CEMENT KILN DUST GROUNDWATER MIGRATION PATHWAY

REPORT

EPA Contract No. 68-C6-0020
Work Assignment No. 1-05

Prepared for:

U.S. Environmental Protection Agency
Office of Solid Waste
Washington DC, 20460

February 11, 1998

CEMENT KILN DUST GROUNDWATER MIGRATION PATHWAY

REPORT

EPA Contract No. 68-C6-0020

Work Assignment No. 1-05

Prepared for:

U.S. Environmental Protection Agency
Office of Solid Waste
Washington DC, 20460

Prepared by:

HydroGeoLogic, Inc.
1155 Herndon Parkway, Suite 900
Herndon, VA 20170

February 11, 1998

TABLE OF CONTENTS

Appendices:

        Appendix A   EPACMTP Input Data
        Appendix B   Metal Isotherms for Highly Alkaline Conditions

LIST OF TABLES

LIST OF TABLES

LIST OF TABLES

LIST OF FIGURES

1.0   INTRODUCTION

Section 3001(b)3(A)(iii) of the Resource Conservation and Recovery Act (RCRA) excludes Cement Kiln Dust (CKD) from regulation under Subtitle C of RCRA, pending completion of a Report to Congress (RTC) required by §8002(o) and a determination by the EPA Administrator either to promulgate regulations under Subtitle C or that such regulations are unwarranted. EPA completed the RTC in December 1993 and the subsequent regulatory determination in January, 1995.

In support of the RTC and subsequent regulatory determination, EPA conducted screening-level groundwater modeling using MMSOILS to determine whether constituents would leach from the CKD management units to the groundwater and then move to a receptor site. The modeling indicated limited potential for contaminants of concern to migrate downgradient to receptor wells at levels of concern. Subsequent modeling performed by HydroGeoLogic using EPACMTP (U.S. EPA, 1996a, b, c) also indicated limited concern for migration to receptor locations. The alkaline conditions associated with CKD leachate, however, suggest that additional evaluation of the MINTEQA2 isotherms calculated using MINTEQA2 (see Allison, et al., 1991 and 1992 for a description of EPA's metal speciation model MINTEQA2) and the revision of these isotherms to reflect high alkaline environments may be appropriate.

This report is the second phase of a two phase work effort to determine migration of contaminants from CKD leachate to receptor wells under high alkalinity conditions. The MINTEQA2 isotherms were evaluated under Phase I of this work assignment (HydroGeoLogic, 1997) by Allison Geoscience Consultants Inc. (Work Assignment 0-07). Five metals, barium, beryllium, cadmium, chromium, and lead were identified from a list of eight metals (lead, antimony, arsenic, barium, beryllium, cadmium, chromium, and thallium) to be most likely to have adsorptive behavior different from the Hazardous Waste Identification Rule (HWIR) Subtitle D landfill scenario. Consequently, new isotherms were generated for these metals during Phase I.

Five facilities were used to determine the risks associated with the groundwater migration pathway using the new revised isotherms. These facilities are identified as A, O, F, G, and J in this report. The sites selected were the same as used earlier (EPA's Report to Congress, 1993; HydroGeoLogic, 1996). The primary source of site specific data is EPA's Report to Congress on Cement Kiln Dust (EPA, 1993), which includes EPA's data accumulation efforts at actual CKD facilities, the Portland Cement Association CKD survey, and previously collected data on facilities in similar geographical regions. The various input parameters for EPACMTP were the same as used earlier (HydroGeoLogic, 1996). The modeling consists of deterministic evaluations using constituent specific concentrations and site-specific parameter values for central tendency as well as high end estimates of risk at these five sites. Since modeling methodology and input data are the same as used earlier (HydroGeoLogic, 1996), the only change was the new isotherms.   The results obtained in this modeling effort reflect the sensitivity to the new isotherms.

The modeling methodology and model input data are described in Sections 2.0 and 3.0. Section 4.0 provides the results from the previous modeling effort (HydroGeoLogic, 1996) and

Section 5.0 provides the results of this modeling effort as well as a comparison of the two modeling efforts. Appendix A has the model input data and Appendix B provides the new revised metal isotherms under high alkaline conditions from Phase I.

2.0   MODELING METHODOLOGY

A detailed discussion of the methodology for evaluating the potential for migration of contaminants from a waste management unit to a receptor location through the groundwater pathway is provided in the EPACMTP Background Document for Metals (U.S. EPA, 1996a). In general, the modeling procedure for metals combines a finite source methodology (U.S. EPA, 1996b) with a metal-specific procedure using MINTEQA2 (Appendix B; Allison et al., 1991 and 1992) for handling geochemical interactions that affect the subsurface fate and transport of metals. The latter procedure has been developed at the EPA-ORD Environmental Research Laboratory in Athens, GA and has been adopted for incorporation into EPACMTP.

In this methodology, the MINTEQA2 metals speciation code is used to generate nonlinear adsorption isotherms for each individual metal species. The isotherms reflect the range in geochemical environments that are expected to be encountered at waste sites across the nation. An isotherm is selected for each model simulation, depending on selected values for four environmental variables that control the mobility of metals: (1) the leachate organic matter content, (2) the subsurface pH, (3) the subsurface concentration of amorphous iron oxide adsorbent, and (4) the subsurface organic matter content.

At present, nonlinear adsorption isotherms have been developed for 10 RCRA metals. Of these, barium, beryllium, cadmium, chromium, and lead are of concern in CKD. For the neutral and moderately alkaline environments beryllium is assumed to have the same isotherm as barium. For highly alkaline conditions, however, separate isotherms were calculated for beryllium using MINTEQA2. Three other metals of concern could not be modeled using MINTEQA2 because adsorption reactions describing the interaction of the metal with an adsorbing surface are not reliably known. These metals are arsenic(III), thallium(I), and antimony (V). Because MINTEQA2 could not be used, empirical relationships developed by Loux et al. (1990), which provide the adsorption distribution coefficient as a function of pH, were used. A complete discussion of the isotherms generated under highly alkaline conditions as compared with the HWIR isotherms generated under neutral and slightly alkaline conditions is provided in Appendix B and by HydroGeoLogic (1997).

The implementation of the metals methodology is based on the assumption that the nonlinearity of the metals sorption isotherms is most important in the unsaturated zone where concentrations are relatively high. Upon reaching the water table and mixing with ambient groundwater, the metals concentration is considered to be low enough that a linear isotherm can be used. The appropriate saturated zone retardation factor is determined based on the maximum groundwater concentration underneath the source leaving the unsaturated zone.

The fate and transport of metal species in the subsurface can be modeled using a conventional advection-dispersion equation. The EPACMTP methodology separates the subsurface domain into two zones: (1) the unsaturated zone above the water table, and (2) the saturated zone beneath the water table. Flow and transport of contaminants, in the unsaturated zone beneath the landfill, is assumed to be vertical only, while flow and transport beneath the water table is three-dimensional. A mass conservative coupling of the two zones occurs at the water-table unsaturated zone interface.

Flow through the unsaturated zone is assumed to occur under steady state conditions representing an average infiltration over the transport simulation time scale. Solution of the unsaturated one-dimensional, steady state flow equation is obtained through analytical solution schemes and is detailed in the EPACMTP Background Document (U.S. EPA, 1996c). Transport through the unsaturated zone follows the finite-source methodology for EPACMTP. The retardation, for metals, is obtained from MINTEQA2 simulations, as discussed earlier. The equation for transient transport of metals is solved by analytical solution methods detailed in the EPACMTP Background Document for Metals (U.S. EPA, 1996a).

Flow in the saturated zone is affected by ambient groundwater gradients, recharge over the modeled area, and infiltration of water (leachate) beneath the landfill. A numerical finite element solution is used for the steady-state saturated flow equation and is detailed in the EPACMTP Background Document (U.S. EPA, 1996c). Contaminant transport in the saturated zone follows the conventional transient advective-dispersive transport equation in three dimensions, i.e., metal transport occurs due to advection, diffusion, and dispersion in the porous medium, subject to adsorption on the soil. Further, we assume that metal concentrations beneath the water table are fairly low, due to mixing of leachate with ambient groundwater, and therefore, the MINTEQA2 derived adsorption isotherm is linearized, since the nonlinearities associated with high metal concentrations are not present. Another assumption made for this analysis is that the highly akaline conditions present in the waste unit persist along the entire transport path of the metal, i.e., the groundwater does not buffer the leachate when it reaches the water table. With the exception of barium and beryllium this assumption is conservative for the transport of these CKD metals constituents (see Section 5.2 and 5.3, Results). The linearized transport equation beneath the water table is solved using the Laplace Transform Galerkin (LTG) scheme detailed in the EPACMTP Background Document (U.S. EPA, 1996c).

Data for the simulation of metal transport at the five facilities of interest include site specific information assimilated in EPA's Report to Congress on Cement Kiln Dust (EPA, 1993), recharge and unsaturated zone soil data from a location database developed for EPACMTP (U.S. EPA, 1997), and data on adsorption isotherms for metals under various conditions. These data are presented in Section 4.0 of this report. Results from an EPACMTP simulation of metals include the concentrations at all receptor well locations at various times up to a simulation period of 160 years.

3.0 MODELING INPUT DATA

A list of EPACMTP modeling data-needs is compiled for simulating the migration of metals at CKD disposal facilities, in this section. The facilities are referred to as A, O, F, G and J, and the metals examined include barium, beryllium, cadmium, chromium, and lead. The primary source of site-specific data is EPA's Report to Congress on Cement Kiln Dust (EPA, 1993), which includes EPA's data accumulation efforts at actual CKD facilities, Portland Cement Association CKD survey, and previously collected data on facilities in similar geographical regions. Additional data needed to run EPACMTP is also identified, along with sources for obtaining this data.

General control parameters required by EPACMTP to guide the simulation are provided in Appendix A (Tables A.1 and A.2). The parameters are the same for all sites and for every metal examined.

Tables 3.1 through 3.5 list site and chemical specific input parameters.

- Table 3.1 provides the source and infiltration boundary data to the system, including source dimensions, leachate concentrations, and water fluxes through the land surface, for each site.

- Table 3.2 provides the chemical specific data for each of the eight metals investigated. The EPACMTP code uses the information on soil pH, iron hydroxide content and organic contents of leachate and soil to determine adsorption/precipitation of metals, from curves generated for low, high, and medium values of these parameters using MINTEQA2.

- Tables 3.3 and 3.4 provide parameters specific to the unsaturated zone and saturated zone, respectively, beneath the 5 sites. These data include conductivity parameters, ambient groundwater gradients, bulk densities, and dispersivities of the saturated and unsaturated zones. Note that observation well locations are dependent on the exposure locations at each site.

- Table 3.5 provides the recharge and infiltration data that are derived from the EPACMTP data base of climate centers, by selecting the climate center closest to the facility. Note that this data is included in the EPACMTP data files, via Table 4.1.

Table 3.1 Input Parameters for Source-Specific Group

Variable	Description		Value					Comments
			A	O	F	G	J	
AREA	Area of disposal unit (m²) C.T. H.E.		209,032 214,500	41,836 48,200	306,330 357,500	13,000 14,500	44,825 46,000	From MMSOILS data files.
XW	Length (x-direction) of disposal C.T. unit (m) H.E.		457.2 463.14	204.5 219.55	553.5 597.91	114.0 120.42	211.7 214.48	From MMSOILS data files.
YD	Width (y-direction) of disposal unit (m)		457.2	204.5	553.5	114.0	211.7	Square area assumed in MMSOILS.
CZERO(I)	Leachate concentration emanating from the waste disposal facility (mg/L). C.T.; H.E. Lead: Antimony: Arsenic: Barium: Beryllium: Cadmium: Chromium: Thallium:		 0.53 0.022; 0.044 0.0038 0.23 0.002; 0.004 0.004; 0.008 0.053 0.011	 0.046 0.022; 0.044 0.0028 0.34 0.002; 0.004 0.004; 0.008 0.077 .026	 0.968; 0.976 0.019; 0.0167 0.0022; 0.0023 0.745; 0.869 0.0013; 0.004 0.0025; 0.008 0.346; 0.373 0.0079; 0.0108	 1.1 0.068 0.013 0.47 0.002; 0.004 0.004; 0.008 0.004; 0.008 0.43	 0.026 0.062 0.0039 0.49 0.002; 0.004 0.004; 0.008 0.038 0.053	From MMSOILS data files. A constant value of leachate concentration was used in the MMSOILS simulation, using the values used in TSOURC below, as the period of leachate generation.
RECHRG	Areal recharge rate (m/y)		0.0686	0.2609	0.2609	0.145	0.0008	Need locations and soil type, as classified by SCS.
SINFIL	Infiltration rate from disposal unit (m/y)		0.0686	0.2609	0.2609	0.145	0.0008	Need locations and soil type, as classified by SCS.
TSOURC	Duration of leaching period (y) for finite source option (KFS= 1) TSOURC should be specified as a <u>derived</u> variable if KFS= 2 (i.e. for landfills).		160	171	160	162	160	From MMSOILS data file.

C.T.: Central Tendency Parameters
H.E.: High End Parameters (shaded)

Table 3.1   Input Parameters for Source-Specific Group (continued)

Variable	Description	Value					Comments
		A	**O**	**F**	**G**	**J**	
DEPTH	Depth of the waste disposal facility (m) for landfill finite source option.	12	6	12	10	3.05	From Exhibit 8-2 of RTC consistent with MMSOILS data files.

C.T.: Central Tendency Parameters
H.E.: High End Parameters (shaded)

Table 3.1   Input Parameters for Source-Specific Group (continued)

Variable	Description	Value					Comments
		A	**O**	**F**	**G**	**J**	
FRACT	Fraction of CKD in the waste disposal facility for landfill finite source option.	1	1	1	1	1	It is assumed that the waste is fully dispersed in the landfill.
CTDENS	Density of CKD C.T. (g/cm^3) H.E.	1.5 1.4	1.5 1.4	1.5 1.4	1.5 1.4	1.733 1.5	From MMSOILS data files.

C.T.: Central Tendency
H.E.: High End Parameters (shaded)

Table 3.2a   Chemical Specific Data

Variable	Description	Value								Comments
		Lead	Antimony	Arsenic	Barium	Beryllium	Cadmium	Chromium	Thallium	
DSTAR(I)	Effective molecular diffusion coefficient (m²/y). For a multispecies simulation, this record should be repeated for each of the components in the decay chain, i.e., NSPECI times.	1×10^{-6}	1×10^{-6}	1×10^{-6}	1×10^{-6}	1×10^{-6}	1×10^{-6}	1×10^{-6}	1×10^{-6}	From MMSOILS data files consistent with Exhibit 8-2 of RTC.
DWS(I)	Drinking water standard (mg/L), i.e., HBL or MCL value for comparison against model predicted average receptor well concentrations.	0.015	0.006	0.05	2.0	0.004	0.005	0.1	0.002	Action levels of MMSOILS data files.
CARC(I)	Base exposure period (y) for calculating average receptor well concentration. Set to 70 y for carcinogens, and 35 y for non-carcinogens. Always specify this parameter as a constant. For a degrader, this record should be repeated for the parent and all daughter products, i.e., NSPECI times.	–	–	–	–	–	–	–	–	Note required for peak concentration computation at receptor well.

Table 3.2a   Chemical Specific Data (continued)

Variable	Description	Value								Comments
		Lead	Antimony	Arsenic	Barium	Beryllium	Cadmium	Chromium	Thallium	
METAL_ID	Identification number for the metal.	6	17	13	1	1 (similar sorption to Barium)	2	3	16	From EPACMTP document.

Table 3.2b   Chemical Specific Data

Variable	Description	Value					Comments
		A	O	F	G	J	
USPH	Soil and aquifer pH. C.T. H.E. Alkaline Cond.	6.8 7.9 11.0 12.0 13.0	6.8 7.9 11.0 12.0 13.0	6.8 7.9 11.0 12.0 13.0	6.8 7.9 11.0 12.0 13.0	6.8 7.9 11.0 12.0 13.0	50 and 10% tile values in HWIR pH data base for C.T. and H.E., respectively and pH values used for highly alkaline conditions.
FEOX	Weight percentage of iron-hydroxide in the soil and aquifer.	0.44	0.44	0.44	0.44	0.44	50% tile value in HWIR FEOX data base.
LOM	Concentration (mg/L) of dissolved organic carbon in the waste leachate.	0.004	0.004	0.004	0.004	0.004	50% tile value in HWIR data base.
USNOM	Unsaturated zone percentage organic matter.	0.105	0.105	0.105	0.105	0.105	Mean value for silt loam in HWIR data base.
ASNOM	Aquifer fraction organic carbon.	0.001	0.0001	0.001	0.001	0.0001	From MMSOILS data files.

