USE OF EPA’S INDUSTRIAL WASTE MANAGEMENT EVALUATION MODEL (IWEM) TO SUPPORT BENIFICIAL USE DETERMINATIONS

A Final Report Submitted to:
The US EPA Office of Solid Waste and Emergency Response (OSWER)

Submitted by:

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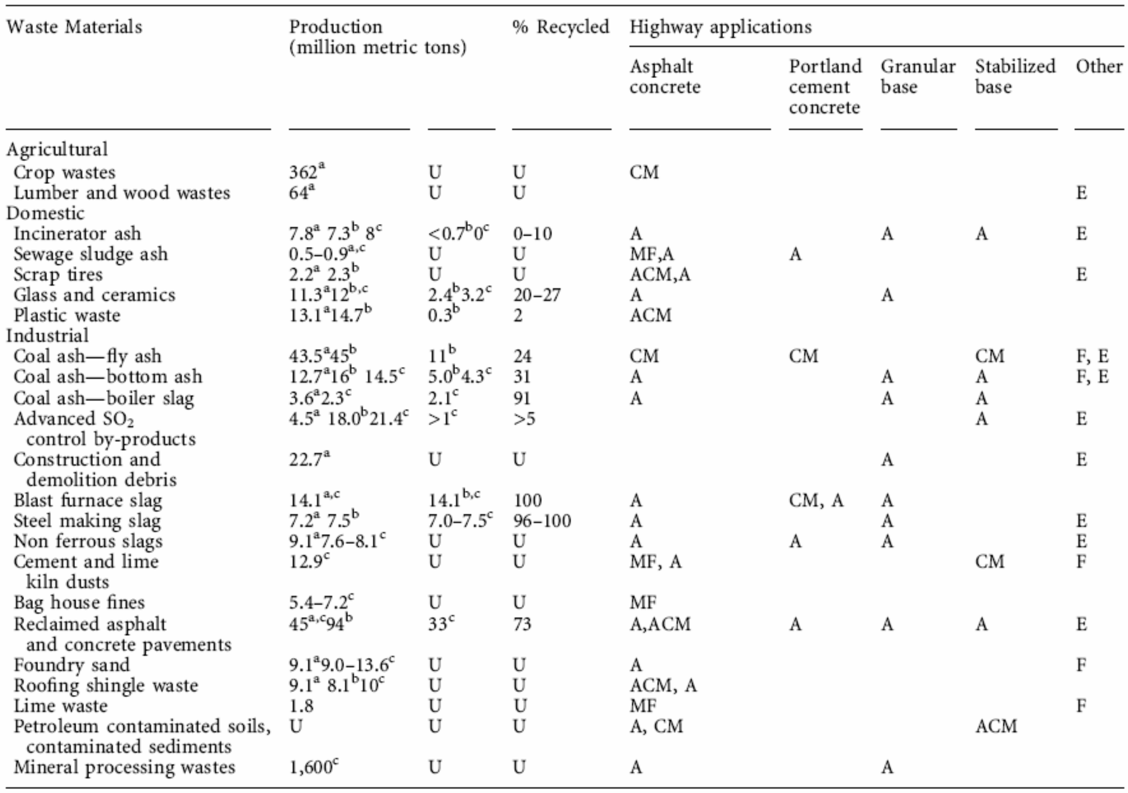
1. INTRODUCTION

1.0 Context

According to the Federal Highway Administration (FHWA, 2001) there are nearly 4 million miles of roads in the U.S. These roads require large volumes of materials for construction and maintenance purposes which generally are harvested from natural sources. Recently, increased interest in recycling has evolved as a measure of promoting sustainable construction and to alleviate issues surrounding the harvesting of natural resources in areas sensitive to environmental perturbations. There are promising results for equal or better engineering performance of recycled materials at comparable or less costs and without significant environmental impact (Apul et al., 2003).

Every year millions of tons of industrial byproducts (secondary materials) are produced in the United States. Such byproducts include foundry sands and slags, as well as coal fly and bottom ashes. In some cases, these “left over” materials are reused in various facets of the construction sector, primarily in relation to roadway applications (Table 1). However, the majority of industrial byproducts are either stockpiled indefinitely or disposed of in landfills. According to the American Coal Ash Association (ACAA), 70 million tons of fly ash was produced in 2003 in the United States with only 39% of it being reused in a variety of applications. The remainder was disposed in waste containment facilities such as landfills. In Wisconsin alone, more than 800,000 tons of gray iron foundry sand is landfilled annually with little or no hope of being reused (Lee and Benson, 2005).

