1993

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'Arif Tabassum
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**Modeling of contaminant transport at the eastern general
services area, site 300, Lawrence Livermore National Laboratory,
San Joaquin County, California**

Arif, Muhammad, M.S.

San Jose State University, 1993

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**300 N. Zeeb Rd.
Ann Arbor, MI 48106**

**Modeling of Contaminant Transport
at the Eastern General Services Area, Site 300,
Lawrence Livermore National Laboratory,
San Joaquin County, California**

A Thesis

Presented to

The Faculty of the Department of Geology

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree of

Master of Science

by
Muhammad Arif
December 1993

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ABSTRACT

The contaminant transport model, Method of Characteristics, was used to determine the groundwater flow velocity and rate of migration of trichloroethylene (TCE) in a shallow aquifer composed of alluvium and the underlying permeable sandstone bedrock and to test remedial options. Wells provided geologic logs, groundwater elevations, drawdowns due to pumping, and contaminant concentrations used in the model calibration. The model predicted a groundwater flow velocity of 15 to 35 feet per day along the axial line of the plume. Movement of the contaminant is retarded by a factor of 1.7 as compared to groundwater velocity. Over an estimated release time of 20 years, 4.1 gallons of TCE have been released. If the source is removed, the contaminant will be flushed out of the study area under natural flow conditions. If the source is left in place, extraction of groundwater at 29.5 gallons per minute using a well located downgradient of the source can reduce the contaminant concentrations by 85%.

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INTRODUCTION

The General Services Area (GSA), Site 300, is a part of Lawrence Livermore National Laboratory (LLNL), Livermore, California (fig. 1). The GSA covers 80 acres along Corral Hollow Creek in Corral Hollow, approximately 15 miles southeast of Livermore and 8.5 miles southwest of Tracy, California. The facilities at the GSA (fig. 2) are used by the administration, security, medical facilities, plant engineering, and electrical and mechanical engineering.

In 1982, one of the production wells in the GSA was discovered to contain 52 $\mu\text{g/l}$ of trichloroethylene (TCE) (McIlvride and others, 1990). Subsequent investigations led to the discovery of six plumes of volatile organic compounds (VOCs) in soil and groundwater at the GSA. Based on the locations of the VOC plumes, the GSA is divided into western, central, and eastern subareas. This study focuses on the eastern GSA plume.

General Geology

Site 300 is located in the Coast Range Physiographic Province of California (McIlvride and others, 1990), which is a system of northwest-trending, fault bounded mountain ranges and valleys underlain by rocks ranging from Jurassic to Holocene in age. The area is occupied by antiformal mountain ranges and deep synformal valleys filled with sediments of late Tertiary to Holocene age (McIlvride and others, 1990).

Figure 1. Location of Lawrence Livermore National Laboratory (LLNL) and Site 300 (from McIlvride and others, 1990).

Figure 2. Location of the General Services Area (GSA), Site 300, LLNL (from McIlvride and others, 1990).

Knowledge of the geology is based on regional geological mapping by Raymond (1969), Dibblee (1980), and Raber and Carpenter (1983). Figure 3 presents the geologic map of Site 300. Most of the bedrock in the area consists of continental and estuarine sedimentary rock of the upper Miocene Neroly Formation (Tn) with some volcanoclastic components. The Neroly Formation is approximately 500 ft (150 m) thick and is composed of blue-weathering sandstone, siltstone, conglomerate with andesitic and basaltic pebbles and cobbles, and interbedded tuffaceous shales. The Neroly Formation is conformably underlain by marine-estuarine sandstone of the Miocene Cierbo Formation (Tmss). The Cierbo Formation is about 300 ft (90 m) thick in the Site 300 area. Other formations underlying and/or exposed in the area are the Pliocene Tulare Formation (Qtl), Eocene Tesla Formation (Tts), and Upper Cretaceous Moreno (Km) and Panoche (Kps) formations of the Great Valley Group.

The GSA (fig. 4) is underlain by unconsolidated ravine fill (Qa), Quaternary terrace deposits (Qoa), and landslide deposits (Qls) consisting of interbedded brown clay, silt, and sand with gravel lenses. The landslide deposits cover bedrock of the upper sandstone of the Neroly Formation. The Quaternary terrace alluvium is composed largely of gravel derived from the Franciscan Assemblage in a silty sand matrix, and it is similar to that present in the Corral Hollow flood plain. The thickness of the unconsolidated ravine fill ranges from zero at the margins of the valley to about 48 ft (15 m) in the eastern GSA.

In Corral Hollow, coarse gravel and cobbles occur as channel fill deposited by Corral Hollow Creek. These deposits are not exposed at the ground surface in the

Figure 3. Geologic map of Site 300 (from Ferry and others, 1990).

10 (from Ferry and others, 1990).

Figure 4. Generalized geologic map of the GSA and vicinity (from Ferr

e GSA and vicinity (from Ferry and others, 1990).

nd others, 1990).

area east of the sewage treatment pond, which is located across the road from California Department of Forestry (CDF) Station (fig. 4). Based on the geologic logs of the wells drilled in Corral Hollow (McIlvride and others, 1990), these coarse-grained sediments are about 20 to 26 ft thick with the maximum thickness along the ancestral channel of the Corral Hollow Creek. In the area around the sewage treatment pond and CDF station, the ancestral channel of the Corral Hollow Creek is located north of the modern stream channel. Along the modern stream channel, the coarse gravel and cobbles are exposed at the ground surface and are about 10 ft thick.

The Elk Ravine and Carnegie faults are the principal faults within Site 300 (fig. 3). The Elk Ravine fault does not show any evidence of Holocene movement in the study area and its vicinity, but the Carnegie fault shows some signs of movement during the Holocene (Raber and Carpenter, 1983; Hoffman, 1988). These faults offset the Pliocene nonmarine unit (Tps) and do not extend into the overlying unconsolidated sediments (Ferry and others, 1990). The Patterson Anticline (fig. 3) is the largest of several folds in the area.

Hydrogeology

Groundwater in the GSA occurs in two aquifer systems: alluvial and bedrock (McIlvride and others, 1990). The alluvial aquifer system is composed of alluvium and shallow permeable sandstone bedrock within Corral Hollow. Permeable sandstones interbedded with less permeable siltstones and claystones of the Miocene Neroly Formation form a deeper and much more extensive bedrock aquifer system.

Alluvium in Corral Hollow is a heterogeneous assemblage of unconsolidated fluvial clay, silt, sand, and gravel, and it is underlain by semi-consolidated to consolidated sediment of the Neroly Formation. The thickness of the alluvium is generally about 48 ft (15 m) or less and varies due to the uneven topography of the contact with the underlying bedrock. Generally, the alluvium is thickest within the scoured channel of the ancestral Corral Hollow Creek.

The shallow groundwater in the alluvium in the eastern GSA is encountered at depths of 15 to 30 ft (5 to 10 m). Groundwater elevations in the alluvial aquifer range from 489 ft (150 m) above mean sea level (MSL), near the upgradient boundary of the eastern GSA, to 444 ft (135 m) above MSL at the downgradient boundary (fig. 5). The sources of groundwater in the alluvial aquifer are precipitation falling on the alluvium and surrounding areas, infiltration from the Corral Hollow Creek during periods of stream flow, lateral inflow of groundwater from the bedrock, and flow of groundwater within the alluvium from further up Corral Hollow.

The Neroly Formation, which contains several deep, water-bearing strata, forms a regional aquifer that extends well beyond the boundaries of Site 300. The bedrock aquifer appears to be in hydraulic communication with the alluvial aquifer where it is truncated by the erosional contact with the alluvium. The hydrogeology of the bedrock aquifer is very complicated due to the presence of faults, fractures, and folds in the area, and no attempt was made to identify and classify every bedrock water bearing zone in the GSA (McIlvride and others, 1990).

Figure 5. Map of groundwater elevations (feet above MSL) in the alluvial/shallow bedrock aquifer in the GSA and off-site, June 1991 (from Carlson and others, 1991).

Previous Studies

In 1982, discovery of TCE in a water supply well at the GSA prompted an extensive and detailed study of soil and groundwater at the facility and adjacent private properties. As a result of this investigation, six plumes of contaminated groundwater have been identified in the shallow alluvial and deeper bedrock aquifers at the GSA (Ferry and others, 1990). Based on distinct VOC plumes in groundwater, the GSA area has been divided into western, central, and eastern GSA subareas (fig. 6). The highest concentrations of TCE in groundwater have been detected in the central GSA. The western GSA plume is now considered to be the distal portion of a VOC plume originating in the High Explosive Process Area to the north. In the eastern GSA, a relatively dilute VOC plume originates in the vicinity of an on-site debris pile (fig. 5) and extends offsite to the adjacent properties along Corral Hollow (fig. 6). Webster-Scholten (1993) used the term 'debris burial trenches' instead of debris pile, because later field investigation revealed that the debris, which was acting as a source of contamination, was buried in trenches. These debris burial trenches are located in the vicinity of the debris pile near the sewage treatment pond (fig. 5). For this study the term debris pile will be used. On the basis of soil and groundwater analyses from the cluster of wells around the debris pile, McIlvride and others (1990) suggested that this debris pile is the source of the VOC release.

