328592 Y^{-1} + 0.00225319 Y^{-2} \\ \quad - 0.00157565 Y^{-3} + 0.00916281 Y^{-4} - 0.02057706 Y^{-5} \\ \quad + 0.02635537 Y^{-6} - 0.01647633 Y^{-7} + 0.00392377 Y^{-8}) & (X \geq 3.75) \end{cases} \end{aligned} \quad (5.7)$$

$$\begin{aligned} \text{EXPBI1}(X, Z) &= e^Z I_1(X) \\ &= \begin{cases} X e^Z (0.5 + 0.87890594 Y^2 + 0.51498869 Y^4 + 0.15084934 Y^6 \\ \quad + 0.02658733 Y^8 + 0.00301532 Y^{10} + 0.00032411 Y^{12}) & (-3.71 \leq X \leq 3.75) \\ e^{(Z+X)/\sqrt{X}} (0.39894228 - 0.03988024 Y^{-1} - 0.00362018 Y^{-2} \\ \quad + 0.00163801 Y^{-3} - 0.01031555 Y^{-4} + 0.02282967 Y^{-5} \\ \quad - 0.02895312 Y^{-6} + 0.01787654 Y^{-7} - 0.00420059 Y^{-8}) & (X \geq 3.75) \end{cases} \end{aligned} \quad (5.8)$$

Goldstein's  $J$ -function, given in Table 3.4, is evaluated with the function **GOLD**. Two approximations are used depending on the values of  $a$  and  $b$  [van Gemuchten, 1981b]. For relatively small values of  $a$  and  $b$ , a series expansion of the Bessel function is integrated [De Smedt and Wierenga, 1979]. For  $a \geq b$  with  $k = 11 + 2b + 0.3a < 25$  we used

$$J(a, b) = \exp(-a-b) \sum_{n=0}^k \frac{b^n}{n!} \sum_{m=0}^n \frac{x^m}{m!} + E, \quad |E| < \frac{b^{k+1}}{(k+1)!} \quad (5.9)$$

where  $E$  is the error in the series expansion containing  $k$  terms, while for  $a < b$  with  $k = 11 + 2a + 0.3b < 25$  we used

$$J(a, b) = 1 - \exp(-a-b) \sum_{n=0}^k \frac{a^n}{n!} \sum_{m=0}^{n-1} \frac{b^m}{m!} + E, \quad |E| < \frac{a^k}{k!} \quad (5.10)$$

For larger values of  $a$  and  $b$ ,  $J(a, b)$  is given by [Goldstein, 1953]

$$J(a, b) = \begin{cases} A + B & (a \geq b) \\ 1 - A + B & (a < b) \end{cases} \quad (5.11)$$

where

$$A = \frac{\sqrt{a} + \sqrt{b}}{4(ab)^{1/4}} \operatorname{erfc}(\sqrt{z}) \quad (5.12)$$

$$B = \frac{1}{2} \exp(-a-b) I_0(2\sqrt{ab}) + \frac{(a-b)e^{-z}}{4\sqrt{\pi}(ab)^{1/4}} \sum_{m=1}^{\infty} \frac{\alpha_m S_m(z)}{(16ab)^{m/2}} \quad (5.13)$$

$$\alpha_m = \frac{\Gamma(m+1/2)}{\Gamma(1/2)m!} \quad (5.14)$$

$$S_{m+1}(z) = \frac{\Gamma(m+1/2)}{\Gamma(1/2)m!} - z S_m(z) \quad (5.15)$$

$$S_1(z) = 1 - \sqrt{\pi z} e^z \operatorname{erfc}(\sqrt{z}) \quad (5.16)$$

$$z = (\sqrt{a} - \sqrt{b})^2 \quad (5.17)$$

The integrals in the nonequilibrium solutions were evaluated with Gauss-Chebyshev quadrature [e.g. Carnahan *et al.*, 1969; Press *et al.*, 1992]. Gauss-Chebyshev quadrature offers flexibility in terms of selecting the number of integration points. We obtained accurate results with 50 integration points for most cases (generally four to five significant digits). In some extreme cases, such as for very small  $\beta$  and  $Z$  or very large  $T$ , the results using 50 points may become inaccurate or incorrect. A greater number of integration points generally results in more accurate results at the expense of additional computer time. The latter effect is especially of concern when solving the inverse problem. The number of integration points, MM, can be changed in subroutine **CONST1**. The parameter

ICHEB in subroutine **CONST1** controls the integration method. If  $ICHEB = 0$ ,  $MM$  is constant at all times. If  $ICHEB = 1$ , the program evaluates the solutions twice, namely with  $MM$  and  $2 \times MM$  in the integration routine. The number of integration points is increased until the relative change in the solution becomes less than 0.1%. We suggest to use a set ( $ICHEB = 0$ ) value of 75 for  $MM$  when solving the inversion problem whereas  $ICHEB = 1$  and  $MM = 75$  appear attractive selections for the direct problem.

An alternative method to achieve computational efficiency and accuracy is to narrow the integration interval. The integrand in (3.17) for a Delta input (i.e.,  $f$  according to (3.15)), or in (3.20) for a pulse input, becomes negligible for small or large  $\tau$  due to the exponential and complementary error functions in  $\Gamma_1^N$ . The modified lower (T1) and upper (T2) integration limits were obtained by restricting integration to the domain where the argument of exponential function exceeds -30:

$$T_1 = \beta R Z + \frac{60 \beta R}{P} \left\{ 1 - \sqrt{1 + \frac{PZ}{30}} \right\} \quad (5.18)$$

$$T_2 = \beta R Z + \frac{60 \beta R}{P} \left\{ 1 + \sqrt{1 + \frac{PZ}{30}} \right\} \quad (5.19)$$

The above modifications may significantly improve the computational efficiency without loss of accuracy, especially for large  $T$ .

The general solution of the deterministic BVP for an arbitrary input  $C_o$  is calculated by numerically evaluating convolution integrals (2.15) for the equilibrium CDE or (3.13) and (3.14) for the nonequilibrium CDE. The input function needs to be specified in function **CINPUT** in file **USER.FOR** (see also Chapter 6). Calculation of the solution should be relatively slow since a double integral is evaluated numerically.



### 5.3. Stochastic CDE

File **STOCDE.FOR** assigns local-scale parameters to each stream tube and evaluates field-scale averaged concentrations. The concentration in each stream tube is determined as described in section 5.2. Numerical integration required for the field-scale concentration and variance is carried out on in subroutines **ROMB** and **ROMB2** on a log-transformed interval using up to 14th order Romberg quadrature. Since a lognormal pdf is used, log-transformation improves the efficiency and accuracy of the numerical integration, especially for a large standard deviation,  $\sigma$ . Similar to Gauss-Chebyshev quadrature, convergence is evaluated by comparing the integration for the  $k$ th and  $k+1$ th order. The relative error criterion is set with variable **STOPER**. Convergence can usually be achieved for order  $k \leq 10$  with  $\text{STOPER} = 5 \times 10^{-7}$  unless the local Peclet number,  $vx/D$ , is high. As with the deterministic CDE, increasing the number of integration points will result in more accurate results at the expense of more computer time. The default upper limit for  $k$  is eight, with  $\text{STOPER} = 5 \times 10^{-5}$  for the evaluation of triple integrals (e.g., the stochastic nonequilibrium CDE with  $\rho_{v\eta} \neq \pm 1$ ) or the solution of the inverse problem. The settings for Romberg quadrature are contained in subroutine **CONST2**, which appears in file **USER.FOR**.

To improve the computational efficiency, the upper and lower limits of integrals in the expressions for the field-scale concentration are restricted by excluding values for  $v$  and  $\eta$  that have a likelihood of occurrence of less than  $1 \times 10^{-7}$ . The integration limits are determined according to the Newton-Raphson method in subroutine **LIMIT**. For a large standard deviation, for example  $\sigma = 2$  ( $\text{CV} = 732\%$ ), the integration range may become too broad for numerical evaluation with this criterion.

### 5.4. Parameter Estimation

**CXTFIT 2.1** estimates unknown model parameters using a nonlinear least-squares optimization approach based on the Levenberg-Marquardt method [Marquardt, 1963]. The inverse problem is solved by fitting an appropriate mathematical solution to observed concentration data. Most of the calculations for the least-squares analysis are carried out in the main program (**Main**). The model parameters are determined by minimizing an objective function (the sum of squared residuals, **SSQ**) defined as

$$\text{SSQ}(\mathbf{b}) = \sum_{i=1}^N [c(x_i) - f(x_i; \mathbf{b})]^2 \quad (5.20)$$

where  $\mathbf{b}$  represents the vector of unknowns containing  $M$  adjustable parameters  $b_j$  ( $j = 1, \dots, M$ ), and  $c$  and  $f$  are the observed and fitted concentrations for the  $i$ th data point as obtained with the independent variable(s)  $x_i$  ( $i = 1, \dots, N$ ). The inversion procedure in CXTFIT 2.1 is essentially the same as used in its precursors [van Genuchten, 1979; 1980; Parker and van Genuchten, 1984b], and hence will be reviewed here only briefly. The optimization routine is a simplification of the nonlinear least-squares curve-fitting program of Meeter [1966]. A detailed description of the method is given by Press *et al.* [1992].

When a model depends nonlinearly on a set of  $M$  unknown parameters  $b_j$ , minimization of (5.20) has to be carried out iteratively. At the  $r$ th iteration, the correction vector  $\delta \mathbf{b}$  is evaluated according to the following linear equation:

$$(\mathbf{A}^r + \lambda^r \mathbf{I}) \delta \mathbf{b} = \mathbf{Q}^r \quad (5.21)$$

where

$$A_{kj} = \sum_{i=1}^N \frac{\partial f(x_i; \mathbf{b}^r)}{\partial b_k} \frac{\partial f(x_i; \mathbf{b}^r)}{\partial b_j} \quad k = 1, \dots, M, \quad j = 1, \dots, M \quad (5.22)$$

$$Q_j = \sum_{i=1}^N \frac{\partial f(x_i; \mathbf{b}^r)}{\partial b_j} [c(x_i) - f(x_i; \mathbf{b}^r)] \quad j = 1, \dots, M \quad (5.23)$$

and  $\lambda^r$  is a nonnegative scalar (a Lagrangian multiplier),  $\mathbf{I}$  is the unit matrix of order  $N$ , and the new trial vector is given by  $\mathbf{b}^{r+1} = \mathbf{b}^r + \delta \mathbf{b}$ . Notice that when  $\lambda$  is very large,  $\mathbf{A} + \lambda \mathbf{I}$  becomes diagonally dominant, and (5.21) can be rewritten to

$$\delta b_j = \frac{1}{A_{jj}(1 + \lambda)} Q_j \quad (5.24)$$

which is identical to the steepest descent method. On the other hand, when  $\lambda$  approaches zero, (5.21) converges to the Taylor series method (the Gauss-Newton method). Since a linear expansion of the Taylor method will be accurate only over a small region, the Levenberg-Marquardt method aims to gradually reduce  $\lambda$  as  $\text{SSQ}(\mathbf{b})$  reaches its minimum.

After an initial estimate for  $\mathbf{b}$  is provided, "best-fit" parameters are determined as follows (most constants for the optimization are stored in subroutine **CONST1** of file **USER.FOR**):

- (1) Compute  $SSQ(\mathbf{b})$ .
- (2) Set  $\lambda = 0.001$  (= GA/GD in **CONST1**).
- (3) Solve (5.21) for  $\delta \mathbf{b}$  and define a scale factor  $\mu = 1$ .
- (4) Compute  $SSQ(\mathbf{b} + \mu \delta \mathbf{b})$ .
- (5) If  $SSQ(\mathbf{b} + \mu \delta \mathbf{b}) < SSQ(\mathbf{b})$ , decrease  $\lambda$  by a factor 10 (GD in **CONST1**), update the trial vector  $\mathbf{b} = \mathbf{b} + \mu \delta \mathbf{b}$ , and go back to (3).
- (6) If  $SSQ(\mathbf{b} + \mu \delta \mathbf{b}) \geq SSQ(\mathbf{b})$ , evaluate the angle  $\vartheta$  between the correction vector  $\delta \mathbf{b}$  and the steepest descent direction  $\mathbf{Q}$ .
- (7) If  $\vartheta < 30^\circ$ , decrease  $\mu$  by a factor 2, and return to (6).
- (8) If  $\vartheta \geq 30^\circ$ , increase  $\lambda$  by a factor 10, and return to (3).

The iteration stops when either of the following conditions is met:

- (a) The relative change in each estimation parameter ( $\mu \delta b_j / b_j$ ) is less than the criterion STOPCR (default value is 0.0005 in **CONST1**).
- (b) The relative decrease in SSQ is less than  $1.0 \times 10^{-6}$  (= STSQ in **CONST1**) for three successive iterations.
- (c) SSQ decreases more than MIT times without meeting either condition (a) or (b) (MIT is defined in the input file).
- (d) SSQ fails to decrease during 50 consecutive iterations (= MAXTRY in **CONST1**).

The derivatives of the fitted concentrations — based on the selected mathematical model — with respect to parameter  $b_j$  are evaluated according to

$$\frac{\partial f(x_i; \mathbf{b})}{\partial b_j} \approx \frac{f(x_i; b_1, \dots, (1+\Delta)b_j, \dots, b_M) - f(x_i; b_1, \dots, b_j, \dots, b_M)}{\Delta b_j} \quad (5.25)$$

The current setting for  $\Delta$  is 0.01 for all parameters (DERL in **CONST1**), which we found to be appropriate for most cases. When  $b_j$  is very small or insensitive to changes in the fitted concentration, however, approximation (5.25) for the derivative may become inaccurate. The restriction  $|\rho_{v\eta}| > 1 \times 10^{-5}$  is placed on the correlation between stochastic parameters in order to evaluate the derivative according to (5.25) for the parameter estimation involving stream tube models.

The iteration procedure sometimes converges to different local minima depending upon the initial estimate for  $\mathbf{b}$ , as will be demonstrated in Table 7.2. It is essential to provide realistic initial estimates

of the parameters, as close to the global minimum as possible. Furthermore, CXTFIT 2.1 allows the use of maximum and minimum constraints on fitted parameters. When the new parameter value exceeds a specified maximum or minimum value during the iteration process, the value for the constraint is used for the next trial.

In addition to user-specified constraints, the program employs an internal constraint on  $\beta$  for the deterministic nonequilibrium CDE. Since the fraction of equilibrium adsorption sites,  $f$ , ranges from 0 to 1 for the two-site model (see Section 3.1), the range of possible  $\beta$  values is

$$\frac{1}{R} \leq \beta < 1 \quad (5.26)$$

A similar range holds for the fraction of adsorption sites in the mobile phase,  $f$ , for the two-region model:

$$\frac{1}{R} \frac{\theta_m}{\theta} \leq \beta < \frac{1}{R} \left( \frac{\theta_m}{\theta} + \frac{\rho_b K_d}{\theta} \right) \quad (5.27)$$

A maximum constraint is also placed on  $\omega$ , the constraint value for this parameter is defined by OMMAX in subroutine CONST1. We note that constrained parameter optimization often results in a slightly slower rate of convergence because of a loss in flexibility.

Finally, we recommend to generally carry out several estimation trials with and without constraints as well as with different initial estimates for  $b$ . Also, parameter optimization ("curve fitting") should never be used as a panacea for a mathematical model that does not reflect the underlying transport processes.



## 6. CXTFIT 2.1 USER'S GUIDE

The previous chapters provided a background of the solute transport models and of the numerical procedures to evaluate their analytical solutions. This chapter serves as a self-contained user manual for CXTFIT 2.1. First, the structure of CXTFIT 2.1 is outlined to give the user a quick overview of the different modeling options. Second, the preparation of the input file is discussed. The input is provided in a modular fashion, by using a series of blocks. Readers may only have to read the text pertaining to the blocks for their specific application. Third, the structure of the input and output files used for examples in this report will be reviewed. Fourth, we will compare the differences in input format between the first version of CXTFIT [Parker and van Genuchten, 1984b] and the current CXTFIT 2.1.

### 6.1. Structure of CXTFIT 2.1

CXTFIT 2.1 contains three different one-dimensional transport models: (i) the conventional CDE; (ii) the chemical and physical nonequilibrium CDE; and (iii) a stochastic stream tube model based on the local-scale CDE. Five different versions of the stochastic model can be selected depending upon the type of adsorption present (equilibrium or nonequilibrium), and the type of random transport parameters. Table 6.1 lists the characteristics of all seven models in CXTFIT 2.1; the models are identified in the program by the parameter MODE. Deterministic transport can be modeled with the equilibrium (MODE = 1) and nonequilibrium (MODE = 2) CDEs. The five versions of the stream tube model are: equilibrium (MODE = 3) and nonequilibrium (MODE = 4) adsorption with random  $v$ ,  $D$ , and  $K_d$  ( $\rho_{vD} = 1$ ); equilibrium (MODE = 5) and nonequilibrium (MODE = 6) adsorption with random  $v$ ,  $D$ , and  $K_d$  ( $\rho_{vKd} = -1$ ); and nonequilibrium adsorption with random  $v$ ,  $D$ ,  $K_d$ , and  $\alpha$  assuming  $\rho_{vD} = 1$  and  $\rho_{vKd} = -1$  (MODE = 7). A stochastic parameter can be made deterministic by setting its standard deviation to zero.

Table 6.1. Overview of Transport Models in CXTFIT 2.1

MODE	Model Type	Parameters	Concentration Mode
<b>Deterministic CDE</b>			
1	Equilibrium	$v, D, R, \mu$ or $\mu^E$	$C_f, C_r, C_T = RC_r$
2	Nonequilibrium	$v, D, R, \beta, \omega, \mu_1, \mu_2$	$C_f, C_r, C_T = \beta RC_{1,r} + (1-\beta)RC_{2,r}$
<b>Stochastic Equilibrium CDE</b>			
3	Random $v, D$ , and $K_d$ with $\rho_{vD}=1$	$\langle v \rangle, \langle D \rangle, \langle K_d \rangle, \mu$ or $\mu^E$ $\sigma_v, \sigma_D, \sigma_{Kd}, \rho_{vKd}$	$\langle C_f \rangle, \hat{C}_f = \langle v C_f \rangle / \langle v \rangle, \hat{C}_r = \langle C_r \rangle$ $\hat{C}_T = \langle RC_r \rangle$
5	Random $v, D$ , and $K_d$ with $\rho_{vKd}=-1$	$\langle v \rangle, \langle D \rangle, \langle K_d \rangle, \mu$ or $\mu^E$ , $\sigma_v, \sigma_D, \sigma_{Kd}, \rho_{vD}$	Same as 3
<b>Stochastic Nonequilibrium CDE</b>			
4	Random $v, D$ , and $K_d$ with $\rho_{vD}=1$	$\langle v \rangle, \langle D \rangle, \langle K_d \rangle, \omega, \mu_1, \mu_2$ , $\sigma_v, \sigma_D, \sigma_{Kd}, \rho_{vKd}$	$\langle C_f \rangle, \hat{C}_f = \langle v C_f \rangle / \langle v \rangle, \hat{C}_r = \langle C_r \rangle$ $\hat{C}_T = \langle C_{1,r} + (R-1)C_{2,r} \rangle$
6	Random $v, D$ , and $K_d$ with $\rho_{vKd}=-1$	$\langle v \rangle, \langle D \rangle, \langle K_d \rangle, \omega, \mu_1, \mu_2$ , $\sigma_v, \sigma_D, \sigma_{Kd}, \rho_{vD}$	Same as 4
7	Random $v, D, K_d$ , and $\alpha$ with $\rho_{vD}=1$ and $\rho_{vKd}=-1$	$\langle v \rangle, \langle D \rangle, \langle K_d \rangle, \langle \alpha \rangle, \mu_1$ , $\mu_2, \sigma_v, \sigma_D, \sigma_{Kd}, \sigma_\alpha, \rho_{v\alpha}$	Same as 4

Table 6.1 also presents the mode in which the concentration is detected or predicted. Resident, flux-averaged, and total resident concentrations can be used. Although a third-type inlet condition is generally preferable [van Genuchten and Parker, 1994], resident concentrations are also given for a first-type inlet condition. Flux-averaged concentrations are derived from the resident concentration for a third-type inlet condition according to (2.13). Two-types of macroscopic flux-averaged concentration are available for stochastic transport, i.e., the ensemble average of the local-scale flux-averaged concentration,  $\langle C_f \rangle$ , and the field-scale flux concentration,  $\hat{C}_f (= \langle v C_f \rangle / \langle v \rangle)$ .