Table 1. Annual production and use of recycled materials. U=undermined, MF=mineral filler, ACM=asphalt cement modifier, A=aggregate, CM=cementitious material, E=embankment or fill, and F=flowablefill (Apul et al., 2003). ^{a}Adapted from Collins and Ciesielski 1994, ^{b}Adapted from Schroeder 1994, ^{c}Adapted from Chesner et. Al 1998.



Waste Materials	Production (million metric tons)		% Recycled	Highway applications				
				Asphalt concrete	Portland cement concrete	Granular base	Stabilized base	Other
Agricultural								
Crop wastes	362^{a}	U	U	CM				
Lumber and wood wastes	64^{a}	U	U					E
Domestic								
Incinerator ash	7.8^{a} 7.3^{b} 8^{c}	$<0.7^{b}0^{c}$	0–10	A		A	A	E
Sewage sludge ash	$0.5–0.9^{a,c}$	U	U	MF,A	A			
Scrap tires	2.2^{a} 2.3^{b}	U	U	ACM,A				E
Glass and ceramics	$11.3^{a}12^{b,c}$	$2.4^{b}3.2^{c}$	20–27	A		A		
Plastic waste	$13.1^{a}14.7^{b}$	0.3^{b}	2	ACM				
Industrial								
Coal ash—fly ash	$43.5^{a}45^{b}$	11^{b}	24	CM	CM		CM	F, E
Coal ash—bottom ash	$12.7^{a}16^{b}$ 14.5^{c}	$5.0^{b}4.3^{c}$	31	A		A	A	F, E
Coal ash—boiler slag	$3.6^{a}2.3^{c}$	2.1^{c}	91	A		A	A	
Advanced SO_2 control by-products	4.5^{a} $18.0^{b}21.4^{c}$	$>1^{c}$	>5				A	E
Construction and demolition debris	22.7^{a}	U	U			A		E
Blast furnace slag	$14.1^{a,c}$	$14.1^{b,c}$	100	A	CM, A	A		
Steel making slag	7.2^{a} 7.5^{b}	$7.0–7.5^{c}$	96–100	A		A		E
Non ferrous slags	$9.1^{a}7.6–8.1^{c}$	U	U	A	A	A		E
Cement and lime kiln dusts	12.9^{c}	U	U	MF, A			CM	F
Bag house fines	$5.4–7.2^{c}$	U	U	MF				
Reclaimed asphalt and concrete pavements	$45^{a,c}94^{b}$	33^{c}	73	A,ACM	A	A	A	E
Foundry sand	$9.1^{a}9.0–13.6^{c}$	U	U	A				F
Roofing shingle waste	9.1^{a} $8.1^{b}10^{c}$	U	U	ACM, A				
Lime waste	1.8	U	U	MF				F
Petroleum contaminated soils, contaminated sediments	U	U	U	A, CM			ACM	
Mineral processing wastes	$1,600^{c}$	U	U	A		A		

In the transportation industry, soft soils encountered during road construction are removed and replaced with crushed rock to form a sturdy working platform for pavement construction. This construction practice can be costly, particularly if the rock needs to be hauled to the construction site. As a result, transportation agencies are seeking less costly methods to stabilize soft soils and construct working platforms. In some cases, industrial byproducts can be used to construct lower cost working platforms that provide equal support as those constructed with crushed rock (Tanyu et al. 2004). Use of industrial byproducts in this manner also facilitates sustainable construction by reusing materials currently being landfilled and reducing the use of virgin natural resources. However, with the re-use of these industrial byproducts comes the concern of whether the leaching of contaminants (primarily heavy metals) contained in the materials will impact the underlying groundwater and if so, to what extent?

Secondary materials are generally the end-products of metal processing and coal combustion. For example, gray iron foundry sand is a byproduct from the metal processing industry that consists of impurities floating to the surface of molten material (Proctor et al. 2000). These impurities often contain metals such as As, Cd, Cr, Pb, Hg, Se and Ag. Fly ash is a fine-textured particulate that is removed from the exhaust during coal combustion. This material also often contains metals that include As, Cd, Cr, Cu, Pb, Ni and Zn. When placed in a roadway setting, these byproducts are subject to infiltration via precipitation. As a result, the metals sorbing to the individual material particles may leach into solution and be carried down into and through the subsurface as leachate. Depending on the concentrations of the metals in solution and the partitioning capabilities of the underlying soils, the leachate may eventually enter the groundwater with the threat of adversely impacting regional groundwater quality.