C.T.: Central Tendency
H.E.: High End Parameters (shaded)

Notes:
1)   Presently the following METAL_ID codes are recognized: 1= Barium; 2= Cadmium; 3= Chromium (4+); 4= Mercury; 5= Nickel; 6= Lead; 7= Silver; 8= Zinc; 9= Copper; 10= Vanadium; 13= Arsenic; 14= Chromium (6+); 15= Selenium; 16= Thallium; 17= Antimony.

2)   The unsaturated zone percentage organic matter varies with soil type and should be the same as that specified under the unsaturated zone specific group (see section 6.5; U.S. EPA, 1997).

3)   The saturated zone fraction organic carbon should be the same as that specified under the aquifer specific group (see section 7.8; U.S. EPA, 1997).

4)   MINTEQA2 nonlinear isotherms have been provided for different combinations of pH, % wt. FeOH, and organic carbon contents.

5)   MINTEQA2 isotherms used in the CKD analysis were based on the combination of % wt. of FeOH and organic carbon values shown above.

Table 3.3 Input Parameters for Unsaturated Zone Specific Data

Variable	Description	Value					Comments
		A	O	F	G	J	
SATK	Saturated hydraulic conductivity, K_s, (cm/hr).	0.15	0.23	0.15	21	21	From MMSOILS data files consistent with Exhibit 8-2 of RTC.
ALPHA	Moisture retention parameter, α, (cm^{-1}).	0.019	0.019	0.019	0.019	0.019	Mean value for silt loam in HWIR data base.
BETA	Moisture retention parameter, β.	1.409	1.409	1.409	1.409	1.409	Mean value for silt loam in HWIR data base.
WCR	Residual water content, θ_r.	0.068	0.068	0.068	0.068	0.068	Mean value for silt loam in HWIR data base.
WCS	Saturated water content, θ_s.	0.471	0.464	0.471	0.437	0.437	From MMSOILS data files.
DSOIL	Thickness of unsaturated zone (m).	1.83	2.13	3.05	0.305	3	From MMSOILS data files consistent with Exhibit 8-2 of RTC.
DISPR	Dispersivity, α, (m).	Derived	Derived	Derived	Derived	Derived	Derived parameter from Gelhar et al. (1992) empirical relation.
POM	Percent organic matter.	1	0.225	1	0.55	0.0001	From MMSOILS data files consistent with Exhibit 8-2 of RTC.
RHOB	Bulk density, ρ_b, (g/cm^3).	1.36	1.39	1.36	1.64	1.64	From MMSOILS data files consistent with Exhibit 8-2 of RTC.

Reference:

Table 3 Input Parameters for Source-Specific Group (cont)

Gelhar, L.W., C. Weltry, K.R. Rehfeldt, 1992. A critical review of data on field-scale dispersion in aquifers. Water Resourc. Res; 28(7), 1955-1974.

Table 3.4 Input Parameters for Aquifer Specific Data

Variable	Description	Value					Comments
		A	O	F	G	J	
DIAM	Average particle diameter (cm)	0.0025	0.0025	0.0025	0.0025	0.0025	Median value from HWIR data base.
POR	Aquifer porosity	0.4	0.1	0.4	0.01	0.36	From MMSOILS data files. Note: Data file has 36 for landfill 5.
BULKD	Aquifer bulk density (g/cm^3)	1.59	1.67	1.59	2.25	1.67	From MMSOILS data files.
ZB	Aquifer Saturated thickness (m)	7.7724	45.7	7.7724	175.26	36.576	From MMSOILS data files.
XKX	Longitudinal hydraulic conductivity, K_x, (m/y) C.T. H.E.	111.252 1112.52	26.70048 267.0048	111.252 1112.52	76897.3824 153794.76	890. 8900.	From MMSOILS data files.
ANIST	Anisotropy ratio, K_x/K_z	1	1	1	1	1	Assumed.
GRADNT	Hydraulic gradient (m/m)	0.005	0.02	0.005	0.0001	0.035	From MMSOILS data files.
AL	Longitudinal dispersivity, α_L (m)	10	0.1	0.1	0.1	0.1	From MMSOILS data files.
AT	Transverse dispersivity, α_T (m)	0.02	0.02	0.02	0.02	0.02	From MMSOILS data files.
AV	Vertical dispersivity, α_V (m)	0.01	0.01	0.01	0.01	0.01	From MMSOILS data files.
PH	Ambient groundwater pH C.T. H.E.	6.8 7.9	6.8 7.9	6.8 7.9	6.8 7.9	6.8 7.9	50 and 10% tile value in HWIR data base.
FOC	Fraction organic carbon (g/g)	0.001	0.0001	0.001	0.001	0.0001	From MMSOILS data files.

C.T.: Central Tendency Parameters
H.E.: High End Parameters (shaded)

Table 3.4 Input Parameters for Aquifer Specific Data (continued)

Variable	Description	Value A	O	F	G	J	Comments
XWELL(I),	Distance in downstream direction (m) between downstream edge of the source and observation well. Repeat this record for each of the NWELLS observation wells.	305,0,0	805,0,0;	305,0,0; 10,0,0	402,0,0; 100,0,0	402,0,0;	Ag field K
		20,0,0	100,0,0	20,0,0	20,0,0	100,0,0	Ex field R
		483,0,0	20,0,0	966,0,0	1610,0,0	20,0,0	Mei H (Nearest receptor well)
		10,0,0	1610,0,0	10,0,0	10,0,0	550,0,0	POC1
		50,0,0	10,0,0	50,0,0	50,0,0	10,0,0	POC2
		201,0,0	50,0,0	201,0,0	201,0,0	50,0,0	Private well point on Center line
YWELL(I),	Horizontal transverse distance of well from the plume centerline (m). Repeat this record for each of the NWELLS observation wells.	603,0,0	201,0,0	603,0,0	603,0,0	201,0,0	Private well point on Center line
		1006,0,0	603,0,0	1006,0,0	1006,0,0	603,0,0	Private well point on Center line
		1408,0,0	1006,0,0	1408,0,0	1408,0,0	1006,0,0	Private well point on Center line
		2011,0,0	1408,0,0	2011,0,0	2011,0,0	1408,0,0	Private well point on Center line
		2816,0,0	2011,0,0	2816,0,0	2816,0,0	2011,0,0	Private well point on Center line
ZWELL(I)	Depth of well below water table (m). Repeat this record for each of the NWELLS observation wells. Note ZWELL should be given as a fraction of the saturated zone thickness, unless distribution type 12 (Section 6.5.13), i.e. constant well depth, is being used.	167,265,0	2816,0,0	167,143,0	167,144,0	2816,0,0	Private well point on 2nd sector
		502,488,0	167,175,0	502,367,0	502,367,0	167,156,0	Private well point on 2nd sector
		836,712,0	502,398,0	836,590,0	836,591,0	502,380,0	Private well point on 2nd sector
		1171,936,0	836,622,0	1171,814,0	1171,815,0	836,604,0	Private well point on 2nd sector
		1672,1271,0	1171,846,0	1672,1149,0	1672,1150,0	1171,827,0	Private well point on 2nd sector
		2341,1718,0	1672,1181,0	2341,1596,0	2341,1597,0	1672,1162,0	Private well point on 2nd sector
			2341,1628,0			2341,1609,0	

C.T.: Central Tendency Parameters
H.E.: High End Parameters (shaded)

Table 3.5 Infiltration Rates Dependent on Location, from HWIR Data Base

Facility ID	Infiltration (m/y)			Nearest Climatic Center	Climatic Center # (from EPACMTP data base)
	Silt Loam	Sandy Loam	Silty Clay Loan		
*A	0.0686	0.1006	0.0456	Tulsa, OK	34
O	0.2609	0.3287	0.2123	Charleston, SC	93
*F	0.2609	0.3287	0.2123	Tulsa, OK	93
G	0.1450	0.2201	0.1019	Miami, FL	97
J	0.0008	0.0008	0.0036	Denver, CO	03

*Facilities where nearest climatic center is not located in the same state.

4.0   SUMMARY OF PREVIOUS MODELING RESULTS

This section summarizes the results of the September 1996 modeling effort (HydroGeoLogic, 1996) involving the EPACMTP code that was used to study the migration of metals from five different landfill facilities via the groundwater pathway. Data required for the simulations has been presented above in Section 3.0 and the modeling methodology is summarized in Section 2.0. Simulations were performed for the central tendency and high end values for parameters at the site. Parameters that were varied for the high end simulations include area of disposal unit, leachate concentration emanating from the waste, density of the waste, soil pH conditions, and hydraulic conductivity of the aquifer. Tables 4.1 through 4.5 provide results of the simulations for the five landfill facilities. Leachate concentration values are reported at the nearest receptor wells for the landfills and at 10 m, 20 m, and 50 m downstream from the landfill. These values are reported for the central tendency and high end simulations at 130 y and 160 y.

None of the metals have reached the water table by 160 y at landfills located at Facilities A and J (see Tables 4.1 and 4.5, respectively) for central tendency or high end simulations. Further, only Facility O (see Table 4.2) shows any metal (specifically barium) reaching a nearest receptor well by 160 years. It should be noted that concentration values below 10^{-7} are unreliable due to roundoff errors in the calculations and convergence tolerance limits. These non-zero values, which may be interpreted as showing trace amounts of contaminant reaching the observation points at Facility O (Table 4.2) include antimony, arsenic, barium, and beryllium for the central tendency simulations, and antimony and arsenic for the high end simulations. The non-linearity of the equations, specifically with respect to pH, allows for situations where the transport of a metal may be slower for high end simulations than the corresponding central tendency case. Barium and arsenic are present at observation points at 160 years for the central tendency simulations at Facility F (Table 4.3), and antimony and arsenic are noted for the high end simulations, at these observation locations. At Facility G (Table 4.4), antimony, arsenic, barium, beryllium, and thallium are calculated to reach the observation locations for both central tendency as well as high end simulations.

Table 4.1a   Concentration of Metals at Various Locations Along the Centerline for Landfill 1 (Facility A)

Metal	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201m	Receptor Well 483 m	10 m	20 m	50 m	201 m	Receptor Well 483 m
M1 Lead					Not reached W.T. @ 160 y					
M2 Antimony					Not reached W.T. @ 160 y					
M3 Arsenic					Not reached W.T. @ 160 y					
M4 Barium					Not reached W.T. @ 160 y					
M5 Beryllium					Not reached W.T. @ 160 y					
M6 Cadmium					Not reached W.T. @ 160 y					
M7 Chromium					Not reached W.T. @ 160 y					
M8 Thallium					Not reached W.T. @ 160 y					

C1 → Landfill 1, Central Tendency

Table 4.1b   Concentration of Metals at Various Locations Along the Centerline for Landfill 1 (Facility A)

Metal	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201 m	Receptor Well 483 m	10 m	20 m	50 m	201 m	Receptor Well 483 m
M1 Lead					Not reached W.T. @ 160 y					
M2 Antimony					Not reached W.T. @ 160 y					
M3 Arsenic					Not reached W.T. @ 160 y					
M4 Barium					Not reached W.T. @ 160 y					
M5 Beryllium					Not reached W.T. @ 160 y					
M6 Cadmium					Not reached W.T. @ 160 y					
M7 Chromium					Not reached W.T. @ 160 y					
M8 Thallium					Not reached W.T. @ 160 y					

H1 → Landfill 1, High End

Table 4.2a Concentration of Metals at Various Locations Along the Centerline for Landfill 2 (Facility O)

Metal	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201 m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
M1 Lead					Not reached W.T. @ 160 y					
M2 Antimony	6.40E-08	4.44E-09	0.0	0.0	0.0	1.35E-08	6.45E-10	0.0	0.0	0.0
M3 Arsenic	9.69E-08	5.35E-09	1.36E-10	0.0	0.0	1.49E-08	1.12E-09	0.0	0.0	0.0
M4 Barium	1.08E-01	3.77E-02	6.46E-03	6.50E-04	1.20E-08	1.04E-01	3.64E-02	5.71E-03	1.69E-04	1.12E-08
M5 Beryllium	6.84E-04	2.32E-04	3.11E-05	3.24E-07	0.0	5.07E-04	1.79E-04	2.64E-05	2.24E-08	0.0
M6 Cadmium					Not reached W.T. @ 160 y					
M7 Chromium					Not reached W.T. @ 160 y					
M8 Thallium					Not reached W.T. @ 160 y					

Column header across top: C2 → Landfill 2, Central Tendency

Table 4.2b Concentration of Metals at Various Locations Along the Centerline for Landfill 2 (Facility O)

Metal	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
M1 Lead					Not reached W.T. @ 160 y					
M2 Antimony	2.43E-05	4.27E-06	2.72E-07	1.40E-10	0.0	2.15E-06	4.46E-07	4.39E-08	0.0	0.0
M3 Arsenic	4.96E-08	1.27E-08	1.33E-09	0.0	0.0	4.20E-08	8.54E-09	5.35E-10	0.0	0.0
M4 Barium					Not reached W.T. @ 160 y					
M5 Beryllium					Not reached W.T. @ 160 y					
M6 Cadmium					Not reached W.T. @ 160 y					
M7 Chromium					Not reached W.T. @ 160 y					
M8 Thallium					Not reached W.T. @ 160 y					

The table is titled **H2 → Landfill 2, High End**

Table 4.3a Concentration of Metals at Various Locations Along the Centerline for Landfill 3 (Facility F)

Metal	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201 m	Receptor Well 966 m	10 m	20 m	50 m	201 m	Receptor Well 966 m
M1 Lead					Not reached W.T. @ 160 y					
M2 Antimony					Not reached W.T. @ 160 y					
M3 Arsenic	5.07E-04	1.79E-04	2.64E-05	2.24E-08	0.0					Not reached W.T. @ 130 y
M4 Barium	9.72E-02	1.07E-04	2.92E-08	0.0	0.0	8.14E-02	6.80E-05	1.17E-08	0.0	0.0
M5 Beryllium					Not reached W.T. @ 160 y					
M6 Cadmium					Not reached W.T. @ 160 y					
M7 Chromium					Not reached W.T. @ 160 y					
M8 Thallium					Not reached W.T. @ 160 y					

The table header row: **C3 → Landfill 3, Central Tendency**

Table 4.3b   Concentration of Metals at Various Locations Along the Centerline for Landfill 3 (Facility F)

	H3 → Landfill 3, High End									
Metal	**@ 160 Y**					**@ 130 Y**				
	10 m	**20 m**	**50 m**	**201m**	**Receptor Well 966 m**	**10 m**	**20 m**	**50 m**	**201 m**	**Receptor Well 966 m**
M1 Lead					Not reached W.T. @ 160 y					
M2 Antimony	5.02E-07	4.06E-08	5.35E-10	0.0	0.0	1.42E-07	1.11E-08	5.35E-10	0.0	0.0
M3 Arsenic	2.14E-07	1.83E-08	5.35E-10	0.0	0.0					Not reached W.T. @ 130 y
M4 Barium					Not reached W.T. @ 160 y					
M5 Beryllium					Not reached W.T. @ 160 y					
M6 Cadmium					Not reached W.T. @ 160 y					
M7 Chromium					Not reached W.T. @ 160 y					
M8 Thallium					Not reached W.T. @ 160 y					

Table 4.4a Concentration of Metals at Various Locations Along the Centerline for Landfill 4 (Facility G)