All analytical solutions given in Chapters 2 and 3 can be evaluated with CXTFIT 2.1. The solution of the CDE is described as the sum of (i) a boundary value problem (BVP), (ii) an initial value problem (IVP), and (iii) a production value problem (PVP). Table 6.2 summarizes the functions that are used to characterize the BVP, IVP, and PVP.

Table 6.2. Functions for the Boundary (BVP), Initial (IVP), and Production (PVP)  
Value Problems in CXTFIT 2.1†

Function	Input Concentration	Initial Profile	Production Profile‡
Dirac Delta	$C_o(T) = M_B \delta(T)$ or $c_o(t) = \frac{m_B}{v} \delta(t)$	$C_i(Z) = M_I \delta(Z - Z_1)$ or $c_i(x) = \frac{m_I}{\theta} \delta(x - x_1)$	-
Stepwise	$C_o(T) = f_i \quad T_i \leq T < T_{i+1}$ $(i = 1, 2, \dots, n;$ $T_1 = 0 \text{ and } T_{n+1} = \infty)$	$C_i(Z) = U_i \quad Z_i \leq Z < Z_{i+1}$ $(i = 1, 2, \dots, n;$ $Z_1 = 0 \text{ and } Z_{n+1} = \infty)$	$\gamma(Z) = \gamma_i \quad Z_i \leq Z < Z_{i+1}$ $(i = 1, 2, \dots, n;$ $Z_1 = 0 \text{ and } Z_{n+1} = \infty)$
Exponential	$C_o(T) = f_1 + f_2 \exp(-\lambda^B T)$	$C_i(Z) = U_1 + U_2 \exp(-\lambda^I Z)$	$\gamma(Z) = \gamma_1 + \gamma_2 \exp(-\lambda^P Z)$
Arbitrary	$C_o(T)$	-	-

†  $f_i, U_i, \gamma_i$  are arbitrary constants.

‡ The production profiles in phases 1 and 2 can be described separately for the nonequilibrium CDE.

## 6.2. Input Data Instruction

The input data are read from an ASCII file. The user is prompted for the name of the input file during execution. Default names for the input and output files can be specified in the main program. The input file consists of up to eight of the following blocks:

- A. Model Description
- B. Inverse Problem Parameters
- C. Transport Parameters
- D. Boundary Value Problem
- E. Initial Value Problem
- F. Production Value Problem
- G. Observed Data for an Inverse Problem
- H. Position and Time for a Direct Problem



Blocks B and G are used for the inverse problem ( $\text{INVERSE} = 1$ ) while Block H is used for the direct problem ( $\text{INVERSE} = 0$  or  $-1$ ).

All data are read in using list-directed formatting (free format) except for the case  $\text{INPUTM}=3$  in Block G. Dummy parameter values may have to be included in the input file to maintain the proper format. Dummy comment lines are provided for each input block to identify the block and the input variables — these may be left blank but should not be omitted. All input data are to be specified in consistent units for mass [M], length [L], and time [T] (see also  $\text{NREDU}$  in Block A). The first line of the input file gives  $\text{NCASE}$ , which specifies the number of cases that are considered. Several different cases (i.e., data sets) can be handled by one input file. The distribution diskette contains all input and output files for the examples in Chapters 4 and 7. Preparation of the input file for a particular example is done most conveniently by modifying an existing input file for a similar case.

The characteristics of each input group (block) in the input file are further discussed below. Line-by-line descriptions of every block are given in Tables 6.3 through 6.11.

#### ***Block A. Model Description*** (Table 6.3)

This block contains the parameters that define the type of problem to be solved. The parameter  $\text{INVERSE}$  controls whether a direct ( $\text{INVERSE} = 0$  or  $-1$ ) or inverse ( $\text{INVERSE} = 1$ ) problem is solved. A further distinction is made for the solution of the direct problem according to the stream tube model.  $\text{CXTFIT 2.1}$  will only calculate field-scale mean concentrations if  $\text{INVERSE} = -1$  while both mean concentrations and variances, the latter according to (4.20) and (4.21), are evaluated if  $\text{INVERSE} = 0$ . The parameter  $\text{MODE}$  specifies the model type while  $\text{MODC}$  denotes the concentration mode (cf. Table 6.1). The input format is different for deterministic ( $\text{MODE} \leq 2$ ) and stochastic transport ( $\text{MODE} \geq 3$ ) for some parameters. The total resident concentration is expressed as the amount of solute per unit volume of solution.

The parameter  $\text{NREDU}$  specifies whether the specified time and positions in the input and output files are dimensional or dimensionless. For dimensional times and positions ( $\text{NREDU} = 1$ ) the dimensional  $\mu$  and  $\gamma$  given by (2.5) and (2.6) should be specified for the equilibrium CDE ( $\text{MODE} = 1, 3, 5$ ). Otherwise, dimensionless degradation and production terms as defined in Table 2.1 and 3.1 should be used. For a unit characteristic concentration, i.e.,  $c_o = 1$ , dimensional and dimensionless

concentrations are obviously equal regardless of the value of NREDU; an exception is the adsorbed concentration in case of chemical nonequilibrium. For the nonequilibrium CDE with a random  $K_d$ , where  $\langle s/K_d c_o \rangle \neq \langle s \rangle / (\langle K_d \rangle c_o)$ , the adsorbed concentration is given as  $\langle s \rangle$  if NREDU = 0, and as  $\langle s/K_d \rangle$  if NREDU  $\geq 1$ .

The characteristic length,  $L$ , for nondimensional parameters is specified at the end of Block A. CXTFIT 2.1 always uses dimensionless parameters for its internal operations; all dimensional parameters, times, and positions in the input file are internally transformed to nondimensional variables using the (dummy) value for  $L$  in Block A. Depending on the value for NREDU, a transformation from the dimensionless back to the dimensional variables is carried out upon completion of all internal operations. It is recommended to use for  $L$  a value of similar magnitude as the observation scale (e.g., column length or soil profile depth).

Table 6.3. Block A - Model Description

Line	Type	Variable	Description
0	Integer	NCASE	Number of cases being considered (only for the first data set).
1	-	-	Comment line.
2,3	Char	TITLE1,2	Descriptive title for simulation.
4	-	-	Comment Line.
5	Integer	INVERSE	Calculation control code: -1 Direct problem (no results for variance in case of the stochastic CDE). 0 Direct problem (results for given parameters). 1 Inverse problem (parameter estimation).
5	Integer	MODE	Model code: 1 Deterministic equilibrium CDE. 2 Deterministic nonequilibrium CDE. 3 Stochastic equilibrium CDE with $f(v, K_d)$ and $\rho_{vD}=1$ . 4 Stochastic nonequilibrium CDE with $f(v, K_d)$ and $\rho_{vD}=1$ . 5 Stochastic equilibrium CDE with $f(v, D)$ and $\rho_{vKd}=-1$ . 6 Stochastic nonequilibrium CDE with $f(v, D)$ and $\rho_{vKd}=-1$ . 7 Stochastic nonequilibrium CDE with $f(v, \alpha)$ , $\rho_{vKd}=-1$ and $\rho_{vD}=1$ .

Table 6.3. (continued)

Line	Type	Variable	Description
5	Integer	NREDU†	Input and output data code: 0 Time and position are dimensional (adsorbed concentration for the stochastic nonequilibrium CDE is $\langle s \rangle$ ). 1 Time and position are dimensional (adsorbed concentration for the stochastic nonequilibrium CDE is $\langle s/K_d \rangle$ ). 2 Time and position are dimensionless. 3 Dimensionless time and dimensional position.
6	-	-	Comment line.
7	Integer	MODC	Concentration mode. <i>Deterministic CDE</i> (MODE=1 or 2): 1,2 Flux-averaged concentration, $C_f$ . 3 Resident concentration (third-type inlet), $C_r$ . 4 Total resident concentration (third-type inlet), $C_T = RC_r$ or $\beta RC_{1,r} + (1-\beta)RC_{2,r}$ . 5 Resident concentration (first-type inlet), $C_r$ . 6 Total resident concentration (first-type inlet), $C_T = RC_r$ or $\beta RC_{1,r} + (1-\beta)RC_{2,r}$ .  <i>Stochastic CDE</i> (MODE $\geq 3$ ): 1 Ensemble-averaged flux concentration, $\langle C_f \rangle$ . 2 Field-scale flux-averaged concentration, $\hat{C}_f = \langle v C_f \rangle / \langle v \rangle$ . 3 Field-scale resident concentration (third-type inlet), $\hat{C}_r = \langle C_r \rangle$ . 4 Field-scale total resident concentration (third-type inlet), $\hat{C}_T = \langle RC_r \rangle$ or $\langle C_{1,r} + (R-1)C_{2,r} \rangle$ . 5 Field-scale resident concentration (first-type inlet), $\hat{C}_r = \langle C_r \rangle$ . 6 Field-scale total resident concentration (first-type inlet), $\hat{C}_T = \langle RC_r \rangle$ or $\langle C_{1,r} + (R-1)C_{2,r} \rangle$ .
7	Real	ZL	Characteristic length for dimensionless parameters (see Table 2.1 and 3.1, leave blank for NREDU=1 in case of equilibrium CDE with MODE=1,3,5).

† Dimensional and dimensionless concentrations are equal if  $c_o=1$  (cf. Table 2.1 and 3.1). Specify dimensional  $\mu$  and  $\gamma$  according to (2.5) and (2.6) for the equilibrium CDE (MODE=1,3,5) when NREDU=0 or 1. Use dimensionless  $\mu$  and  $\gamma$  (cf. Table 2.1 and 3.1) in all other cases.

### **Block B. Inverse Problem Parameters (Table 6.4)**

This block contains data for the parameter estimation procedure. The parameter MIT specifies the maximum number of iterations. A value between 50 and 100 is recommended for MIT, a further reduction in SSQ is unlikely for MIT greater than 100. The inversion part is bypassed when MIT=0; the program then calculates concentrations for the specified initial parameters. This option is equivalent to solving the direct problem (INVERSE=1), provided that values for time and position are specified in Block G. The arrays INDEX(I) in Block C and C(I) in Block G are now read in as dummy information.

The parameter ILMT serves as a flag for parameter constraints. If the range of an estimated parameter is known, e.g., based on physical considerations or from experimental observations, maximum and minimum constraints can be specified by setting ILMT = 1. Although unrealistic parameter estimates are avoided in this manner, the rate of convergence is usually slower. If the same value is used as maximum and minimum constraint, there will be no constraint on that particular parameter during the optimization.

The input mass can be estimated along with transport parameters for either a Dirac input, step input, or pulse input by setting MASS = 1. When MASS = 1, it is necessary to give parameters for the mass estimation in Block D (ILMT, maximum and minimum constraints). This option should only be used as a last resort since a poor mass balance generally reflects discrepancies between the experiment and the conceptual transport model.

The parameter MNEQ specifies the type of nonequilibrium model being implemented. For the one-site model (MNEQ=1),  $\beta$  is always equal to  $1/R$ . This option may be useful when  $R$  is a fitting parameter. For the two-region model, no internal constraints on  $\beta$  are applied if MNEQ=0 ( $0 < \beta \leq 0.9999$  for ILMT=0 or the user can specify constraints for ILMT=1). When MNEQ $\geq 2$ , internal constraints according to (5.26) or (5.27) are applied during the iteration. The user can still impose additional constraints (ILMT=1).

The relation between degradation coefficients for phase 1 ( $\mu_1$ ) and phase 2 ( $\mu_2$ ) is specified with the parameter MDEG (cf. Table 3.5). When MDEG=0, these coefficients are estimated independently; they are related according to Table 6.4 when MDEG>0. The fraction of mobile water,  $\phi_m$ , should be given if MNEQ=3 or if MNEQ=0 and MDEG $\geq 2$ .

Table 6.4. Block B - Parameters for Inverse Problem

Line	Type	Variable	Description
1,2	-	-	Comment lines.
3	Integer	MIT	Maximum number of iterations (the inverse part is bypassed if MIT = 0, the program calculates concentrations at specified Z(I) and T(I) using the initial estimates as model parameters).
3	Integer	ILMT	Parameter constraint code: 0 No constraints for parameter estimation. 1 Use minimum and maximum constraints.
3	Integer	MASS	Total mass estimation code. This option is only available for the BVP in case of a Dirac, step-type, or single pulse input (see Block D; enter a dummy value or zero if MODB=0 or $\geq 4$ ). 0 No estimation for total mass. 1 Total mass included in estimation procedure.
Omit the following lines for the equilibrium CDE (MODE=1,3,5).			
4	-	-	Comment line.
5	Integer	MNEQ	Nonequilibrium model code (MNEQ=1 for the stochastic one-site model): 0 Two-region physical nonequilibrium model ( $0 < \beta \leq 0.9999$ ). 1 One-site chemical nonequilibrium model ( $\beta = 1/R$ ). 2 Two-site chemical nonequilibrium model ( $1/R \leq \beta \leq 0.9999$ ). 3 Two-region physical nonequilibrium model with internal constraints ( $\phi_m/R \leq \beta \leq (\phi_m + R - 1)/R$ ).
5	Integer	MDEG	Degradation estimation code for the nonequilibrium CDE (enter a dummy value if $\mu_1$ and $\mu_2$ are not fitted): 0 Solution and adsorbed phase degradation rates are independent. 1 Degradation everywhere the same ( $\mu_t = \mu_s$ ). 2 Degradation only in the liquid phase ( $\mu_t > 0, \mu_s = 0$ ). 3 Degradation only in the adsorbed phase ( $\mu_t = 0, \mu_s > 0$ ).
The following lines should only be provided if MNEQ=3 or MNEQ=0 and MDEQ $\geq 2$ .			
6	-	-	Comment line.
7	Real	PHIM	Mobile water fraction, $\phi_m = \theta_m/\theta$ .

### Block C. Transport Parameters (Tables 6.5 and 6.6)

This block contains general transport parameters. If  $\text{NREDU} = 1$ , dimensional values for  $\mu$  and  $\gamma$  should be specified according to (2.5) and (2.6) for the equilibrium CDE ( $\text{MODE} = 1, 3, 5$ ). If  $\text{NREDU} \neq 1$ , dimensionless values for  $\mu^E$  and  $\gamma^E$  are used in the input and output files (see Table 2.1). The degradation and production parameters are always dimensionless for the nonequilibrium CDE ( $\text{MODE} = 2, 4, 6, 8$ ).

Since  $K_d$  is used as an input parameter for the stream tube model ( $\text{MODE} \geq 3$ ), the (deterministic) value for  $\rho_s/\theta$  needs to be entered for evaluating  $R$ . For nonreactive solutes ( $K_d = 0$  and  $R = 1$ ), the value for  $\rho_s/\theta$  is immaterial and a dummy value can be entered. The program uses ensemble averages to generate dimensionless variables, for example:

$$T = \frac{\langle v \rangle t}{L}, \quad \omega = \frac{\alpha(\langle R \rangle - 1)L}{\langle v \rangle} \quad (6.1a, b)$$

We assume that the degradation coefficients in the liquid and adsorbed phases are identical ( $\mu_l = \mu_s$ ) for stochastic equilibrium transport. Hence,  $\mu = \mu_l \langle R \rangle$  for a stochastic  $K_d$ .

Stochastic parameters can be made deterministic by simply setting  $\sigma = 0$ . If  $v$  is deterministic ( $\sigma_v = 0$ ), any parameter that is perfectly correlated with  $v$  will become deterministic as well ( $D$  for  $\text{MODE} = 3, 4$ ;  $K_d$  for  $\text{MODE} = 5, 6$ ; and  $D$  and  $K_d$  for  $\text{MODE} = 8$ ). Since the pdf is bivariate, only one parameter will remain stochastic in this case ( $K_d$  for  $\text{MODE} = 3, 4$ ;  $D$  for  $\text{MODE} = 5, 6$ ;  $\alpha$  for  $\text{MODE} = 8$ ). CXTFIT 2.1 cannot be executed if the standard deviation of each parameter in the stream tube model is zero. Instead, the deterministic CDE should be used as the transport model. If the same initial estimate is provided for the standard deviations of  $v$  and  $\eta$ , CXTFIT 2.1 will assume that  $\sigma_v = \sigma_\eta$  throughout the optimization procedure.

Table 6.5. Block C - Transport Parameters†

Line	Type	Variable	Description
1,2	-	-	Comment lines.
			<b>Transport parameter values.</b>
			<i>Deterministic CDE</i> (MODE=1,2):
3	Real	B(1)	Initial value for each coefficient.
3	Real	B(2)	
:	:	:	
3	Real	B(NP)	
			<i>Stochastic CDE</i> (MODE≥3):
3	Real	B(1)	Initial value for each coefficient.
3	Real	B(2)	
:	:	:	
3	Real	B(NP)	
3	Real	RHOTH	Value for $\rho/\theta$ .
Omit the following if INVERSE=0 (direct problem).			
4	Integer	INDEX(1)	Parameter estimation index for B(1). 0 Coefficient is known and kept constant during optimization. 1 Coefficient is unknown and estimated by curve fitting the data.
4	Integer	INDEX(2)	Parameter estimation index for B(2).
:	:	:	:
4	Integer	INDEX(NP)	Parameter estimation index for B(NP).
Omit the following if ILMT=0 (no constraints).			
5	Real	BMIN(1)‡	Minimum constraint for B(1) (dummy value if INDEX(1)=0).
5	Real	BMIN(2)	Minimum constraint for B(2) (dummy value if INDEX(2)=0).
:	:	:	:
5	Real	BMIN(NP)	Minimum constraint for B(NP) (dummy value if INDEX(NP)=0).
6	Real	BMAX(1)‡	Maximum constraint for B(1) (dummy value if INDEX(1)=0).
6	Real	BMAX(2)	Maximum constraint for B(2) (dummy value if INDEX(2)=0).
:	:	:	:
6	Real	BMAX(P)	Maximum constraint for B(NP) (dummy value if INDEX(NP)=0).