The extent to which leachate produced from industrial byproducts will effect subsurface soils and groundwater is poorly understood. This is primarily due to the lack of studies concerning the topic. In the past, field studies have been performed to understand the short term impacts secondary materials may or may not have on groundwater. However, few long term efforts have been made to address this topic thus little is known concerning the potential risks such materials may pose to human health and the environment. This is the limiting factor to the beneficial reuse of secondary materials. In order to evaluate the long term impacts of secondary materials, modeling becomes necessary. The remainder of this report addresses how the use of IWEM may aid in the determination of whether secondary materials are safe enough for beneficial-use applications in the highway environment.

1.1 Significance and Objectives of this Study

Groundwater is a crucial element in maintaining a sustainable world. According to the National Ground Water Association (NGWA), of the total 341 billion gallons of fresh water the United States uses each day, about 83.2 billion gallons, or 24 percent is groundwater. In the United States, 47 percent of the population relies on groundwater for drinking water. There are nearly 16 million water wells in the U.S., supplying groundwater for public supply, private supply, irrigation, livestock, manufacturing, mining, thermoelectric power, and other purposes (www.wellowner.org). Figure 1 illustrates groundwater usage by category for the U.S. in 2000.

Based on this data, it is clear that groundwater is essential to maintaining everyday life. Thus extreme care must be taken to avoid contaminating it or at least there must be tools available for a particular situation (e.g. leaching from secondary materials) that allow us to predict if groundwater contamination is going to occur in order to take the necessary precautions to minimize damage to human health and the environment. Groundwater models provide us with such tools.

While a great deal is already known about groundwater contamination, minimal research has been conducted concerning modeling of impacts from recycled material use in a highway environment. It is hypothesized that the USEPA's *Industrial Waste Management Evaluation Model* (IWEM) may aid in the evaluation of whether secondary materials are safe enough for beneficial-use applications in a roadway setting. *The primary objective of this research is to investigate IWEM's potential benefits with proper input from field and laboratory testing.* Validation of IWEM was tested using data from field studies from sites in Wisconsin and North Carolina. In this research, outputs from IWEM have been compared with those of another solute transport model (HYDRUS-2D) and actual field data to determine IWEM's predictive accuracy.

Additionally, this modeling provides an assessment of groundwater impact in the scenarios investigated.

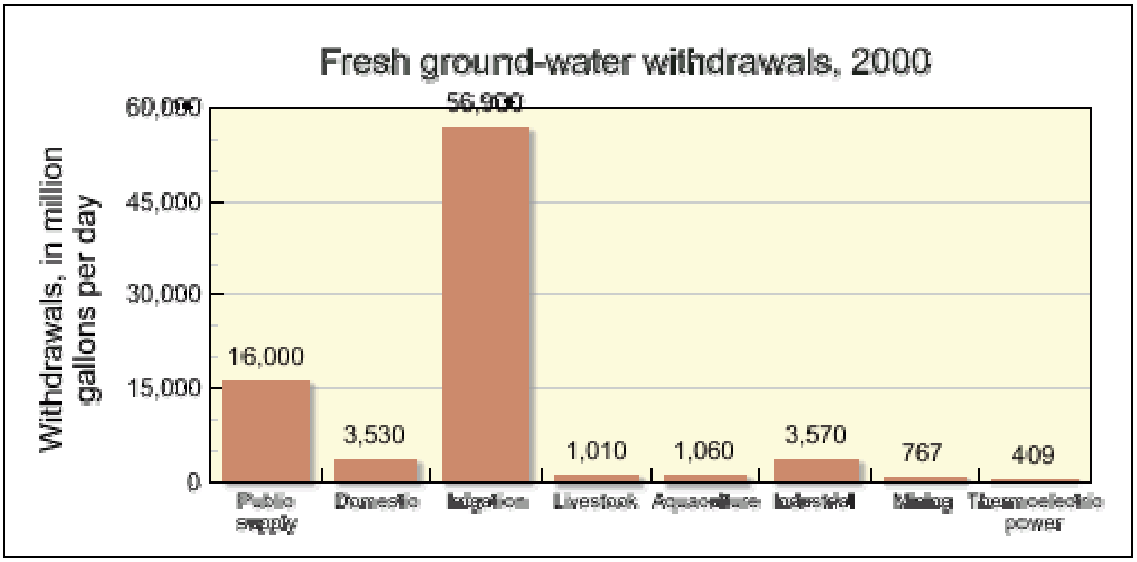


Figure 1. Groundwater usage by category for U.S. in 2000. http://ga.water.usgs.gov/edu/wugw.html.