As of October 21, 1991, 13 soil borings, 30 monitor wells, and two soil vapor surveys (totaling 110 locations) have been completed in the eastern GSA and offsite. In 1989, several hydraulic tests were performed on the alluvial aquifer in the eastern

Figure 6. Subareas of the GSA (from Ferry and others, 1990).

GSA in order to determine the aquifer parameters. A pumping test on well W-25N-01 (fig. 5), screened within the deposits filling the buried stream channel, indicated that the transmissivity of the alluvial aquifer in that area exceeds 100,000 gallons per day per foot (gpd/ft) (McIlvride and others, 1990).

The VOC plume in the eastern GSA has a maximum concentration of 70 $\mu\text{g/l}$ total VOCs, dominated by TCE. The plume is about 200 ft (60 m) wide, 30 ft (9 m) thick, and extends from the southeastern corner of the GSA onto the adjacent Connolly Ranch and the CDF properties and about 1 mile (1.6 km) down Corral Hollow (Ferry and others, 1990).

Statement of the Problem

Based on monitoring wells data, the extent of contamination in the eastern GSA was well understood. However, knowledge about the average velocity of the groundwater flow and the rate of the contaminant transport was limited. During this study, a two-dimensional computer model was used to simulate the flow of groundwater and contaminants in the eastern GSA to gain a better understanding of flow velocities and likely VOC concentrations at potential exposure points. The efficacy of various remedial approaches was also evaluated.

CONCEPTUAL MODEL

The material included in the conceptual model is the unconfined alluvial aquifer, including the uppermost permeable portions of the underlying bedrock. The zone of simulation extends from about 500 ft (150 m) west of well W-35A-04 to about 240 ft (70 m) north of well W-25N-06 (fig. 7). The unconfined aquifer in the GSA area is composed of fine silty sand and sandy gravel deposited by Corral Hollow Creek. The lateral extent and thickness of the unconsolidated sediment in Corral Hollow varies along the channel depending on the topography of the underlying and side-wall-forming bedrock. The thickness of these deposits ranges from zero at the lateral margins to about 48 ft (15 m) in the middle of the channel fill. The maximum thickness of the saturated zone occurs along the buried stream channel of ancestral Corral Hollow Creek (fig. 8). This buried stream channel is mainly composed of gravelly sand and sandy gravel and, as a result, forms a zone of very high transmissivity. The alluvium is about 700 ft (210 m) wide near the western boundary, 1000 ft (300 m) wide near the CDF station, and about 360 ft (110 m) wide at the northern boundary of the simulated area.

The model is bordered by constant head and no-flow boundaries. Most of the water flowing through the alluvium in the Corral Hollow Creek enters the zone of simulation from the west and south sides, simulated as constant head boundaries. Based on the groundwater elevation contours of the GSA (McIlvride and others, 1990), the hills to the northwest of the study area contribute groundwater, simulated

Figure 7. Monitoring wells completed in the alluvial/shallow bedrock aquifer and outline of the modeled area (after Carlson and others, 1991).

Figure 8. Saturated thickness of the alluvial

Figure 8. Saturated thickness of the alluvium in Corral Hollow (after McIvride and others, 1990).

in Corral Hollow (after McIvride and others, 1990).

as a constant head boundary. Because of the small zone of simulation as compared to the vast catchment basin that feeds the alluvial aquifer, the aerial recharge and evapotranspiration are considered to be negligible. The hills to the southeast and east of the eastern GSA are composed of strata that dip away from Corral Hollow and, therefore are not anticipated to contribute a significant amount of groundwater to the alluvial aquifer under study. Furthermore, pumping tests performed on the wells screened in the alluvium did not indicate any communication between the alluvial and the underlying deeper bedrock aquifer systems (McIlvride and others, 1990). Therefore, the southeastern, eastern, and bottom boundaries are thought to act as no-flow boundaries. The groundwater leaves the study area through the northern boundary, which is simulated as a constant head boundary in the alluvium deposited in Corral Hollow.

The system is believed to be near a steady-state condition with no significant changes in groundwater elevation and contaminant concentration. The debris pile located near well W-26R-01 (fig. 5) is releasing contaminants. The debris pile is acting as a continuous source of contamination and is located at the edge of the low transmissivity region near well W-26R-01. The groundwater flowing into the study area through the northwestern boundary mobilizes the leached contaminants. The contaminated groundwater then mixes with the water in the highly transmissive zone where the contaminants are advected down gradient with some longitudinal dispersion. The distribution of the contaminant, as observed in the monitoring wells at the eastern

GSA (Ferry and others, 1990; and McIlvride and others, 1990), indicates minimal transverse dispersion.

COMPUTER CODE: METHOD OF CHARACTERISTICS

Method of Characteristics (MOC) is a two-dimensional, numerical model that simulates groundwater flow and solute transport in groundwater through an aquifer, which may be heterogenous and/or anisotropic (Konikow and Bredehoeft, 1978). It computes changes in concentration over time caused by convection, hydrodynamic dispersion, and mixing from fluid sources. Goode and Konikow (1989) modified the program to handle changes in concentration caused by decay, reversible equilibrium-controlled sorption, and monovalent-divalent ion exchange.

The model solves the groundwater flow equation in conjunction with the solute transport equation. The computer program uses the alternating direction implicit (ADI) procedure to solve the finite difference approximation to the groundwater flow equation, and it uses the method of characteristics to solve the solute transport equation. MOC utilizes a particle tracking procedure to represent convective transport and a two-step, explicit procedure to solve the finite difference equation that describes the effects of hydrodynamic dispersion, fluid sources and sinks, and divergence of velocity.

The computer program is written in FORTRAN IV. The model is based on a rectangular, block centered, finite difference grid. The program allows any number of injection or extraction wells and spatial variability in recharge or discharge, saturated thickness, transmissivity, boundary conditions, and initial heads and concentrations.

Theoretical Background

Flow Equation

The flow equation describes the transient two-dimensional areal flow of a homogeneous fluid through a nonhomogeneous, anisotropic aquifer. The equation is written in Cartesian tensor notation as

$$\frac{\partial}{\partial x_i} \left(T_{ij} \frac{\partial h}{\partial x_j} \right) = S \frac{\partial h}{\partial t} + W \quad i, j = 1, 2 \quad (1)$$

where

T_{ij} is the transmissivity tensor, L^2/T ;

h is the hydraulic head, L ;

S is the storage coefficient, (dimensionless);

t is the time, T ;

W $W(x, y, t)$ is the volume flux per unit area (positive sign for outflow and negative for inflow), L/T ; and

x_i and x_j are the Cartesian coordinates, L .

If the fluxes considered in equation (1) are (a) direct withdrawal or recharge, such as well pumpage, well injection, or evapotranspiration, and (b) steady leakage into or out of the aquifer through a confining layer, streambed, or lakebed, then $W(x, y, t)$ may be expressed as

$$W(x,y,t) = Q(x,y,t) - \frac{K_z}{m}(H_s - h) \quad (2)$$

where

- Q is the rate of withdrawal (positive sign) or recharge (negative sign), L/T ;
- K_z is the vertical hydraulic conductivity of the confining layer, streambed, or lakebed, L/T ;
- m is the thickness of the confining layer, streambed, or lakebed, L ; and
- H_s is the hydraulic head in the source bed, stream, or lake, L .

Lohman (1972) used Darcy's law to derive the average seepage velocity of groundwater. The expression can be written in Cartesian tensor notation as

$$V_i = -\frac{K_{ij}}{\epsilon} \frac{\partial h}{\partial x_j} \quad i,j=1,2 \quad (3)$$

where

- V_i is the seepage velocity in the direction of x_i , L/T ;
- K_{ij} is the hydraulic conductivity tensor, L/T ; and
- ϵ is the effective porosity of the aquifer, (dimensionless).

Transport Equation

The transport equation can be written as

$$\frac{\partial(Cb)}{\partial t} = \frac{\partial}{\partial x_i} \left(b D_{ij} \frac{\partial C}{\partial x_j} \right) - \frac{\partial}{\partial x_i} (b C V_i) - \frac{\zeta W}{\epsilon} \quad i, j = 1, 2 \quad (4)$$

where

- C is the concentration of the dissolved chemical species, M/L^3 ;
- D_{ij} is the coefficient of hydrodynamic dispersion (a second-order tensor), L^2/T ;
- b is the saturated thickness of the aquifer, L ; and
- ζ is the concentration of the dissolved chemical in a source or sink fluid, M/L^3 .

The first term on the right side of equation 4 represents the change in concentration due to hydrodynamic dispersion. The second term describes the effects of advective transport, while the third term represents a fluid source or sink.

Dispersion Coefficient

Hydrodynamic dispersion in subsurface groundwater flow is accomplished by:

(1) mechanical dispersion, which depends upon both the velocity of the fluid and the nature of the pore system through which the flow takes place, and (2) molecular and ionic diffusion, which is more significant at low flow velocities and depends on the length of time span (Bear, 1972). MOC, however, is based on the assumption that the contribution of molecular and ionic diffusion to hydrodynamic dispersion is negligible (Konikow and Bredehoeft, 1978). For this study, this appears to be a reasonable assumption because the groundwater in the eastern GSA is assumed to

have a very high flow velocity.

The dispersion coefficient can be related to the velocity of groundwater flow and to the nature of the aquifer using Scheidegger's (1961) equation:

$$D_{ij} = \alpha_{ijxy} \frac{V_x V_y}{|V|} \quad i,j = 1,2 \quad (5)$$

where

α_{ijxy} is the dispersivity of the aquifer, L ;

V_x and V_y are components of the velocity vector in the x and y directions, respectively, L/T ; and

$|V|$ is the magnitude of the velocity, L/T .