† Parameters for B(I) are given in Table 6.6.

‡ No constraints will be imposed on B(I) if BMIN(I)=BMAX(I).

Table 6.6. Parameters for B(I) in Block C

MODE	NP	B(1)	B(2)	B(3)	B(4)	B(5)	B(6)	B(7)	B(8)	B(9)	B(10)	B(11)	-
1	4	$v$	$D$	$R$	$\mu$ or $\mu^E$	-	-	-	-	-	-	-	-
2	7	$v$	$D$	$R$	$\beta$	$\omega$	$\mu_1$	$\mu_2$	-	-	-	-	-
3	8	$\langle v \rangle$	$\langle D \rangle$	$\langle K_d \rangle$	$\mu$ or $\mu^E$	$\sigma_v$	$\sigma_{Kd}$	$\sigma_D$	$\rho_{vkd}$	$\rho_b/\theta$	-	-	-
4	10	$\langle v \rangle$	$\langle D \rangle$	$\langle K_d \rangle$	$\omega$	$\mu_1$	$\mu_2$	$\sigma_v$	$\sigma_{Kd}$	$\sigma_D$	$\rho_{vkd}$	$\rho_b/\theta$	-
5	8	$\langle v \rangle$	$\langle D \rangle$	$\langle K_d \rangle$	$\mu$ or $\mu^E$	$\sigma_v$	$\sigma_{kd}$	$\sigma_D$	$\rho_{vD}$	$\rho_b/\theta$	-	-	-
6	10	$\langle v \rangle$	$\langle D \rangle$	$\langle K_d \rangle$	$\omega$	$\mu_1$	$\mu_2$	$\sigma_v$	$\sigma_{kd}$	$\sigma_D$	$\rho_{vD}$	$\rho_b/\theta$	-
7	11	$\langle v \rangle$	$\langle D \rangle$	$\langle K_d \rangle$	$\langle \alpha \rangle$	$\mu_1$	$\mu_2$	$\sigma_v$	$\sigma_{kd}$	$\sigma_D$	$\sigma_\alpha$	$\rho_{v\alpha}$	$\rho_b/\theta$

**Block D. Boundary Value Problem** (Table 6.7)

Table 6.2 lists the different functions that can be used for the input concentration as a function of time in the boundary value problem (BVP). The same format should be followed for the deterministic and the stream tube model. The dimension for time in the input function should be consistent with NREDU in Block A. The step (MODB = 2) and pulse (MODB = 3) input functions are special cases of the general multiple pulse input scenario (MODB = 4). The maximum number of pulses is 10. Solutions of the BVP for a user-defined input function (MODB = 6) are obtained according to (2.15) for the equilibrium CDE, and (3.13) and (3.14) for the nonequilibrium CDE. The input function needs to be specified by the user in the routine **CINPUT** in source program **USER.FOR**. The program always needs to be recompiled when the input function is being changed. This option (MODB = 6) is not available for the stream tube model (MODE = 4,6,8).

Note that INDEX, and the minimum and maximum constraints, should be specified if the total solute mass is a fitting parameter for either Dirac delta, step, or pulse input (MASS = 1 in Block B). For the stochastic CDE with a random  $v$ , the parameter MASSST specifies the mass distribution between stream tubes for a Dirac delta input and a pulse input (cf. Figures 4.3 and 4.4).



Table 6.7. Block D - Boundary Value Problem†

Line	Type	Variable	Description
1,2	-	-	Comment lines.
<u>(0) Solute free water input</u>			
3	Integer	MODB	0
<u>(1) Dirac Delta input</u>			
3	Integer	MODB	1
4	Real	PULSE(1)	$m_B/v$ or $\langle m_B \rangle / \langle v \rangle$ for dimensional $\delta(t)$ , $M_B$ or $\langle M_B \rangle$ for dimensionless $\delta(T)$ .
4	Real	MASSST	Mass distribution index for the stochastic CDE (leave blank for the deterministic CDE, i.e., $MODE \leq 2$ ). 0 Amount of solute in each tube is proportional to $v$ ( $m_B = v \langle m_B \rangle / \langle v \rangle$ ). 1 Amount of solute in each tube is constant regardless of $v$ ( $m_B = \langle m_B \rangle$ ).
Omit the following if INVERSE=0 (Block A) or MASS=0 (Block B).			
5	Integer	INDEX(NP+1)	Parameter estimation index for solute mass (=B(NP+1)). 0 Coefficient is known and kept constant. 1 Coefficient is assumed to be unknown and fitted to data.
Omit the following if there are no constraints (ILMT=0, Block B).			
6	Real	BMIN(NP+1)	Minimum constraint for B(NP+1) (dummy value if INDEX(NP+1)=0).
7	Real	BMAX(NP+1)	Maximum constraint for B(NP+1) (dummy value if INDEX(NP+1)=0).
<u>(2) Step input</u>			
3	Integer	MODB	2
4	Real	PULSE(1)	Input concentration, $f_i$ .
Omit the following if INVERSE=0 (Block A) or MASS=0 (Block B).			
5	Integer	INDEX(NP+1)	Parameter estimation index for input concentration (=B(NP+1)). 0 Coefficient is known and kept constant. 1 Coefficient is assumed to be unknown and fitted to the data.
Omit the following if there are no constraints (ILMT=0, Block B).			
6	Real	BMIN(NP+1)	Minimum constraint for B(NP+1) (dummy value if INDEX(NP+1)=0).
7	Real	BMAX(NP+1)	Maximum constraint for B(NP+1) (dummy value if INDEX(NP+1)=0).

Table 6.7. (continued)

Line	Type	Variable	Description
<u>(3) Pulse input of application time, <math>T_2</math></u>			
3	Integer	MODB	3
4	Real	PULSE(1)	Input concentration, $f_1$ .
4	Real	TPULSE(2)	Application time, $T_2$ or $\langle T_2 \rangle$ .
4	Real	MASSST	Mass distribution index for the stochastic CDE (leave blank if $\text{MODE} \leq 2$ ). 0 Application time, $T_2$ , is constant for all stream tubes and the amount of solutes in each stream tube is proportional to $v$ ( $\text{MODE}=5$ and 6 in prior CXTFIT version as discussed in section 6.6). 1 Application time, $T_2$ , is equal to $\langle T_2 \rangle \langle v \rangle / v$ for each stream tube. All stream tubes have the same amount of solutes ( $\text{MODE}=7$ and 8 in prior CXTFIT version as discussed in section 6.6).

Omit the following if  $\text{INVERSE}=0$  (Block A) or  $\text{MASS}=0$  (Block B).

5	Integer	INDEX(NP+1)	Parameter estimation index for PULSE(1)(=B(NP+1)). 0 Coefficient is known and kept constant. 1 Coefficient is assumed to be unknown and fitted to data.
5	Integer	INDEX(NP+2)	Parameter estimation index for PULSE(2)(=B(NP+2)).

Omit the following if there are no constraints ( $\text{ILMT}=0$ , Block B).

6	Real	BMIN(NP+1)	Minimum constraint for B(NP+1) (dummy value if $\text{INDEX}(\text{NP}+1)=0$ ).
6	Real	BMIN(NP+2)	Minimum constraint for B(NP+2) (dummy value if $\text{INDEX}(\text{NP}+2)=0$ ).
7	Real	BMAX(NP+1)	Maximum constraint for B(NP+1) (dummy value if $\text{INDEX}(\text{NP}+1)=0$ ).
7	Real	BMAX(NP+2)	Maximum constraint for B(NP+2) (dummy value if $\text{INDEX}(\text{NP}+2)=0$ ).

(4) Multiple pulse input\* (see Figure 2.1)

3	Integer	MODB	4
4	Integer	NPULSE	Number of pulses, $n$ .
5	Real	PULSE(1)	Input concentration of the first pulse, $f_1$ .
5	Real	TPULSE(1)	Starting time of the first pulse, $T_1=0$ .
6	Real	PULSE(2)	Input concentration of the second pulse, $f_2$ .
6	Real	TPULSE(2)	Starting time of the second pulse, $T_2$ .
:	:	:	:
NPULSE+4	Real	PULSE(NPULSE)	Input concentration of the last pulse, $f_n$ .
NPULSE+4	Real	TPULSE(NPULSE)	Starting time of the last pulse, $T_n$ .

Table 6.7. (continued)

Line	Type	Variable	Description
<u>(5) Exponential input concentration, <math>f_1 + f_2 \exp(-\lambda^B T)</math></u>			
3	Integer	MODB	5
4	Real	PULSE(1)	Value of $f_1$ .
4	Real	PULSE(2)	Value of $f_2$ .
4	Real	TPULSE(1)	Value of $\lambda^B$ .
<u>(6) Arbitrary function, <math>C_o(T)^*</math></u>			
3	Integer	MODB	6

† The dimension for time in the input function should be specified according to the value of NREDU (Block A). Use dimensional time,  $t$  (i.e., d, h, min, sec) when  $NREDU \leq 1$ .

‡ Step and pulse input are special cases of the multiple pulse input function.

\* Specify the general  $C_o(T)$  in routine CINPUT in source program USER.FOR. This option is not available for the stream tube model (MODE=4,6,8)

#### **Block E. Initial Value Problem (Table 6.8)**

Table 6.2 also lists the functions that can be used to define the initial concentration in the initial value problem (IVP). Data entry for this block is identical for the deterministic and the stream tube model. Similar to the BVP in Block D, the dimension for position in the initial distribution should be consistent with the value for NREDU specified in Block A. The maximum number of steps for a stepwise initial distribution is 10. Since a first-type inlet condition specifies the concentration at the surface, we can define a Dirac initial condition (MODI = 4) at the surface ( $x_1 = 0$ ,  $Z_1 = 0$ ) in case MODC is 5 or 6 (see (2.23) and (3.33)).

Table 6.8. Block E - Initial Value Problem†

Line	Type	Variable	Description
1,2	-	-	Comment lines.
<u>(0) Zero initial concentration</u>			
3	Integer	MODI	0
<u>(1) Constant initial concentration</u>			
3	Integer	MODI	1
4	Real	CINI(1)	Concentration, $U_1$ .
<u>(2) Stepwise Initial Distribution† (see Figure 2.2)</u>			
3	Integer	MODI	2
4	Integer	NINI	Number of steps, $n$ .
5	Real	CINI(1)	Concentration of the first step, $U_1$ .
5	Real	ZINI(1)	Starting position of the first step, $Z_1=0$ .
6	Real	CINI(2)	Concentration of the second step, $U_2$ .
6	Real	ZINI(2)	Starting position of the second step, $Z_2$ .
⋮	⋮	⋮	⋮
NINH-4	Real	CINI(NINI)	Concentration of the last step, $U_n$ .
NINH-4	Real	ZINI(NINI)	Starting position of the last step, $Z_n$ .
<u>(3) Exponential initial distribution, <math>U_1 + U_2 \exp(-\lambda' Z)</math></u>			
3	Integer	MODI	3
4	Real	CINI(1)	Value of $U_1$ .
4	Real	CINI(2)	Value of $U_2$ .
4	Real	ZINI(1)	Value of $\lambda'$ .
<u>(4) Dirac delta initial condition, <math>m_i/\theta\delta(x-x_1) + U_1</math>, or <math>M_i/\delta(Z-Z_1) + U_1</math></u>			
3	Integer	MODI	4
4	Real	CINI(2)	Value of $m_i/\theta$ or $M_i$ .
4	Real	ZINI(2)	Value of $x_1$ or $Z_1$ ( $x_1, Z_1 \neq 0$ when MODC=5,6).
4	Real	CINI(1)	Value of $U_1$ .

† The dimension for depth in the initial condition should be specified according to the value of NREDU (Block A).

‡ Zero and constant initial concentrations are special cases of a stepwise initial distribution.

**Block F. Production Value Problem** (Table 6.9)

Possible mathematical expressions for the production profiles in the production value problem (PVP) are listed in Table 6.2. The input format for the PVP is almost identical to that for the IVP (Block E). The dimension of position in the production function should again be consistent with the value of NREDU in Block A. For the equilibrium CDE with dimensional times and positions (NREDU = 0,1), the production function given by (2.6) is also dimensional. Different production functions can be specified for phases 1 and 2 in the nonequilibrium CDE when MPRO = 1.

Table 6.9. Block F - Production Value Problem†

Line	Type	Variable	Description
1,2	-	-	Comment lines.
<u>(0) No production term</u>			
3	Integer	MODP	0
<u>(1) Constant production</u>			
3	Integer	MODP	1
4	Real	GAMMA1(1)	Production value in the equilibrium phase, $\gamma_1$ , or $\gamma_{1,1}$ .
Omit the following for the equilibrium CDE (MODE=1,3,5).			
5	Real	GAMMA2(1)	Production value in the nonequilibrium phase, $\gamma_{2,1}$ .
<u>(2) Stepwise production profile†</u>			
3	Integer	MODP	2
3	Integer	MPRO	Production function code for a nonequilibrium phase (leave blank if MODE=1,3, or 5, i.e., the equilibrium CDE): 0 Same conditions for equilibrium and nonequilibrium phases. 1 Different conditions for equilibrium and nonequilibrium phases.
4	Integer	NPRO1	Number of steps in an equilibrium phase, $n$ .
5	Real	GAMMA1(1)	Production of the first step in the equilibrium phase, $\gamma_1$ , or $\gamma_{1,1}$ .
5	Real	ZPRO1(1)	Starting position of the first step, $Z_1$ or $Z_{1,1}$ =0.

Table 6.9. (continued)

Line	Type	Variable	Description
6	Real	GAMMA1(2)	Production of the second step in the equilibrium phase, $\gamma_2$ , or $\gamma_{1,2}$ .
6	Real	ZPRO1(2)	Starting position of the second step, $Z_2$ or $Z_{1,2}$ .
:	:	:	:
NPRO1+4	Real	GAMMA1(NPRO1)	Production of the NPRO1 <sup>th</sup> step in the equilibrium phase, $\gamma_n$ , or $\gamma_{1,n}$ .
NPRO1+4	Real	ZPRO1(NPRO1)	Starting position of the NPRO1 <sup>th</sup> step, $Z_n$ or $Z_{1,n}$ .

Omit the following for the equilibrium CDE (MODE=1,3,5) or if MPRO=0.

NPRO1+5	Integer	NPRO2	Number of steps in the nonequilibrium phase, $m$ .
NPRO1+6	Real	GAMMA2(1)	Production of the first step for the nonequilibrium phase, $\gamma_{2,1}$ .
NPRO1+6	Real	ZPRO2(1)	Starting position of the first step, $Z_{2,1}=0$ .
NPRO1+7	Real	GAMMA2(2)	Production of the second step in the nonequilibrium phase, $\gamma_{2,2}$ .
NPRO1+7	Real	ZPRO2(2)	Starting position of the second step, $Z_{2,2}$ .
:	:	:	:
NPRO1 +NPRO2+5	Real	GAMMA2(NPRO1)	Production of the NPRO2 <sup>th</sup> step in the nonequilibrium phase, $\gamma_{1,m}$ .
NPRO1 +NPRO2+5	Real	ZPRO2(NPRO1)	Starting position of the NPRO2 <sup>th</sup> step, $Z_{2,m}$ .

**(3) Exponential production profiles,  $\gamma_i + \gamma_j \exp(-\lambda^p Z)$**

3	Integer	MODP	<b>3</b>
3	Integer	MPRO	Production function code for nonequilibrium models (leave blank if MODE=1,3, or 5, i.e., the equilibrium CDE): <b>0</b> Same conditions for equilibrium and nonequilibrium phases. <b>1</b> Different conditions for equilibrium and nonequilibrium phases.
4	Real	GAMMA1(1)	Value of $\gamma_1$ or $\gamma_{1,1}$ .
4	Real	GAMMA1(1)	Value of $\gamma_2$ or $\gamma_{1,2}$ .
4	Real	ZPRO1(1)	Value of $\lambda^p$ or $\lambda_{1,1}^p$ .

Omit the following if MPRO=0 or for the equilibrium CDE (MODE=1,3,5).

5	Real	GAMMA2(1)	Value of $\gamma_{2,1}$ .
5	Real	GAMMA2(1)	Value of $\gamma_{2,2}$ .
5	Real	ZPRO2(1)	Value of $\lambda_{2,1}^p$ .

† Provide dimensional  $\gamma$  according to (2.6) for the equilibrium CDE (MODE=1,3,5) with NREDU=1. Otherwise, use dimensionless  $\gamma$  as shown in Table 2.1 and 3.1 (see NREDU in Block A).

‡ Constant production is a special case of a stepwise production profile.

**Block G. Observed Data for Inverse Problem** (Table 6.10)

Observed data can be given in four different formats: (a) position, time, and observed concentration (INPUTM=0); (b) time and observed concentration at a particular position (INPUTM = 1); (c) position and concentration at a particular time (INPUTM = 2); and (d) similar as (a) but the data are now given in a fixed format to allow the use of input files consistent with the previous CXTFIT version (INPUTM = 3). Hence, data from breakthrough curves or concentration profiles versus depth should be described with INPUTM equal to 1 and 2, respectively. It is not necessary to specify the number of observations — the end of a data set should be marked by a line having dummy zeroes. The maximum number of observed concentrations is determined by the parameter MAXOB, which is defined at the top of the main program (the current default setting is 401).

Table 6.10 Block G - Observed Data for Inverse Problem†

Line	Type	Variable	Description
1,2	-	-	Comment lines.
3	Integer	INPUTM	Input data code: 0 Z(I), T(I), C(I) 1 T(I), C(I) for a fixed depth (breakthrough curve). 2 Z(I), C(I) for a fixed time (concentration vs. depth). 3 C(I), Z(I), T(I) (Fixed format, 3F10.0, for CXTFIT version 1 data).
<u>(a) INPUTM=0</u>			
4	-	-	Comment line.
5	Real	Z(1)	Position of the first observation.
5	Real	T(1)	Time of the first observation.
5	Real	C(1)	Value of the first observed concentration (dummy value if MIT=0).
6	Real	Z(2)	Position of the second observation.
6	Real	T(2)	Time of the second observation.
6	Real	C(2)	Value of the second observed concentration (dummy value if MIT=0).
:	:	:	:
NOB+4	Real	Z(NOBS)	Position of the NOBS <sup>th</sup> observation.
NOB+4	Real	T(NOBS)	Time of the NOBS <sup>th</sup> observation.
NOB+4	Real	C(NOBS)	Value of the NOBS <sup>th</sup> observed concentration (dummy value if MIT=0).
NOB+5	Real	Dummy	Enter 0 to mark end of data set.
NOB+5	Real	Dummy	Enter 0 to mark end of data set.
NOB+5	Real	Dummy	Enter 0 to mark end of data set.