Proper use of groundwater modeling tools such as IWEM should support making scientific risk-based decisions concerning the appropriate recycling of secondary industrial materials. In other words, these types of models can be effective in promoting recycling or avoiding it if they can show groundwater contamination will result. With this objective, it was hoped that IWEM could accurately predict the fate and transport of leachate from these secondary materials in order to evaluate potential adverse effects on groundwater. The ultimate long term goal upon validating IWEM is its adoption by State DOTs, State environmental agencies, and construction companies to help aid them in determining whether a secondary material can be used in a particular situation.

1.2 Study Areas

Testing of IWEM was conducted using field and laboratory data from three U.S. sites where secondary material applications are currently being used with respect to roadway settings (i.e. structural sub-base support):

1. Wisconsin State Highway 60 near Lodi, Wisconsin;
2. U.S. Highway 301 at Swift Creek near Battleboro, North Carolina;
3. Routes 213/301 and Interstate 695 overpasses in Maryland.

All three sites provided sufficient data for IWEM input which includes:

- site geology/hydrogeology
- initial secondary material leachate concentrations
- groundwater sampling data for comparison purposes
- regional climate data

The information from these locations was used for input into IWEM in order to obtain groundwater concentrations at a point down gradient from the secondary material source. Detailed observations and conclusions were made on model results to interpret IWEM's capabilities in predicting the fate-and-transport of groundwater with respect to secondary material reuse. Methods of input and testing are discussed in the next chapter.

1.2.1 Wisconsin State Highway 60

The majority of the project's data came from a Wisconsin Department of Transportation (WisDOT) project along a 1.4 km stretch of Wisconsin State Highway 60 (STH 60) between

Lodi and Prairie du Sac, WI in Columbia County (Figure 2). Information pertaining to this project was provided by The University of Wisconsin at Madison's Department of Civil Engineering. At this location, four test sections, covering areas between 790 and 1600-m^2, have been built during the re-construction of STH 60 in the summer of 2000. Each test section includes a sub-base layer composed of secondary byproduct materials (Figure 3). These materials consist of fly ash amended soil, bottom ash from coal-fired power plants, and foundry sand and foundry slag from gray iron casting industries. Two additional sections have also been constructed, each consisting of traditional highway support earthen materials for control purposes. Additionally, within each section, two 3.5 m x 4.8 m lysimeters have been installed to collect leachate draining from the bottom of the sub-base layers (Lee and Benson, 2005).