Scheidegger (1961) stated that, for an isotropic aquifer, the dispersivity tensor can be defined by longitudinal dispersivity (α_L) and transverse dispersivity (α_T). These are related to the longitudinal and transverse dispersion coefficients (D_L and D_T , respectively) by

$$D_L = \alpha_L |V| \quad (6)$$

and

$$D_T = \alpha_T |V| \quad (7)$$

Modification of the Solute-transport Model for Chemical Reactions

Goode and Konikow (1989) modified the USGS solute transport model (Konikow

and Bredehoeft, 1978) to incorporate the following types of chemical reactions: (1) radioactive or chemical decay; (2) sorption with linear, Freundlich, or Langmuir isotherms; and (3) ion exchange for monovalent or divalent ions. For this study linear sorption with no radioactive decay was used; therefore, only linear sorption, based on Konikow and Grove (1977), is discussed in detail.

The modified form of the transport equation can be written as

$$R_f \frac{\partial C}{\partial t} = \frac{1}{b} \frac{\partial}{\partial x_i} \left(b D_{ij} \frac{\partial C}{\partial x_j} \right) - V_i \frac{\partial C}{\partial x_i} + \frac{W(C-Q)}{\epsilon b} - R_f \lambda C \quad i, j = 1, 2 \quad (8)$$

where

R_f is the retardation factor, dimensionless; and

λ is the decay rate constant, $1/T$.

Because R_f is constant for linear sorption, the solution to equation 8 is identical to the solution to the equation with no sorption effects, except that the velocity, dispersion coefficient, and source strength are reduced by a factor R_f which is expressed as

$$R_f = 1 + \frac{\rho_b K_d}{\epsilon} \quad (9)$$

where

ρ_b is the bulk density of the aquifer material, M/L^3 ; and

K_d is the distribution coefficient, L^3/M .

The computer code handles the linear sorption by incorporating the retardation factor into the dispersion and particle tracking calculations explicitly. As each

particle is moved along a characteristic curve, its velocity is decreased by a factor of linearized retardation computed by equation 9. Changes in concentration resulting from dispersion are then calculated. For a higher retardation factor, a relatively smaller amount of contaminant is transported in the direction of lower concentration, which leads to a steeper concentration gradient.

Numerical Methods

The numerical methods require that the study area be subdivided by a grid into a number of smaller subareas or cells. MOC utilizes a rectangular, uniformly spaced, finite difference grid in which nodes are defined at the center of rectangular cells. The spacing in the x direction may differ from the spacing in the y direction.

Flow Equation

Pinder and Bredehoeft (1968) showed that, if the coordinate axes are aligned with the principal directions of the transmissivity tensor, equation 1 may be approximated by the following implicit finite difference equation:

$$\begin{aligned}
 & T_{xx[i-1/2,j]} \left[\frac{h_{i-1,j,k} - h_{i,j,k}}{(\Delta x)^2} \right] + T_{xx[i+1/2,j]} \left[\frac{h_{i+1,j,k} - h_{i,j,k}}{(\Delta x)^2} \right] \\
 & T_{yy[i,j-1/2]} \left[\frac{h_{i,j-1,k} - h_{i,j,k}}{(\Delta y)^2} \right] + T_{yy[i,j+1/2]} \left[\frac{h_{i,j+1,k} - h_{i,j,k}}{(\Delta y)^2} \right] \\
 & = S \left[\frac{h_{i,j,k} - h_{i,j,k-1}}{\Delta t} \right] + \frac{q_{w(i,j)}}{\Delta x \Delta y} - \frac{K_z}{m} [H_{s(i,j)} - h_{i,j,k}]
 \end{aligned} \tag{10}$$

where

i, j, k are indices in the x, y, and time dimensions, respectively;

$\Delta x, \Delta y, \Delta t$ are increments in the x , y , and time dimensions, respectively; and

q_w is the volumetric rate of withdrawal or recharge at the node (i,j) , L^3/T .

In equation 10, k represents the new time step and $k-1$ represents the previous time step. The finite difference equation is solved numerically for each node in the grid using an iterative alternating-direction implicit (ADI) procedure (Wang and Anderson, 1982).

After the head distribution has been computed for a given time step, the velocity of the groundwater flow is computed at each node using an explicit form of equation 3. For example, the velocity in the x direction at node (i,j) would be computed as

$$V_{x(i,j)} = \frac{K_{xx(i,j)} (h_{i-1,j,k} - h_{i+1,j,k})}{\epsilon \quad 2\Delta x} \quad (11)$$

The velocity in the x direction can also be computed on the boundary between node (i,j) and node $(i+1,j)$ using the following equation:

$$V_{x(i+1/2,j)} = \frac{K_{xx(i+1/2,j)} (h_{i,j,k} - h_{i+1,j,k})}{\epsilon \quad \Delta x} \quad (12)$$

Expressions similar to equation 11 and 12 are used to compute the velocities in the y direction at (i,j) and $(i,j+1/2)$ respectively.

Transport Equation

Method of Characteristics. The method of characteristics is used in this model to solve the solute transport equation. Konikow and Grove (1977) showed that, by

considering the saturated thickness as a variable and expanding the advective transport term, equation 4 may be rewritten as

$$\frac{\partial C}{\partial t} = \frac{1}{b} \frac{\partial}{\partial x_i} \left(b D_{ij} \frac{\partial C}{\partial x_j} \right) - V_i \frac{\partial C}{\partial x_i} + \frac{C \left(S \frac{\partial h}{\partial t} + W - \epsilon \frac{\partial b}{\partial t} \right) - \zeta W}{\epsilon b} \quad (13)$$

Equation 13 is the form of solute transport equation that is solved by the MOC computer program. For convenience, equation 13 can also be written as

$$\frac{\partial C}{\partial t} = \frac{1}{b} \frac{\partial}{\partial x_i} \left(b D_{ij} \frac{\partial C}{\partial x_j} \right) - V_x \frac{\partial C}{\partial x} - V_y \frac{\partial C}{\partial y} + \frac{C \left(S \frac{\partial h}{\partial t} + W - \epsilon \frac{\partial b}{\partial t} \right) - \zeta W}{\epsilon b} \quad (14)$$

Equation 14 can be further simplified as

$$\frac{\partial C}{\partial t} = \frac{1}{b} \frac{\partial}{\partial x_i} \left(b D_{ij} \frac{\partial C}{\partial x_j} \right) - V_x \frac{\partial C}{\partial x} - V_y \frac{\partial C}{\partial y} + F \quad (15)$$

where

$$F = \frac{C \left(S \frac{\partial h}{\partial t} + W - \epsilon \frac{\partial b}{\partial t} \right) - \zeta W}{\epsilon b} \quad (16)$$

The concentration of fluid particles that are advected with the flowing groundwater changes with time. Their concentration can be determined 1) at fixed points within a stationary coordinate system as successive fluid particles pass these locations, or 2) for reference particles as they move along their respective paths past fixed points in space. These determinations are expressed as the rate of change of

concentration as observed from a fixed point ($\partial C/\partial t$), or the rate of change as observed from a point moving with fluid particles (dC/dt). The latter is called a material derivative and is expressed as

$$\frac{dC}{dt} = \frac{\partial C}{\partial t} + \frac{\partial C}{\partial x} \frac{\partial x}{\partial t} + \frac{\partial C}{\partial y} \frac{\partial y}{\partial t} \quad (17)$$

The second and third terms on the right side of equation 17 include material derivatives of position. These derivatives are defined by the velocity as

$$\frac{\partial x}{\partial t} = V_x \quad (18)$$

and

$$\frac{\partial y}{\partial t} = V_y \quad (19)$$

If we substitute the right sides of equations 15, 18, and 19 for the corresponding terms in 17, we get

$$\frac{dC}{dt} = \frac{1}{b} \frac{\partial}{\partial x_i} \left(b D_{ij} \frac{\partial C}{\partial x_j} \right) + F \quad (20)$$

The solutions to equations 18, 19, and 20 may be given as

$$x = x(t); y = y(t); C = C(t) \quad (21)$$

and are called characteristic curves of equation 15.

The characteristic curves are calculated by introducing a set of moving reference particles that can be traced within the stationary coordinate system of the finite

difference grid. Each particle corresponds to one characteristic curve (Garder and others, 1964). The values of x , y , and C are calculated as functions of t for each characteristic. According to Konikow and Bredehoeft (1978), each particle has a concentration and position associated with it and is moved through the flow field in proportion to the flow velocity at its location.

Particle Tracking. The first step in the method of characteristics is the placement of reference particles in each cell of the finite difference grid. These particles are distributed in a geometrically uniform pattern. For two-dimensional problems, four to nine particles per cell provide satisfactory results (Konikow and Bredehoeft, 1978). The position of each particle is specified by x and y coordinates within the finite difference grid. The initial concentration assigned to each particle is the initial concentration associated with the node of the cell containing the particle.