C4 → Landfill 4, Central Tendency										
Metal	**@ 160 Y**					**@ 130 Y**				
	10 m	**20 m**	**50 m**	**201 m**	**Receptor Well 1610 m**	**10 m**	**20 m**	**50 m**	**201 m**	**Receptor Well 1610 m**
M1 Lead					Not reached W.T. @ 160 y					
M2 Antimony	1.71E-04	4.19E-05	8.40E-07	0.0	0.0	7.17E-05	1.41E-05	2.05E-07	0.0	0.0
M3 Arsenic	9.62E-05	3.10E-05	9.81E-07	0.0	0.0	4.59E-05	1.23E-05	2.84E-07	0.0	0.0
M4 Barium	2.08E-02	9.74E-03	6.91E-04	1.72E-09	0.0	1.33E-02	5.63E-03	3.06E-04	2.66E-10	0.0
M5 Beryllium	6.89E-05	3.06E-05	1.88E-06	0.0	0.0	4.16E-05	1.63E-05	7.42E-07	0.0	0.0
M6 Cadmium					Not reached W.T. @ 160 y					
M7 Chromium					Not reached W.T. @ 160 y					
M8 Thallium	6.14E-05	7.40E-06	5.95E-08	0.0	0.0	1.66E-05	1.52E-06	9.29E-09	0.0	0.0

Table 4.4b   Concentration of Metals at Various Locations Along the Centerline for Landfill 4 (Facility G)

Metal	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
M1 Lead					Not reached W.T. @ 160 y					
M2 Antimony	1.92E-03	9.92E-04	9.71E-05	2.37E-09	0.0	9.41E-04	4.27E-04	3.00E-05	2.99E-10	0.0
M3 Arsenic	1.25E-04	5.28E-05	3.16E-06	0.0	0.0	5.38E-05	1.96E-05	8.43E-07	0.0	0.0
M4 Barium	8.97E-03	4.07E-03	2.64E-04	1.41E-09	0.0	4.42E-03	1.69E-03	7.22E-05	1.72E-10	0.0
M5 Beryllium	3.17E-05	1.17E-05	4.52E-07	0.0	0.0	9.65E-06	2.42E-06	4.64E-08	0.0	0.0
M6 Cadmium					Not reached W.T. @ 160 y					
M7 Chromium					Not reached W.T. @ 160 y					
M8 Thallium	1.23E-05	1.81E-06	2.13E-08	0.0	0.0	2.38E-06	2.79E-07	2.82E-09	0.0	0.0

H4 → Landfill 4, High End

Table 4.5a   Concentration of Metals at Various Locations Along the Centerline for Landfill 5 (Facility J)

	C5 → Landfill 5, Central Tendency									
Metal	**@ 160 Y**					**@ 130 Y**				
	10 m	**20 m**	**50 m**	**201 m**	**Receptor Well 549 m**	**10 m**	**20 m**	**50 m**	**201 m**	**Receptor Well 549 m**
M1 Lead					Not reached W.T. @ 160 y					
M2 Antimony					Not reached W.T. @ 160 y					
M3 Arsenic					Not reached W.T. @ 160 y					
M4 Barium					Not reached W.T. @ 160 y					
M5 Beryllium					Not reached W.T. @ 160 y					
M6 Cadmium					Not reached W.T. @ 160 y					
M7 Chromium					Not reached W.T. @ 160 y					
M8 Thallium					Not reached W.T. @ 160 y					

Table 4.5b   Concentration of Metals at Various Locations Along the Centerline for Landfill 5 (Facility J)

	H5 → Landfill 5, High End									
Metal	**@ 160 Y**					**@ 130 Y**				
	10 m	**20 m**	**50 m**	**201m**	**Receptor Well 549 m**	**10 m**	**20 m**	**50 m**	**201 m**	**Receptor Well 549 m**
M1 Lead					Not reached W.T. @ 160 y					
M2 Antimony					Not reached W.T. @ 160 y					
M3 Arsenic					Not reached W.T. @ 160 y					
M4 Barium					Not reached W.T. @ 160 y					
M5 Beryllium					Not reached W.T. @ 160 y					
M6 Cadmium					Not reached W.T. @ 160 y					
M7 Chromium					Not reached W.T. @ 160 y					
M8 Thallium					Not reached W.T. @ 160 y					

This page intentionally left blank.

5.0   HIGHLY ALKALINE MODELING RESULTS

This section presents the modeling results using the revised MINTEQA2 isotherms developed in June 1997 (HydroGeoLogic, 1997). A comparison of the modeling results for the neutral/slightly alkaline HWIR conditions versus the modeling results for the highly alkaline CKD conditions (Tables 5.1 - 5.25) shows that, in general, the highly alkaline conditions produce higher well concentrations. The reason for the enhanced transport of the metal cations under the highly alkaline conditions can be explained by comparing the isotherms at the various pH values. In the previous modeling effort (HydroGeoLogic, 1996), the central tendency analysis was performed only at pH 6.8 and the high-end analysis was performed only at pH 7.9. In this analysis, pH levels of 11, 12, and 13 were used. Tables 5.1 through 5.25 provide the modeling results for all pH levels for each constituent (barium, beryllium, cadmium, chromium, and lead) for each of the five facilities.

Comparison of the metal isotherms indicate a general decrease in sorption with increasing pH; however, for each metal, sorption reaches a maximum at a particular pH level, but then drops as pH continues to increase (Tables 5.1 - 5.25). (See Appendix B and HydroGeoLogic, 1997). The pH at which the maximum sorption occurs varies from one metal to another. For the conditions involved in this analysis, it appears that the maximum sorption in the unsaturated zone for lead and chromium (III) occurs at a lower pH than for cadmium and barium. A more detailed discussion of the mechanisms controlling metal sorption at different values of pH is presented in Appendix B of this report.

In the following subsections a detailed discussion of the results is presented from two perspectives, landfill specific and metal specific. Please note that in Tables 5.1 through 5.25 well concentrations are listed as the maximum concentration occurring within 130 years and 160 years; they are not the concentrations at 130 or 160 years.

5.1   MODELING ASSUMPTIONS

All of the assumptions inherent in EPACMTP and in MINTEQA2 are discussed in their respective background documents (USEPA, 1996 a,b,c and Allison et al, 1991 and 1992). Listed below are the assumptions critical and/or specific to this modeling exercise:

- The aquifer is homogeneous and isotropic and groundwater flow is steady-state

- The aquifer is assumed to be initially contaminant free

- All metal concentrations are assumed to be at thermodynamic equilibrium

- The unsaturated and saturated transport path of the metals from the landfill to the observation point is assumed to be at a constant pH

5.2   LANDFILL SPECIFIC RESULTS

The following landfill specific observations can be made about the modeling results presented in Tables 5.1 through 5.25:

- Landfill 1 (Tables 5.1 - 5.5) - None of the five metals reach the water table within 160 years, using the old HWIR isotherms. Beryllium and chromium reach the nearest receptor well within 160 years at pH 12 and pH 13, while lead and barium reach it within 160 years only at pH 13. It should be noted that although the metals do not reach the nearest receptor well within 160 years in some cases, in most cases the metals do reach one of the closer observation points within 130 years (see Tables 5.1 - 5.5).

- Landfill 2 (Tables 5.6 - 5.10) - Barium and beryllium were the only metals observed to reach the nearest receptor well within 160 years in the central tendency simulation (pH = 6.8) using the previous HWIR isotherms. Using the revised (highly alkaline) isotherms, beryllium, chromium, and lead were observed at the nearest receptor well. All metals were observed to reach closer observation points within 130 years at least at pH 13 and in some cases at pH 11 and 12.

- Landfill 3 (Tables 5.11 - 5.15) - No metals were observed to reach the nearest receptor well for either the high-end or central tendency cases at any pH. Although the metals do not reach the nearest receptor well within 160 years, all of the metals do reach one of the closer observation points within 160 years (see Tables 5.11 - 5.15).

- Landfill 4 (Tables 5.16 - 5.20) - Only lead reached the nearest receptor well at pH 13 within 160 years; however, all of the metals do reach one of the closer observation points within 160 years (see Tables 5.16 - 5.20).

- Landfill 5 (Tables 5.21 - 5.25) - None of the metals reach the water table.

5.3   METAL SPECIFIC RESULTS

It should be noted that separate isotherms are used for the saturated and unsaturated zones. In the case of barium, the saturated zone sorption is actually greatest at pH levels 11 and 12 and lowest at pH 6.8. Whereas the unsaturated zone sorption is greatest at pH 8 and lowest at pH levels 11 and 12 (Appendix B and HydroGeoLogic, 1997). Consequently, the likelihood of a metal reaching the water table at a particular pH may not be related to its relative concentration in the saturated zone when compared to other pH levels.

- Barium (Tables 5.1, 5.6, 5.11, 5.16, and 5.21) - Under highly alkaline conditions, barium was observed to reach the nearest receptor well only at landfill 1, at only pH 13. Under neutral conditions, barium reached the nearest observation well at landfill 2 and reached closer observation points at landfills 3 and 4. Comparison between results at neutral conditions and at highly alkaline conditions at landfills 2, 3, and 4 shows that the highest receptor well concentrations for barium are observed at pH 6.8.

- Beryllium (Tables 5.2, 5.7, 5.12, 5.17, and 5.22) - Under highly alkaline conditions, beryllium reached the nearest receptor well at landfills 1 and 2. Under neutral conditions, beryllium did not reach the nearest receptor at any of the landfills. For all observation points (10 m, 20 m, 50 m, 201 m, and nearest receptor well) the highest concentrations occur at pH 13; however, the lowest concentrations occur at pH 11 rather than at neutral conditions. The isotherms presented in Appendix B (Figure B.10) provide an explanation for this behavior. The sorption at pH 11 is much greater than at the other pH levels.

- Cadmium (Tables 5.3, 5.8, 5.13, 5.18, and 5.23) - Under highly alkaline conditions cadmium was not observed to reach the nearest receptor well at any landfill. In fact it did not reach the water table at pH levels 6.8, 7.9, and 11. The highest concentration of cadmium occurs at pH 13 and the only significant level occurs at landfill 3 at 10 meters.

- Chromium (Tables 5.4, 5.9, 5.14, 5.19, and 5.24) - Under highly alkaline conditions, chromium was observed to reach the nearest receptor well at landfills 2 and 3. Whereas, under neutral and slightly alkaline conditions chromium did not reach the water table at any landfill. For all observation points (10 m, 20 m, 50 m, 201 m, and nearest receptor well) the highest concentrations occur at pH 13.

- Lead (Tables 5.5, 5.10, 5.15, 5.20, and 5.25) - Under highly alkaline conditions lead was observed to reach the nearest receptor well at landfills 1, 2, and 4. Whereas, under neutral and slightly alkaline conditions, lead did not reach the water table at any landfill. As with all of the other metals except barium, the highest well concentrations were observed at pH 13 at all observation points (10 m, 20 m, 50 m, 201 m, and nearest receptor well).

5.4 DISCUSSION OF RESULTS

Under highly alkaline conditions, the modeling results for beryllium, cadmium, chromium, and lead indicate that breakthrough of one or more of these metals occurred at four of the five facilities. However, the current modeling may not capture all of the complex geochemical reactions that may occur. As discussed in the Phase I report of this study (HydroGeoLogic, 1997), no data were available on the concentrations of major ions in CKD leachate. There may be elevated concentrations of certain inorganic constituents such as calcium, sodium, and sulphate from CKD leaching that would alter complexation reactions. Therefore, the MINTEQA2 model was used in preliminary modeling to simulate the Toxicity Characteristic Leaching Procedure (TCLP) on CKD. The purpose of this simulation was to estimate the concentrations of major inorganic ions in CKD leachate so that these could be included in subsequent MINTEQA2 modeling runs for K_d values. In that way competing compounds were included in the transport model. Complexation reactions not accounted for may serve to reduce or enhance the groundwater transport of the metals. In addition, the transport modeling did not include expected changes in subsurface pH as the leachate moves away from the landfill, which also may affect metal transport. Any interpretation of the above modeling results should consider these caveats.

**Table 5.1   Concentration of Barium at Various Locations Along the Centerline for Landfill 1
(Facility A)**

C1 → Landfill 1, Central Tendency, Barium, MCL= 2.0 mg/l									
pH	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201m	Receptor Well 483 m	10 m	20 m	50 m	201 m	Receptor Well 483 m
6.8					Not reached W.T. @ 160 y					
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11	7.30E-04	2.42E-04	2.81E-06	0.0	0.0	1.64E-07	5.60E-08	3.19E-09	0.0	0.0
12	6.78E-04	2.24E-04	2.42E-06	0.0	0.0	1.53E-07	5.20E-08	2.88E-09	0.0	0.0
13	2.82E-02	1.20E-02	1.76E-03	3.01E-07	0.0	2.71E-02	1.14E-02	1.38E-03	1.22E-07	0.0

H1 → Landfill 1, High End, Barium, MCL= 2.0 mg/l									
pH	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201 m	Receptor Well 483 m	10 m	20 m	50 m	201 m	Receptor Well 483 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11	5.82E-04	1.98E-04	4.99E-06	0.0	0.0	1.31E-07	4.76E-08	5.43E-09	0.0	0.0
12	4.92E-04	1.67E-04	3.56E-06	0.0	0.0	1.12E-07	4.00E-08	4.32E-09	0.0	0.0
13	2.61E-02	1.38E-02	3.67E-03	5.54E-06	1.29E-10	2.49E-02	1.29E-02	2.83E-03	2.24E-06	0.0

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.2 Concentration of Beryllium at Various Locations Along the Centerline for Landfill 1 (Facility A)

C1 → Landfill 1, Central Tendency, Beryllium. MCL= 0.004 mg/l									
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201m	Receptor Well 483 m	10 m	20 m	50 m	201 m	Receptor Well 483 m
6.8					Not reached W.T. @ 160 y					
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11	7.35E-06	2.40E-06	1.01E-08	0.0	0.0	4.64E-07	1.50E-07	0.0	0.0	0.0
12	5.14E-04	2.97E-04	9.53E-05	1.14E-06	9.66E-10	4.88E-04	2.72E-04	7.72E-05	5.29E-07	2.16E-10
13	1.10E-03	8.58E-04	5.90E-04	3.15E-04	2.12E-04	1.09E-03	8.47E-04	5.69E-04	2.77E-04	1.63E-04

H1 → Landfill 1, High End, Beryllium, MCL= 0.004 mg/l									
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201 m	Receptor Well 483 m	10 m	20 m	50 m	201 m	Receptor Well 483 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11	3.04E-05	1.03E-05	2.35E-07	0.0	0.0	1.70E-05	5.66E-06	7.26E-08	0.0	0.0
12	1.31E-03	9.81E-04	5.43E-04	4.42E-05	3.40E-07	1.22E-03	8.90E-04	4.42E-04	2.32E-05	8.61E-08
13	2.36E-03	2.05E-03	1.58E-03	8.86E-04	5.44E-04	2.36E-03	2.05E-03	1.58E-03	8.84E-04	5.44E-04

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.3 Concentration of Cadmium at Various Locations Along the Centerline for Landfill 1 (Facility A)

	C1 → Landfill 1, Central Tendency, Cadmium, MCL= 0.005 mg/l									
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201 m	Receptor Well 483 m	10 m	20 m	50 m	201 m	Receptor Well 483 m
6.8					Not reached W.T. @ 160 y					
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11					Not reached W.T. @ 160 y					
12					Not reached W.T. @ 160 y					
13	2.38E-04	8.87E-05	5.83E-06	0.0	0.0	2.02E-04	7.29E-05	3.83E-06	0.0	0.0

	H1 → Landfill 1, High End, Cadmium, MCL= 0.005 mg/l									
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201 m	Receptor Well 483 m	10 m	20 m	50 m	201 m	Receptor Well 483 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11					Not reached W.T. @ 160 y					
12					Not reached W.T. @ 160 y					
13	4.67E-04	2.06E-04	2.92E-05	2.44E-09	0.0	3.97E-04	1.66E-04	1.97E-05	8.31E-10	0.0