Table 6.10. (continued)

Line	Type	Variable	Description
<b>(b) INPUTM=1</b>			
4	Real	DUMTZ	Position of the breakthrough curve.
5	-	-	Comment line.
6	Real	T(1)	Time of the first observation.
6	Real	C(1)	Value of the first observed concentration (dummy value if MIT=0).
7	Real	T(2)	Time of the second observation.
7	Real	C(2)	Value of the second observed concentration (dummy value if MIT=0).
:	:	:	:
NOB+5	Real	T(MOB)	Time of the NOB <sup>th</sup> observation.
NOB+5	Real	C(NOBS)	Value of the NOB <sup>th</sup> observed concentration (dummy value if MIT=0).
NOB+6	Real	Dummy	Give 0 to mark end of data set.
NOB+6	Real	Dummy	Give 0 to mark end of data set.
<b>(c) INPUTM = 2</b>			
4	Real	DUMTZ	Time of the solute profile.
5	-	-	Comment line.
6	Real	Z(1)	Position of the first observation.
6	Real	C(1)	Value of the first observed concentration (dummy value if MIT=0).
7	Real	Z(2)	Position of the second observation.
7	Real	C(2)	Value of the second observed concentration (dummy value if MIT=0).
:	:	:	:
NOB+5	Real	Z(NOBS)	Position of the NOB <sup>th</sup> observation.
NOB+5	Real	C(NOBS)	Value of the NOB <sup>th</sup> observed concentration (dummy value if MIT=0).
NOB+6	Real	Dummy	Give 0 to mark end of data set.
NOB+6	Real	Dummy	Give 0 to mark end of data set.
<b>(d) INPUTM = 3 (Fixed format, 3F10.0, for CXTFIT version 1 data)</b>			
4	-	-	Comment line.
5	Real	C(1)	Value of the first observed concentration (dummy value if MIT=0).
5	Real	Z(1)	Position of the first observation.
5	Real	T(1)	Time of the first observation.
6	Real	C(2)	Value of the second observed concentration (dummy value if MIT=0).
6	Real	Z(2)	Position of the second observation.
6	Real	T(2)	Time of the second observation.
:	:	:	:
NOB+4	Real	C(NOBS)	Value of the NOB <sup>th</sup> observed concentration (dummy value if MIT=0).
NOB+4	Real	Z(NOBS)	Position of the NOB <sup>th</sup> observation.
NOB+4	Real	T(MOB)	Time of the NOB <sup>th</sup> observation.
NOB+5	Real	Dummy	Give 0 to mark end of data set.
NOB+5	Real	Dummy	Give 0 to mark end of data set.
NOB+5	Real	Dummy	Give 0 to mark end of data set.

† If MIT=0 concentrations are calculated at specified Z(I) and T(I) using the initial parameter estimates.



**Block H. Position and Time for Direct Problem** (Table 6.11)

The concentration is calculated for a user-defined grid system of times and positions. The maximum number of concentrations that can be calculated in this way is given by MAXOB (= 401). If MPRINT = 1, the concentration is assumed to be given as a function of time, while for MPRINT = 2 the concentration is given versus depth.

Table 6.11. Block H - Position and Time for Direct Problem

Line	Type	Variable	Description
1,2	-	-	Comment lines.
3	Integer	NZ	Number of output positions.
3	Real	DZ	Spatial increment for output.
3	Real	ZI	Initial value of output position.
3	Integer	NT	Number of output times.
3	Real	DT	Time increment for output.
3	Real	TI	Initial value of output time.
3	Integer	MPRINT	Output print code: 1 Concentration vs. time. 2 Concentration vs. depth.

### 6.3. Example Input and Output Files

We will present in this section some typical examples of direct and inverse problems. All input and output files for the examples are provided on the distribution diskette.

#### 6.3.1. Direct Problem

Tables 6.12 and 6.13 are input and output files for the deterministic nonequilibrium CDE (cf. Figure 7.6a). Block H in the input file is used to specify the grid of times and positions for which concentrations are to be calculated. The parameter NCASE, on the first line of the input file, specifies the number of cases considered. The output file shows the conditions for the simulation as well as calculated results for times and positions specified in Block H. The concentration is given as a function of time if MPRINT = 1 (Block H), or as a function of position (distance) if MPRINT = 2. To check the mass balance, *zeroth* time (MPRINT = 1) and depth (MPRINT = 2) moments are calculated according to:

$$\text{Sum}(C \cdot dT) = \sum_{i=1}^{n-1} (C_i + C_{i+1}) \Delta T / 2 \quad (6.2)$$

$$\text{Sum}(C \cdot dZ) = \sum_{i=1}^{n-1} (C_i + C_{i+1}) \Delta Z / 2 \quad (6.3)$$

Table 6.12. Input File for Figure 7.6a

```

1
*** BLOCK A: MODEL DESCRIPTION *****
Fig7-6a. Two-site CDE (Alpha=0.08,f=0.7)
Effect of the fraction of equilibrium site, f
INVERSE   MODE   NREDU
  0         2     1
MODC      ZL
  1        50
*** BLOCK C: TRANSPORT PARAMETERS *****
  V      D      R   Beta   omega   Mu1   Mu2
 20.    10.    5.0  0.44   0.56   0.0   0.0
** BLOCK D: BVP; MODB=0 ZERO; =1 Dirac; =2 STEP; =3 A PULSE *****
MODB
  1
  1.0
*** BLOCK E: IVP; MODI=0 ZERO; =1 CONSTANT; =2 STEPWISE; =3 EXPONENTIAL **
MODI
  0
*** BLOCK F: PVP; MODP=0 ZERO; =1 CONSTANT; =2 STEPWISE; =3 EXPONENTIAL **
MODP
  0
*** BLOCK H: POSITION AND TIME FOR DIRECT PROBLEM *****
  NZ      DZ      ZI      NT      DT      TI      MPRINT
   1      1.0    50.0    101     0.2     0.0       1

```

Table 6.13. Output File for Figure 7.6a

```

$
*****
*
*   CXTFIT VERSION 2.0 (1/2/95)
*   ANALYTICAL SOLUTIONS FOR ONE-DIMENSIONAL CDE
*   DIRECT PROBLEM
*
*   Fig7-6a. Two-site CDE (Alpha=0.08,f=0.7)
*   Effect of the fraction of equilibrium site, f
*
*   DATA INPUT FILE: FIG7-6A.IN
*
*****

MODEL DESCRIPTION
=====
DETERMINISTIC NONEQUILIBRIUM CDE (MODE=2)
FLUX-AVERAGED CONCENTRATION
REAL TIME (t), POSITION(x)
(D AND V ARE DIMENSIONAL;
  R,beta,omega,mu, AND gamma ARE DIMENSIONLESS)
CHARACTERISTIC LENGTH = 50.0000
FOR DIMENSIONLESS PARAMETERS

INITIAL VALUES OF COEFFICIENTS
=====
NAME          INITIAL VALUE
V.....      .2000E+02
D.....      .1000E+02
R.....      .5000E+01
beta.....    .4400E+00
omega.....    .5600E+00
mu1.....     .0000E+00
mu2.....     .0000E+00

BOUNDARY, INITIAL, AND PRODUCTION CONDITIONS
=====
DIRAC DELTA INPUT , MASS = 1.0000
SOLUTE FREE INITIAL CONDITION
NO PRODUCTION TERM

$ Z= 50.0000      (FLUX CONC. VS. TIME)
$ Sum(C1*dT)=    .8207, Sum(C2*dT)=    .5062
$   TIME          C1          C2
.0000   .00000E+00   .00000E+00
.5000   .00000E+00   .00000E+00
1.0000   .00000E+00   .00000E+00
:
:
:
49.0000   .93484E-03   .51409E-02
49.5000   .90217E-03   .49753E-02
50.0000   .87064E-03   .48150E-02

```

### 6.3.2. Parameter Estimation

Tables 6.14 and 6.15 are input and output files for parameter optimization. Observed data were fitted with the deterministic nonequilibrium two-region model (cf. Figure 7.9b). In the input file, Block B specifies the conditions for the parameter estimation, while the observed data are given in Block G.

Table 6.14. Input File for Figure 7.9b

---

```

1
*** BLOCK A: MODEL DESCRIPTION *****
Fig 6.9b: BORON EFFLUENT (Exp3-1, van Genuchten, 1974)
(Kd=1.04, unit, cm, d, micro g) (CXTFIT, EX.4A, Fig.5)
INVERSE    MODE    NREDU
  1         2       2
MODC       ZL
  1       30.0
*** BLOCK B: INVERSE PROBLEM *****
MIT        ILMT    MASS
  50        0       0
MNEQ       MDEG
  0         0
*** BLOCK C: TRANSPORT PARAMETERS *****
  V         D       R      Beta    omega    Mu1     Mu2
 38.5      15.5     3.9     0.5     0.2     0.       0.
  0         0       0       1       1       0       0
*** BLOCK D: BVP; MODB=0 ZERO; =1 DIRAC; =2 STEP; =3 A PULSE *****
MODB (Reduced Conc.& time) =4 MULTIPLE; =5 EXPONENTIAL; =6 ARBITRARY
  3
  1.0      6.494
*** BLOCK E: IVP; MODI=0 ZERO; =1 CONSTANT; =2 STEPWISE; =3 EXPONENTIAL **
MODI
  0
*** BLOCK F: PVP; MODP=0 ZERO; =1 CONSTANT; =2 STEPWISE; =3 EXPONENTIAL **
MODP
  0
*** BLOCK G: DATA FOR AN INVERSE PROBLEM ** *****
INPUTM =0; Z,T,C =1; T,C FOR SAME Z =2; Z,C FOR SAME T
  1
  1.0
      TIME      CONC      (Give "0 0 0" after last data set.)
      1.80      0.015
      1.95      0.075
      :         :
      :         :
      17.00     0.040
      18.50     0.029
      20.00     0.025
      0         0

```

---

The first part of the output file gives the conditions for the simulation and parameter estimation. The goodness of fit is described with the coefficient of determination,  $r^2$ , for the regression of observed versus fitted concentrations:

$$r^2 = 1 - \frac{\sum_{i=1}^N (C_i - f_i)^2}{\sum_{i=1}^N (C_i - \bar{C})^2} = 1 - \frac{SSQ}{\sum_{i=1}^N (C_i - \bar{C})^2} \quad (6.4)$$

where  $C_i$  and  $f_i$  are observed and fitted data, respectively, and  $\bar{C}$  is the mean of all  $N$  observed concentrations. A value for  $r^2$  close to unity indicates a good fit whereas values close to zero indicate a relatively poor description of the observed data by the selected model. The reliability of the parameter estimation may also be assessed with the parameter covariance matrix [Kool and Parker, 1988]. Once an acceptable minimum of the objective function (SSQ) has been found, a first-order approximation of the parameter covariance matrix is obtained from

$$C = s^2 A^{-1} \quad (6.5)$$

where  $s^2$  is an estimate of the variance due to error for  $M$  fitted parameters. The variance is approximated by the mean square for error (MSE):

$$MSE = \frac{SSQ}{N - M} \quad (6.6)$$

and  $A$  is given by (5.22). The standard error of the parameter  $b_j$  (denoted as S.E. COEFF. in the output file) is given by  $(C_{jj})^{1/2}$  while the  $T$ -value is given by  $b_j / (C_{jj})^{1/2}$ . The values for  $T$  and the standard error provide relative and absolute measures of deviations around the mean parameter value; a high value for  $T$  is desirable. The covariance matrix,  $\alpha$ , for the fitted parameters is obtained by simply dividing the elements of  $C$  by the parameter standard error:

$$\alpha_{ij} = \frac{C_{ij}}{(C_{ii})^{1/2} (C_{jj})^{1/2}} \quad (6.7)$$

In addition, the boundaries of the 95 % confidence region are calculated using the appropriate value of Student's  $t$  distribution:

$$b_{j,\min} = b_{j,\text{fit}} - t_{N-M,0.975} (C_{jj})^{1/2} \quad (6.8)$$

$$b_{j,\max} = b_{j,\text{fit}} + t_{N-M,0.975} (C_{jj})^{1/2} \quad (6.9)$$

where  $b_{j,\text{fit}}$  is the fitted parameter value, and  $t_{N-M,0.975}$  is the value of the  $t$  distribution for confidence level 0.95 with  $N - M$  degrees of freedom.

It should be noted that since (6.5), (6.8), and (6.9) are based on linear regression analysis, they hold only approximately for the nonlinear analysis as was discussed by *Kool and Parker* [1988]. However, (6.8) and (6.9) will yield reasonable approximations for individual parameter confidence intervals if no constraints are used and  $b_{j,\text{fit}}$  represents the true global minimum of the objective function.

Table 6.15. Output File for Figure 7.9b

```

$
*****
*
*      CXTFIT VERSION 2.1 (4/17/99)
*      ANALYTICAL SOLUTIONS FOR ONE-DIMENSIONAL CDE
*      NON-LINEAR LEAST-SQUARES ANALYSIS
*
*      Fig 6.9b: BORON EFFLUENT (Exp3-1, van Genuchten, 1974)
*      (Kd=1.04, unit, cm, d, micro g) (CXTFIT, EX.4A, Fig.5)
*
*      DATA INPUT FILE: FIG7-9B.IN
*
*****

MODEL DESCRIPTION
=====
DETERMINISTIC NONEQUILIBRIUM CDE (MODE=2)
FLUX-AVERAGED CONCENTRATION
REDUCED TIME (T), POSITION(Z)
  (ALL PARAMETERS EXCEPT D AND V ARE DIMENSIONLESS)
CHARACTERISTIC LENGTH = 30.0000
  FOR DIMENSIONLESS PARAMETERS

INITIAL VALUES OF COEFFICIENTS
=====
NAME           INITIAL VALUE   FITTING
V.....      .3850E+02        N
D.....      .1550E+02        N
R.....      .3900E+01        N
beta.....    .5000E+00        Y
omega.....   .2000E+00        Y
mu1.....     .0000E+00        N
mu2.....     .0000E+00        N

```

Table 6.15. (continued)

## BOUNDARY, INITIAL, AND PRODUCTION CONDITIONS

SINGLE PULSE OF CONC. = 1.0000 & DURATION = 6.4940  
 SOLUTE FREE INITIAL CONDITION  
 NO PRODUCTION TERM

## PARAMETER ESTIMATION MODE

MAXIMUM NUMBER OF ITERATIONS = 50  
 TWO-REGION PHYSICAL NONEQUILIBRIUM MODEL

ITER	SSQ	beta.	omega
0	.1563E+01	.500E+00	.200E+00
1	.1628E+00	.554E+00	.564E+00
2	.8561E-01	.571E+00	.712E+00
3	.8460E-01	.576E+00	.707E+00
4	.8459E-01	.578E+00	.700E+00
5	.8459E-01	.578E+00	.700E+00

## COVARIANCE MATRIX FOR FITTED PARAMETERS

	beta.	omega
beta.	1.000	
omega	-.756	1.000

RSQUARE FOR REGRESSION OF OBSERVED VS PREDICTED = .96970540  
 (COEFFICIENT OF DETERMINATION)

MEAN SQUARE FOR ERROR (MSE) = .3021E-02

## NON-LINEAR LEAST SQUARES ANALYSIS, FINAL RESULTS

NAME	VALUE	S.E.COEFF.	T-VALUE	95% CONFIDENCE LIMITS	
				LOWER	UPPER
beta.	.5780E+00	.1410E-01	.4100E+02	.5492E+00	.6069E+00
omega	.6999E+00	.8397E-01	.8336E+01	.5279E+00	.8720E+00

## -----ORDERED BY COMPUTER INPUT-----

\$	NO	DISTANCE	TIME	CONCENTRATION		RESI- DUAL
				OBS	FITTED	
	1	1.0000	1.8000	.0150	.0594	-.0444
	2	1.0000	1.9500	.0750	.1253	-.0503
	3	1.0000	2.1000	.1700	.2120	-.0420
	4	1.0000	2.2500	.2650	.3050	-.0400
	5	1.0000	2.4000	.3400	.3902	-.0502
	6	1.0000	2.6000	.4300	.4794	-.0494
	7	1.0000	2.8500	.5350	.5523	-.0173
	:	:	:	:	:	:
	25	1.0000	12.7000	.1330	.1356	-.0026
	26	1.0000	14.0000	.0900	.0912	-.0012
	27	1.0000	15.5000	.0540	.0573	-.0033
	28	1.0000	17.0000	.0400	.0358	.0042
	29	1.0000	18.5000	.0290	.0222	.0068
	30	1.0000	20.0000	.0250	.0137	.0113

## 6.4. CXTFIT 1.0

This section outlines the difference in input format for CXTFIT 2.1 and its predecessor, version 1 [Parker and van Genuchten, 1984]. This information is included to quickly familiarize users of the prior CXTFIT program with the current version. All functions in CXTFIT 1.0 are also included in version 2, except for parameter estimation of the constant production term,  $\gamma$ , in the equilibrium CDE (MODE = 1,2 in version 1). Many examples were tested using the two versions; identical results were obtained in most cases, while at times the parameter optimization was slightly better for CXTFIT 2.1. Changes in the input structure are outlined below.

### *Model Type and Concentration Mode*

In version 1, the parameter MODE specified model type and concentration mode. In version 2, the parameters MODE and MODC in *Block A* specify the model type and the concentration mode, respectively. The resident concentration in version 1 is identical to the resident concentration for a third-type inlet condition in version 2 (MODC = 3). Field-scale flux averaged concentrations in version 1 are specified by MODC = 2 in CXTFIT 2.1 (cf. Table 6.1).

### *Estimation of Solute Application Time*

The pulse duration was estimated as a transport parameter in version 1. In this version, the user also needs to set MASS = 1 in *Block B* and INDEX = 1 for the application time in *Block D*.

### *Degradation Coefficient*

The degradation coefficient  $\mu$  for the deterministic CDE was always dimensional in version 1. As explained in *Block C*,  $\mu$  may be dimensional or dimensionless in version 2, depending upon the value of NREDU in *Block A*.



### ***Characteristic Length***

The characteristic length  $L$  for nondimensional parameters in version 1 was defined internally as the maximum value of the independent variable,  $x$ . Instead, a value for  $L$  now has to be entered by the user in *Block A*. This modification allows greater flexibility, while nondimensional parameters, such as  $\omega$ , can also be made independent from the maximum depth for a particular set of observations.

### ***Stochastic Model with Random $v$***

The stochastic model in version 1 consisted of a stream tube model with random pore-water velocity,  $v$ . Additional stochastic parameters can be used in version 2 as discussed in Chapter 4. The case of only a stochastic  $v$  can be modeled in CXTFIT 2.1 by setting the other standard deviations of all other parameters to zero.

### ***Constant Local-Scale Dispersivity***

In version 1 only a constant dispersivity,  $\lambda$ , could be used (see (4.25)). To do this in version 2, identical initial estimates for  $\sigma_v$  and  $\sigma_D$  (MODE = 3) should be entered to keep  $\lambda$  constant during the parameter estimation in process. The input parameter is  $\langle D \rangle$ .