For each time step, every particle is moved a distance proportional to the length of the time increment and the velocity at the location of the particle. The new position of a particle is computed with the following equations

$$x_{p,k} = x_{p,k-1} + \delta x_p = x_{p,k-1} + \Delta t V_{x[x_{(p,k)}, y_{(p,k)}]} \quad (22)$$

and

$$y_{p,k} = y_{p,k-1} + \delta y_p = y_{p,k-1} + \Delta t V_{y[x_{(p,k)}, y_{(p,k)}]} \quad (23)$$

where

p is the index number of the point of identification; and

δx_p and δy_p are the distances moved in the x and y directions, respectively.

The x and y velocities at the position of any particular point p , indicated as $V_{[x(p,k),y(p,k)]}$, for time k are calculated through bilinear interpolation over the area of half of a cell using x and y velocities computed at adjacent nodes and cell boundaries.

After all the particles have been moved, each node is temporarily assigned the average of the concentrations of all particles then located within that cell. This temporarily assigned, average concentration is at the new time level with respect to advective transport. The concentration at each node of the grid will change with each time step as different particles with different concentrations enter and leave the cell.

MODEL CONFIGURATION

On the basis of the conceptual model, a finite difference grid of 35 x 35 cells (fig. 9) was designed to simulate groundwater flow in a single-layered, unconfined aquifer. For solute transport the model uses a subgrid of 20 x 20 cells. In order to make figures clear, names of the monitoring wells have been shortened by removing W-25 or W-26 from their names as they appeared in the preceding figures. Each cell is 40 ft (12 m) wide and 40 ft long. The finite difference grid covers the portion of the plume that has the highest concentration of the contaminant and greatest number of wells in order to calibrate and verify the simulations. In addition, the limited extent of the simulation area provides an appropriately small grid size to achieve optimum resolution of the water level and the concentration changes.

The western, southern, and northern boundaries, and a part of northwestern boundary are constant head boundaries (fig. 10). The boundary to the east of the simulation zone and the segment of the northwestern boundary near the downstream end, which do not have a significant amount of cross-flow of groundwater, are no-flow boundaries. The groundwater elevation (490 ft) in well W-7ES for June 1991 was used as an initial head value for the western boundary. The initial head of 473 ft for the northern boundary was determined by using the hydraulic gradient between wells W-25N-05 and W-25N-06 and extrapolating to the model boundary. The initial head values for the southern boundary were taken from the earlier simulations of groundwater flow in the modeled area, but these elevations were modified during

Figure 9. Finite difference grid with wells completed in the alluvial/shallow bedrock aquifer.

Figure 10. Simulated region showing boundary conditions.

calibration. Head values along the southern boundary decline gradually from 490 ft at the western edge to 487.6 ft at the eastern edge. Based on the knowledge of hydrogeology and the shape of groundwater elevation and contaminant concentration contours in the eastern GSA, a head elevation of 490 ft was chosen for the northwestern constant head boundary. The specific head elevations used in this model are included in the MOC input file presented in the Appendix.

The aquifer thickness at the well locations was determined from well logs (McIlvride and others, 1990), while in other cells it was interpolated or extrapolated by using known thicknesses at the well locations. The groundwater flow simulation was initially started by using a single transmissivity value of 0.186 ft²/s, which was determined by the pumping test performed at well W-25N-01 on July 12, 1989 (McIlvride and others, 1990), within the modeled area. The transmissivity distribution was modified in the course of the model calibration to more closely correlate with the type of geologic material identified in individual boreholes. Values of 0.088 cm³/g (Webster-Scholten, 1993), 0.25, and 2.0 g/cm³ (Freeze and Cherry, 1979) were used for the distribution coefficient, effective porosity, and bulk density, respectively. The value for bulk density was calculated by using the particle density value of 2.65 g/cm³ for alluvial material (Freeze and Cherry, 1979). The source term was determined from the historical trends in TCE concentration in the wells located near the source (debris pile, fig. 11). The source was simulated by introducing the contaminant into the aquifer by injection wells. The flow rates and concentrations for

Figure 11. Total VOC concentrations in groundwater in the alluvial/shallow bedrock aquifer in the eastern GSA and off-site (after Carlson and others, 1991).

the injection wells were determined during the model calibration by matching the contaminant distribution in the source area and its vicinity.

MODEL CALIBRATION

Groundwater Flow

Calibration for Hydraulic Conductivity

Calibration for hydraulic conductivity was a two-step process. The first step produced a flow regime using regions of hydraulic conductivity and reproducing the historical hydraulic gradient. The second step determined the appropriate magnitude of hydraulic conductivity to yield appropriate average linear velocities.

Calibration of the model required more than a hundred computer runs. In order to match the simulated and observed water levels in the monitoring wells at the eastern GSA, changes were made in the transmissivity matrix of the MOC input file by using the trial and error method. The best match between simulated and observed water levels was achieved by dividing the modeled area into a number of hydraulic conductivity regions (fig. 12). Division of the modeled area into different regions of hydraulic conductivity is roughly based on the lithologic characteristics of the aquifer. The maximum variation of hydraulic conductivity in the simulated zone is by a factor of 18. This variation seems small because hydraulic conductivity in natural sediments ranges over many orders of magnitude. This small variation may be due to the fact that these are "spatially averaged" values of hydraulic conductivity, which average out natural variabilities within a cell.

The saturated horizon of the aquifer, in the region containing W-25N-22 and W-

Figure 12. Regions of hydraulic conductivity (ft/s) in the calibrated model.

25N-23, occurs in the bedrock of the upper Neroly Formation, composed of sandstone and siltstone with a low estimated permeability. This region has the lowest predicted hydraulic conductivity (0.001 ft/s). The regions containing wells W-25N-01 and W-25N-06 are thought to cover the highly transmissive part of the aquifer (hydraulic conductivities of 0.0076 and 0.012 ft/s, respectively) comprising of the ancestral channel of Corral Hollow Creek. The region containing well W-25N-06 represents the part of the aquifer that has the maximum saturated thickness (16 ft) in the modeled area and is composed mainly of sandy gravel with a very high estimated hydraulic conductivity. In addition, the width of the aquifer in this zone is at a minimum for the modeled area and the amount of water flowing in from the vast aquifer on the upgradient side is large. Therefore, this region has a relatively high hydraulic conductivity value (0.012 ft/s). Based on the geology of the aquifer, the regions containing wells W-7ES, W-35A-04, W-35A-06, CON-1, and W-25N-07 are thought to have high hydraulic conductivities, but the predicted values of hydraulic conductivity (0.0045 to 0.0178 ft/s) in these regions are the result of numerous computer runs. The hydraulic conductivity values in the regions of 0.0025 ft/s and 0.0037 ft/s, which lack well logs, were also assigned during model calibration.

Because the saturated thickness of the aquifer is not constant in the modeled area, the transmissivity value in a hydraulic conductivity region is not the same throughout each region. To maintain identical hydraulic conductivity in all cells within a hydraulic conductivity region, transmissivity was calculated by the following equation from Freeze and Cherry (1979):

$$T = Kb \quad (24)$$

where

T is the transmissivity, L^2/T ;

K is the hydraulic conductivity, L/T ; and

b is the saturated thickness of the aquifer in a cell, L .

Figure 13 shows the groundwater elevation map produced by the calibrated model. The observed and predicted water levels are presented in Table 1. Wells W-25N-20, W-25N-22, W-25N-23, CON-1, and W-7ES were not used to compare the water levels. Wells W-25N-20, W-25N-22, W-25N-23 are new wells, and the groundwater elevations in these wells were not known at the time of this study. Well CON-1 could not be used because it is a production well completed in more than one water bearing zone, and it is also affected by the pumping of well CDF-1. The location of CDF-1 is not indicated on the figures presented in this report because it is completed in a deeper zone and is not part of this study. Well 7-ES did not show a noticeable variation in the simulated groundwater elevation for different values of hydraulic conductivity tested during model calibration because it was located close to the western constant head boundary.

The simulated groundwater elevations are within 0.5 ft of the observed groundwater elevations, except in well W-25N-07 where the simulated elevation is 1.15 ft lower than the observed elevation. In general, the simulated elevations are slightly lower than the observed elevations, except in wells W-35A-04, W-35A-06,

Figure 13. Map of simulated groundwater elevations (feet above MSL) in the eastern GSA.

Table 1: Observed and Predicted Groundwater Elevations at the Observation Wells.

Observation Wells	Observed Elevation (feet above MSL)	Predicted Elevation (feet above MSL)	Difference (ft)
W-7DS	487.90	487.68	- 0.22
W-26R-01	487.59	487.29	- 0.30
W-26R-03	487.34	486.97	- 0.37
W-25N-01	486.96	486.79	- 0.17
W-25N-05	482.61	482.81	+ 0.20
W-25N-06	478.73	478.38	- 0.35
W-25N-07	488.21	487.06	- 1.15
W-25N-15	485.42	485.24	- 0.18
W-35A-04	488.41	488.87	+ 0.46
W-35A-06	488.57	488.98	+ 0.41

MSL: Mean Sea Level

Average Absolute Difference: 0.38 ft

and W-25N-05. Higher simulated elevations in wells W-35A-04 and W-35A-06 may be due to the fact that these wells are located close to the southern constant head boundary, and the groundwater elevations assigned to the boundary cells may be slightly higher than the actual elevations. The lower elevation in well W-25N-07 and higher elevation in well W-25N-05 may be related to each other. Based on initial field evidence and several computer runs, to get a closer match between the observed and simulated groundwater elevations, a less permeable region was inserted

temporarily between wells W-25N-07 and W-25N-05. This less permeable region provided a better water elevation match at wells W-25N-07 and W-25N-05. As predicted by the model, the less permeable region would cause elevations higher in well W-25N-07 and lower in well W-25N-05. This low permeability region would also elevate the water levels in wells W-25N-01 and W-26R-03, thereby decreasing the difference between field and simulated water elevations. Initial field evidence for the presence of such a region was discarded (personal communication with Mr. Jack Gardner, October 1992), and the low permeability region was not used in the calibrated model.