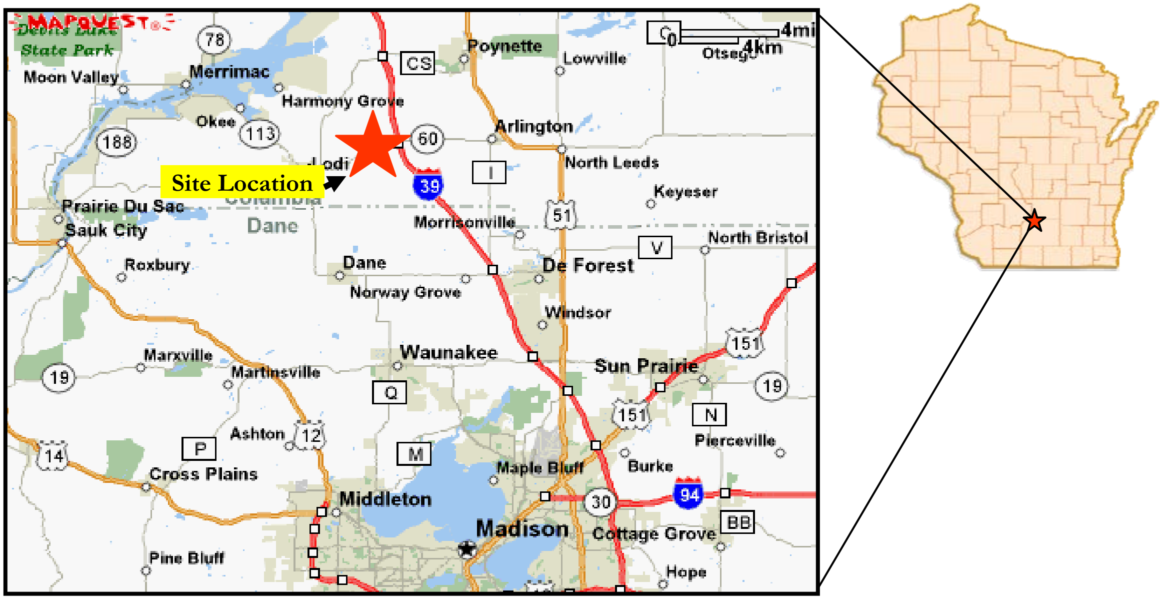


Figure 2. Site location: Wisconsin State Highway 60 (www.mapquest.com).

Between 2000 and 2004, leachate samples were collected periodically from the lysimeters to characterize the secondary materials. The leachate was analyzed for the trace elements cadmium, chromium, selenium and silver. Additionally, throughout the monitoring, volumetric leachate fluxes were also recorded. Element analytical and leachate flux data was used for input into IWEM for initial characterization of the model's fate-and-transport capabilities (see Chapter 3).

Knowledge of the region's subsurface geology also becomes important as it is required input into IWEM for the model to make an accurate assessment of how water will flow through the specified domain. Review of USGS logs and maps show a bedrock geology dominated by Silurian dolomite and Ordovician dolomite with some limestone, sandstone, and shale. Cambrian sandstone, with some dolomite and shale, is present to a lesser extent in the area. Bedrock is overlain by drift usually less than 50 feet thick and soils in the area consist of silt loam at the surface, but subsoils are generally calcareous loam (till) or calcareous sand and gravel outwash. The loess cap is typically about 2 feet thick (www.npwrc.usgs.gov).

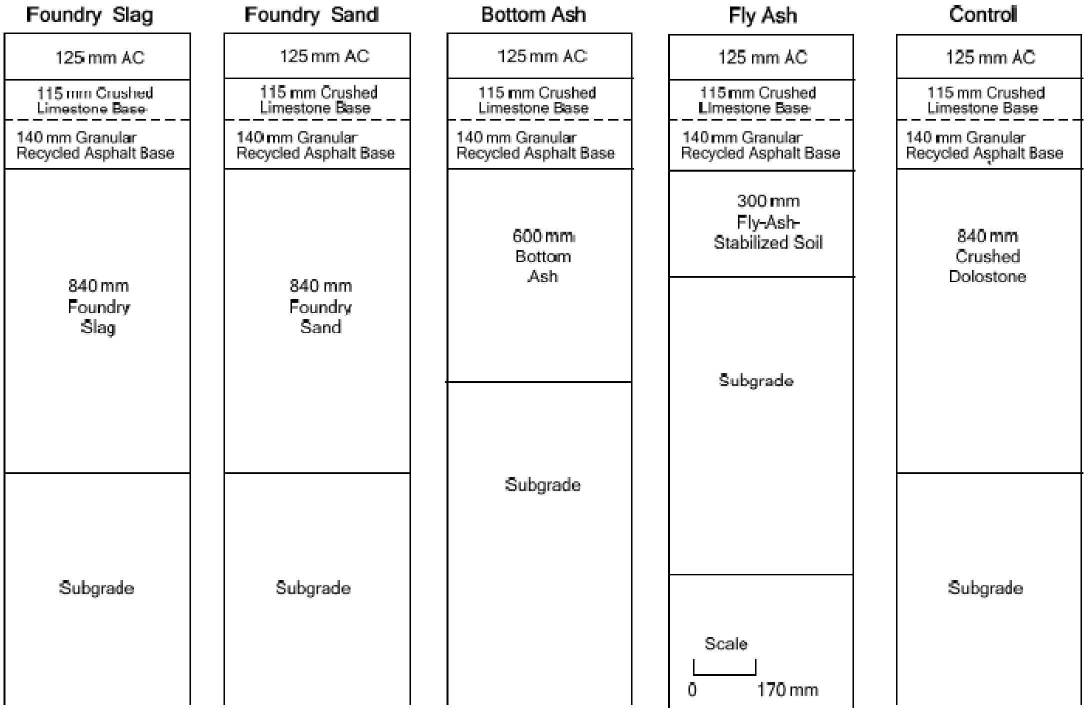


Figure 3. Profiles of the test sections constructed using foundry slag, foundry sand, bottom ash, fly ash and crushed rock (control) and STH 60 near Lodi, WI (AC = asphalt concrete) (Lee and Benson, 2005).