### ***Stochastic Model for Pulse Input of Constant Duration***

A constant application time for the stochastic model (MODE = 5,6 in version 1) can now be given by setting MASSST = 0 for MODB = 3 in *Block D* (see Figure 4.4).

### ***Stochastic Model with Constant Mass***

The stochastic model with constant mass (MODE = 7,8 in version 1) can be evaluated in version 2 by setting MASSST = 1 for MODB = 3 in *Block D*.

## 7. EXAMPLE PROBLEMS

This chapter contains several examples to illustrate the application of CXTFIT 2.1 to different transport scenarios. Both solutions of the direct and the inverse problem will be discussed for several types of boundary value (BVP), initial value (IVP), and production value (PVP) problems. A third-type inlet condition is used in all example problems, while concentrations in the examples are always normalized with respect to the input concentration or initial concentration (Tables 2.1 and 3.1). The input and output files for each example can be found on the distribution diskette.

### 7.1. Deterministic Equilibrium CDE (MODE = 1)

#### 7.1.1. Direct Problem

The first two examples deal with the solution of the direct problem for the equilibrium CDE. Figure 7.1 illustrates the effect of the first-order decay constant  $\mu$ , as given by (2.5), on solute

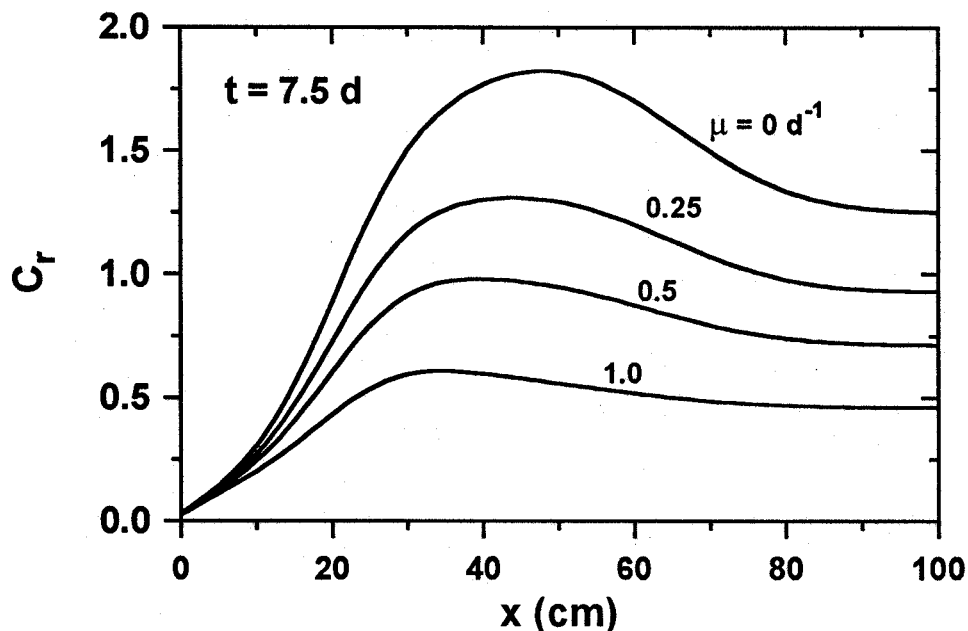


Fig. 7.1. Effect of the first-order decay constant,  $\mu$ , on calculated  $C_r$ -profiles.

distributions. The resident concentration was calculated 7.5 d after applying a single pulse input at  $t = 0$  with duration  $t_2 = 5$  d to a solute-free soil profile assuming  $v = 25 \text{ cm d}^{-1}$ ,  $D = 37.5 \text{ cm}^2 \text{ d}^{-1}$ ,  $R = 3$ , and a constant rate of production  $\gamma = 0.5 \text{ mg kg}^{-1} \text{ d}^{-1}$  [van Genuchten, 1981a]. Notice that when  $\mu$  increases, the concentration decreases as a result of the rise in degradation. Concentrations were evaluated according to (2.34) for  $\mu = 0 \text{ d}^{-1}$  while (2.33) was used for  $\mu > 0 \text{ d}^{-1}$ .

Differences between resident ( $C_r$ ) and flux-averaged ( $C_f$ ) concentrations for the BVP have been discussed extensively by several authors [cf. Kreft and Zuber, 1978; Jury and Roth, 1990; van Genuchten and Parker, 1984b]. We will illustrate the differences in concentration mode for the IVP [Toride et al., 1993b]. Figure 7.2 shows  $C_r$  and  $C_f$  as a function of relative distance,  $Z$ , at dimensionless time  $T = 0.05$  for two values of  $P$  when solute-free water is applied to a soil having a stepwise initial resident distribution as indicated by the dashed line. Dispersive transport dominates convective transport when  $P = 2$ , causing considerable spreading to occur in both the upstream and downstream directions (Figure 7.2a). Notice that at this small time ( $T = 0.05$ ),  $C_f$  is negative for  $Z \approx 0.5$ , and greater than unity (the initial resident concentration) for  $Z \approx 1$ . These somewhat odd results are a direct result of the definition of  $C_f$  according to (2.13). Since the solute flux,  $J_s$ , and the water flux,  $J_w$ , are vectors,  $C_f$  becomes negative when the directions of these two fluxes are opposite. The negative  $C_f$  near the surface is the result of an upward dispersive solute flux in spite of a downward convective solute flux. Similarly,  $C_f$  is greater than  $C_r$  if the gradient of  $C_r$  becomes negative. For relatively large negative gradients such as those in Figure 7.2 around  $Z = 1$ ,  $C_f$  can become greater than the initial resident concentration  $C_r(Z, 0)$ . Notice from Figure 7.2b that the differences between  $C_f$  and  $C_r$  become smaller for an increased Peclet number,  $P$ .

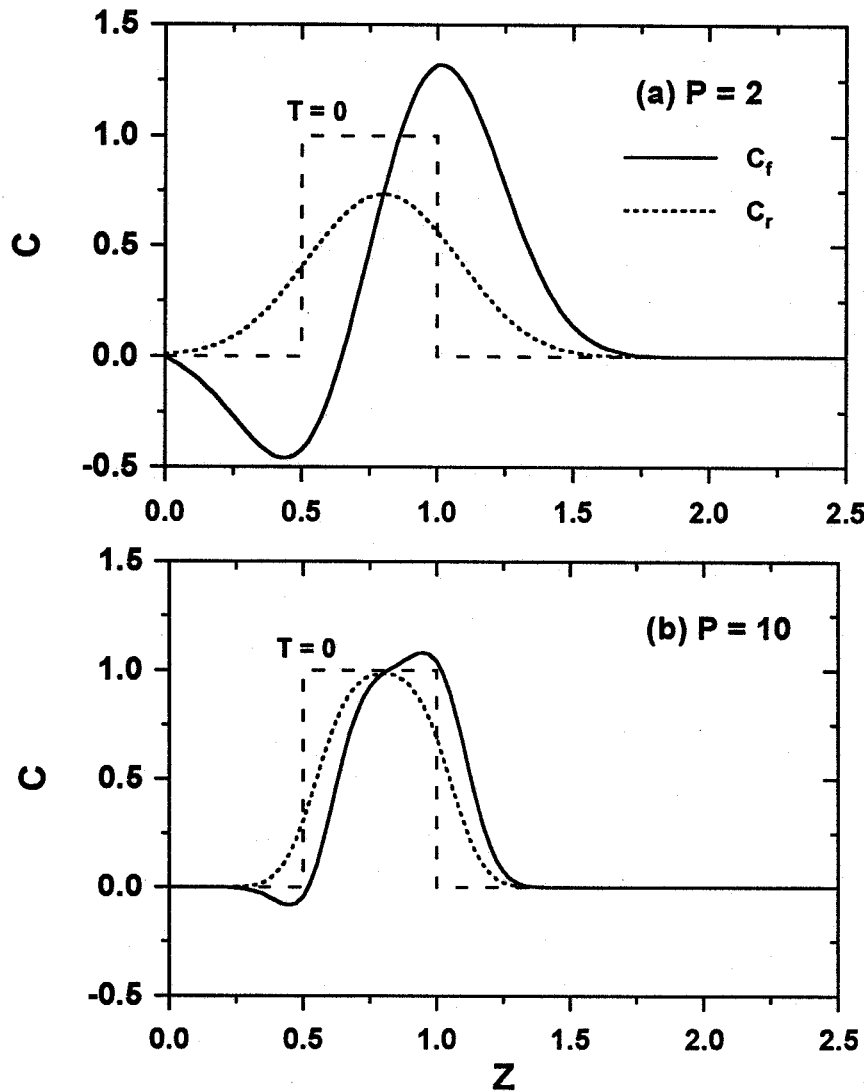


Fig. 7.2. Flux and resident concentrations versus depth at  $T=0.05$  for a solute-free input to a stepwise initial distribution: (a)  $P = 2$ , and (b)  $P = 10$ .

#### 7.1.2. Parameter Estimation

Figure 7.3 presents breakthrough curves (BTCs) measured by *Shiozawa* [1994, personal communication] with four-electrode EC sensors at three different depths as a result of: (a) continuous application of a 0.01 M NaCl solution to an initially solute-free saturated sand ( $\theta = 0.3$ ), and (b) leaching with solute free water during unsaturated condition ( $\theta = 0.12$ ). The observations were analyzed in terms of the equilibrium CDE with CXTFIT 2.1 assuming a resident mode (MODC = 3),

yielding estimates of the pore-water velocity,  $v$ , and the dispersion coefficient,  $D$ . The results are given in Table 7.1. The fitted  $v$  and  $D$  for each depth were almost identical. These results show that the CDE is an appropriate model for describing transport in this column. Note from the data in Table 7.1 that the dispersivity,  $\lambda (= D/v)$ , is smaller for the saturated soil than for the unsaturated soil.

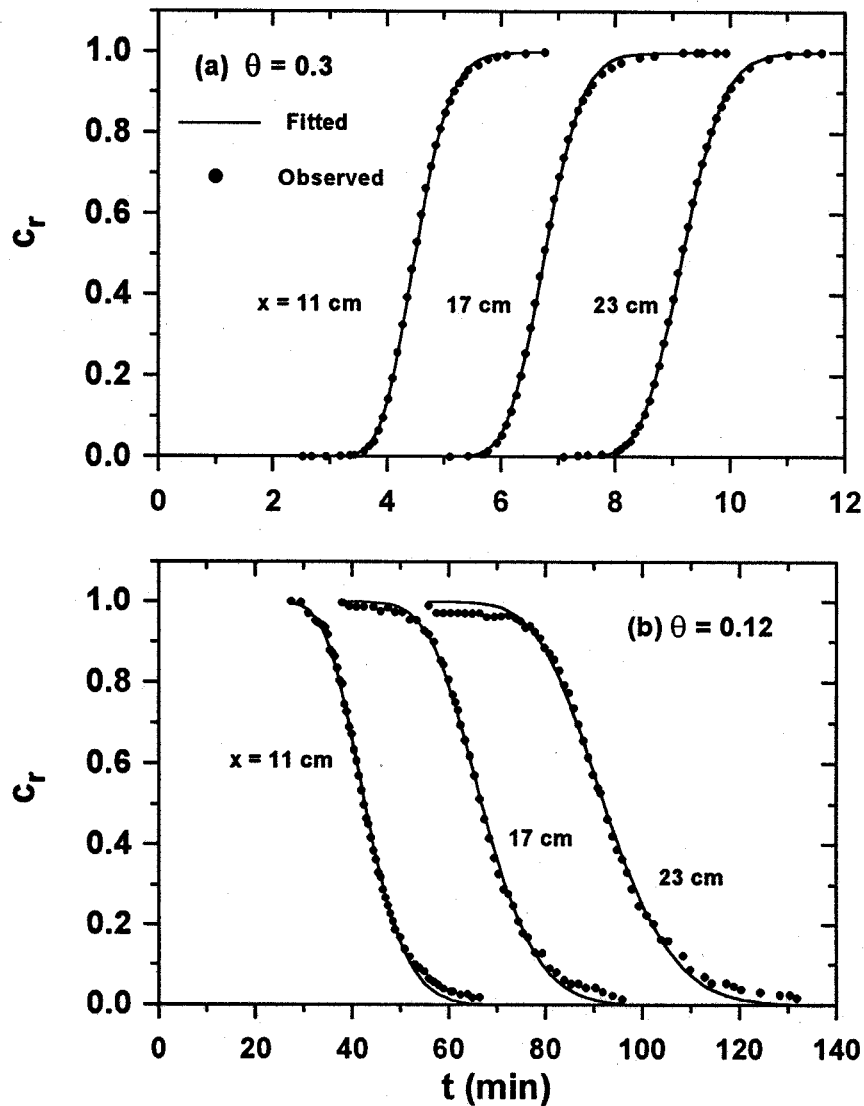


Fig. 7.3. Experimental and fitted breakthrough curves for (a) saturated ( $\theta = 0.3$ ) and (b) unsaturated ( $\theta = 0.12$ ) sand.

Table 7.1. Pore-Water Velocity,  $v$ , Dispersion Coefficient,  $D$ , and Dispersivity,  $\lambda$ , Obtained by Fitting the Data of Figure 7.3

Depth cm	$v$ cm min <sup>-1</sup>	$D$ cm <sup>2</sup> min <sup>-1</sup>	$\lambda$ cm
(a) Saturated ( $\theta = 0.3$ )			
11	2.45	0.154	0.063
17	2.51	0.126	0.050
23	2.51	0.110	0.044
(b) Unsaturated ( $\theta = 0.12$ )			
11	0.258	0.0357	0.14
17	0.254	0.0393	0.15
23	0.249	0.0429	0.17

The input mass can be used as a fitting parameter by setting  $MASS = 1$  for a Dirac delta input and a pulse input. For a pulse input either the application time or the input concentration can be estimated. Figure 7.4 shows observations and the breakthrough curve obtained by fitting the duration of the application for a pulse input,  $t_2$ , in addition to  $v$  and  $D$ . The concentration was measured with a TDR probe at a depth of 10 cm for a pulse application of KCl solution to an undisturbed sandy soil column [Mallants *et al.*, 1994]. The fitted parameters are  $v = 2.34$  cm d<sup>-1</sup>,  $D = 12.8$  cm<sup>2</sup> d<sup>-1</sup>, and  $t_2 = 0.8$  h. We again note that mass balance errors are likely to have an adverse effect on the estimation of all transport parameters.

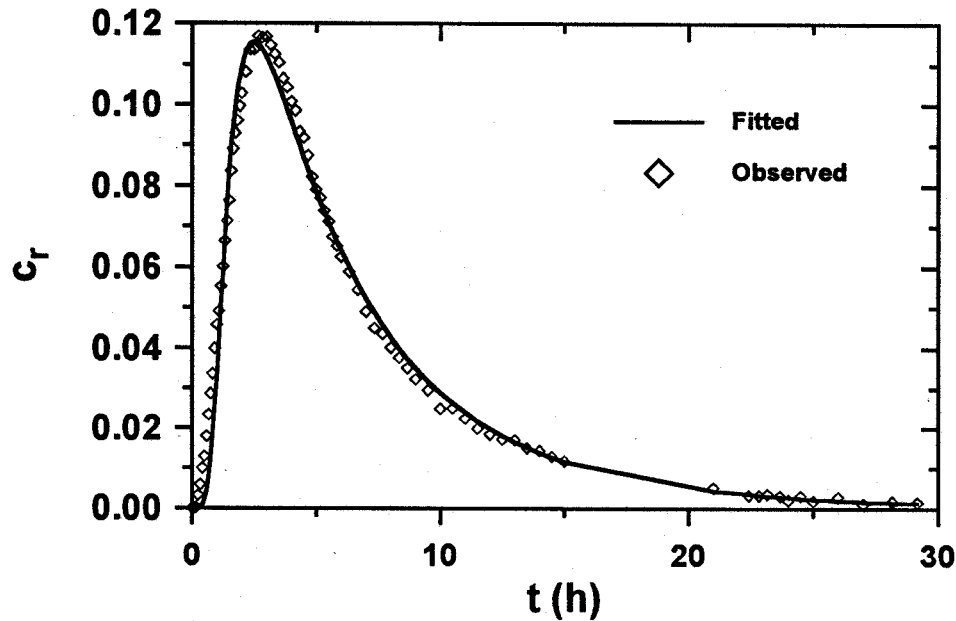


Fig. 7.4. Observed concentrations for a pulse input and breakthrough curve obtained by fitting  $\nu$ ,  $D$ , and  $t_2$ .

## 7.2. Deterministic Nonequilibrium CDE (MODE = 2)

### 7.2.1. Direct Problem

The first two examples below are included to demonstrate differences between the one-site and two-site nonequilibrium models. The one-site model is a special case of the two-site model (cf. Section 3.1.1); it is obtained by assuming that the fraction of equilibrium adsorption sites is zero ( $f = 0$ ). The kinetic rate coefficient,  $\alpha$ , is then the only remaining nonequilibrium parameter in the dimensional one-site nonequilibrium model.

Figure 7.5 shows the effect of  $\alpha$  on the BTCs in terms of the flux-averaged concentration at  $x = 50$  cm, as the result of applying a Dirac delta input function to an initially solute free soil. Other parameters are  $\nu = 20$  cm d<sup>-1</sup>,  $D = 10$  cm<sup>2</sup> d<sup>-1</sup>, and  $R = 5$ . Note that  $\beta = 0.2$ , regardless of the values for  $\alpha$ , and that the solution of the equilibrium CDE (MODE = 1) was used to predict the BTC for  $\alpha \rightarrow \infty$ . The effect of  $\alpha$  may be interpreted in terms of the adsorption time scale,  $1/\alpha$ , a smaller  $\alpha$  suggests slower adsorption. For equilibrium adsorption, the solute peak occurs at  $t \approx 12.5$  d which corresponds closely to the value for  $Rx/\nu$ . As  $\alpha$  decreases, solute spreading increases. Some of the

solutes are not readily adsorbed and move fairly quickly through the soil, while the remaining solutes move much slower since, once adsorbed, solutes will move back into the solution phase at a relatively slow pace. A concentration peak appears at  $t = 2.5$  d as  $\alpha$  decreases ( $\alpha < 0.2$  d<sup>-1</sup>). In the extreme case of  $\alpha = 0$  (i.e., no adsorption), solute transport is described with the equilibrium CDE for nonreactive solute ( $R = 1$ ).