Head distribution is sensitive to the hydraulic conductivity values assigned to each region. If hydraulic conductivity is changed in one or two regions only, the head distribution changes throughout the modeled area. Figure 14 shows the effect of a change in hydraulic conductivity from 0.012 to 0.0064 ft/s in the region containing well W-25N-06. This decrease in hydraulic conductivity created a less permeable region and decreased the efficiency of this portion of the aquifer to transmit the water flowing through it. As a result, the water levels rose throughout most of the modeled area. The maximum increase of about 1 ft in water level was observed in wells W-25N-05 and W-25N-06, with the increases gradually becoming smaller up the hydraulic gradient. The head distribution is not affected, however, if the hydraulic conductivity in all the regions is changed by the same factor. This behavior of the model suggests that the hydraulic conductivities in different regions are related to each other by a fixed ratio in order to transmit a constant amount of water without

Figure 14. Map of simulated groundwater elevations (feet above MSL) with altered hydraulic conductivity in the zone containing well W-25N-06.

disturbing the head distribution. Therefore, the calibrated combination of hydraulic conductivities shown in Figure 12 was used for this study.

Once the hydraulic conductivity distribution was determined, the hydraulic conductivity in all regions was altered by changing the multiplication factor for the transmissivity matrix in the input file. While maintaining the ratios between hydraulic conductivity in different regions constant, a wide range of transmissivity multipliers was tested. This was performed to determine the best fit values of the resulting average linear pore water velocities at the observation wells. Table 2 shows the multiplication factors for the transmissivity matrix and corresponding hydraulic conductivities and average linear pore water velocities for several of the observation wells. Figure 15 presents the average linear velocity at each of these observation wells plotted as a function of the hydraulic conductivity at that well. These velocities were compared with the velocities calculated from the transmissivity values (Table 3) determined by the pumping test performed on August 27, 1992 (LLNL unpublished data), using Darcy's Law, the hydraulic gradient in the vicinity of each well, and the effective porosity of 0.25.

Based on historical field studies and discussions with the Project Manager (Robert Ferry, personal communication, October 1992) of the eastern GSA, probable average linear velocities are within the range of 10 to 20 ft/d for the area around wells W-25N-01 and W-26R-03. In this case, such values were achieved in the model by using the multiplication factor of $5.1\text{E-}04$ (Table 2). The pore water velocities achieved by the multiplication factor of $5.1\text{E-}04$ are reasonably close to

Table 2: Summary of Hydraulic Conductivity Calibration.

Multiplication Factor	Observation Well I.D.	Transmissivity (ft ² /d)	Hydraulic Conductivity (ft/d)	Average Linear Velocity (ft/d)
1.0E-05	W-7DS	116.64	12.96	0.29
	W-26R-01	77.76	12.96	0.19
	W-25N-01	194.40	12.96	0.30
	W-25N-05	129.60	12.96	0.69
	W-25N-06	324.00	20.25	0.54
1.0E-04	W-7DS	1166.40	129.60	3.00
	W-26R-01	777.60	129.60	1.90
	W-25N-01	1944.00	129.60	3.00
	W-25N-05	1296.00	129.60	6.90
	W-25N-06	3240.00	202.50	5.40
5.1E-04	W-7DS	5948.64	660.96	15.29
	W-26R-01	3965.76	660.96	9.80
	W-25N-01	9914.40	660.96	15.65
	W-25N-05	6609.60	660.96	35.12
	W-25N-06	16524.00	1032.75	29.76
1.0E-03	W-7DS	11664.00	1296.00	30.00
	W-26R-01	7776.00	1296.00	19.00
	W-25N-01	19440.00	1296.00	31.00
	W-25N-05	12960.00	1296.00	69.00
	W-25N-06	32400.00	2025.00	54.00

Figure 15. Plots of average linear velocity versus hydraulic conductivity at observation wells.

those determined from the pumping test (August 1992) data from well W-26R-03 (Table 3). The pore water velocity was not calculated for wells W-25N-05 and W-25N-06 from the pumping test data because they were not affected by the pumping of well W-26R-03 due to their distant locations.

Table 3: Calculated and Predicted Pore Water Velocities (ft/d).

Observation Wells	Pore Water Velocity Calculated from Pumping Test at well W-26R-03 (August 1992)	Predicted Pore Water Velocity
W-7DS	17.32	15.29
W-26R-01	9.8	19.38
W-25N-01	10.77	15.65
W-25N-05	Beyond the cone of depression	35.12
W-25N-06	Beyond the cone of depression	27.96

Calibration for Storativity

In order to determine the storativity (specific yield) of the unconfined aquifer, the 72-hour pumping test performed on well W-26R-03 beginning on August 27, 1992 (LLNL unpublished data) was simulated. The extraction rate during the pumping test was 0.066 ft³/s (29.5 gpm). Wells W-7DS, W-26R-01, W-26R-03, W-25N-01, and W-25N-20 were used as observation wells. Figure 16 presents the plots of simulated drawdown at the end of the 72-hour pumping period versus storativity for each of the

Figure 16. Plots of simulated drawdown versus storativity at observation wells.

observation wells. A storativity of 0.25 gives the best match between the simulated and observed drawdowns. Table 4 contains the calculated storativities and observed and predicted drawdowns at the observation wells for different values of storativity. Wells W-25N-01, W-25N-20, and W-26R-01, which are located within 100 ft of the pumping well, provide a close match between the predicted and observed drawdowns. Well W-7DS, which is located at a greater distance (180 ft), did not match as well. These discrepancies may be the result of the differences in distances between the real wells and between their corresponding nodes in the finite difference grid. The pumping well was not particularly useful due to well bore storage and well losses. Also, the predicted drawdown for the pumping-well-cell could be considerably less than the observed drawdown because it is spatially averaged over the area of the cell.

Figures 17 through 21 present the plots of real and simulated drawdowns versus the time of pumping. The slopes of the plots are very similar, which suggests a very good agreement between the predicted and calculated transmissivities. The comparison of real and predicted data suggests that well W-26R-01 provides the closest match between the predicted and calculated storativity. For wells W-7DS, W-25N-01, and W-25N-20, the predicted storativity is greater by less than an order of magnitude. Since MOC accepts only a single storativity value, the model could not be further adjusted with respect to storativity. This difference in storativity may be related to differences between the real field conditions and the simulated conditions of the aquifer.

Table 4: Calculated Storativities and Observed and Predicted Drawdowns (feet) at the Observation Wells for Different Modeled Storativity Values.

Observation Wells	Calculated Storativity	Observed Drawdown	Predicted Drawdowns for Different Storativity Values					
			0.1	0.2	0.25	0.3	0.4	0.5
W-7DS	0.11	0.16	0.17	0.11	0.09	0.08	0.06	0.04
W-26R-01	0.023	0.19	0.33	0.25	0.23	0.21	0.17	0.15
W-26R-03	Pumping Well	0.48	0.53	0.45	0.43	0.41	0.38	0.36
W-25N-01	0.053	0.25	0.36	0.29	0.27	0.25	0.22	0.20
W-25N-20	0.032	0.20	0.25	0.18	0.16	0.15	0.12	0.11

Figure 17. Drawdown versus time plots of real and simulated pumping tests at well W-7DS.

Figure 18. Drawdown versus time plots of real and simulated pumping tests at well W-26R-01.

Figure 19. Drawdown versus time plots of real and simulated pumping tests at well W-26-R-03 (pumping well).

Figure 20. Drawdown versus time plots of real and simulated pumping tests at well W-25N-01.

Figure 21. Drawdown versus time plots of real and simulated pumping tests at well W-25N-20.

Contaminant Transport

The groundwater at the eastern GSA is contaminated by a number of volatile organic compounds. Simulation of the plume containing all these contaminants is very complex. To simplify the task, TCE, which is the predominant constituent (95% or more) of the contaminant plume at the eastern GSA (McIlvride and others, 1990), has been used to simulate the migration of the plume. This study assumes that TCE does not decay.

The contaminant source was simulated by eight injection wells, which were located in eight cells covering the source area (debris pile). In order to keep the aquifer free of increased hydraulic head resulting from injection, the contaminant source liquid was injected at a very low rate with a very high concentration of TCE (1,000,000 $\mu\text{g/l}$). However, the specific rate of injection ($0.96\text{E-}7 \text{ ft}^3/\text{s}$ per well with one well, located in the southeastern corner of the source area, injecting at $0.6\text{E-}6 \text{ ft}^3/\text{s}$) was calibrated by matching the predicted concentrations of the contaminant to the observed concentrations in the vicinity of the source area. This was achieved by running the model several times using the trial and error method with varying injection rates.

Table 5 presents the input parameters used in the simulation of contaminant transport. Effective porosity, bulk density, and distribution coefficient for TCE in the aquifer were not determined for the site. Therefore, the most typical values of effective porosity and bulk density for an alluvial aquifer commonly found in literature (Freeze and Cherry, 1979) were used in this study. As a result of several

Table 5: Calibrated Model Input Parameters.