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

**Table 5.4 Concentration of Chromium at Various Locations Along the Centerline for Landfill 1
(Facility A)**

		C1 → Landfill 1, Central Tendency, Chromium, MCL= 0.1 mg/l								
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201m	Receptor Well 483 m	10 m	20 m	50 m	201 m	Receptor Well 483 m
6.8					Not reached W.T. @ 160 y					
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11	6.28E-04	2.09E-04	2.70E-06	0.0	0.0	4.72E-04	1.56E-04	1.49E-06	0.0	0.0
12	1.20E-02	6.49E-03	1.79E-03	9.36E-06	2.61E-09	1.13E02	5.92E-03	1.42E-03	4.13E-06	5.52E-10
13	2.91E-02	2.27E-02	1.56E-02	8.30E-03	5.57E-03	2.88E-02	2.24E-02	1.50E-02	7.29E-03	4.26E-03

		H1 → Landfill 1, High End, Chromium, MCL= 0.1 mg/l								
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201 m	Receptor Well 483 m	10 m	20 m	50 m	201 m	Receptor Well 483 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11	6.30E-04	2.19E-04	7.54E-06	0.0	0.0	4.74E-04	1.62E-04	4.20E-06	0.0	0.0
12	1.46E-02	1.04E-02	5.13E-03	2.17E-04	5.49E-07	1.34E-02	9.30E-03	4.02E-03	1.05E-04	1.28E-07
13	3.13E-02	2.71E-02	2.10E-02	1.17E-02	7.21E-03	3.13E-02	2.71E-02	2.10E-02	1.17E-02	7.21E-03

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

**Table 5.5 Concentration of Lead at Various Locations Along the Centerline for Landfill 1
(Facility A)**

	C1 → Landfill 1, Central Tendency, Lead, Action Level= 0.015 mg/l									
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201m	Receptor Well 483 m	10 m	20 m	50 m	201 m	Receptor Well 483 m
6.8					Not reached W.T. @ 160 y					
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11					Not reached W.T. @ 160 y					
12	4.88E-03	1.61E-03	1.62E-05	0.0	0.0	3.72E-03	1.22E-03	9.27E-06	0.0	0.0
13	2.49E-01	1.86E-01	1.14E-01	3.91E-02	1.16E-02	2.45E-01	1.81E-01	1.07E-01	3.04E-02	6.44E-03

	H1 → Landfill 1, High End, Lead, Action Level= 0.015 mg/l									
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201 m	Receptor Well 483 m	10 m	20 m	50 m	201 m	Receptor Well 483 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11					Not reached W.T. @ 160 y					
12	4.89E-03	1.68E-03	4.56E-05	0.0	0.0	3.74E-03	1.26E-03	2.62E-05	0.0	0.0
13	3.11E-01	2.69E-01	2.08E-01	1.14E-01	6.48E-02	3.10E-01	2.68E-01	2.06E-01	1.09E-01	5.46E-02

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.6 Concentration of Barium at Various Locations Along the Centerline for Landfill 2 (Facility O)

C2 → Landfill 2, Central Tendency, Barium, MCL= 2.0 mg/l										
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
6.8	1.08E-01	3.77E-02	6.46E-03	6.50E-04	1.20E-08	1.04E-01	3.64E-02	5.71E-03	1.69E-04	1.12E-08
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11	9.08E-03	3.46E-04	2.60E-06	0.0	0.0	5.89E-03	1.45E-04	7.00E-07	0.0	0.0
12	8.79E-03	3.25E-04	2.37E-06	0.0	0.0	5.83E-03	1.42E-04	6.76E-07	0.0	0.0
13	3.96E-02	5.84E-03	2.01E-04	1.12E-09	0.0	3.32E-02	4.14E-03	1.17E-04	3.49E-10	0.0

H2 → Landfill 2, High End, Barium, MCL= 2.0 mg/l										
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201 m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11	7.13E-03	8.81E-04	2.14E-05	0.0	0.0	4.41E-03	3.65E-04	5.72E-06	0.0	0.0
12	6.00E-03	6.48E-04	1.35E-05	0.0	0.0	3.81E-03	2.79E-04	3.82E-06	0.0	0.0
13	5.20E-02	2.15E-02	2.66E-03	4.32E-07	0.0	4.13E-02	1.52E-02	1.56E-03	1.36E-07	0.0

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.7   Concentration of Beryllium at Various Locations Along the Centerline for Landfill 2 (Facility O)

pH	C2 → Landfill 2, Central Tendency, Beryllium, MCL= 0.004 mg/l									
	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
6.8	6.84E-04	2.32E-04	3.11E-05	3.24E-07	0.0	5.07E-04	1.79E-04	2.64E-05	2.24E-08	0.0
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11	1.21E-05	1.07E-07	1.81E-10	0.0	0.0	9.18E-06	6.09E-08	0.0	0.0	0.0
12	5.66E-04	1.85E-04	2.13E-05	9.64E-09	0.0	5.46E-04	1.68E-04	1.75E-05	4.88E-09	0.0
13	6.48E-04	2.51E-04	7.16E-05	4.37E-05	1.15E-06	6.45E-04	2.49E-04	7.01E-05	4.11E-05	1.15E-06

pH	H2 → Landfill 2, High End, Beryllium, MCL= 0.004 mg/l									
	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201 m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11	2.42E-05	1.04E-06	8.04E-09	0.0	0.0	1.86E-05	6.21E-07	3.70E-09	0.0	0.0
12	1.95E-03	1.31E-03	4.87E-04	7.54E-06	0.0	1.88E-03	1.24E-03	4.31E-04	4.40E-06	0.0
13	2.09E-03	1.45E-03	6.17E-04	8.95E-05	4.19E-06	2.09E-03	1.45E-03	6.16E-04	8.93E-05	4.19E-06

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.8   Concentration of Cadmium at Various Locations Along the Centerline for Landfill 2 (Facility O)

C2 → Landfill 2, Central Tendency, Cadmium, MCL= 0.005 mg/l									
pH	**@ 160 Y**					**@ 130 Y**				
	10 m	**20 m**	**50 m**	**201m**	**Receptor Well 1610 m**	**10 m**	**20 m**	**50 m**	**201 m**	**Receptor Well 1610 m**
6.8					Not reached W.T. @ 160 y					
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11					Not reached W.T. @ 160 y					
12	1.52E-07	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	1.6E-04	8.89E-06	1.00E-07	0.0	0.0	1.31E-04	5.91E-06	5.38E-08	0.0	0.0

H2 → Landfill 2, High End, Cadmium, MCL= 0.005 mg/l									
pH	**@ 160 Y**					**@ 130 Y**				
	10 m	**20 m**	**50 m**	**201 m**	**Receptor Well 1610 m**	**10 m**	**20 m**	**50 m**	**201 m**	**Receptor Well 1610 m**
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11					Not reached W.T. @ 160 y					
12	1.17E-06	1.42E-09	0.0	0.0	0.0	8.06E-08	0.0	0.0	0.0	0.0
13	3.75E-04	8.09E-05	3.89E-06	0.0	0.0	2.94E-04	5.37E-05	2.10E-06	0.0	0.0

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.9 Concentration of Chromium at Various Locations Along the Centerline for Landfill 2 (Facility O)

pH	C2 → Landfill 2, Central Tendency, Chromium, MCL= 0.1 mg/l									
	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
6.8					Not reached W.T. @ 160 y					
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11	5.81E-04	6.40E-06	1.35E-08	0.0	0.0	4.66E-04	4.07E-06	6.81E-09	0.0	0.0
12	1.99E-02	5.98E-03	5.77E-04	1.16E-07	0.0	1.85E-02	5.11E-03	4.29E-04	5.01E-08	0.0
13	2.50E-02	9.64E-03	2.74E-03	1.66E-03	4.43E-05	2.48E-02	9.57E-03	2.68E-03	1.56E-03	4.43E-05

pH	H2 → Landfill 2, High End, Chromium, MCL= 0.1 mg/l									
	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201 m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11	5.67E-04	2.91E-05	2.70E-07	0.0	0.0	4.49E-04	1.85E-05	1.37E-07	0.0	0.0
12	3.46E-02	2.26E-02	7.47E-03	5.73E-05	0.0	3.21E-02	2.01E-02	6.01E-03	2.79E-05	0.0
13	4.03E-02	2.79E-02	1.19E-02	1.72E-02	8.07E-05	4.03E-02	2.79E-02	1.19E-02	1.72E-02	8.06E-05

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.10   Concentration of Lead at Various Locations Along the Centerline for Landfill 2
(Facility O)

pH	C2 → Landfill 2, Central Tendency, Lead, Action Level= 0.015 mg/l									
	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
6.8					Not reached W.T. @ 160 y					
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11					Not reached W.T. @ 160 y					Not reached W.T. @
12	2.38E-04	1.81E-06	2.61E-09	0.-0	0.0	1.91E-04	1.15E-06	1.32E-09	0.0	0.0
13	1.42E-02	5.08E-03	9.52E-04	1.58E-04	3.50E-09	1.42E-02	5.05E-03	8.93E-04	9.37E-05	1.11E-09

pH	H2 → Landfill 2, High End, Lead, Action Level= 0.015 mg/l									
	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201 m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11					Not reached W.T. @ 160 y					
12	1.10E-04	2.00E-06	6.28E-09	0.0	0.0	8.81E-05	1.27E-06	3.17E-09	0.0	0.0
13	2.41E-02	1.66E-02	7.08E-03	1.03E-03	2.68E-05	2.40E-02	1.66E-02	7.08E-03	1.03E-03	5.23E-06

NA - not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.11 Concentration of Barium at Various Locations Along the Centerline for Landfill 3 (Facility F)

	C3 → Landfill 3, Central Tendency, Barium, MCL= 2.0 mg/l									
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201m	Receptor Well 966 m	10 m	20 m	50 m	201 m	Receptor Well 966 m
6.8	9.72E-02	1.07E-04	2.92E-08	0.0	0.0	8.14E-02	6.80E-05	1.17E-08	0.0	0.0
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11	8.32E-02	7.84E-05	1.59E-08	0.0	0.0	7.75E-02	5.76E-05	8.75E-09	0.0	0.0
12	8.21E-02	7.49E-05	1.45E-08	0.0	0.0	7.59E-02	5.45E-05	7.93E-09	0.0	0.0
13	9.92E-02	1.30E-04	5.58E-08	0.0	0.0	9.81E-02	1.27E-04	4.68E-08	0.0	0.0

	H3 → Landfill 3, High End, Barium, MCL= 2.0 mg/l									
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201 m	Receptor Well 966 m	10 m	20 m	50 m	201 m	Receptor Well 966 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11	1.32E-01	1.26E-02	2.13E-05	0.0	0.0	1.20E-01	9.01E-03	1.15E-05	0.0	0.0
12	1.31E-01	1.30E-02	1.76E-05	0.0	0.0	1.18E-01	9.23E-03	9.41E-06	0.0	0.0
13	1.76E-01	2.43E-02	1.06E-04	0.0	0.0	1.72E-01	2.29E-02	8.70E-05	0.0	0.0

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.12   Concentration of Beryllium at Various Locations Along the Centerline for Landfill 3 (Facility F)

C3 → Landfill 3, Central Tendency,Beryllium, MCL= 0.004 mg/l									
pH	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201m	Receptor Well 966 m	10 m	20 m	50 m	201 m	Receptor Well 966 m
6.8					Not reached W.T. @ 160 y					
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11	3.00E-05	3.72E-09	0.0	0.0	0.0	2.20E-05	1.93E-09	0.0	0.0	0.0
12	1.76E-04	2.83E-07	2.28E-10	0.0	0.0	1.76E-04	2.82E-07	2.16E-10	0.0	0.0
13	1.77E-04	2.89E-07	2.56E-10	0.0	0.0	1.77E-04	2.89E-07	2.56E-10	0.0	0.0

H3 → Landfill 3, High End, Beryllium, MCL= 0.004 mg/l									
pH	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201 m	Receptor Well 966 m	10 m	20 m	50 m	201 m	Receptor Well 966 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11	1.59E-04	3.21E-06	7.06E-10	0.0	0.0	1.24E-04	1.88E-06	3.11E-10	0.0	0.0
12	1.04E-03	2.37E-04	2.13E-06	0.0	0.0	1.03E-03	2.21E-04	1.55E-06	0.0	0.0
13	1.27E-03	3.91E-04	1.26E-05	0.0	0.0	1.27E-03	3.91E-04	1.26E-05	0.0	0.0

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.13   Concentration of Cadmium at Various Locations Along the Centerline for Landfill 3 (Facility F)

C3 → Landfill 3, Central Tendency, Cadmium, MCL= 0.005 mg/l									
pH	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201m	Receptor Well 966 m	10 m	20 m	50 m	201 m	Receptor Well 966 m
6.8					Not reached W.T. @ 160 y					
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11					Not reached W.T. @ 160 y					
12					Not reached W.T. @ 160 y					
13	2.50E-04	1.87E-07	0.0	0.0	0.0	2.33E-04	1.45E-07	0.0	0.0	0.0

H3 → Landfill 3, High End, Cadmium, MCL= 0.005 mg/l									
pH	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201 m	Receptor Well 966 m	10 m	20 m	50 m	201 m	Receptor Well 966 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11					Not reached W.T. @ 160 y					
12					Not reached W.T. @ 160 y					
13	1.03E-03	8.22E-05	8.24E-08	0.0	0.0	9.44E-04	6.21E-05	5.09E-08	0.0	0.0

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.14   Concentration of Chromium at Various Locations Along the Centerline for Landfill 3 (Facility F)

C3 → Landfill 3, Central Tendency, Chromium, MCL= 0.1 mg/l										
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201m	Receptor Well 966 m	10 m	20 m	50 m	201 m	Receptor Well 966 m
6.8					Not reached W.T. @ 160 y					
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11	1.11E-02	1.96E-06	0.0	0.0	0.0	9.07E-03	1.26E-06	0.0	0.0	0.0
12	4.68E-02	7.35E-05	5.26E-08	0.0	0.0	4.68E-02	7.26E-05	4.79E-08	0.0	0.0
13	4.71E-02	7.70E-05	6.80E-08	0.0	0.0	4.71E-02	7.70E-05	6.80E-08	0.0	0.0

H3 → Landfill 3, High End, Chromium, MCL= 0.1 mg/l										
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201 m	Receptor Well 966 m	10 m	20 m	50 m	201 m	Receptor Well 966 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11	1.28E-02	2.22E-04	4.16E-08	0.0	0.0	1.04E-02	1.41E-04	2.09E-08	0.0	0.0
12	9.14E-02	1.84E-02	1.14E-04	0.0	0.0	9.02E-02	1.69E-02	8.14E-05	0.0	0.0
13	1.18E-01	3.65E-02	1.18E-03	0.0	0.0	1.18E-01	3.65E-02	1.18E-03	0.0	0.0

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.15 Concentration of Lead at Various Locations Along the Centerline for Landfill 3 (Facility F)

C3 → Landfill 3, Central Tendency, Lead, Action Level= 0.015 mg/l										
pH	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201m	Receptor Well 966 m	10 m	20 m	50 m	201 m	Receptor Well 966 m
6.8					Not reached W.T. @ 160 y					
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11					Not reached W.T. @ 160 y					
12	2.40E-02	3.20E-06	0.0	0.0	0.0	1.96E-02	2.06E-06	0.0	0.0	0.0
13	1.32E-01	2.15E-04	1.90E-07	0.0	0.0	1.32E-01	2.15E-04	1.90E-07	0.0	0.0

H3 → Landfill 3, High End, Lead, Action Level= 0.015 mg/l										
pH	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201 m	Receptor Well 966 m	10 m	20 m	50 m	201 m	Receptor Well 966 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11					Not reached W.T. @ 160 y					
12	2.56E-02	3.35E-04	4.70E-08	0.0	0.0	2.07E-02	2.14E-04	2.39E-08	0.0	0.0
13	3.07E-01	9.45E-02	2.98E-03	0.0	0.0	3.07E-01	9.43E-02	2.91E-03	0.0	0.0

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.16   Concentration of Barium at Various Locations Along the Centerline for Landfill 4 (Facility G)

	C4 → Landfill 4, Central Tendency, Barium, MCL= 2.0 mg/l									
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
6.8	2.08E-02	9.74E-03	6.91E-04	1.72E-09	0.0	1.33E-02	5.63E-03	3.06E-04	2.66E-10	0.0
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11	9.52E-04	1.62E-04	1.61E-06	0.0	0.0	6.95E-04	9.88E-05	7.70E-07	0.0	0.0
12	6.62E-04	9.22E-05	6.94E-07	0.0	0.0	4.92E-04	5.68E-05	3.37E-07	0.0	0.0
13	8.35E-03	3.16E-03	1.31E-04	0.0	0.0	5.79E-03	1.98E-03	6.54E-05	0.0	0.0