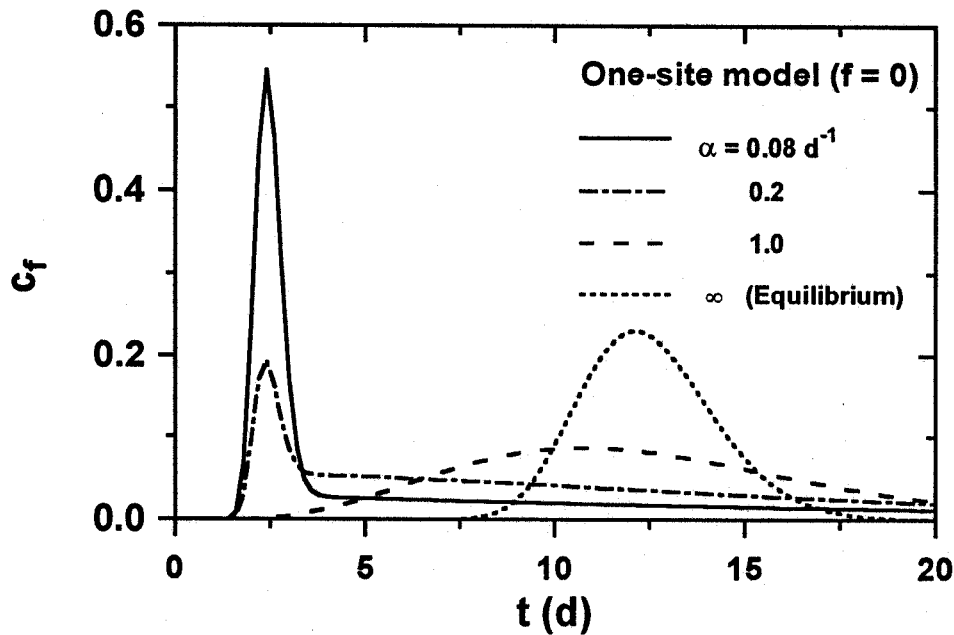


Fig. 7.5. Breakthrough curves at  $x = 50$  cm for four values of  $\alpha$  as calculated with the one-site nonequilibrium model.

Figure 7.6 presents BTCs according to the two-site nonequilibrium CDE for four values of  $f$  using the same condition as in Figure 7.5. The results for the one-site model ( $f = 0$ ) are identical to those given in Figure 7.5. For  $f = 1$  the problem is again reduced to the equilibrium CDE with  $R = 5$ ; this case is identical to the BTC for  $\alpha \rightarrow \infty$  in Figure 7.5. Notice that the concentration peak appears earlier as  $f$  decreases, while at the same time the concentration peak increases.



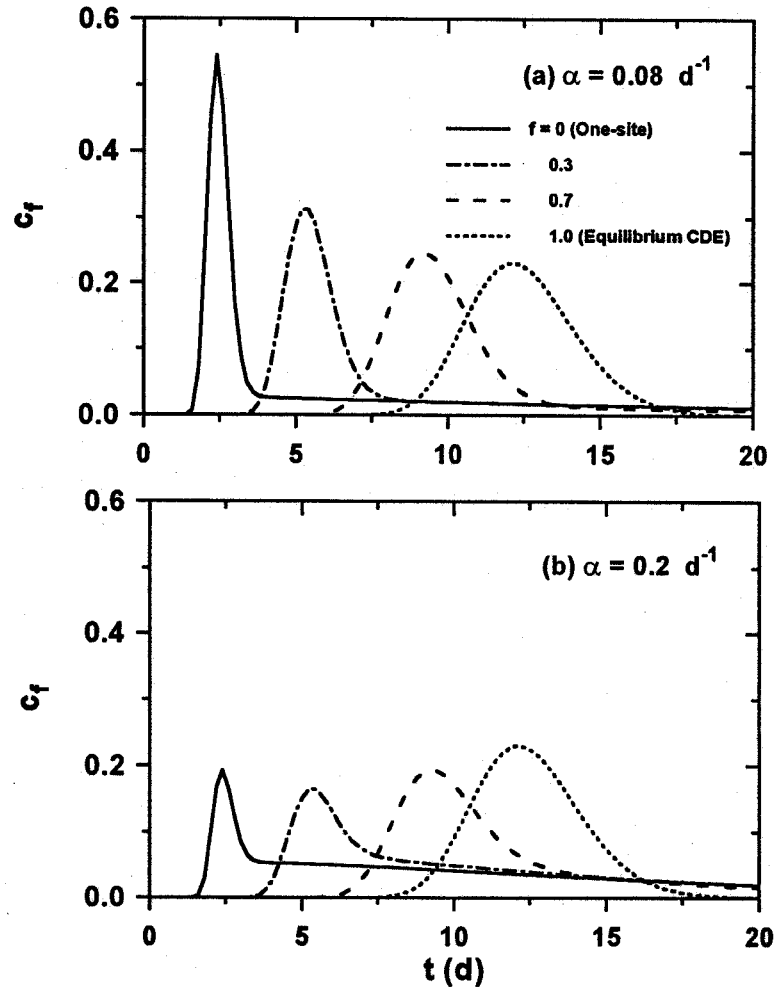


Fig. 7.6. Breakthrough curves according to the two-site nonequilibrium CDE for four values of  $f$  assuming: (a)  $\alpha = 0.08 \text{ d}^{-1}$  and (b)  $\alpha = 0.2 \text{ d}^{-1}$ .

The additional nonequilibrium parameter in the two-site model,  $f$ , gives more flexibility in the estimation procedure than the one-site model. However, if  $R$  needs to be estimated in addition to the nonequilibrium parameters,  $\alpha$  and  $f$ , it is not always possible to find a unique solution to the inverse problem. As an example, Figure 7.7a presents two breakthrough curves calculated with different values for  $R$ ,  $\alpha$ , and  $f$ . The solid line in Figure 7.7a is identical to the curves for  $f = 0.3$  in Figure 7.6a. If we neglect the effects of dispersion (i.e.,  $P \rightarrow \infty$ ) and kinetic adsorption (i.e.,  $\omega = 0$ ) in equation (3.3), the product  $\beta R$  is equivalent to the number of pore volumes,  $T$ , at which the solute initially appears in the effluent [Parker and van Genuchten, 1984b]. We used  $R = 10$  and  $f = 0.135$  to calculate the

BTC given by the dashed line in Figure 7.7a — this curve has the same value of 0.22 for  $\beta R$  as the solid curve. Furthermore, we can adjust  $\alpha$  to obtain the same peak concentration and an almost identical BTC with some minor differences in the tailing end of the BTC. Figure 7.7a implies that, in general, at least  $R$  (i.e., the distribution coefficient,  $K_d$ ) should be estimated independently.

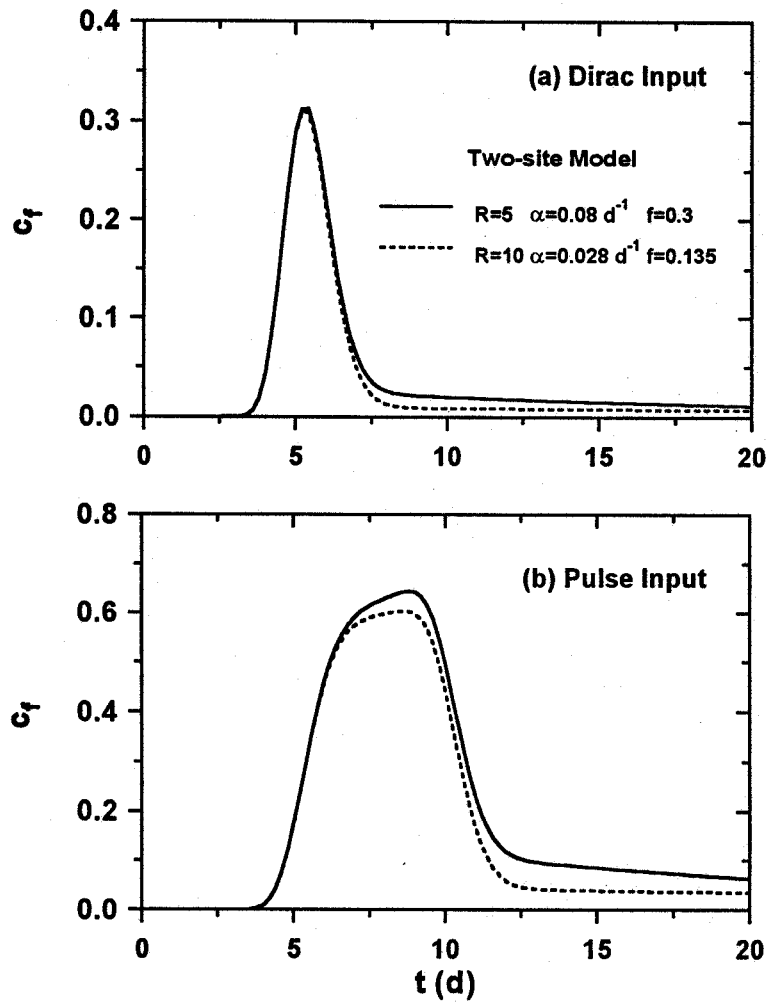


Fig. 7.7. Breakthrough curves for  $\beta R = 0.22$ , using different sets of  $R$ ,  $\alpha$ , and  $f$ , calculated with the two-site nonequilibrium CDE for: (a) Dirac delta input, and (b) pulse input of 5d.

Figure 7.7b presents two BTCs for a pulse input of 5 days using the same set of parameters as in Figure 7.7a. Differences between the BTCs predicted with the two different data sets are more pronounced for the pulse input than for the Dirac input. The enhanced tailing for the pulse input will likely somewhat improve the estimated transport parameters in the two-site model.

Since the two-region nonequilibrium model is mathematically identical to the two-site model (cf. Section 3.1.3), we may conclude from the above that different sets of  $R$ ,  $\alpha$ , and  $\theta_m$  also may lead to nearly identical concentration profiles. For reactive solutes, the fraction,  $f$ , of adsorption sites in contact with the mobile liquid phase will cause additional uncertainty in the parameter estimation. When the BTCs for reactive solutes are analyzed in terms of the two-region model, it is best to estimate  $\theta_m$  from data for a nonreactive tracer (see also Figure 7.9).

The last example involving a direct problem concerns deterministic nonequilibrium transport as described by an initial value problem (IVP). Figure 7.8 shows equilibrium ( $C_1$ ) and nonequilibrium ( $C_2$ ) resident concentration profiles at  $T = 1.0$  for three values of the partitioning coefficient  $\beta$ . The example involves the application of a solute-free solution to a soil with a stepwise initial solute distribution (dashed line in Fig. 7.8), assuming  $P = 10$ ,  $R = 2$ ,  $\omega = 1$ , and  $\mu_1 = \mu_2 = 0.2$ . Figure 7.8 shows that solutes are transported more slowly when  $\beta$  is relatively small, i.e., when a relatively large amount of solute resides in the nonequilibrium phase. Hence, leaching is not as effective when  $\beta$  is small. Notice also that the discontinuity in the nonequilibrium concentration,  $C_2$ , persists much longer when  $\beta$  is small. The discontinuity persists because solute removal and subsequent leaching from the nonequilibrium phase can only occur indirectly through the equilibrium phase after the solute has kinetically desorbed from the adsorbed to the solution phase (the one- or two-site adsorption models), or has diffused from immobile to mobile water (the two-region model). The nonequilibrium profiles closely resemble the equilibrium when  $\beta$  is large because of increased opportunity for the relatively small amount of solute in the nonequilibrium phase to move to the equilibrium phase.

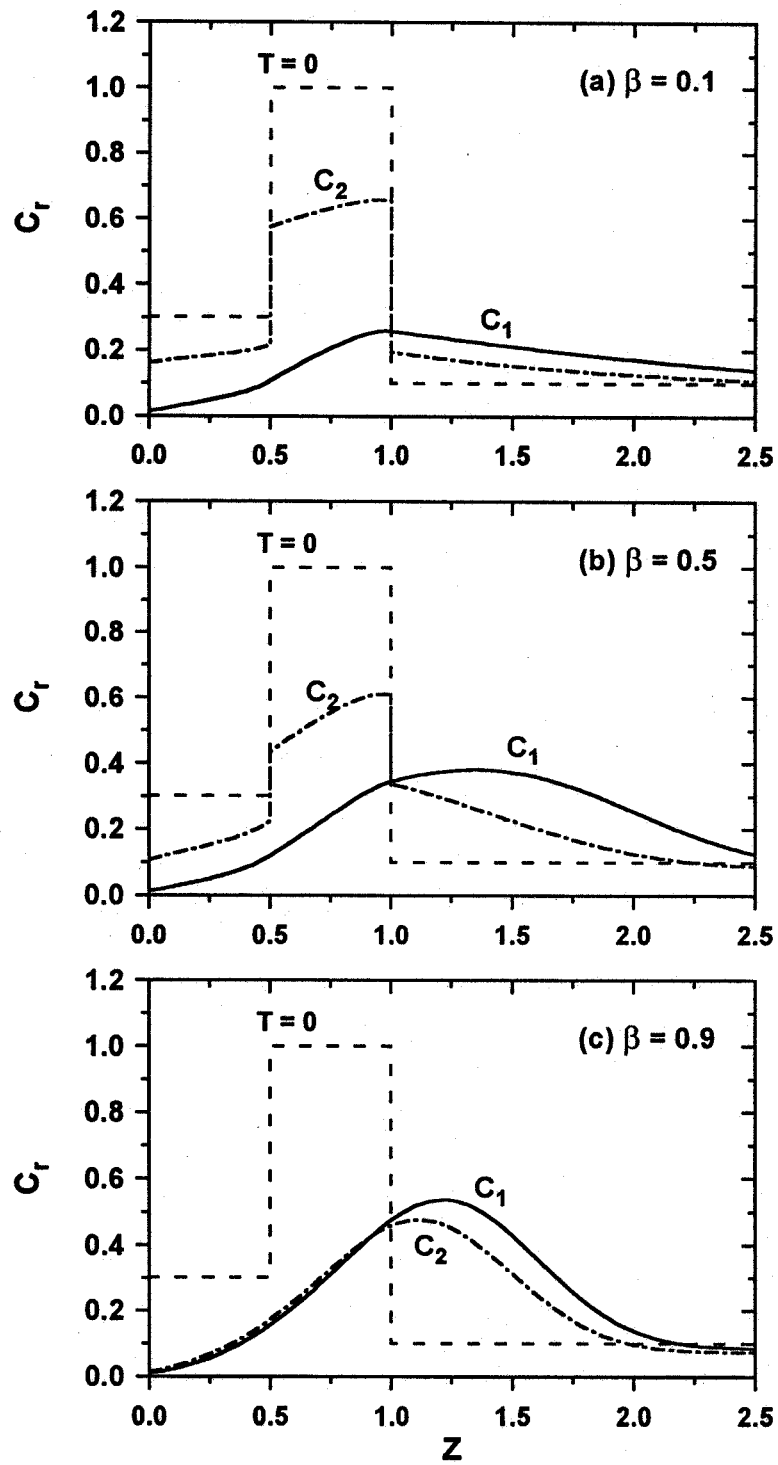


Fig. 7.8. Calculated concentration versus depth for an IVP using:  
(a)  $\beta = 0.1$ , (b)  $\beta = 0.5$ , and (c)  $\beta = 0.9$ .

### 7.2.2. Parameter Estimation

Several examples below illustrate the use of CXTFIT 2.1 to estimate parameters involving the nonequilibrium deterministic model. The first example deals with two-region nonequilibrium transport of tritiated water through a Glendale clay loam [Experiment 3-2 of *van Genuchten*, 1974]. A  $^3\text{H}_2\text{O}$  pulse of duration  $T_2 = 3.102$  was applied to a 30-cm long column, and the BTC was determined from the effluent. The volumetric water content,  $\theta$ , was 0.454 while the pore-water velocity,  $v$ , was equal to  $37.5 \text{ cm d}^{-1}$ . Assuming that  $R = 1$  for  $^3\text{H}_2\text{O}$ , we only have to estimate  $\beta (= \theta_m/\theta)$  and  $\omega$  from the measured BTC. Figure 7.9a compares the observed and fitted BTCs. The number of pore volumes,  $T$ , was used as the dimensionless time in this example (NREDU = 2). We emphasize that  $v (= v_m \theta_m/\theta)$  and  $D (= D_m \theta_m/\theta)$  are used as the unknown input parameters, instead of  $v_m$  and  $D_m$ , which appear in the two-region physical nonequilibrium model (Table 6.7). The fitted values were  $D = 15.5 \text{ cm}^2 \text{ d}^{-1}$ ,  $\theta_m/\theta = 0.822$ , and  $\omega = 0.85$ . These values correspond to  $v_m = 45.6 \text{ cm d}^{-1}$ ,  $D_m = 18.9 \text{ cm}^2 \text{ d}^{-1}$ , and  $\alpha = 0.48 \text{ d}^{-1}$ .

A pulse of boron tracer was also applied for  $T_2 = 6.494$  pore volumes to the same column as used in Figure 7.9a [Exp. 3-1 of *van Genuchten*, 1974]. The estimated parameters were  $v = 38.5 \text{ cm d}^{-1}$  and  $R = 3.9$  ( $K_d = 1.04 \text{ g}^{-1} \text{ cm}^3$ ,  $\rho_b = 1.222 \text{ g cm}^{-3}$ , and  $\theta = 0.445$ ). We assumed that  $D$  and  $\theta_m/\theta$  are identical for boron and  $^3\text{H}_2\text{O}$  (Figure 7.9a). Figure 7.9b shows the observed and fitted BTCs with parameters  $\beta = 0.578$  and  $\omega = 0.70$  ( $\alpha = 0.40 \text{ d}^{-1}$ ). Substituting  $\theta_m/\theta = 0.822$ , as obtained from the  $^3\text{H}_2\text{O}$  BTC, into the expression for  $\beta$  (cf. Table 3.1) yields  $f = 0.49$  for the fraction of sorption sites in contact with the mobile phase.

The boron data are the same as those shown in Figure 5 of the previous CXTFIT manual [*Parker and van Genuchten*, 1984b] when four parameters ( $D$ ,  $R$ ,  $\beta$ , and  $\omega$ ) were estimated. Table 7.2 shows the effect of having different initial estimates and number of unknown parameter on the optimization of the boron BTC given in Figure 7-9b — similar information was previously shown in Table 3 of *Parker and van Genuchten* [1984b]. Two different sets of initial estimates were used to estimate either two (i.e.,  $\beta$  and  $\omega$ , with  $D$  obtained by fitting the  $^3\text{H}_2\text{O}$  BTC) or three (i.e.,  $D$ ,  $\beta$ , and  $\omega$ ) parameters. For the two-parameter estimation,  $\beta$  and  $\omega$  converged to almost identical results regardless of the initial estimates. If  $D$  was also optimized, the final results depended greatly on the initial estimates. The results for the three-parameter estimation in Table 7.2 were quite dissimilar

although only the initial value for  $\beta$  was different in the two examples. Since the product  $\beta R$  determines the number of pore-volumes,  $T$ , at which the tracer initially appears in the effluent, it is important to provide a reasonable initial estimate for  $\beta R$ . If  $R$  is fitted as well — in addition to  $D$ ,  $\beta$ , and  $\omega$  such as in Table 3 in *Parker and van Genuchten* [1984b] — the likelihood that the optimization does not converge to the correct solution will increase. Figure 7.7 suggests that different parameter sets can yield very similar curves. This occurs when the response surface (i.e., the objective function,  $SSQ(b)$ ) has a flat surface near the global minimum or when multiple local minima exist.