Effective Porosity	0.25
Bulk Density	2.0 g/cm ³
Longitudinal Dispersivity	5.0 ft
Ratio of Transverse to Longitudinal Dispersivity	0.0
Ratio of T_{yy} to T_{xx}	1.0
Linear Distribution Coefficient (K_d)	0.088 cm ³ /g

computer runs, a distribution coefficient (K_d) of 0.088 cm³/g was estimated, which according to Equation 9 gives a retardation factor of 1.704. This value is comparable to the retardation factor of 1.8 used in the analytical modeling for contaminant fate and transport at the central and eastern GSA (Webster-Scholten, 1993).

Figure 22 shows the predicted distribution of TCE in the modeled area. Table 6 presents the observed and predicted concentrations of TCE at the selected wells. It was observed that the contaminant concentrations predicted by the model under transient flow conditions were 1 to 5 µg/l greater than those predicted by the model under steady-state flow conditions. Calibration of the model was performed under transient flow conditions, because the size of the MOC output file generated under transient flow conditions was less than half the size of the file generated under steady-state flow conditions. The computer time in running the model under transient and steady-state flow conditions was approximately the same. The wells W-25N-20, W-25N-22, and W-25N-23 are not included in Table 6 because these wells are new and

Figure 22. Concentrations of TCE ($\mu\text{g/l}$) in the simulated region predicted by the calibrated model.

Table 6: Observed and Predicted Concentrations of TCE ($\mu\text{g/l}$) at the Observation Wells.

Observation Wells	Observed Concentration	Predicted Concentration
W-26R-01	47.0	48.22
W-26R-03	58.0	58.96
W-25N-01	46.0	53.61
W-25N-05	24.0	20.76
W-25N-15	4.7	4.6
W-25N-06	10.0	5.9
W-7DS	0.0	4.6

the observed concentrations of TCE in these wells are not known at this time. The predicted concentration at well W-7DS is $4.6 \mu\text{g/l}$, whereas this well has consistently shown non-detectable levels of TCE. The predicted concentration at this well may be due to numerical dispersion caused by the model. The model shows a mass balance error of -8.4% for the contaminant for 20 years time period. This error falls within the range of -10% to +2%, which El-Kadi (1988) reported as reasonably small.

Calibration for Longitudinal Dispersivity

The calibration for longitudinal dispersivity suggests that the magnitude of longitudinal dispersivity controls the numerical dispersion of the contaminant over a long period of time. Wells W-26R-01, W-26R-03, W-25N-01, W-25N-05, and W-

25N-15 were used as observation points. Because the version of MOC used for this study allows only five observation points, the aforementioned wells were selected based on their locations along the plume pathway. Table 7 presents the predicted steady-state contaminant concentrations at the observation wells over a period of 20 years for different values of longitudinal dispersivity. The α_T/α_L for these runs was zero. The wells located along the axial length of the plume did not show a significant change in concentration as the longitudinal dispersivity varied. Well W-25N-15, which is located away from the axial line of the plume, shows the most significant effects from the changing longitudinal dispersivity. Because of this behavior, the model was tested for the effect of different longitudinal dispersivity values on the lateral spread (numerical dispersion) of the contaminant. A longitudinal dispersivity of 5 ft appeared to give the closest match between the observed and predicted concentrations of TCE.

Calibration for Transverse Dispersivity

The calibration for transverse dispersivity was performed by changing the ratio of transverse to longitudinal dispersivity (α_T/α_L). For these runs α_L was 5 ft. Results of the calibration for transverse dispersivity are presented in Table 8. Like longitudinal dispersivity, changes in the transverse dispersivity do not have a significant effect on the contaminant distribution along the axial length of the plume. The well that is most affected by changing the transverse dispersivity is well W-25N-15. The contaminant distribution for $\alpha_T/\alpha_L = 0$ provides the best match between the predicted

Table 7: Observed and Predicted Concentrations of TCE ($\mu\text{g/l}$) for Different Longitudinal Dispersivities, $\alpha_T/\alpha_L = 0$, $t = 20$ years.

Observation Wells	Observed Concentrations	Longitudinal Dispersivities (feet)					
		2	3	4	5	6	10
W-26R-01	47	48.72	48.54	48.83	48.22	48.09	47.21
W-26R-03	58	57.82	58.39	58.94	58.96	59.51	61.27
W-25N-01	46	52.08	52.72	53.38	53.61	54.29	56.88
W-25N-05	24	21.06	20.86	20.56	20.76	21.28	24.64
W-25N-15	4.7	0.4	1.3	2.7	4.6	7.0	18.7

Table 8: Observed and Predicted Concentrations of TCE ($\mu\text{g/l}$) for Different Transverse Dispersivities, $\alpha_L = 5$ feet.

Observation Wells	Observed Concentrations	Ratio of Transverse to Longitudinal Dispersivity (α_T/α_L)			
		0.0	0.1	0.2	0.3
W-26R-01	47.0	48.22	48.35	48.35	48.31
W-26R-03	58.0	58.96	56.91	55.13	53.41
W-25N-01	46.0	53.61	51.65	49.66	47.82
W-25N-05	24.0	20.76	22.1	21.43	20.75
W-25N-15	4.7	4.6	13.1	15.3	16.0

and observed concentrations of TCE at the observation wells, particularly those off the central portion of the plume.

Although changes in dispersivities greatly affect the concentration of TCE in the southeastern part of the transport subgrid, the simulated distribution of contaminant in this part of the transport subgrid is uniform. Such uniform distribution might occur as a result of numerical dispersion over a long period of simulated time.

Results of Model Calibration

The calibrated model predicted groundwater flow velocities of 15 to 35 ft/d along the axial line of the plume. According to the calibrated model, 22.75 kilograms of TCE have been released over a period of 20 years. This corresponds to a volume of 4.1 gallons, which is reasonable based on what is known of the use and disposal of solvents at the site (personal communication with Mr. Robert Ferry, 1992).

Based on the calibrated model, the steady-state contaminant distribution in the zone of simulation was established in 0.54 years. Calibration of the model showed that changes in the K_d value did not affect the steady-state contaminant distribution, but an increase in the value of K_d increases the time to establish the steady-state contaminant distribution. For the K_d values of 0.088, 0.1, and 0.5 cm^3/g , the model predicted 0.54, 0.65, 1.5 years, respectively, as the time to establish the steady-state contaminant distribution.

MODELING OF REMEDIAL ACTIVITY

After calibration, the model was applied to design a remedial strategy for cleaning the aquifer. Six different remedial options were tested. These remedial options are described as Remedial Option # 1 through # 6. These remedial options differ from each other in number of extraction wells and/or number of pumping periods. A pumping period is the time period during which all input and output rates to an aquifer are held constant. Once a pumping period has started, then its setup for pumping or injection wells does not change.

Remedial Option # 1

For this remedial option, the model was run for two pumping periods. The first pumping period was 20 years long, during which time the contaminant was introduced into the system through hypothetical injection wells to simulate a continuous release over 20 years and to achieve the steady-state contaminant distribution predicted by the calibrated model (fig. 22). At the end of the first pumping period, the injection wells were turned off to simulate the removal of the contaminant source. During the second pumping period, the model was run with no pumping or injection to simulate groundwater flow under natural conditions. The second pumping period was 5 years long.

The model predicted that the contaminant is completely flushed out of the source area in 0.5 years after the removal of the source (fig. 23). A significant decrease in

Figure 23. Remedial Option # 1: Predicted concentrations of TCE ($\mu\text{g/l}$) 0.5 years after removal of the source.

the concentration of contaminant was observed along the axial line of the plume, but a very small change was observed near the southern and eastern borders of the transport subgrid. The contaminant concentration in this area decreased from $6 \mu\text{g/l}$ to $5 \mu\text{g/l}$ of contaminant in 5 years (fig. 24). A uniform contaminant concentration of $5 \mu\text{g/l}$ was predicted for the entire area bounded by $5 \mu\text{g/l}$ contours in Figure 24.

Remedial Option # 2

This remedial option involved two pumping periods. As in remedial option # 1, the contaminant was injected into the system for 20 years during the first pumping period, and at the end of 20 years the injection wells were turned off to simulate the removal of the source. During the second pumping period, which was 5 years long, the contaminated water was pumped out by 6 recovery wells, labeled in Figure 25. Table 9 presents the names of the recovery wells and their pumping rates. The pumping rates for wells REC-03, REC-04, and REC-05 were selected after running the model for several simulations. These wells would run dry at higher pumping rates because wells REC-03 and REC-04 are located near the eastern no-flow boundary and well REC-05 is located near the least permeable zone ($K = 0.001 \text{ ft/s}$) of the modeled area, which represents the bedrock portion of the modeled aquifer.

Figure 25 shows the distribution of contaminant after 5 years of remedial pumping. The result of this option is similar to that of remedial option # 1, which does not involve any pumping. However, the contaminant concentration near the southern and eastern borders decreased from $6 \mu\text{g/l}$ to $4 \mu\text{g/l}$. A uniform contaminant

Figure 24. Remedial Option # 1: Predicted concentrations of TCE ($\mu\text{g/l}$) 5 years after removal of the source.