	H4 → Landfill 4, High End, Barium, MCL= 2.0 mg/l									
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201 m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9	8.97E-03	4.07E-03	2.64E-04	1.41E-09	0.0	4.42E-03	1.69E-03	7.22E-05	1.72E-10	0.0
11	1.26E-03	3.30E-04	6.39E-06	0.0	0.0	8.81E-04	1.98E-04	3.00E-06	0.0	0.0
12	7.69E-04	1.64E-04	2.26E-06	0.0	0.0	5.52E-04	9.98E-05	1.09E-06	0.0	0.0
13	1.50E-02	7.58E-03	6.65E-04	3.37E-09	0.0	1.01E-02	4.68E-03	3.24E-04	6.25E-10	0.0

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.17 Concentration of Beryllium at Various Locations Along the Centerline for Landfill 4 (Facility G)

C4 → Landfill 4, Central Tendency, Beryllium, MCL= 0.004 mg/l									
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
6.8	6.89E-05	3.06E-05	1.88E-06	0.0	0.0	4.16E-05	1.63E-05	7.42E-07	0.0	0.0
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11	5.61E-07	2.43E-08	0.0	0.0	0.0	4.40E-07	1.54E-08	0.0	0.0	0.0
12	7.02E-04	5.90E-04	2.34E-04	2.37E-07	0.0	5.83E-04	4.42E-04	1.29E-04	4.89E-08	0.0
13	9.28E-04	8.94E-04	7.96E-04	4.42E-04	0.0	9.28E-04	8.94E-04	7.96E-04	4.42E-04	0.0

H4 → Landfill 4, High End, Beryllium, MCL= 0.004 mg/l									
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201 m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9	3.17E-05	1.17E-05	4.52E-07	0.0	0.0	9.65E-06	2.42E-06	4.64E-08	0.0	0.0
11	1.34E-06	1.13E-07	4.56E-04	0.0	0.0	1.04E-06	7.20E-08	2.33E-10	0.0	0.0
12	1.13E-03	1.08E-03	9.70E-04	3.72E-05	0.0	9.87E-04	9.69E-04	7.58E-04	9.33E-06	0.0
13	1.09E-03	1.06E-03	9.99E-04	7.35E-04	0.0	1.09E-03	1.06E-03	9.99E-04	7.35E-04	0.0

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.18 Concentration of Cadmium at Various Locations Along the Centerline for Landfill 4 (Facility G)

C4 → Landfill 4, Central Tendency, Cadmium, MCL= 0.005 mg/l									
	@ 160 Y					@ 130 Y			
pH	10 m	20 m	50 m	201m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
6.8					Not reached W.T. @ 160 y					
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11					Not reached W.T. @ 160 y					0.0
12	3.60E-08	0.0	0.0	0.0	0.0	2.67E-08	0.0	0.0	0.0	0.0
13	1.37E-05	3.00E-06	4.33E-08	0.0	0.0	1.01E-05	1.92E-06	2.24E-08	0.0	0.0

H4 → Landfill 4, High End, Cadmium, MCL= 0.005 mg/l									
	@ 160 Y					@ 130 Y			
pH	10 m	20 m	50 m	201 m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11					Not reached W.T. @ 160 y					
12	9.22E-08	3.92E-10	0.0	0.0	0.0	7.12E-08	2.23E-10	0.0	0.0	0.0
13	4.23E-05	1.38E-05	4.13E-07	0.0	0.0	2.98E-05	8.71E-06	2.09E-07	0.0	0.0

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.19 Concentration of Chromium at Various Locations Along the Centerline for Landfill 4 (Facility G)

	C4 → Landfill 4, Central Tendency, Chromium, MCL= 0.1 mg/l									
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
6.8					Not reached W.T. @ 160 y					
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11	1.65E-06	9.83E-08	2.66E-10	0.0	0.0	1.31E-06	6.39E-08	1.39E-10	0.0	0.0
12	9.82E-04	6.97E-04	1.67E-04	3.31E-08	0.0	7.23E-04	4.66E-04	8.43E-05	6.51E-09	0.0
13	1.86E-03	1.79E-03	1.59E-03	8.83E-04	0.0	1.86E-03	1.79E-03	1.59E-03	8.83E-04	0.0

	H4 → Landfill 4, High End, Chromium, MCL= 0.1 mg/l									
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201 m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11	3.89E-06	4.25E-07	2.34E-09	0.0	0.0	3.02E-06	2.74E-07	1.22E-09	0.0	0.0
12	1.83E-03	1.78E-03	1.19E-03	6.93E-06	0.0	1.67E-03	1.51E-03	7.43E-04	1.50E-06	0.0
13	2.17E-03	2.13E-03	2.00E-03	1.47E-03	0.0	2.17E-03	2.13E-03	2.00E-03	1.47E-03	0.0

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.20   Concentration of Lead at Various Locations Along the Centerline for Landfill 4 (Facility G)

C4 → Landfill 4, Central Tendency, Lead, Action Level= 0.015 mg/l									
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
6.8					Not reached W.T. @ 160 y					
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11					Not reached W.T. @ 160 y					
12	3.24E-04	1.46E-05	2.91E-08	0.0	0.0	2.58E-04	9.48E-06	1.52E-08	0.0	0.0
13	5.22E-01	5.04E-01	4.69E-01	2.58E-01	0.0	5.22E-01	5.04E-01	4.69E-01	2.58E-01	0.0

H4 → Landfill 4, High End, Lead, Action Level= 0.015 mg/l									
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201 m	Receptor Well 1610 m	10 m	20 m	50 m	201 m	Receptor Well 1610 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11					Not reached W.T. @ 160 y					
12	3.65E-04	3.06E-05	1.22E-07	0.0	0.0	2.85E-04	1.98E-05	6.38E-08	0.0	0.0
13	3.01E-01	2.96E-01	2.79E-01	2.18E-01	1.48E-04	3.01E-01	2.96E-01	2.79E-01	2.18E-01	1.48E-04

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.21   Concentration of Barium at Various Locations Along the Centerline for Landfill 5 (Facility J)

	C5 → Landfill 5, Central Tendency, Barium, MCL= 2.0 mg/l									
pH	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201m	Receptor Well 549 m	10 m	20 m	50 m	201 m	Receptor Well 549 m
6.8					Not reached W.T. @ 160 y					
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11					Not reached W.T. @ 160 y					
12					Not reached W.T. @ 160 y					
13					Not reached W.T. @ 160 y					

	H5 → Landfill 5, High End, Barium, MCL= 2.0 mg/l									
pH	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201 m	Receptor Well 549 m	10 m	20 m	50 m	201 m	Receptor Well 549 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11					Not reached W.T. @ 160 y					
12					Not reached W.T. @ 160 y					
13					Not reached W.T. @ 160 y					

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.22   Concentration of Beryllium at Various Locations Along the Centerline for Landfill 5 (Facility J)

C5 → Landfill 5, Central Tendency, Beryllium, MCL= 0.004 mg/l									
pH	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201m	Receptor Well 549 m	10 m	20 m	50 m	201 m	Receptor Well 549 m
6.8					Not reached W.T. @ 160 y					
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11					Not reached W.T. @ 160 y					
12					Not reached W.T. @ 160 y					
13					Not reached W.T. @ 160 y					

H5 → Landfill 5, High End, Beryllium, MCL= 0.004 mg/l									
pH	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201 m	Receptor Well 549 m	10 m	20 m	50 m	201 m	Receptor Well 549 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11					Not reached W.T. @ 160 y					
12					Not reached W.T. @ 160 y					
13					Not reached W.T. @ 160 y					

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.23   Concentration of Cadmium at Various Locations Along the Centerline for Landfill 5 (Facility J)

C5 → Landfill 5, Central Tendency, Cadmium, MCL= 0.005 mg/l										
pH	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201m	Receptor Well 549 m	10 m	20 m	50 m	201 m	Receptor Well 549 m
6.8					Not reached W.T. @ 160 y					
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11					Not reached W.T. @ 160 y					
12					Not reached W.T. @ 160 y					
13					Not reached W.T. @ 160 y					

H5 → Landfill 5, High End, Cadmium, MCL= 0.005 mg/l										
pH	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201 m	Receptor Well 549 m	10 m	20 m	50 m	201 m	Receptor Well 549 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11					Not reached W.T. @ 160 y					
12					Not reached W.T. @ 160 y					
13					Not reached W.T. @ 160 y					

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.24   Concentration of Chromium at Various Locations Along the Centerline for Landfill 5 (Facility J)

C5 → Landfill 5, Central Tendency, Chromium, MCL= 0.1 mg/l										
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201m	Receptor Well 549 m	10 m	20 m	50 m	201 m	Receptor Well 549 m
6.8					Not reached W.T. @ 160 y					
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11					Not reached W.T. @ 160 y					
12					Not reached W.T. @ 160 y					
13					Not reached W.T. @ 160 y					

H5 → Landfill 5, High End, Chromium, MCL= 0.1 mg/l										
	@ 160 Y					@ 130 Y				
pH	10 m	20 m	50 m	201 m	Receptor Well 549 m	10 m	20 m	50 m	201 m	REcEptor WEll 549 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11					Not reached W.T. @ 160 y					
12					Not reached W.T. @ 160 y					
13					Not reached W.T. @ 160 y					

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.25   Concentration of Lead at Various Locations Along the Centerline for Landfill 5 (Facility J)

C5 → Landfill 5, Central Tendency, Lead, Action Level= 0.015 mg/l										
pH	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201m	Receptor Well 549 m	10 m	20 m	50 m	201 m	Receptor Well 549 m
6.8					Not reached W.T. @ 160 y					
7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11					Not reached W.T. @ 160 y					
12					Not reached W.T. @ 160 y					
13					Not reached W.T. @ 160 y					

H5 → Landfill 5, High End, Lead, Action Level= 0.015 mg/l										
pH	@ 160 Y					@ 130 Y				
	10 m	20 m	50 m	201 m	Receptor Well 549 m	10 m	20 m	50 m	201 m	Receptor Well 549 m
6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7.9					Not reached W.T. @ 160 y					
11					Not reached W.T. @ 160 y					
12					Not reached W.T. @ 160 y					
13					Not reached W.T. @ 160 y					

NA - Not applicable; central tendency scenario was run for only pH 6.8 and high-end scenario was run for only pH 7.9 in previous analysis.

Table 5.26   M.C.L. Exceedances

M.C.L. Facility	Metal				
	Ba 2.0 mg/l	Be 4.0×10^{-3} mg/l	Cd 5.0×10^{-3} mg/l	Cr 1.0×10^{-1} mg/l	Pb 1.5×10^{-2} mg/l
A	0	0	0	0	pH 13
O	0	0	0	0	pH 13
F	0	0	0	pH 13	pH 12 & pH 13
G	0	0	0	0	pH13
J	0	0	0	0	0

This page intentionally left blank.

6.0 REFERENCES

Allison, J.D., D.S. Brown, and K.H. Novo-Gradic, 1991. MINTEQA2/PRODEFA2, A Chemical Assessment Model for Environmental Systems: Version 4.0 User's Manual. EPA/600/3-91/021, U.S. Environmental Protection Agency, Athens, GA.

Allison, J.D., B.R. Bicknell, T.L. Allison, and K.J. Novo-Gradic, 1992. Development of the Finite Source Methodology for Wastes Containing Metals. Prepared for U.S. Environmental Protection Agency, Athens, GA.

Dzombak, D.A., 1986. Toward a Uniform Model for the Sorption of Inorganic Ions on Hydrous Oxides. Ph.D Thesis. Massachusetts Institute of Technology, Cambridge, MA.

Dzombak, D.A. and F.M.M. Morel, 1990. Surface Complexation Modeling: Hydrous Ferric Oxide, John Wiley and Sons, New York.

Haynes, B.W. and G.W. Kramer, 1982. Characterization of U.S. Cement Kiln Dust. U.S. Bureau of Mines, Dept. of the Interior, Information Circular 8885.

HydroGeoLogic, 1996. Letter Reports of Cement Kiln Dust Groundwater Pathway Modeling Based on HWIR Metals Isotherms.

HydroGeoLogic, 1997. Examination of Metals Transport under Highly Alkaline Conditions. Prepared under EPA Contract No. 68-C6-0020, Work Assignment No. 0-07.

Loux, N.T., C.R. Chafin, and S. M. Hassan, 1990. Statistics of aquifer material properties and empirical pH-dependent partitioning relationships for As(III), As(V), Ba(II), Cd(II), Cr(VI), Cw(II), Hg(II), Ni(II), Pb(II), $S_b(V)$, $S_e(IV)$, $T\ell(I)$, and Zn(II). U.S. Environmental Protection Agency, Athens, GA.

U.S. EPA, 1993. Report to Congress on Cement Kiln Dust.

U.S. EPA, 1996a. EPACMTP Background Document for Metals. U.S. Environmental Protection Agency, Washington, DC.

U.S. EPA, 1996b. EPACMTP Finite Source Background Document. U.S. Environmental Protection Agency, Washington, DC.

U.S. EPA, 1996c. EPACMTP Background Document. U.S. Environmental Protection Agency, Washington, DC.

U.S. EPA, 1997. EPACMTP User's Guide. U.S. Environmental Protection Agency, Washington, DC.

This page intentionally left blank.

APPENDIX A

EPACMTP INPUT DATA

This page intentionally left blank.

Table A.1   EPACMTP Control Parameters

Variable	Description	Value	Comments
GRPCOD	Record identifier; must be 'GP' always.	GP	
MC	Monte Carlo control parameter = F(alse) for deterministic run = T(rue) for Monte Carlo run (Default).	F	
IVADOS	Control parameter for unsaturated zone simulation. = 0 if <u>no</u> unsaturated zone modeling is required, = 1 if unsaturated zone modeling is required (Default).	1	
ISTMOD	Control parameter for saturated zone simulation. = 0 if <u>no</u> saturated zone modeling is required, = 1 if saturated zone modeling is required (Default).	1	
NSPECI	Number of contaminant component species. Default = 1.	1	
KFDM	Dummy parameter, set = 1.	1	
KFS	Control parameter for selecting continuous (infinite) source or finite source modeling option = 0 if continuous source option = 1 if finite source option with prescribed leaching duration. = 2 if landfill finite source option.	1	Technical document on CKD uses constant source for prescribed finite duration. Landfill finite source option is a physically better justified assumption (KFS= 2).
FULL3D	Logical control parameter for selecting fully 3D or quasi-3D saturate zone modeling option = T(rue) for fully 3D simulation = F(alse) for quasi-3D simulation Note: FULL3D = F(alse) should be used for Monte Carlo simulations.	T	
METAL	Logical control parameter for metals simulation = T(rue) for metals modeling = F(alse) for non-metals modeling.	T	

Table A.1   EPACMTP Control Parameters (continued)

Variable	Description	Value	Comments
KDEVAL	Integer control parameter for selecting the scheme for determining the metals sorption isotherm (Leave blank if METAL= FALSE) = 1 Use the method of Loux for calculating k_d from pH = 2 Use linearized MINTEQA2 isotherm = 3 Use nonlinear MINTEQA2 isotherm.	3	For Antimony, Arsenic, and Thallium, KDEVAL= 1 is used since MINTEQA2 isotherms for these metals are unreliable and have been excluded from EPACMTP.
ISRC_TYP	Control parameter for selecting the type of waste source = 0 for landfill = 1 for surface impoundment = 2 for waste pile = 3 for land treatment.	0	

Table A.2   EPACMTP's Deterministic Control Parameters

Variable	Description	Value	Comments
GRPCOD	Record identifier; must be 'GP' always.	GP	

ISBC	Contaminant source boundary condition
	= 0 if contaminant flux is given
	       (Default),
	= 1 if contaminant concentration is
	       given.
		0	