More recently, a groundwater-monitoring program has been implemented at the site. In January 2004, groundwater monitoring wells were installed adjacent to the bottom ash and fly ash test sections. Both wells were installed 6 meters from the edge of the highway shoulder. Continuous monitoring of these wells via groundwater samples and water-table measurements has been conducted since the installation of the wells with laboratory analyses of the groundwater samples revealing no concentrations of Ag, Cd, Cr, or Se above the method detection limit (MDL) to date (Lee and Benson, 2005).

1.2.2 U.S. Highway 301, North Carolina

In the early 1990s, coal ash was reused on a 12-acre portion of commercial property along U.S. Highway 301 at Swift Creek near Battleboro. NC (Figure 4). A site investigation in 2002 followed by a subsequent groundwater analysis in June 2004 revealed groundwater concentrations of arsenic and lead above applicable limits (0.28 and 0.068 ppm respectively) in a monitoring well located approximately 25 feet from the edge of the fill (Sherrill, 2003). This scenario provided the perfect opportunity to verify whether IWEM could have successfully identified the contamination during planning stages so a scientific risk-based decision could have been made as to whether the material was safe enough for reuse.

Figure 4. Site location: U.S. highway 301 near Battleboro, NC (www.mapquest.com)

The soils underlying the coal ash for this aquifer consist largely of Altavista. Altavista soils are alluvial deposits that formed on flood plains. This layer of soil under the ash is approximately 6.5 ft thick and is characterized as a dense sandy clay alluvial material that has a very low permeability of about $7x10^{-8}$ cm/sec. Prior to construction of the coal ash structural fill the water table was at least 1.5 ft below ground surface. However, the 2002 site investigation showed that groundwater was present within the majority of the coal ash (4 meters below ground surface). This is likely a result of the impermeable nature of the Altsvista which acts as a barrier to vertical migration of groundwater because of the very slow travel time through this confining bed (Sherrill, 2003).

All data for the site was provided by Sherrill Environmental, Inc. of Durham, NC who subcontracted ReUse Technology, Inc. of Rocky Mount, NC to perform the investigative procedures. Additional site-specific parameters used for IWEM input are outlined in the next chapter.

1.2.3 Routes 213/301 and Interstate 695 overpasses, Maryland

During the 1990s, two projects were completed in Maryland in which Class F fly ash (CCPs) were used to form highway embankments (Figure 5). In 1993 and 1994, Baltimore Gas & Electric (BGE) (now Constellation Energy Group) and Delmarva Power (now Conectiv) provided approximately 40,000 tons and 20,000 tons of CCPs, respectively, to the Maryland State Highway Administration (SHA) to create the highway embankments for the Route 213 overpass over Route 301 near Centerville on Maryland's eastern shore. Between 1996 and 1998, BGE provided 320,000 tons of CCPs to support the Maryland Transportation Authority (MdTA) with the construction of three overpasses during the reconstruction of a portion of I-695 near Sparrows point (ERM, 2004).

Following coal ash application at the overpass study areas, instrument clusters consisting of lysimeters and monitoring wells were installed on the shoulders of the overpasses to characterize the water quality in the unsaturated and saturated zones within several feet of the embankments. The purpose of the lysimeters was to monitor leachate produced by the CCPs and the wells to monitor groundwater.

At the Route 213/301 overpass, two monitoring instrument clusters consisting of three lysimeters and one well were installed on the shoulder of each side of the overpass. Sample sites were labeled with the prefix 101 for the north embankment (e.g., L101-12 for the lysimeter installed to a depth of 12 feet on the north embankment) and 102 for the south embankment as shown on Figure 6 (ERM, 2004). Figure 7 displays a schematic cross-section of the study area.

Figure 5. Site location map: Route 213/301 and I-695 overpasses (ERM, 2004).