Figure 25. Remedial Option # 2: Predicted concentrations of TCE ($\mu\text{g/l}$) 5 years after removal of the source and start-up of remedial pumping. Pumping rates of recovery wells are listed in Table 9.

Table 9. Pumping Rates of Recovery Wells.

Well I.D.	Pumping Rate (ft ³ /s)
W-26R-03	0.066
REC-01	0.022
REC-02	0.022
REC-03	0.015
REC-04	0.011
REC-05	0.011

concentration of 4 $\mu\text{g/l}$ was predicted for the entire area bounded by 4 $\mu\text{g/l}$ contours in Figure 25.

Remedial Option # 3

After the failure of the simulations involving two pumping periods in cleaning the aquifer, a new input data set was developed involving one 5-year-long pumping period beginning with the steady-state TCE distribution. This new data set contained the groundwater elevations and TCE distribution as predicted by the calibrated model. Parameters such as porosity, dispersivity, saturated thickness, regions of hydraulic conductivity, and the constant-head boundaries remained unchanged in the new input data set. For this remedial option, groundwater was extracted by the recovery wells operating at the extraction rates tabulated in Table 9. The result of this simulation (fig. 26) was similar to those described above.

Figure 26. Remedial Option # 3: Predicted concentrations of TCE ($\mu\text{g/l}$) 5 years after removal of the source and start-up of remedial pumping using steady-state initial distribution of contaminant.

Remedial Option # 4

The incomplete removal of the contaminant near the southern and eastern portions of the transport subgrid raised suspicion about the way the model deals with contaminants at the boundary nodes of the transport subgrid. After several computer runs, it was realized that, once the contaminant reaches the inflow-boundary nodes of the transport subgrid, these boundary nodes start acting as source cells. In order to verify this suspicion, the data set developed for Remedial Option # 3 was modified by changing the contaminant concentrations to zero at the boundary cells. This option includes the remedial pumping of the groundwater. The pumping wells with their extraction rates are listed in Table 9. This remedial option was simulated for 0.7 years.

The model predicted that the contaminant is flushed out of the aquifer within four months. Figures 27 through 31 show the distribution of contaminants in the transport sub-grid after 1 week, 1 month, 2 months, 3 months, and 4 months.

Cleansing of the aquifer by changing the steady-state concentration of the boundary nodes to zero suggests that there is a limitation to the MOC computer code. Once the contaminant reaches the inflow boundaries (western and southern), it cannot be removed due to fact that these cells begin to act as contaminant source cells. Inflow at the boundary cells occurs at the concentrations achieved at those cells and this artifact is irreversible.

Figure 27. Remedial Option # 4: Predicted concentrations of TCE ($\mu\text{g/l}$) 1 week after removal of the source and start-up of remedial pumping.

Figure 28. Remedial Option #4: Predicted concentrations of TCE ($\mu\text{g/l}$) 1 month after removal of the source and start-up of remedial pumping.

Figure 29. Remedial Option # 4: Predicted concentrations of TCE ($\mu\text{g/l}$) 2 months after removal of the source and start-up of remedial pumping.

Figure 30. Remedial Option # 4: Predicted concentrations of TCE ($\mu\text{g/l}$) 3 months after removal of the source and start-up of remedial pumping.

Figure 31. Remedial Option # 4: Predicted concentrations of TCE ($\mu\text{g/l}$) 4 months after removal of the source and start-up of remedial pumping.

Remedial Option # 5

This remedial option involved the data set with initial concentrations similar to those used for Remedial Option # 4. The model was run for 0.7 years with no groundwater extraction. A no-pumping scenario was simulated to examine the flushing of the contaminant under natural flow conditions. The model predicted that flushing of contaminant out of the transport subgrid takes four days more than the remediation of the aquifer with pumping. Figures 32 through 36 show the contaminant distribution after 1 week, 1 month, 2 months, 3 months, and 4 months.

Cleansing of the aquifer in such a short time is primarily related to the high pore water velocity. Due to this high pore water velocity, pumping is not efficient for cleaning the aquifer, if the source is removed.

Remedial Option # 6

Remedial Option # 6 is the simulation of the remedial pumping of groundwater employed at the eastern GSA through 1992. This involves pumping of well W-26R-03 at 29.5 gpm without removing the source of contamination. For this simulation, the groundwater was pumped at a rate of 0.066 ft³/s (29.5 gpm) from well W-26R-03 while the injection wells were injecting contaminant into the aquifer to simulate a continuous source during the remedial pumping. This option was started with the steady-state contaminant distribution, but the contaminant concentrations at the boundary nodes were changed to zero. The purpose of this option was to evaluate how effective the current remedial pumping is and to predict how long it would take

Figure 32. Remedial Option # 5: Predicted concentrations of TCE ($\mu\text{g/l}$) 1 week after removal of the source.

Figure 33. Remedial Option # 5: Predicted concentrations of TCE ($\mu\text{g/l}$) 1 month after removal of the source.

Figure 34. Remedial Option # 5: Predicted concentrations of TCE ($\mu\text{g/l}$) 2 months after removal of the source.

Figure 35. Remedial Option # 5: Predicted concentrations of TCE ($\mu\text{g/l}$) 3 months after removal of the source.

Figure 36. Remedial Option # 5: Predicted concentrations of TCE ($\mu\text{g/l}$) 4 months after removal of the source.

to remove the contaminant. This remedial option was simulated for 1 year. The model predicted that two months after the start-up of remedial pumping, the pumping well was catching most of the contaminant, thereby decreasing the amount of contaminant by 85 percent downgradient of the pumping well (W-26R-03). Figures 37 through 41 show the distribution of contaminant after 1 month, 2 months, 3 months, 6 months, and 1 year. The small portion of highly concentrated contaminant that escapes the pumping well in Figures 39, 40, and 41 is diluted by the clean water flowing in from the southern inflow boundary. The model predicted that, 1 year after the startup of remedial pumping, the highest concentration of TCE in the groundwater flowing out of the model boundary would be 4 $\mu\text{g/l}$, which is below the maximum contaminant level (5 $\mu\text{g/l}$) for the State of California Drinking Water Standards (State of California Department of Health Services, 1990).

Figure 37. Remedial Option # 6: Predicted concentrations of TCE ($\mu\text{g/l}$) 1 month after start-up of remedial pumping.

Figure 38. Remedial Option # 6: Predicted concentrations of TCE ($\mu\text{g/l}$) 2 months after start-up of remedial pumping.

Figure 39. Remedial Option # 6: Predicted concentrations of TCE ($\mu\text{g/l}$) 3 months after start-up of remedial pumping.

Figure 40. Remedial Option # 6: Predicted concentrations of TCE ($\mu\text{g/l}$) 6 months after start-up of remedial pumping.

Figure 41. Remedial Option # 6: Predicted concentrations of TCE ($\mu\text{g/l}$) 1 year after start-up of remedial pumping.

LIMITATIONS OF THE MODEL

The accuracy of a groundwater flow and solute transport simulation depends on the availability of the data for the simulated region and on the extent to which the field conditions are translated into the simulated conditions. In most cases, there are areas in the zone of simulation where no data are available. For this study, such an area occupies the southeastern part of the zone of simulation. There the aquifer thickness and hydraulic head were inferred from the data available from the closest shallow groundwater wells and by using the conceptual model. Therefore, the accuracy of this extrapolation depends on the accuracy of the conceptual model.

The formulation of the source code and its relation to the processes it represents also play an important role in the accuracy of a model. MOC assumes uniform storativity, porosity, bulk density, and distribution coefficient, whereas in the real field conditions these parameters may not be uniform. For this study, the most common values of porosity and bulk density for sandy gravel and gravely sand were picked from the literature, however, the actual porosity, bulk density, and distribution coefficient may be different and/or variable within the study area.

The MOC source code has limitations in the formatting of some of the aquifer parameters and factors that control the simulation. During this study, the aquifer thickness is one parameter that is rounded off due to formatting limitations. MOC uses the aquifer thickness as an integer value, whereas the aquifer thickness based on the well logs was in real numbers. For example, aquifer thicknesses of 14.6 and 15.4

ft both were rounded to 15 ft. There is a similar limitation for the pumping rate for an injection or extraction well, which is saved by the MOC preprocessor with only 2 significant figures to a power of ten. Formatting limitations for the initial heads signified that only three significant figures were input. A value of 400 was subtracted from all the field head values in order to have initial heads to one decimal place. This 400 was added to the output heads before data analysis.

DISCUSSION

The calibrated model provided a good correlation between the simulated and observed groundwater elevations. All the simulated groundwater elevations are within 0.5 ft of the observed elevations, except well W-25N-07 where the predicted water level is 1.15 ft lower than the observed elevation. On the other hand, well W-25N-05, which is located on the downgradient side of well W-25N-07, has a slightly higher water level (0.22 ft) than the observed elevation. These differences in water levels in wells W-25N-05 and W-25N-07 may be related to each other. In the field, there may be a low-permeability region that is local in extent and is not encountered in the surrounding wells. This impermeable unit might be causing the higher observed water level in well W-25N-07 and lower observed water level in well W-25N-05.