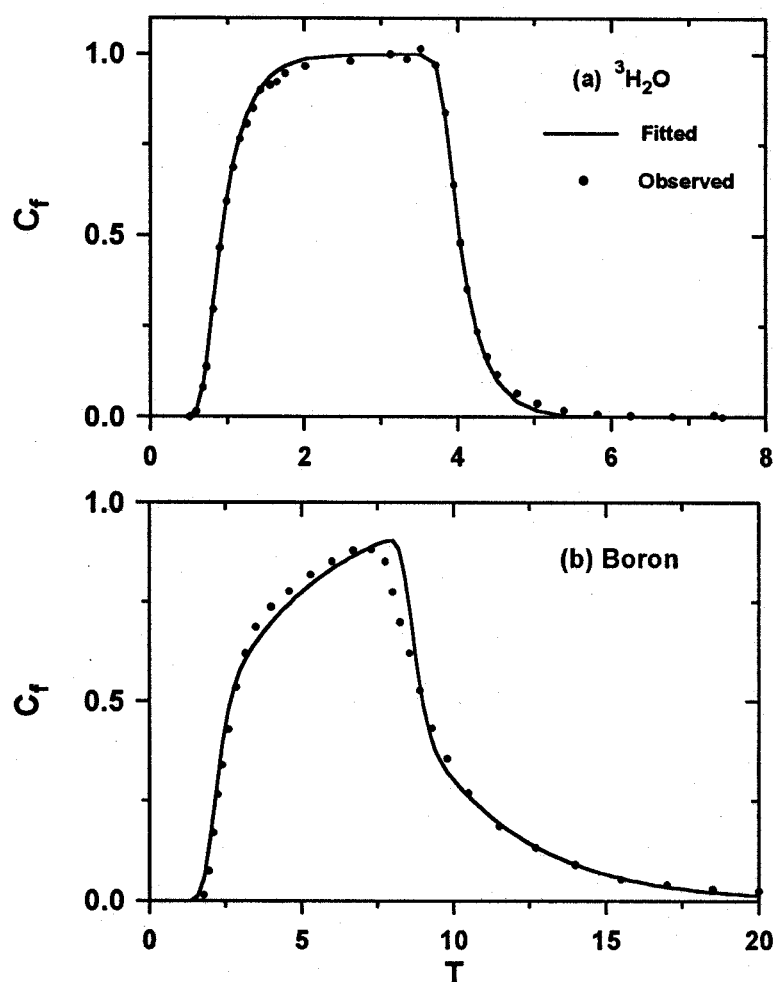


Fig 7.9. Breakthrough curves for a Glendale clay loam described by the two-region physical nonequilibrium model for nonreactive  $^3\text{H}_2\text{O}$  and reactive boron.

Table 7.2. Fitted Parameter Values and the Coefficient of Determination,  $r^2$ , for the Optimization of the boron BTC for Different Sets of Initial Estimates

Example	$\nu$	$D$	$R$	$\beta$	$\omega$	$r^2$
(a) Two parameter ( $\beta$ , $\omega$ ) estimation						
Initial values	38.5	15.5	3.9	0.5	0.2	-
Final values	fixed	fixed	fixed	0.58	0.70	0.970
Initial values	38.5	15.5	3.9	0.1	0.2	-
Final values	fixed	fixed	fixed	0.58	0.70	0.970
(b) Three parameter ( $D$ , $\beta$ , $\omega$ ) estimation						
Initial values	38.5	15.5	3.9	0.5	0.2	-
Final values	fixed	50.2	fixed	0.647	0.46	0.978
Initial values	38.5	15.5	3.9	0.1	0.2	-
Final values†	fixed	303.6	fixed	0.9999	100.0	0.942

†  $\beta$  and  $\omega$  reached the internal maximum constraints  $\beta=0.9999$  and  $\omega=100$ . The estimate for  $D$  is almost identical to that obtained by fitting the equilibrium CDE to the observed data.

In most cases  $\beta$  and  $\omega$  will be obtained from a simultaneously fit. Rao *et al.* [1980], on the other hand, attempted to independently predict  $\omega$  from the aggregate size for a medium consisting of uniform spherical aggregates. Nonequilibrium transport of a reactive solutes is probably best studied with experiments that observe the movement of reactive and nonreactive solutes (cf. Figure 7.9). As a first approximation, we can then assume that such parameters as  $D$  and  $\theta_m$  are the same for both types of solute.

### 7.3. Stochastic CDE (MODE $\geq 3$ )

#### 7.3.1. Nonreactive Solute Transport

##### *Direct Problem*

First we consider equilibrium transport of a nonreactive solute ( $R = 1$ ) at the local scale as discussed in Section (4.2). Figure 7.10 shows the mean,  $\hat{c}_r = \langle c_r \rangle$ , and the variance according to (4.20) as a function of depth at  $t = 3$  d for three values of  $\sigma_v$ , as result of a 2-d solute application to a solute-free soil assuming  $\langle v \rangle = 20$  cm d $^{-1}$  and  $\langle D \rangle = 20$  cm $^2$  d $^{-1}$  with a constant dispersivity ( $\sigma_v = \sigma_D$ ).

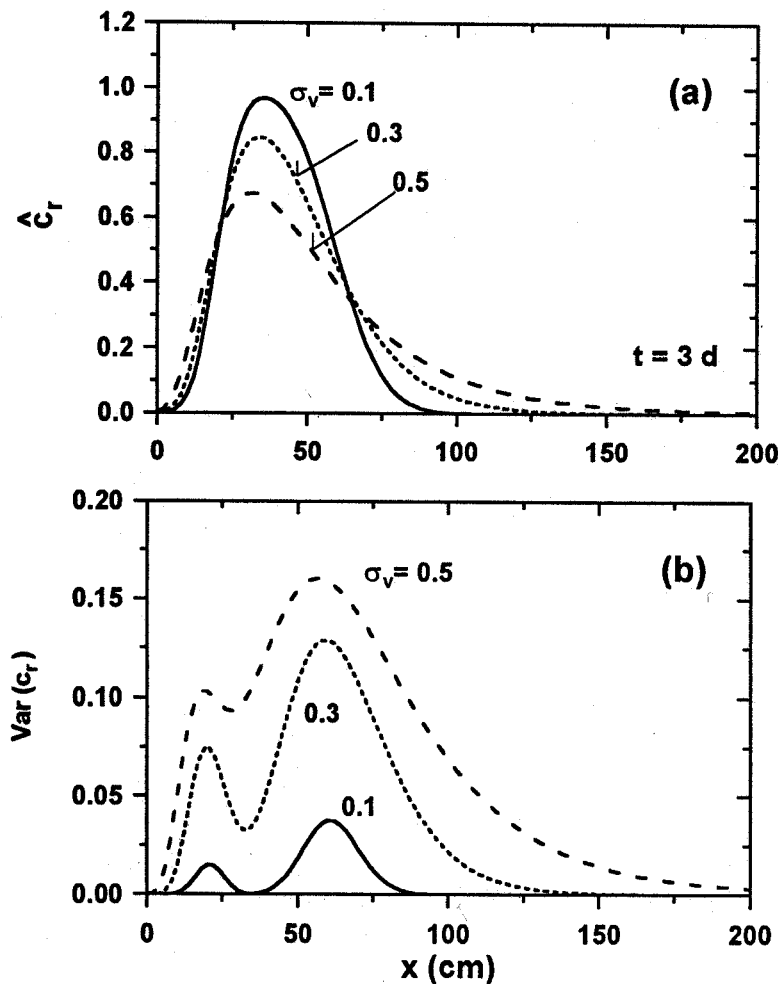


Fig. 7.10. The effect of the variability in the pore-water velocity,  $v$ , on: (a) the field-scale resident concentration ( $\hat{c}_r$ ) profile, and (b) the distribution of the variance for  $c_r$  in the horizontal plane.



Solute spreading in the  $\hat{c}_r$ -profile increased with  $\sigma_v$  as indicated in Figure 7.10a. Figure 7.10b shows that variations in the local-scale  $c_r$  also increased with  $\sigma_v$ , thereby suggesting that a more heterogeneous solute distribution will occur in the horizontal plane. Because flow and transport become increasingly heterogeneous as  $\sigma_v$  increases, more observations are needed to reliably estimate field-scale concentrations. Note that the variance profiles have a double peak (Figure 7.10b). The variance has a relative minimum around  $x = 30$  cm where the highest concentration occurs (Figure 7.10a). Similar bimodal behavior of the variance was observed numerically by Burr *et al.* [1994] for transport in a three-dimensional heterogeneous medium. The variance also depends on the duration of the solute application time. As the application time increases, continued solute injection will counteract the randomness due to variations in transport properties between stream tubes.

Figure 7.11 presents BTCs for three types of field-scale concentrations ( $\hat{c}_r$ ,  $\hat{c}_f$  and  $\langle c_f \rangle$ ) as a result of a Dirac input assuming  $\langle v \rangle = 50$  cm d<sup>-1</sup>,  $\langle D \rangle = 200$  cm<sup>2</sup> d<sup>-1</sup>, and  $\sigma_v = \sigma_D = 0.5$ . The BTC for  $\hat{c}_f$  has the highest peak at a relatively early time, while  $\hat{c}_r$  and  $\langle \hat{c}_f \rangle$  show similar distributions. The local-scale concentration mode apparently has little influence on the field-scale average when the velocity is stochastic. A relatively large value for  $\langle D \rangle$  was selected to demonstrate the difference between  $\hat{c}_r$  and  $\langle c_f \rangle$ . These two concentrations would be very similar for smaller  $\langle D \rangle$  (e.g., 20 cm<sup>2</sup> d<sup>-1</sup>).

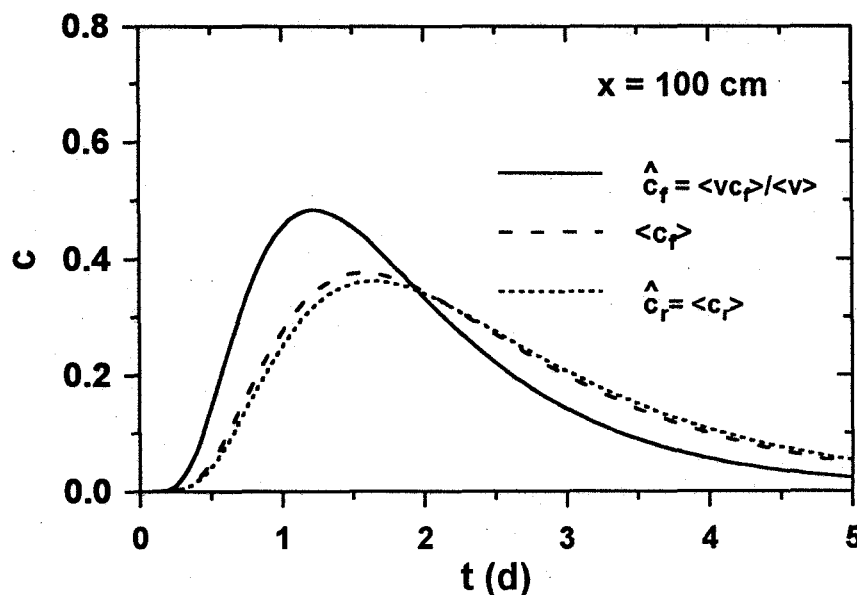


Fig. 7.11. Breakthrough curves for three types of field-scale concentration modes.

The mean breakthrough time and the amount of spreading are smaller for  $\hat{c}_f$  than for  $\hat{c}_r$  or  $\langle c \rangle$ . All concentrations are almost identical at  $t = 2$  d, which is the mean breakthrough time for  $\hat{c}_f$  [Toride and Leij, 1996a]. Solutes will only reach  $x = 100$  cm prior to  $t = 2$  d if it travels in stream tubes with a velocity greater than the ensemble average,  $\langle v \rangle$ . The velocity-weighted concentration,  $\hat{c}_f$  should therefore be greater than the ensemble-averaged concentrations,  $\hat{c}_r$  and  $\langle c \rangle$ , during the initial stages of the displacement process ( $t < 2$  d). On the other hand,  $\hat{c}_f$  becomes less than  $\hat{c}_r$  or  $\langle c \rangle$  at later times ( $t > 2$  d).

### Parameter Estimation

There are very few data sets that allow solution of the inverse problem for the stream tube model. The same data as those of Figure 7a in the CXTFIT manual by Parker and van Genuchten [1984b] were used to demonstrate parameter estimation for the stochastic stream tube model. The example pertains to resident concentrations of a 0.64-ha field to which a bromide pulse was applied for 1.69 d followed by leaching with solute-free water [Jury et al., 1982]. The stream tube model can be adapted for transient flow conditions as shown by Parker and van Genuchten [1984b, p. 41].

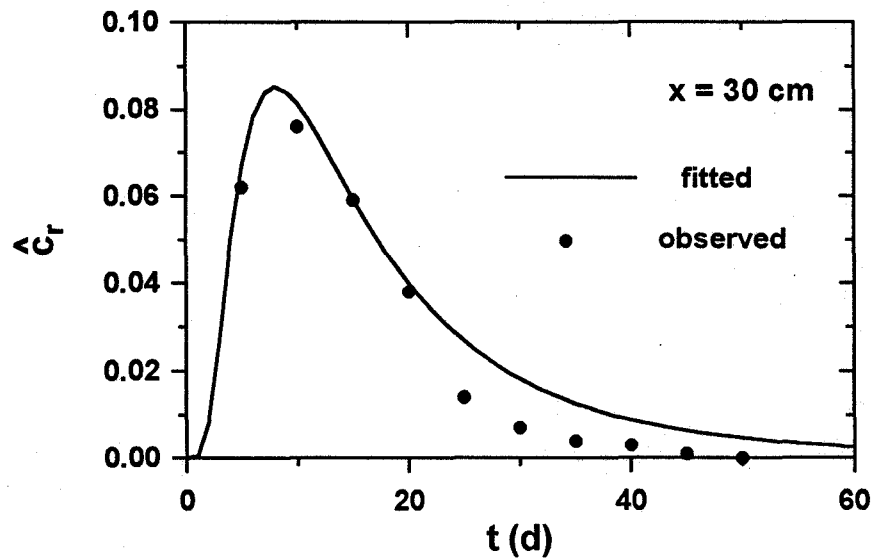


Figure 7.12. Observed and fitted values of  $\hat{c}_f$  for field-scale transport of bromide (after Jury et al. [1982]).

The dispersivity,  $\lambda$ , was assumed to be constant with  $\rho_{vD} = 1$ ; the following parameters should hence be used in the input file: MODE = 3 and  $\sigma_v = \sigma_D$  (cf. Eq. (4.25) and Table 6.7). Solution of the inverse problem yielded:  $\langle v \rangle = 30.5 \text{ mm d}^{-1}$ ,  $\langle D \rangle = 2.5 \text{ mm}^2 \text{ d}^{-1}$ , and  $\sigma_v = 0.8 \text{ mm d}^{-1}$ , and  $\sigma_D = 0.8 \text{ mm}^2 \text{ d}^{-1}$ . The estimates for  $\langle v \rangle$  and  $\sigma_v$  are identical to those by *Parker and van Genuchten* [1984b], whereas  $\langle D \rangle$  was about ten times smaller. Local dispersion typically has a minor effect on the field-scale concentration (cf. *Parker and van Genuchten* [1984b] and *Toride and Leij* [1996a]).

### 7.3.2. Reactive Solute Transport

#### Direct Problem

In addition to the variability in  $v$  and  $D$ , we may also need to consider the variability in the distribution coefficient,  $K_d$ , and the nonequilibrium rate parameter,  $\alpha$ , when modeling the field-scale transport of reactive solutes. The effect of a stochastic  $v$  or  $K_d$  on field-scale concentrations is first demonstrated for equilibrium transport using MODE = 3. The field-scale resident concentration,  $\hat{c}_r$ , at  $t = 5 \text{ d}$  resulting from a Dirac delta input at  $t = 0$ , is plotted versus depth in Figure 7.13 for either perfect or no correlation between  $v$  and  $K_d$ . Values of the transport parameters are:  $\langle v \rangle = 50 \text{ cm d}^{-1}$ ,  $D = 20 \text{ cm}^2 \text{ d}^{-1}$ ,  $\langle K_d \rangle = 1 \text{ g}^{-1} \text{ cm}^3$ ,  $\sigma_{Kd} = 0.2 \text{ g}^{-1} \text{ cm}^3$ ,  $\langle R \rangle = 5$ , and  $\rho_b/\theta = 4 \text{ g cm}^{-3}$ .

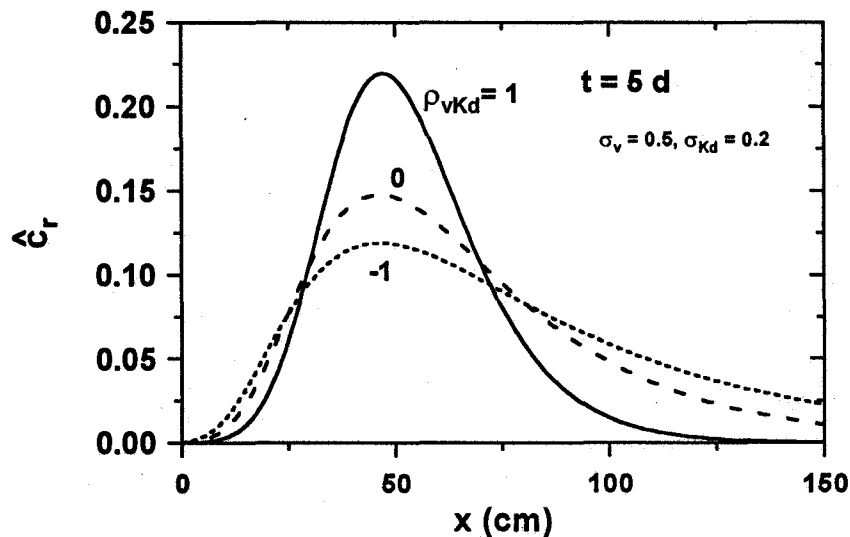


Fig. 7.13. Effect of the correlation between  $v$  and  $K_d$  on field-scale resident concentration ( $\hat{c}_r$ ) profiles.

A negative correlation between  $\nu$  and  $K_d$  implies that  $R$  and  $\nu$  are inversely related; such a correlation causes additional spreading in the field-scale concentration. The effect of variability in  $K_d$  on solute spreading, as observed from the results of the relatively simple stream tube model, is quite similar as observed using more general stochastic approaches [e.g., *Bosma et al.*, 1993].

If solutes are not adsorbed instantaneously, the field-scale concentration may be predicted with the nonequilibrium transport models defined by (4.1) and (4.2). In the next example we assume that the nonequilibrium rate coefficient,  $\alpha$ , is deterministic (MODE = 4). Figure 7.14 shows the field-scale resident ( $\hat{c}_r$ ) and total resident ( $\hat{c}_T$ ) concentrations versus depth at  $t = 1$  d. The stochastic parameters are  $\nu$  and  $K_d$ , with  $\rho_{\nu K_d} = -1$ , while the deterministic rate parameter (actually the dimensionless parameter,  $\omega$ ) is given by: (a)  $\alpha = 2.5 \text{ d}^{-1}$ , (b)  $\alpha = 0.5 \text{ d}^{-1}$ , and (c)  $\alpha = 0.1 \text{ d}^{-1}$ . All other parameters were taken to be the same as those used for Figure 7.13. Differences between  $\hat{c}_T$  and  $\hat{c}_r$  reflect the amount of adsorbed solutes. As  $\alpha$  decreases, some of the solute will not be readily adsorbed and hence is transported downgradient relatively quickly. On the other hand, a relatively large fraction of the solutes will be adsorbed near the surface in case of an increased  $\alpha$ .