IBAT	Control parameter for decaying source boundary condition, = 0 if no (continuous source or non-degrader finite source) = 1 Biochemical decay (hydrolysis) = 2 Physical decay due to leaching (source depletion) = 3 Combine 1+ 2 (IBAT > = 1 for degrader finite sources) Note: If IBAT = 1 or 3 is selected, it is assumed that the effective hydrolysis transformation coefficients in the waste source are the same as in the unsaturated and saturated zone.	0	A value of 2 may be used if landfill finite source (KFS= 2) is used.
IUSTED	Control parameter indicating whether transport is in the unsaturated zone is steady-state or transient, = 0 for transient (if KFS= 1 or 2), = 1 for steady-state (if KFS= 0). Leave blank if IVADOS (see record GP01) = 0.	0	
ISSTED	Control parameter indicating whether transport in the saturated zone is steady-state or transient = 0 for transient (if KFS= 1 or 2) = 1 for steady-state (if KFS= 0). Leave blank if ISTMOD (see record GP01) = 0.	0	
NUTOBS	Number of time values at which concentration at the exit point of the unsaturated zone is to be computed Leave blank if ISTMOD= 1, and/or IUSTED= 1, and/or MC= T(rue).	0	

Table A.2   EPACMTP's Deterministic Control Parameters (continued)

Variable	Description	Value	Comments
NTS	Number of time values at which receptor well concentrations in the saturated zone are to be computed Leave blank if ISTMOD= 0, or ISSTED= 1.	128	Exposure point concentrations are evaluated every year for the 128 y simulation period.
NWELLS	Number of receptor wells in the saturated zone. Leave blank if ISTMOD (see record GP01)= 0.	17	Each simulation has 17 exposure points to evaluate concentrations.
QRMAX	Maximum groundwater vertical to horizontal flux ratio (see Eq. 2.3.34) for selecting between analytical and numerical saturated zone contaminant transport solution. Recommended value is 0.02. Leave blank if ISTMOD (see record GP01)= 0.	1	Select numerical solution to avoid assumptions of analytical solution of no vertical flow.
NRATIO	Number of ratios of C_W/C_L to be used for finite source scenario (KFS= 2). Default value is 8. Leave blank for continuous source analysis (KFS= 0).	0	The C_W/C_L ratio for the landfill may be used if the landfill finite source option (KFS= 2) is used.
ICRW	Control parameter indicating the time-dependent receptor well concentration to be computed for the finite source analysis = 0 compute peak receptor well concentration (Default) = 1 compute temporarily averaged receptor well concentration When ICRW= 1 is used, the averaging period for each of the species must be specified in variable CARC, in the chemical-specific data records. The default period is 70 years.	0	

APPENDIX B

METAL ISOTHERMS FOR HIGHLY ALKALINE CONDITIONS

This page intentionally left blank.

B.1 MINTEQA2

MINTEQA2 input files were developed for each of the five metals (Ba, Be, Cd, Cr(III), and Pb) at three pH's (11, 12, and 13) in both the unsaturated and saturated zones for a total of 30 input files (HydroGeoLogic, 1997). Each file was designed to solve the equilibrium composition at each of the 48 total metal concentrations. For each total metal concentration, the K_d is obtained by dividing the total sorbed by the total dissolved. The resulting dimensionless K_d is normalized by the phase ratio (the mass of adsorbing soil/aquifer material with which one liter of solution is equilibrated). In keeping with the HWIR modeling scenario, the phase ratio in the unsaturated zone was 4.57 kg per liter of solution. The phase ratio in the saturated zone was 3.56 kg per liter of solution. These values were determined for HWIR by assuming an average density and porosity of aquifer material and assuming a water saturation of 77% in the unsaturated zone and 100% in the saturated zone.

A special output option in MINTEQA2 allows the total dissolved, total sorbed, and total precipitated metal concentration at equilibrium to be written to a file (with filename extension PRN) suitable for import to a spreadsheet. This facilitates calculation of K_d from the MINTEQA2 results. The PRN file also serves as an input file for using the MINTEQA2 K_d values in transport modeling. There were 30 PRN files generated; six files for each of the five metals (3 pH's in the unsaturated zone, 3 in the saturated zone for each metal). Each contains 48 lines in ASCII format. Each of the 48 lines represents an equilibration point for a specific metal concentration. For consistency and ease of identification, the naming convention aaMMbbcc.PRN was used where "aa" is the two-letter designator of the metal (e.g., Pb, Cd, etc.), "bb" is the pH (11, 12, or 13), and "cc" is a two-letter designator of the zone (ux = unsaturated, sx = saturated). The "MM" appears in all names as an indicator that the results pertain to the medium concentration setting for HFO and organic matter. As an example, PbMM11ux.PRN is the output file for Pb at pH 11 in the unsaturated zone. This file contains 48 lines, each representing an equilibration at a specific metal concentration. Each line has eight entries as follows: pH, three-digit ID # for Pb, total dissolved Pb concentration (mol/L), total sorbed Pb concentration (mol/L), total precipitated Pb concentration (mol/L), the normalized K_d (L/kg), an experimental quantity (irrelevant in this study), and the total Pb concentration (mg/L).