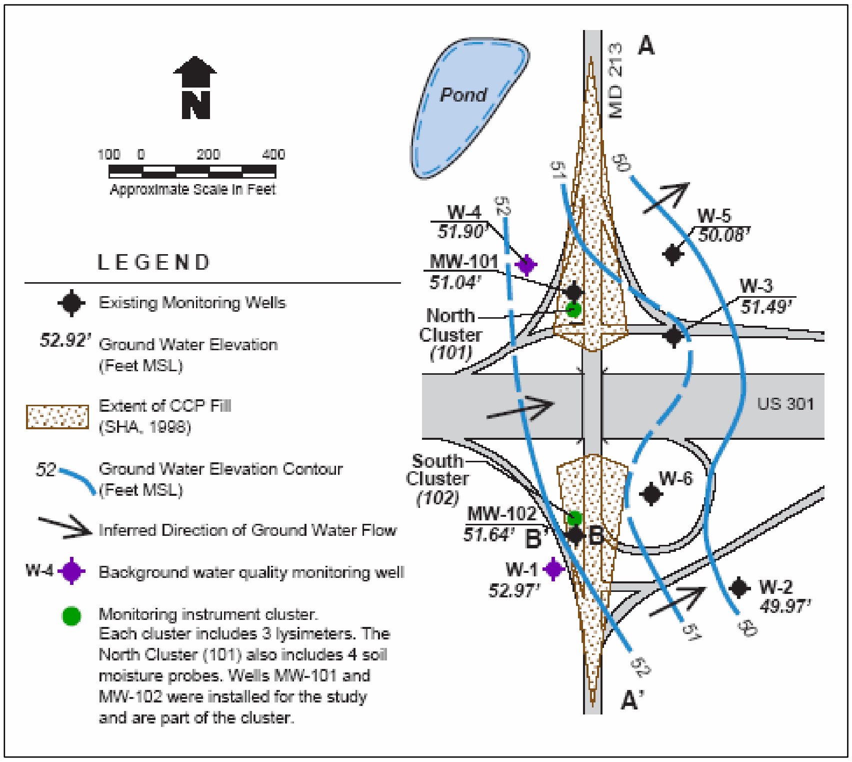
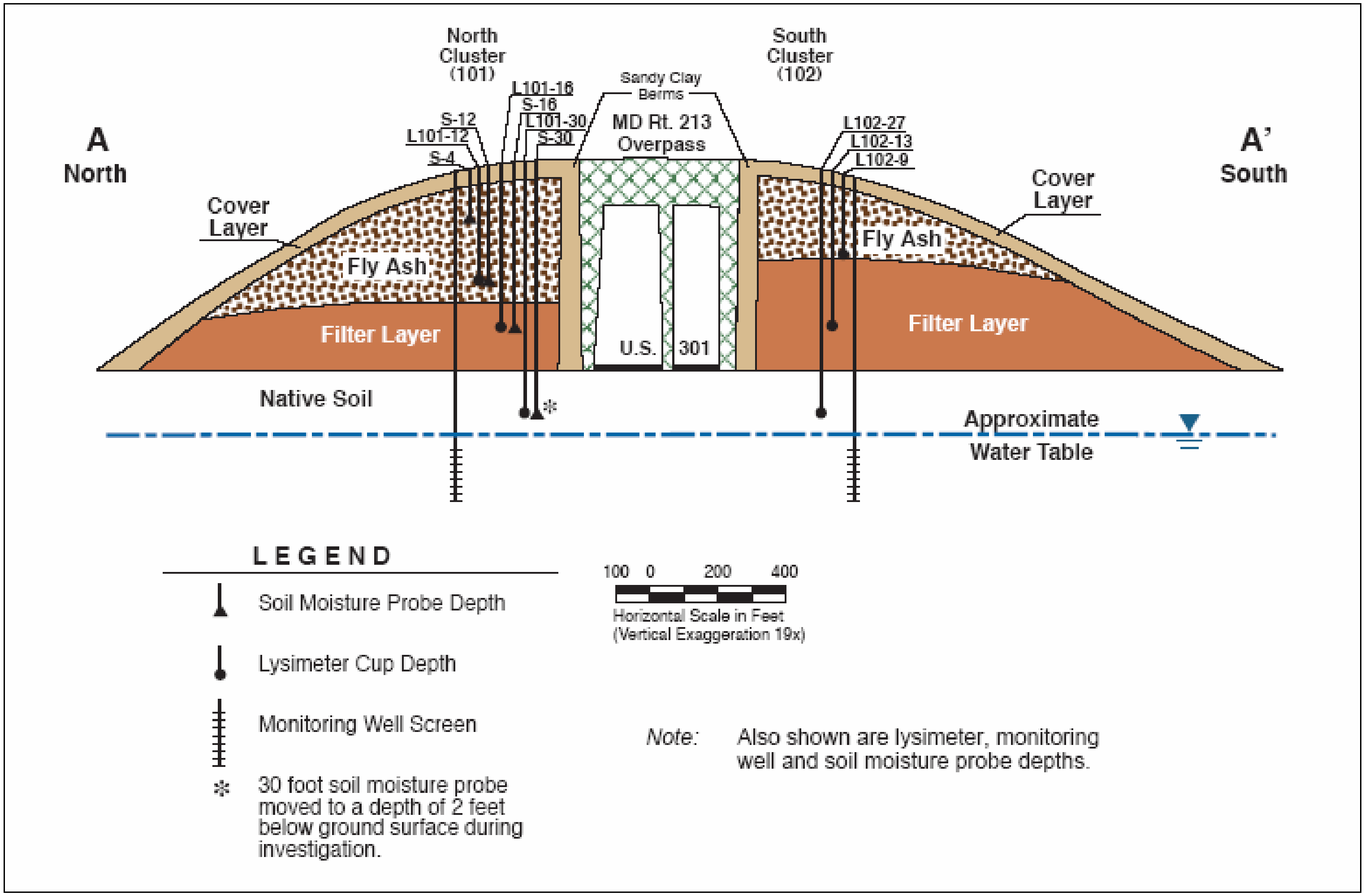