Regions of hydraulic conductivity predicted by the calibrated model (fig. 12) correlate with the geologic materials of the saturated aquifer. The region of minimum hydraulic conductivity (0.001 ft/s) represents the part of the aquifer where groundwater occurs in the bedrock. The region containing wells W-26R-03, W-25N-01, and W-25N-05 occurs in the coarse-grained alluvium deposited in the channel of Corral Hollow Creek. This alluvium is assumed to have a high hydraulic conductivity. The hydraulic conductivity predicted by the calibrated model (0.0076 ft/s) supports that assumption. The region containing well W-25N-06 is composed of coarse-grained alluvium and has the minimum width of the aquifer. Because

materials of coarsest grain size tend to deposit in narrow, high-velocity reaches of stream channels, this region was assigned the highest hydraulic conductivity (0.012 ft/s) within the simulated area.

Time versus drawdown plots of the real and simulated pumping test data suggest that the transmissivities based on these two methods are very similar, thus increasing the confidence in the transmissivity values used. The predicted storativity (0.25) is slightly higher than the value determined from pumping test data. In some cases the storativity value used yields drawdown curves very close to those observed in the field. In others, field data indicate an earlier water level response, but the drawdown after 24 hours of pumping is similar. Because the model permits input of only a single storativity value, it is not possible to match all the field data.

The observed and predicted concentrations of TCE are very close. During the calibration for longitudinal and transverse dispersivities, it was observed that well W-25N-15 was more sensitive to changes in dispersivity than the wells located along the axial length of the plume. The calibration for longitudinal and transverse dispersivities (Tables 7 and 8) suggested that greater variations in the values of these parameters were required to bring noticeable changes in the concentration of contaminants along the axial length of the plume.

During the search for appropriate remedial options, it was observed that the contaminant was not removed from the aquifer near the western and southern boundaries of the transport subgrid. Review of the MOC source code revealed that the water flowing into the transport subgrid is assumed to have the same concentration

as that of the boundary cell through which it enters. As a result of several computer runs, it was observed that the contaminant reached the western upgradient boundary of the transport subgrid very quickly. Once the contaminant reaches a boundary cell, it spreads along the boundary and long time periods of flushing are required to reduce the concentration by a very small amount. According to Goode (1993, personal communication), this problem occurs because of the close proximity of the source to the boundary of the contaminant transport subgrid. This problem can be solved in three ways: 1) moving the boundary of the transport subgrid away from the source, 2) increasing the cell dimensions, and 3) using a modified version of MOC which permits a 40 x 40 transport grid identical to the groundwater flow grid. The purpose of these approaches is to move the boundary of the transport grid far away from the source area so that the contaminant will not reach the boundary cells and the contaminant distribution will not be affected by the boundary conditions.

In order to determine the uncertainty introduced by the problematic boundary conditions, a trial run was performed using a transport subgrid identical to the groundwater flow grid. This trial run predicted concentrations which were about 10 to 15 $\mu\text{g/l}$ greater than those predicted by the calibrated model for the axial stretch of the plume. The southern and southeastern parts of the simulated region had zero predicted concentration. This suggests that the problematic boundary behavior has introduced a moderate uncertainty by slightly overestimating the amount of contaminant released during 20 years by about 20%.

Although the contaminant transport simulation is affected by the problematic

boundary behavior, the predictions using the remedial options # 4, 5, and 6 are useful in evaluating the remedial alternatives. The remedial options # 4 and # 5 suggest that the contaminant can be flushed away very quickly if the source is removed. The quick flushing of the contaminant is due to the very high pore water velocity. In addition, the water flowing in from the hydraulically upgradient sides immediately dilutes the contaminants. Furthermore, the remedial option # 5 suggests that the remedial pumping of groundwater does not significantly accelerate the cleanup process if the source is removed. The remedial option # 6 suggests that the pumping of groundwater using well W-26R-03 without removing the source can effectively decrease the amount of contaminants. After 1 year of remedial pumping, the maximum contaminant concentration in the groundwater leaving the eastern GSA is predicted to be 4 $\mu\text{g/l}$.

CONCLUSION

The groundwater flow simulation predicts a close match between the observed and simulated groundwater elevations. The pore water velocities of 10 to 15 ft/d around W-26R-03 match very closely to the velocities calculated from the pumping test results. The model predicted velocity values of 27 to 35 ft/d for the part of the aquifer where the groundwater passes through the narrowest area in the simulated region. Based on the subsurface geology, these values are fairly reasonable. The calibrated model predicted that the debris pile released 4.1 gallons of TCE over a period of 20 years, which is reasonable based on what is known of the use and disposal of solvents at the site. If the source is removed, the contaminant will be flushed away by the natural flow of groundwater due to the high pore water velocity. If the source is not removed, pumping of groundwater by well W-26R-03 will capture 85% of the contaminant. The contaminant escaping past the pumping well will be diluted by the clean water flowing into the area from the southern boundary and the groundwater flowing out of the simulated region is predicted to contain 4 $\mu\text{g/l}$ of TCE, which is below the maximum contaminant level for drinking water in the State of California.

REFERENCES CITED

- Bear, J., 1972, Dynamics of fluids in porous media: Elsevier, New York, N.Y., 764 p.
- Carlson, T.M. (editor), and others, 1991, LLNL Site 300 Environmental Investigations Quarterly April-June 1991 (UCAR-10194-91-2), 81 p.
- Dibblee, T.W., Jr., 1980, A preliminary map of Midway quadrangle, Alameda and San Joaquin counties, California, in McIlvride, W.A., Ferry, R.A., Vonder Haar, S.P., Wade, W.M., and Glick, L.L., 1990, Remedial investigation of the General Services Area (GSA), Lawrence Livermore National Laboratory Site 300, Lawrence Livermore National Laboratory, Livermore, California (UCRL-AR-103161).
- El-Kadi, A.I., 1988, Applying the USGS mass-transport model (MOC) to remedial actions by recovery wells: Groundwater, v. 26, p. 281-288.
- Ferry, R.A., Lamarre, A.L., and Landgraf, R.K., 1990, Draft feasibility study of the General Services Area (GSA), Lawrence Livermore National Laboratory Site 300, Lawrence Livermore National Laboratory, Livermore, California (UCRL-AR-104510).
- Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Prentice-Hall, Inc., Englewood Cliffs, N.J., 604 p.
- Garder, A.O., Peaceman, D.W., and Pozzi, A.L., Jr., 1964, Numerical calculation of multidimensional miscible displacement by the method of characteristics in Konikow, L.F., and Bredehoeft, J.D., 1978, Computer model of two dimensional solute transport and dispersion in groundwater: Techniques of Water-Resources Investigations of the United States Geological Survey, Book 7, Chapter C2, 90 p.
- Goode, D.J., and Konikow, L.F., 1989, Modifications of method-of-characteristics solute transport model to incorporate decay and equilibrium controlled sorption or ion exchange: USGS Water-Resources Investigations Report 89-4030, 63 p.
- Hoffman, F., 1988, Fault investigation at Pit 1, LLNL Site 300, a letter to Michael Higgins, Regional Water Quality Control Board-Central Valley Region, December 15, 1988.
- Konikow, L.F., and Bredehoeft, J.D., 1978, Computer model of two dimensional solute transport and dispersion in groundwater: Techniques of Water- Resources

- Investigations of the United States Geological Survey, Book 7, Chapter C2, 90 p.
- Konikow, L.F., and Grove, D.B., 1977, Derivation of equations describing solute transport in groundwater: U.S. Geological Survey Water-Resources Investigation Report 77-19, 30 p.
- Lohman, S.W., 1972, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.
- McIlvride, W.A., Ferry, R.A., Vonder Haar, S.P., Wade, W.M., and Glick, L.L., 1990, Remedial investigation of the general services area (GSA), Lawrence Livermore National Laboratory Site 300, Lawrence Livermore National Laboratory, Livermore, California (UCRL-AR-103161).
- Pinder, G.F., and Bredehoeft, J.D., 1968, Application of the digital computer for aquifer evaluation: Water Resources Research, v. 4, p. 1069-1093.
- Raber, E., and Carpenter, D.W., 1983, An evaluation of the hydrology and groundwater chemistry associated with landfills at LLNL's Site 300, Lawrence Livermore National Laboratory, Livermore, California (UCRL-53416).
- Raymond, L.A., 1969, The stratigraphy and structural geology of Northern Lone Creek and Southern Tracy quadrangles, California [M.S. Thesis]: San Jose State University, San Jose, California, 143 p.
- Scheidegger, A.E., 1961, General theory of dispersion in porous media: Journal of Geophysical Research, v. 66, p. 3273-3278.
- State of California Department of Health Services (1990), Summary of California Drinking Water Standards: Office of Drinking Water, Berkeley, California, 4 p.
- Wang, H.F., and Anderson, M.P., 1982, Introduction to computer modeling: Finite difference and finite element methods: W. H. Freeman and Company, San Francisco, California, 237 p.
- Webster-Scholten, P.C., 1993, Draft sitewide remedial investigation of Site 300, Lawrence Livermore National Laboratory, Livermore, California, Chapter 14, GSA Study Area.

APPENDIX: MOC INPUT FILE FOR STEADY-STATE REGIONAL FLOW WITH CONTAMINANT RELEASE

The following MOC input file was generated by using the MOC preprocessor available through International Groundwater Modeling Center (IGWMC), Colorado School of Mines, Golden, Colorado. Konikow and Bredehoeft (1978) and the MOC program manual from IGWMC explains input data format.

Simulation of Groundwater Flow and Solute Transport in the Alluvial Aquifer at the Eastern GSA, Site 300, LLNL, Livermore, California

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