Graphical results obtained by plotting the log K_d versus the log total metal concentration for each of the 30 PRN files is shown on the following pages. Results at each of the 3 pH values are shown together on one page for each metal.
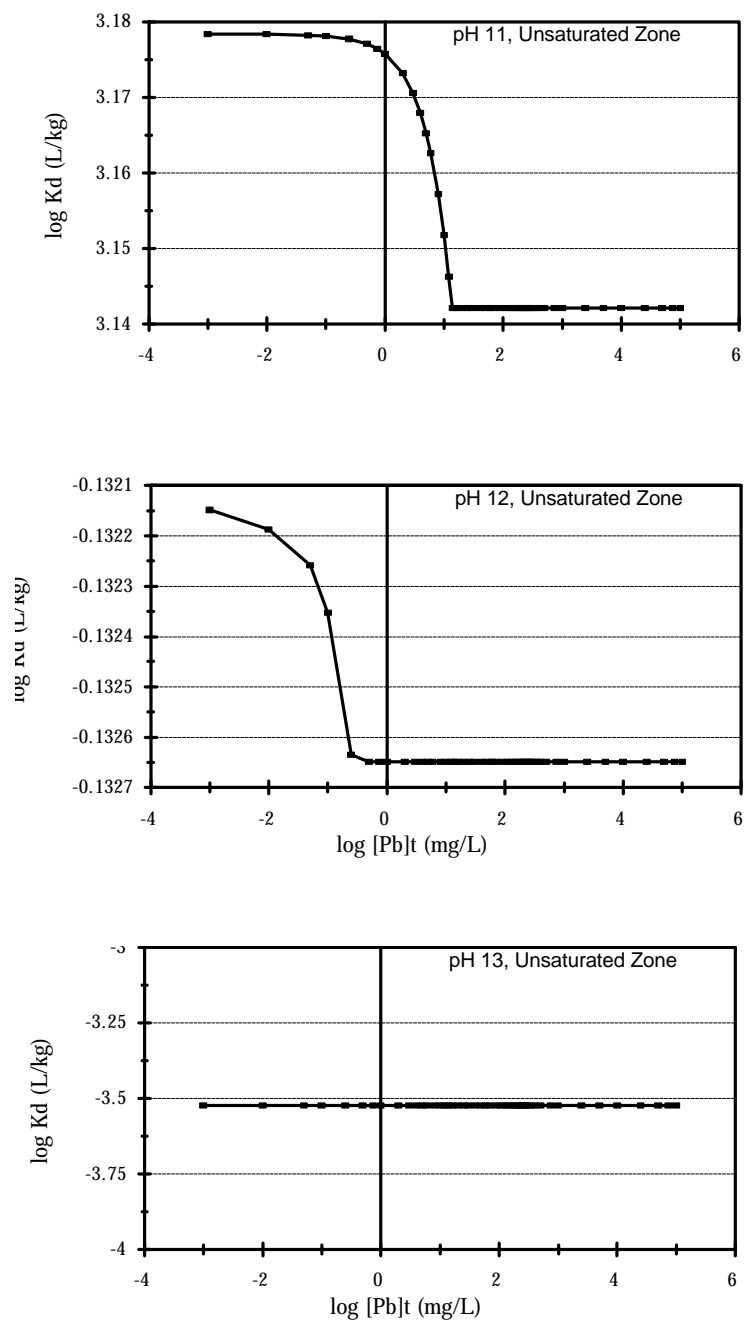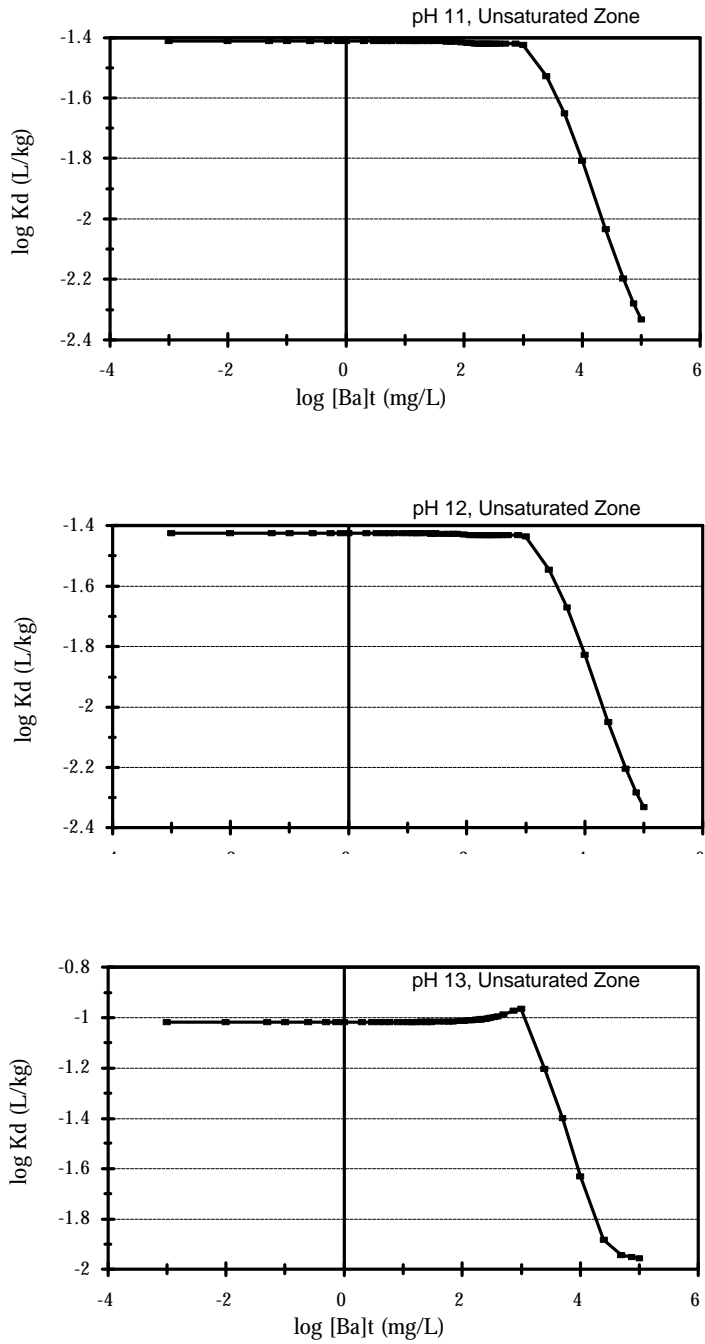
Figure B.1   Log K_d (L/kg) vs. log total Pb (mg/L) at pH 11, 12, and 13 in the unsaturated zone.
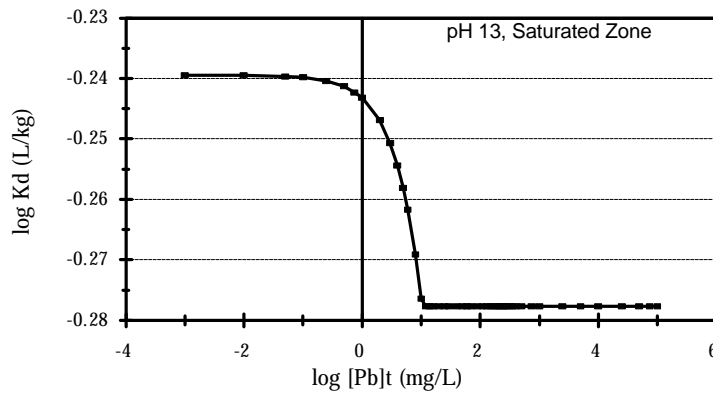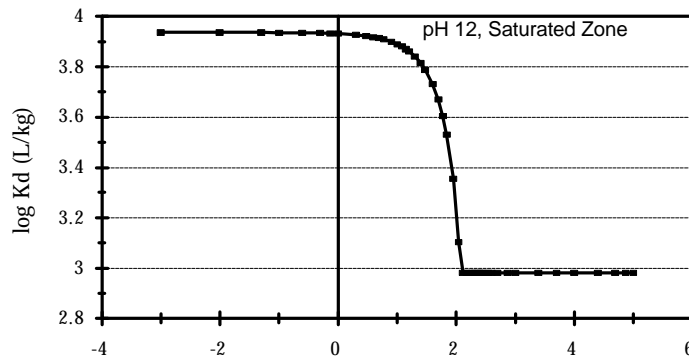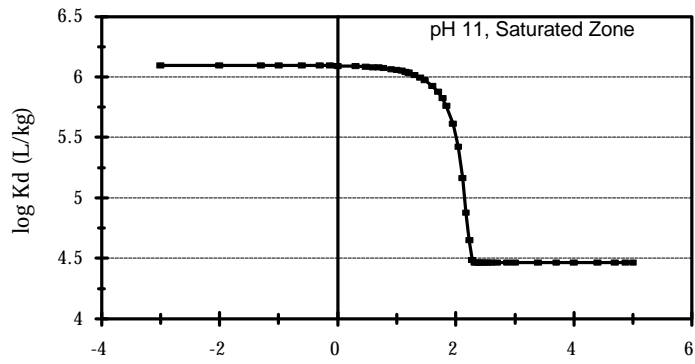
Figure B.2   Log K_d (L/kg) vs. log total Pb (mg/L) at pH 11, 12, and 13 in the saturated zone.
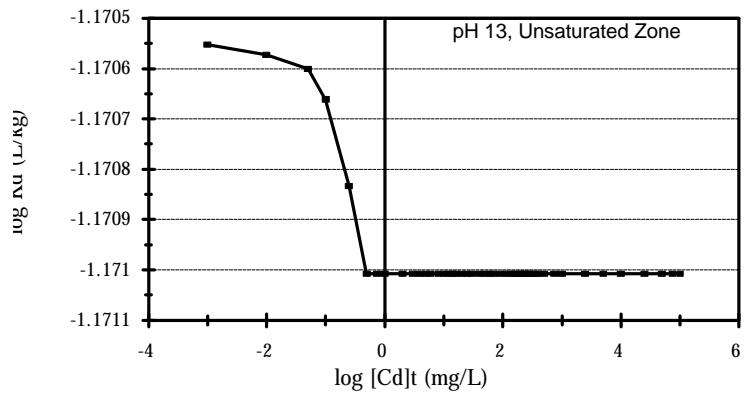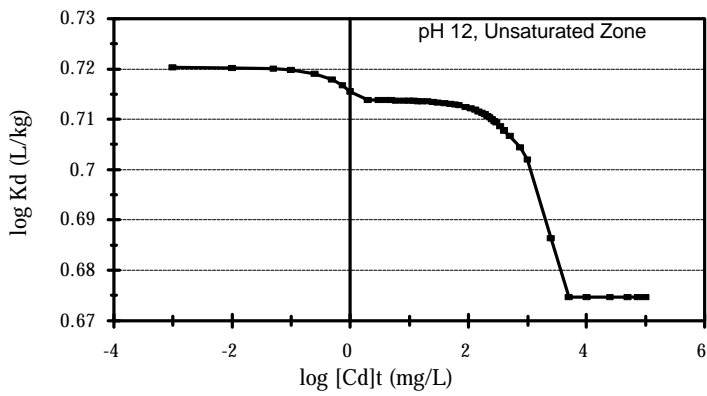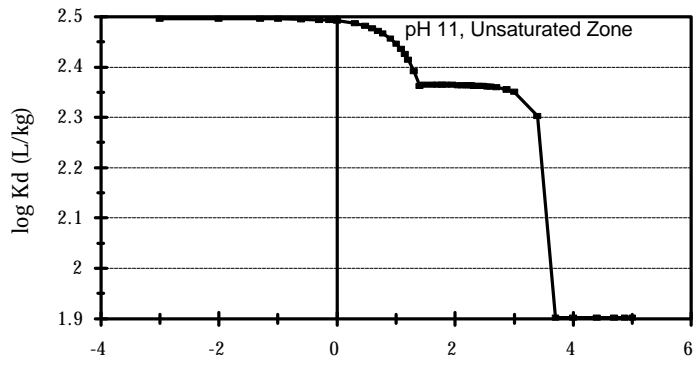
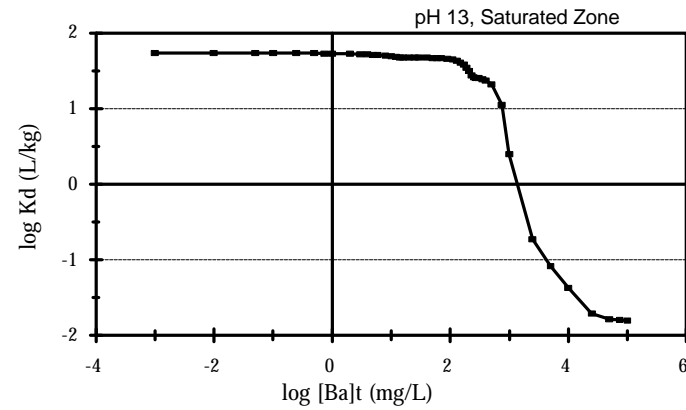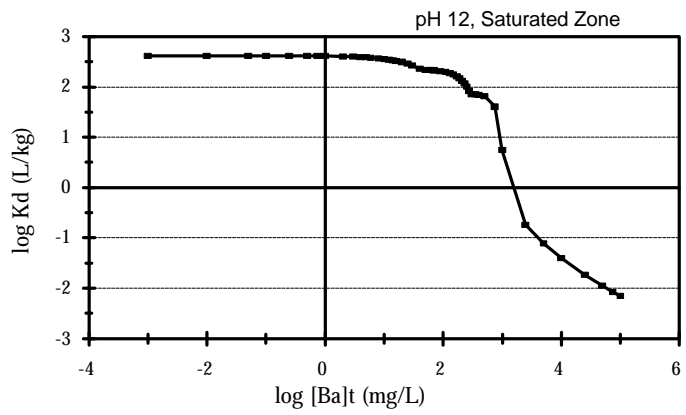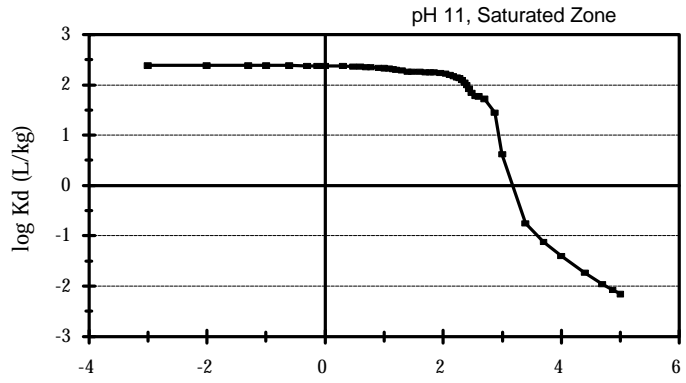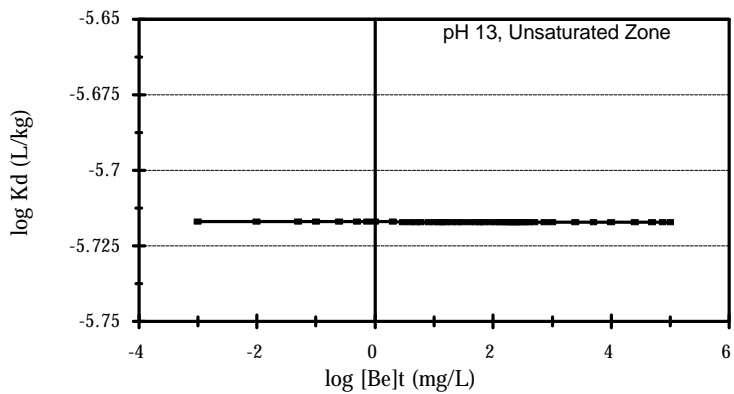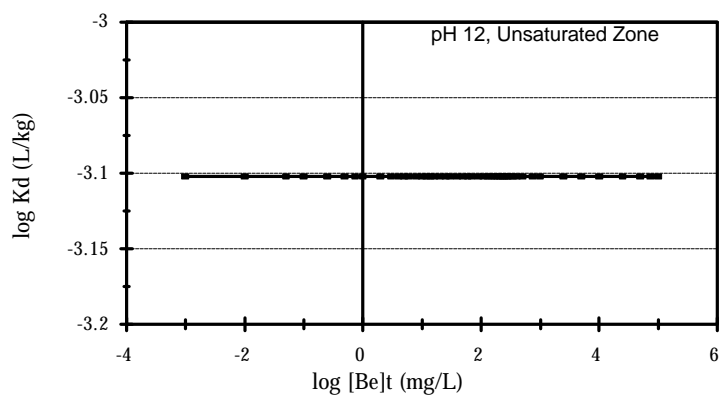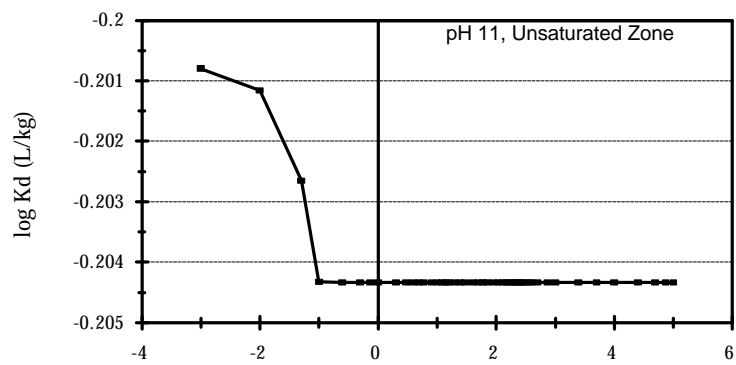Figure B.3   Log K_d (L/kg) vs. log total Cd (mg/L) at pH 11, 12, and 13 in the unsaturated zone.
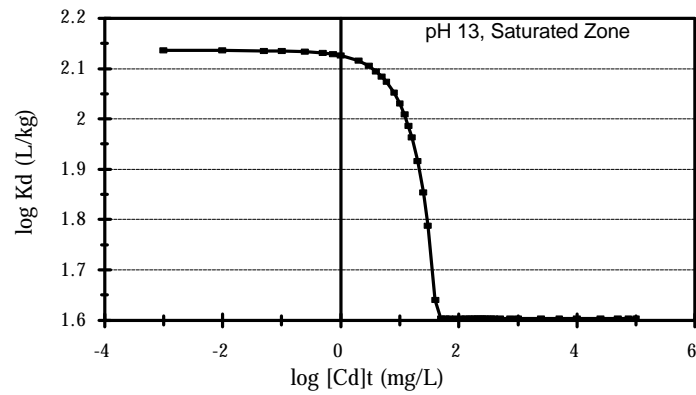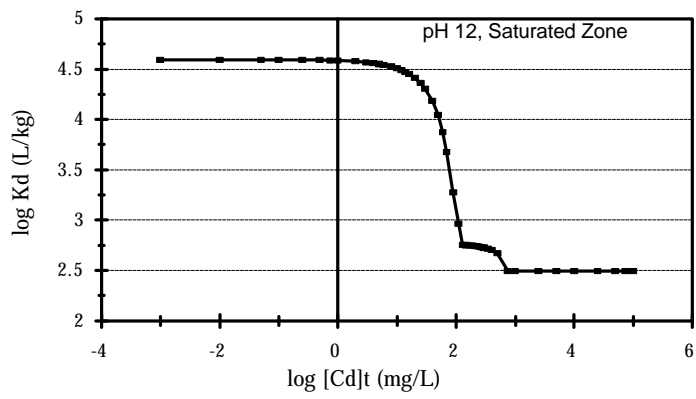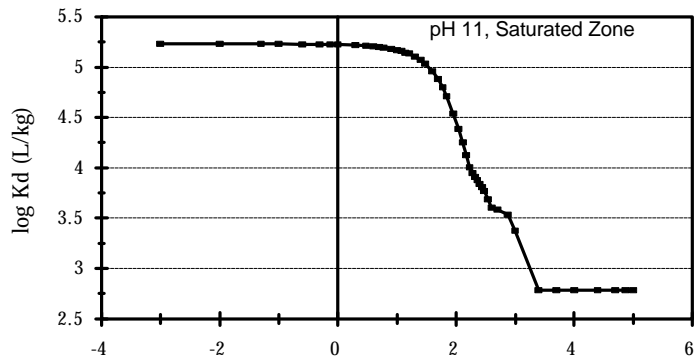
Figure B.4   Log K_d (L/kg) vs. log total Cd (mg/L) at pH 11, 12, and 13 in the saturated zone.
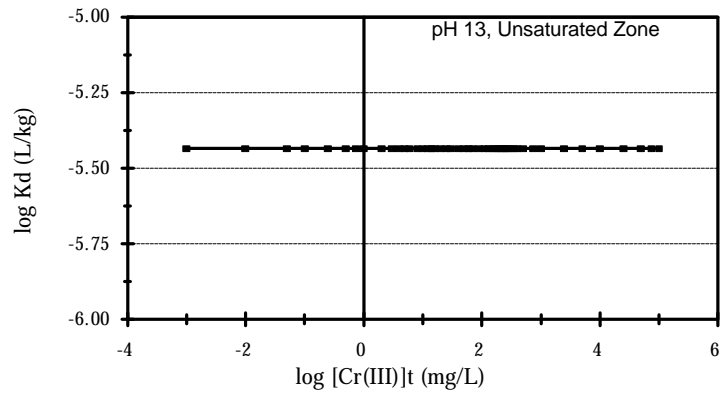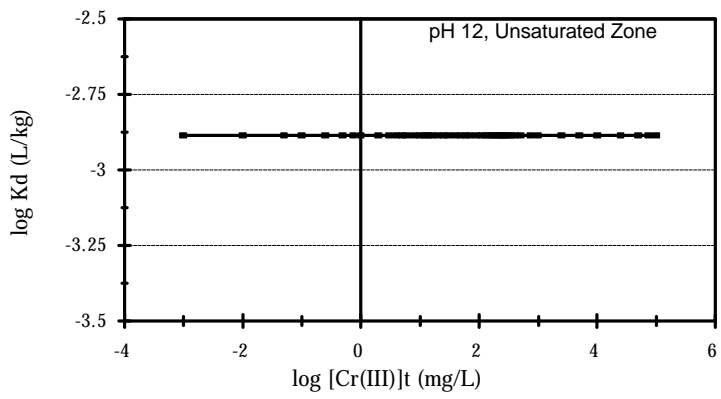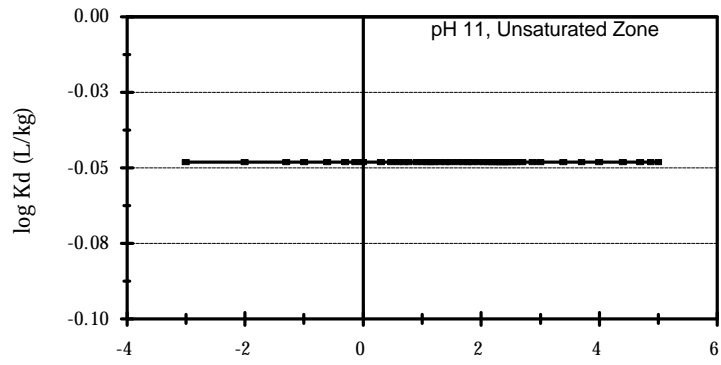
Figure B.5   Log K_d (L/kg) vs. log total Cr(III) (mg/L) at pH 11, 12, and 13 in the unsaturated zone.
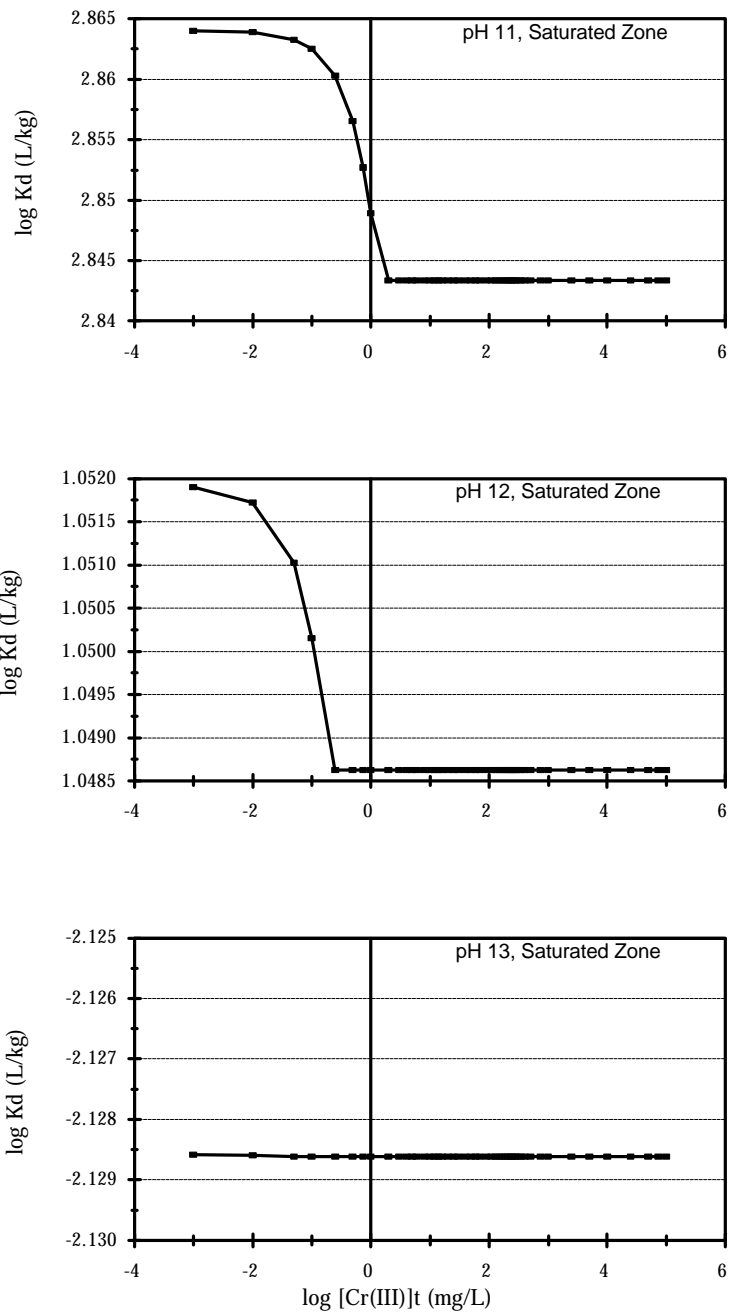
Figure B.6   Log K_d (L/kg) vs. log total Cr(III) (mg/L) at pH 11, 12, and 13 in the saturated zone.

Figure B.7   Log K_d (L/kg) vs. log total Ba (mg/L) at pH 11, 12, and 13 in the unsaturated zone.

Figure B.8   Log K_d (L/kg) vs. log total Ba (mg/L) at pH 11, 12, and 13 in the saturated zone.