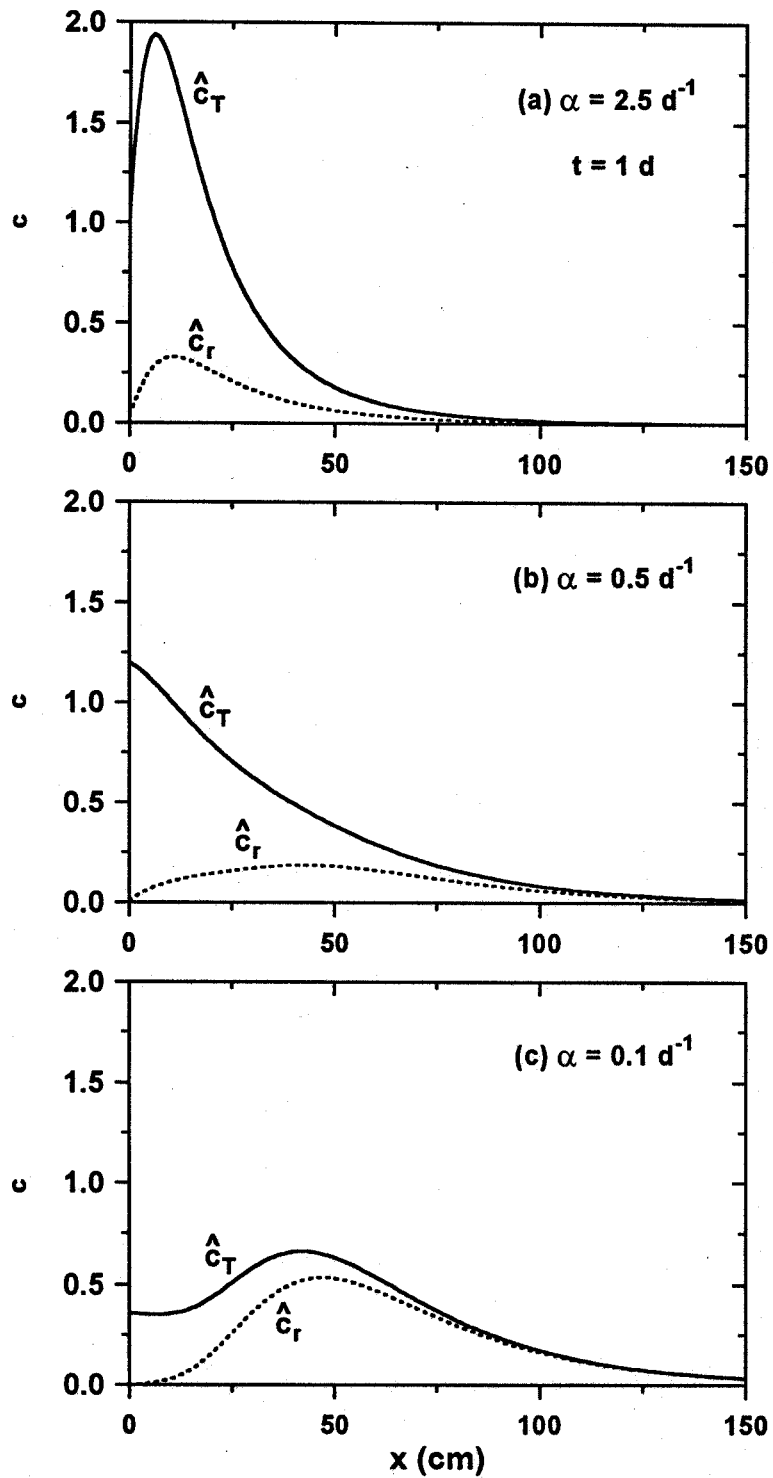


Fig. 7.14. Nonequilibrium field-scale transport for negatively correlated  $v$  and  $K_d$ .

### Parameter Estimation

As for nonreactive solutes, there is a general lack of suitable data for estimating transport parameters in the stream tube model for reactive solutes. We will therefore use a hypothetical data set to illustrate the solution of the inverse problem in CXTFIT 2.1 for stochastic transport of reactive solutes. Furthermore, the solution of the inverse problem is far more complicated since both the variability in  $v$  or  $D$  as well as  $\alpha$  or  $K_d$  [Robin *et al.*, 1991] may have to be considered. Figure 7.15 shows predicted resident concentrations,  $\hat{c}_r$ , after a solute pulse is applied for one day; the following model parameters were used:  $\langle v \rangle = 50 \text{ cm d}^{-1}$ ,  $D = 20 \text{ cm}^2 \text{ d}^{-1}$ ,  $\langle K_d \rangle = 1 \text{ g}^{-1} \text{ cm}^3$ ,  $\sigma_{Kd} = 0.3 \text{ g}^{-1} \text{ cm}^3$ ,  $\langle R \rangle = 5$ ,  $\rho_b / \theta = 4 \text{ g cm}^{-3}$ , and  $\rho_{vKd} = -0.8$  (MODE = 3). The standard deviation,  $\sigma_{Kdb}$  and the coefficient of correlation between  $v$  and  $K_d$ ,  $\rho_{vKdb}$  were fitted to the hypothetical data while keeping  $\langle v \rangle$ ,  $\sigma_v$ , and  $\langle K_d \rangle$  constant at the above values. The latter parameters could also have been estimated from data for a nonreactive solute. The program converged to the correct parameter values, i.e., those that were used to generate the hypothetical data set, after just a few iterations. Unfortunately, such good results are unlikely for most practical cases since the experimental conditions in most heterogeneous fields will not conform exactly to the assumptions made for the stream tube model (cf. Chapter 4).

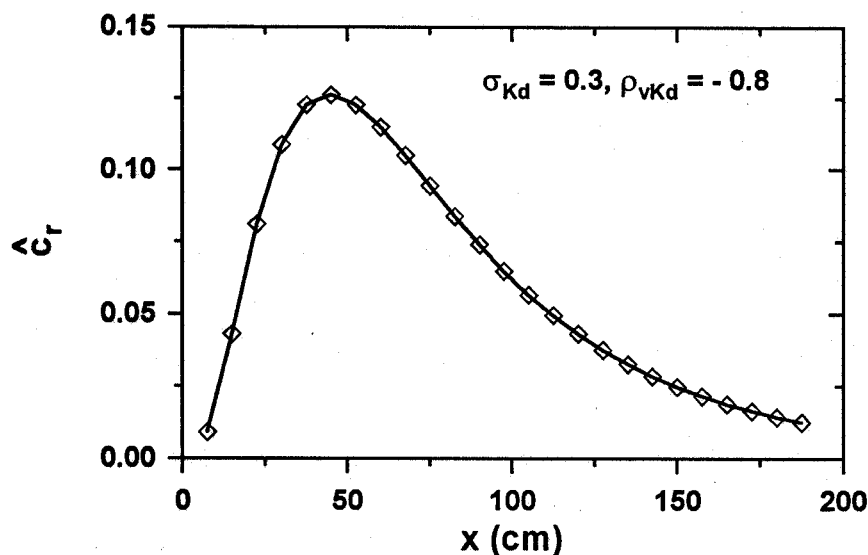


Fig. 7.15. Estimation of  $\sigma_{Kd}$  and  $\rho_{vKd}$  by fitting the solution for the stream tube model to hypothetical data, generated with a stochastic  $v$  and  $K_d$ , assuming that  $\langle v \rangle$ ,  $\sigma_v$ , and  $\langle K_d \rangle$  are known.



## 8. SUMMARY AND CONCLUSIONS

The CXTFIT 2.1 program provides a convenient way of solving direct and inverse problems for one-dimensional solute transport during steady water flow. Both equilibrium and two-site/two-region type nonequilibrium transport models can be implemented — the transport equation contains terms for convection, dispersion, linear adsorption, zero-order production, and first-order decay. Analytical solutions for deterministic transport were given for a large number of boundary, initial, and production value problems. CXTFIT 2.1 also includes a stochastic transport model that views the field as an assembly of deterministic flow and transport paths; these are referred to as stream tubes for one-dimensional flow and transport. Transport in each stream tube is modeled deterministically with the convection-dispersion equation using as random parameters  $v$  and either  $D$ ,  $K_d$ , or  $\alpha$ . The random parameters are described with a bivariate lognormal probability density function. Solute concentrations across the field, in either the resident or flux-averaged mode, were obtained by averaging the concentrations of individual stream tubes.

Various transport parameters in the deterministic and stochastic transport models can be estimated by CXTFIT 2.1 by fitting the pertinent analytical solution to solute (tracer) concentrations obtained in the laboratory or field. As discussed in Chapter 5, the estimation procedure uses a nonlinear least-squares inversion method according to *Marquardt* [1963]. While the procedure has been shown to work for many examples, users should remain cognizant of potential problems involving convergence and parameter uniqueness. This is especially true when the stream tube model is used for optimizing data obtained across the field. Chapter 6 contains a detailed and schematic outline of the settings and variables for each solution of the direct or inverse problem in CXTFIT 2.1. The use of the program is further illustrated in Chapter 7, which contains a variety examples regarding the prediction of solute profiles and the analysis of experimental data to estimate parameters in deterministic and stochastic solute transport models.





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## APPENDIX: LIST OF SIGNIFICANT PROGRAM VARIABLES

Table A1. List of Integer Variables

ICHEB	Integration code for Gauss Chebyshev. If ICHEB = 1, the number of integration points will increase until the result satisfies the error criterion (default is ICHEB = 1 in the subroutine <b>CONST1</b> , blank common).
ILMT	Parameter constraint code (Table 6.4).
ISKIP	Calculation control code for the evaluation of the integral limits; ISKIP = 0 to evaluate the limits; = 1 to skip evaluation (the subroutine <b>Model</b> , <b>MODAT</b> common).
INTM	Calculation control code for the numerical integration for the stochastic CDE in subroutine <b>STOCDE</b> (INTM = 1 for log-transformed Romberg; = 2 for log-transformed Gauss-Chebyshev, default is INTM = 1).
INVERSE	Calculation control code for direct and inverse problems (Table 6.3, <b>MODAT</b> common).
KP	File unit number.
MIT	Maximum number of iterations (Table 6.4, <b>MODAT</b> common).
MASS	Total mass estimation code (Table 6.4, <b>MODAT</b> common).
MASSST	Mass distribution index for the stochastic CDE (MODB = 1, 3 in Table 6.7, <b>BOUND</b> common).
MAXTRY	Maximum number of trials to find new parameter values without a decrease in the SSQ (It is suggested that MAXTRY be in the range 10 to 50; smaller values may reduce the run time but no convergent solution may be found. Default is 50 in the subroutine <b>CONST1</b> ).
MAXOB	Maximum number of data ( <b>Main program</b> ).
MCON	Calculation control code for concentrations (MCON = 0, Calculate equilibrium and nonequilibrium concentrations; = 1 only equilibrium; = 3 only nonequilibrium, blank common).
MCORR	Index for stochastic $\nu$ and $\eta$ defined in subroutine <b>MODEL</b> ; MCORR = -1 for perfect negative correlation between $\nu$ and $\eta$ ; = 0 for uncorrelated $\nu$ and $\eta$ ; = 1 for perfect positive correlation between $\nu$ and $\eta$ ; = 2 for other correlation ( <b>STOCH</b> common).
MDEG	Degradation estimation code for the nonequilibrium CDE (Table 6.4, <b>MODAT</b> common).
MM	Initial number of integration points for Gauss Chebyshev (default is 75 in subroutine <b>CONST1</b> , blank common).
MNEQ	Nonequilibrium model code (Table 6.4, <b>MODAT</b> common).
MODB	Boundary value problem code (Table 6.7, <b>BOUND</b> common).
MODC	Concentration mode (Table 6.3, blank common).
MODD	Index for a stochastic dispersion coefficient defined in subroutine <b>CHECK</b> ; MODD = -1, perfect negative correlation between $\nu$ and $D$ ; = 0, deterministic $D$ ; = 1 perfect positive correlation; = 2, $\sigma_v = \sigma_D$ , constant field-scale dispersivity ( <b>STOCH</b> common).
MODE	Model code (Table 6.3, blank common).
MODI	Initial value problem code (Table 6.8, <b>INITI</b> common).
MODJH	Calculation control code for step input in subroutine <b>BOUND</b> (MODJH = 0, evaluate (3.23) or (3.24); = 1, (3.21) or (3.22) based on Goldstein's $J$ -function, default is MODJH = 1).
MODK	Index for a stochastic distribution coefficient defined in subroutine <b>CHECK</b> ; MODK = -2 for $\sigma_v = \sigma_{K_d}$ ; = -1 for perfect negative correlation between $\nu$ and $K_d$ ; = 0 for deterministic $K_d$ ; = 1 for perfect positive correlation ( <b>STOCH</b> common).
MODP	Production value problem code (Table 6.9, <b>PROD</b> common).
MODP1	Calculation control code for constant production for the equilibrium CDE in subroutine <b>PRODUC</b> (MODP1 = 0 to evaluate the integral in (2.32); = 1 for (2.33) or (2.34), default is MODP1 = 1).



Table A1. (continued)

MPRINT	Output print code for direct problem (Table 6.11).
MPRO	Production function code for a nonequilibrium phase (Table 6.9).
MSD	Calculation control code for ensemble averages defined in subroutine STOCDE; MSD = 0, <C>; = 1, <C <sup>2</sup> >, (STOCH common).
MSTOCH	Index for stochastic $\nu$ and $\eta$ defined in subroutine MODEL; MSTOCH = 1 for variable $\nu$ and deterministic $\eta$ ; = 2 for deterministic $\nu$ and variable $\eta$ ; = 3 for perfect correlation between $\nu$ and $\eta$ ; = 4 for variable $\nu$ and variable $\eta$ (STOCH common).
NC	Number of cases considered (Table 6.3, Main program).
NERR	Number of errors in an input file (subroutine CHECK).
NINI	Number of steps for stepwise initial distribution (Table 6.8, INITI common).
NIT	Number of iteration trials in the least square analysis (Main program).
NOB	Number of observations (cannot exceed MAXOB).
NP	Number of parameters to be fitted to the data (Main program).
NPRO1	Number of steps for stepwise production profile in an equilibrium phase (Table 6.9, PROD common).
NPRO2	Number of steps for stepwise production profile in an nonequilibrium phase (Table 6.9, PROD common).
NPULSE	Number of pulses for multiple pulse input (Table 6.7, BOUND common).
NREDU	Data input and output code (Table 6.3, MODAT common).
NT	Number of output times for a direct problem (Table 6.11).
NTP	Number of transport parameters (subroutine DATAIN).
NTRIAL	Number of trials to decrease SSQ (Main program).
NU1	Value of NVAR + 1 (Main program, subroutine DATAIN).
NU2	Value of NVAR $\times$ 2 (Main program, subroutine DATAIN).
NVAR	Total number of parameters (subroutine DATAIN, MODAT common).
NZ	Number of output positions for a direct problem (Table 6.11).

Table A2. List of Real Variables

A or AA	$\omega^2/(\omega+\mu_2)\beta R$ defined in subroutine DETCDE (blank common).
AVEV	Mean pore-water velocity, $\langle v \rangle$ (subroutine CONPROV).
ALPHA	First-order kinetic rate coefficient, $\alpha$ (STOCH common).
ANGLE	Deviation of the correction vector from the steepest descent direction (Main program).
B or BB	$(\omega+\mu_2)/(1-\beta)R$ defined in subroutine DETCDE (blank common).
BETA	Partition coefficient, $\beta$ (blank common).
BETR	Value of $\beta \times R$ (blank common).
BMASS	Mass for Dirac delta input (subroutine BOUND).
CBOU1	Equilibrium concentration for boundary value problem (subroutine DETCDE).
CBOU2	Nonequilibrium concentration for boundary value problem (subroutine DETCDE).
CINT1	Equilibrium concentration for initial value problem (subroutine DETCDE).
CINT2	Nonequilibrium concentration for initial value problem (subroutine DETCDE).
CORR	Correlation coefficient between $v$ and $\eta$ for stochastic model, $\rho_{v\eta}$ (STOCH common).
CPRO1	Equilibrium concentration for production value problem (subroutine DETCDE).
CPRO2	Nonequilibrium concentration for production value problem (subroutine DETCDE).
CX	$\omega/(\omega+\mu_2)$ defined in subroutine DETCDE (blank common).
D or DIS	Dispersion coefficient, $D$ (STOCH common).
DA	$\omega\mu_2/(\omega+\mu_2)$ defined in subroutine DETCDE (blank common).
DK	Distribution coefficient for linear adsorption, $K_d$ (STOCH common).
DMASS	Mass for a Dirac delta initial condition (subroutine INITIAL).
DMU1	First-order decay coefficient in an equilibrium phase, $\mu^E$ or $\mu_1$ , (blank common).
DMU2	First-order decay coefficient in a nonequilibrium phase, $\mu_2$ , (blank common).
DT	Time increment for output in a direct problem.
DUMTZ	Time or position for the solute profile or breakthrough for INPUTM = 1 in an inverse problem (Table 6.10).
DZ	Spatial increment for output in a direct problem.
GA	Constant for the Levenberg-Marquardt method (default is 0.01 in subroutine CONST1).
GD	Trial and error factor for GA for the Levenberg-Marquardt method (default is 10 in subroutine CONST1).
LEVEL	The maximum order for the log-transformed Romberg integration (the value will be adjusted internally depending on the Peclet number in subroutine CONST2, blank common).
OMEGA	Mass transfer coefficient, $\omega$ (blank common).
OMMAX	Maximum constraint for $\omega$ (default is 100 in subroutine CONST1).
P or PEC	Peclet number (blank common).
R or RE	Retardation factor (blank common).
PHIIM	Immobile water fraction for the physical nonequilibrium CDE, $\theta_m/\theta$ (MODAT common).
PHIM	Mobile water fraction for the physical nonequilibrium CDE, $\phi_m = \theta_m/\theta$ (Table 6.4, MODAT common).
RHOTH	$\rho_b/\theta$ for the stochastic CDE (STOCH common).
SDLND	Standard deviation of $\ln D$ , $\sigma_D$ (STOCH common).
SDLNV	Standard deviation of $\ln v$ , $\sigma_v$ (STOCH common).
SDLNY	Standard deviation of $\ln \eta$ , $\sigma_\eta$ (STOCH common).
SSQ	Sum of squared residuals (Main program).
STEP	Scale factor for the correction vector (Main program).
STOPCR	Iteration criterion. The curve-fitting process stops when the relative change in the ratio of all coefficients becomes less than STOPCR (default is 0.0005 in subroutine CONST1).