Figure B.9   Log K_d (L/kg) vs. log total Be (mg/L) at pH 11, 12, and 13 in the unsaturated zone
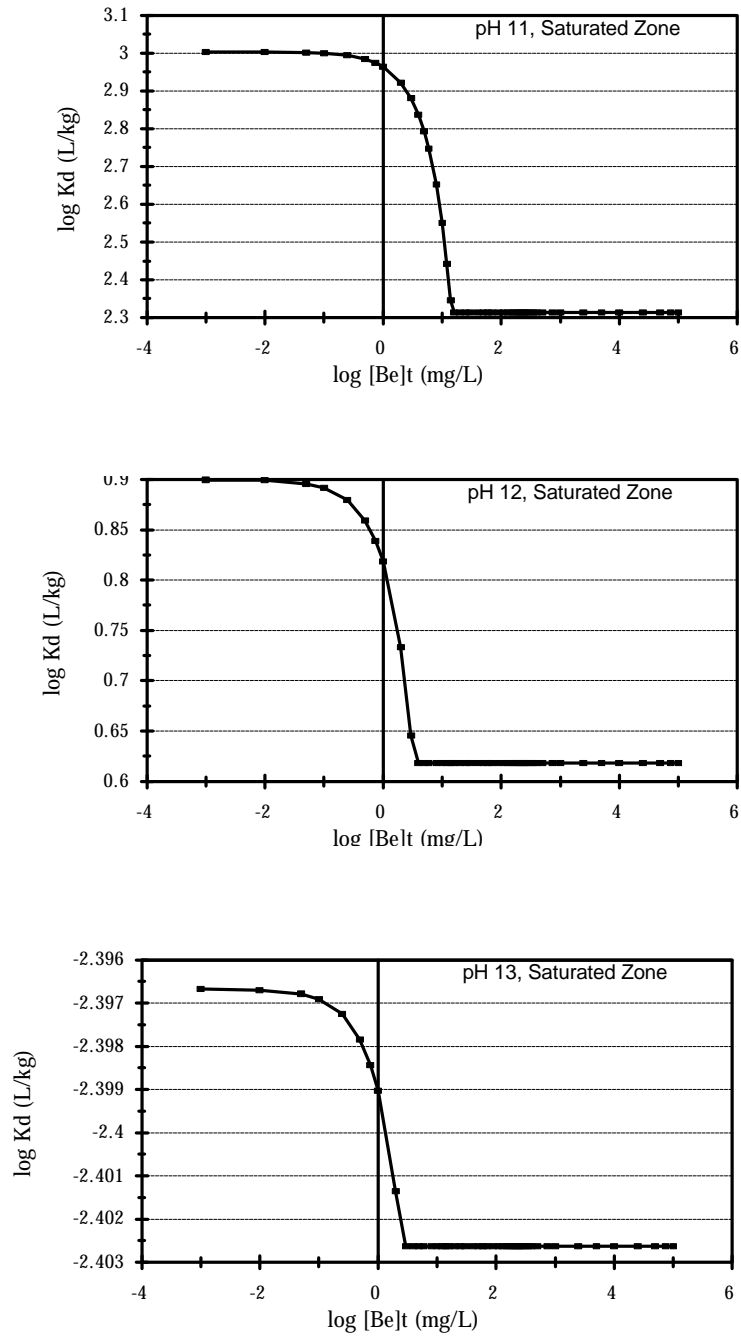
Figure B.10   Log K_d (L/kg) vs. log total Be (mg/L) at pH 11, 12, and 13 in the saturated zone.

B.2 COMPARISON WITH HWIR RESULTS

An observed trend in previous modeling as well as from the literature is that adsorption of metal cations tends to increase with increasing pH, and adsorption of metal anions tends to decrease. The low pH trend reflects the tendency of sorbed protons to build positive charge on the sorbent surface and thus enhance metal anion adsorption.   The high pH trend of enhanced metal cation sorption results from the decreased competition for sorption sites because of the paucity of protons. This study deals with metal cations at high pH. Other factors that effect metal cation adsorption include the concentrations of ligands that complex the metal (in competition with sorption sites), metal cation competition with other specifically adsorbed cations, and changes in ionic strength. (The ionic strength affects the activity coefficients of all species and directly influences the electrostatic potential associated with the HFO surface.) An example of competition from other ligands that is important in this study is formation of aqueous metal hydroxide species. This effect increases with pH, reducing the amount of metal sorbed. As pH increases, the increased tendency for sorption of metal cations due to less competition from protons is offset by the increased affinity of complex formation with hydroxide.

In the current study, an additional complicating factor is the increased concentration of calcium and other major ions from the CKD leachate. Calcium is adsorbed on HFO in accordance with reactions that are similar to those of barium (Dzombak and Morel, 1990). Elevated Ca concentrations tend to reduce the adsorption of other cations. In addition, the increased Na and K concentrations from CKD leachate impact adsorption via their effect on the ionic strength, and increased SO_4 may complex Ba, Pb, and Cd.

In examining the plots presented in Figures B.1-B.10, one should note that the saturated zone model conditions correspond much more closely with HWIR modeling than those of the unsaturated zone. This is because of the seven times greater concentration of CKD leachate constituents in the unsaturated zone modeling. Some general observations concerning the plots in Figures B.1-B.10 are:

- In every case, the unsaturated zone K_d values are significantly lower than their saturated zone counterparts at the same pH. This is primarily due to the increased competition from the CKD leachate Ca, with some added reduction in sorption due to metal complexing with the added SO_4. An additional effect on K_d may be produced by the impact of the added Na, K, and Cl on the ionic strength, although the direction of change that this would induce is metal-dependent.

- In every case except one, within a particular zone (unsaturated or saturated), the sorption of metal decreases significantly as the pH increases. This is most clearly seen by looking at the progression of results down each page of plots. The one exception is Ba, for which sorption is not much different at pH 12 than for pH 11. At pH 13, Ba sorption is increased slightly in the unsaturated zone and decreased slightly in the saturated zone. This behavior is peculiar to Ba because the Site 1 HFO adsorption reaction for Ba differs from its counterpart for all the other metals in this study. For all HFO reactions except the Site 1 Ba reaction, the neutral SOH site is deprotonated to SO$^-$, and the metal cation is

adsorbed to give SOM (with a $+1$ charge if M is divalent). For the Site 1 Ba reaction, like its Ca counterpart, the neutral site adsorbs the Ba to give $SOHBa^{++}$. Another reason for the "anomalous" behavior of Ba is that it does not have as great a tendency to form aqueous hydroxide species as do the other metals.

- Results that appear as a flat line actually do include the characteristic decrease in K_d as total metal increases. The flat line appearance occurs when the amount of sorption is so small that variation in it cannot reasonable be calculated or displayed.

The plots on the following pages show the HWIR results corresponding to the highest pH used in HWIR (8.0) and the lowest concentration of leachate organic acids. The concentrations of HFO and natural organic matter were set to medium in the modeling that produced these results. These model conditions were selected to most closely match those of the current study. Results with these conditions are shown for both the unsaturated and saturated zones for the metals Pb, Cd, Cr(III), and Ba. No HWIR results are shown for beryllium because separate modeling was not done for that metal in HWIR. Instead, the K_d values for barium were used for beryllium as well. As noted above, the saturated zone conditions of the current study (Figures B.1-B.10) most closely match the HWIR modeling because of the much smaller concentrations of CKD leachate constituents. Comparison of the HWIR plots with the pH 11 saturated zone plots shows the most similar model conditions. In comparing the magnitude of the K_d values between the pH 11 saturated zone plot and the corresponding HWIR plot, some metals show an increase in the CKD result and some show a decrease. For example, the CKD Pb plots (Figure B.2) show a general decrease in K_d with increasing pH. The HWIR plot at pH 8.0 has larger K_d values than the pH 11 CKD plot, and is thus in keeping with this trend. However, the CKD Cd plots (Figure B.4) also shows a general decrease with increasing pH, but the HWIR plots at pH 8.0 have smaller K_d values than the corresponding pH 11 CKD plots. This suggest that for each metal, K_d increases with pH up to a point, but then begins to fall as pH continues to increase. The pH at which the maximum K_d is reached varies from one metal to another. Examination of the CKD unsaturated zone results indicates that the pH of maximum K_d must also depend on the presence or absence of other competitors and complexers in the system. For the current systems, it appears that the K_d maximum for Pb and Cr(III) occurs at lower pH than for Cd and Ba.
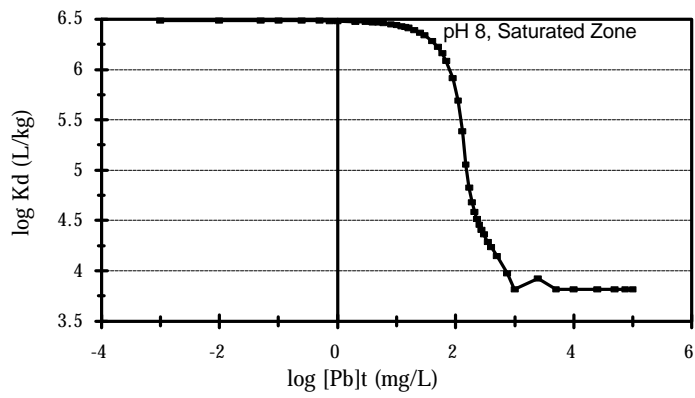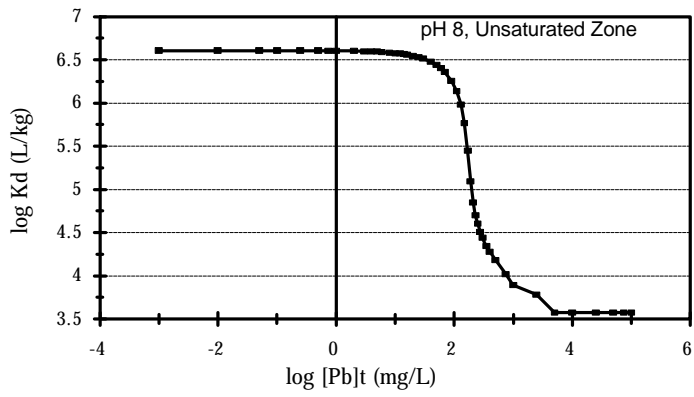
Figure B.11   HWIR results: log K_d (L/kg) vs. log total Pb (mg/L) at pH 8 in the unsaturated and saturated zones.   Compare with Figures B.1 and B.2.
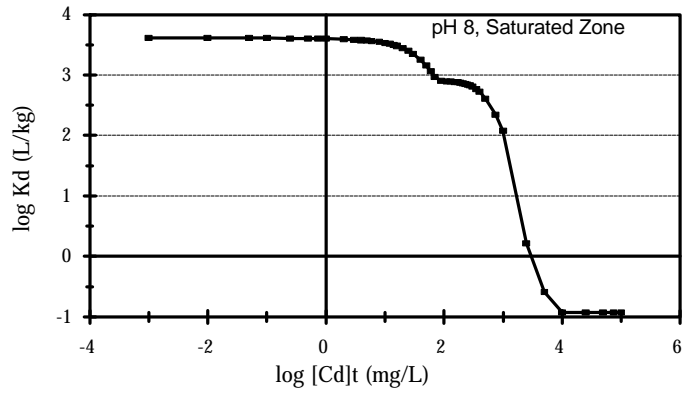
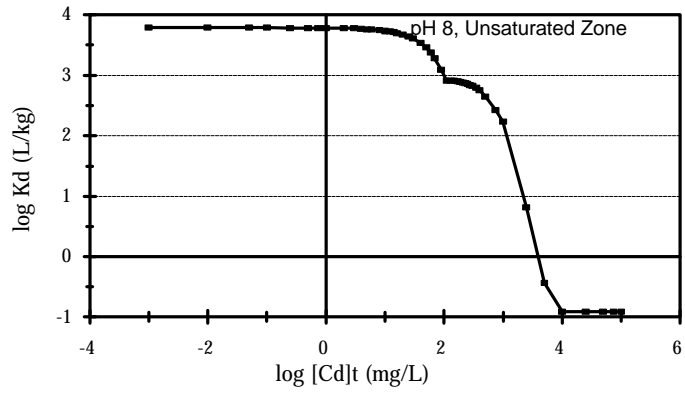Figure B.12   HWIR results: log K_d (L/kg) vs. log total Cd (mg/L) at pH 8 the unsaturated and saturated zones. Compare with Figures B.3 and B.4.
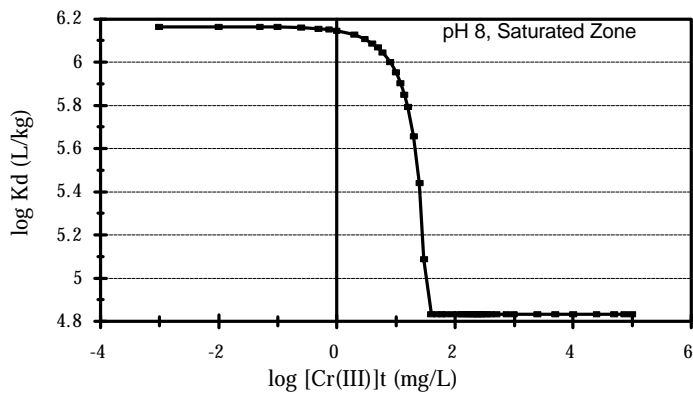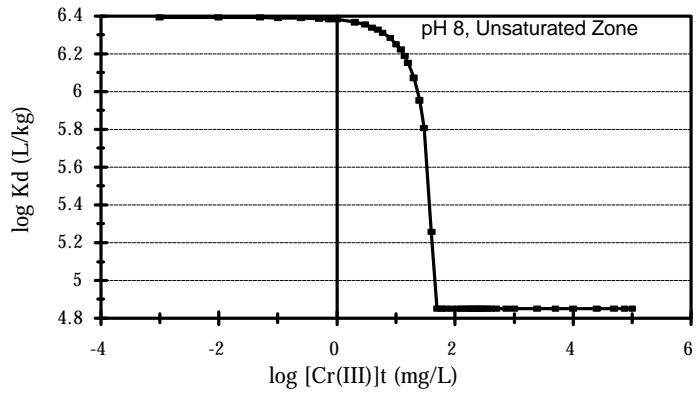
Figure B.13   HWIR results: log K_d (L/kg) vs. log total Cr(III) (mg/L) at pH 8 in the unsaturated and saturated zones.   Compare with Figures B.5 and B.6.
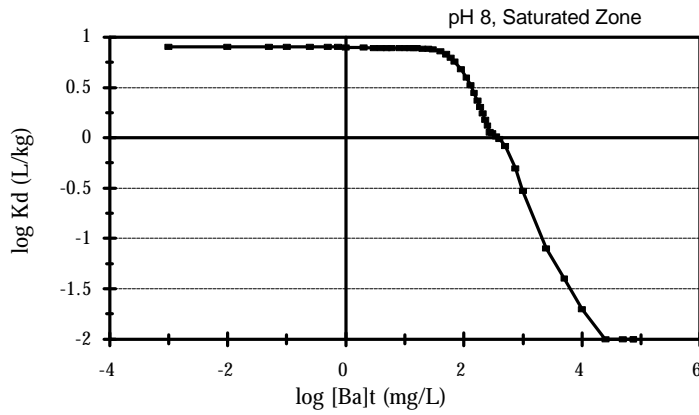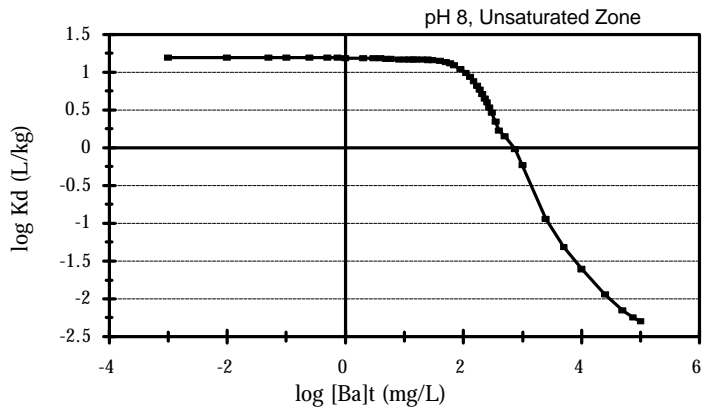
Figure B.14 HWIR results: log K_d (L/kg) vs. log total Ba (mg/L) at pH 8 in the unsaturated and saturated zones. Compare with Figures B.7 and B.8.