Figure 6. Map of Route 213 study area with instrumentation locations (ERM, 2004).



Note: Also shown are lysimeter, monitoring well and soil moisture probe depths.

Figure 7. Schematic cross-section of Rt. 213 site along A – A' shown on Figure 6 (ERM, 2004).

At the I-695 overpass (Figure 8), three monitoring instrument clusters consisting of two lysimeters and one well were installed on the shoulders of the overpass. Sample sites were labeled with the prefix 1 for the first cluster location (e.g., L1-18 for the lysimeter installed to a depth of 18 feet at first monitoring station), 2 for the second cluster location, and 3 for the third cluster location adjacent to Route 151 (ERM, 2004). Figure 9 displays a schematic cross-section of the study area.

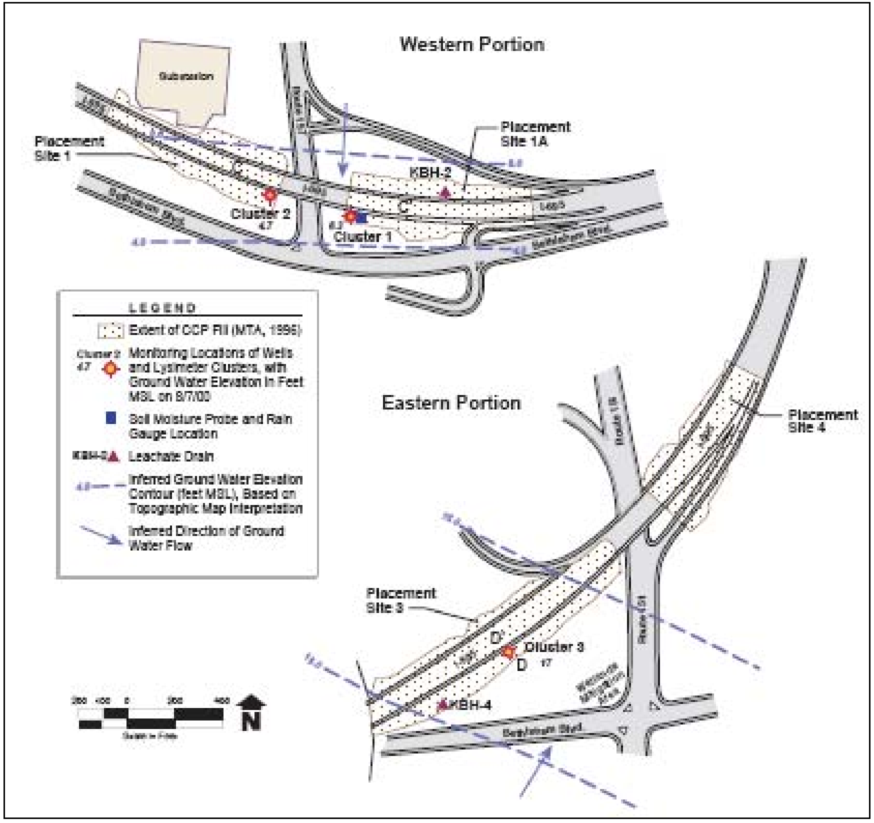


Figure 8. Map of I-695 overpasses with well and instrumentation locations (ERM, 2004).

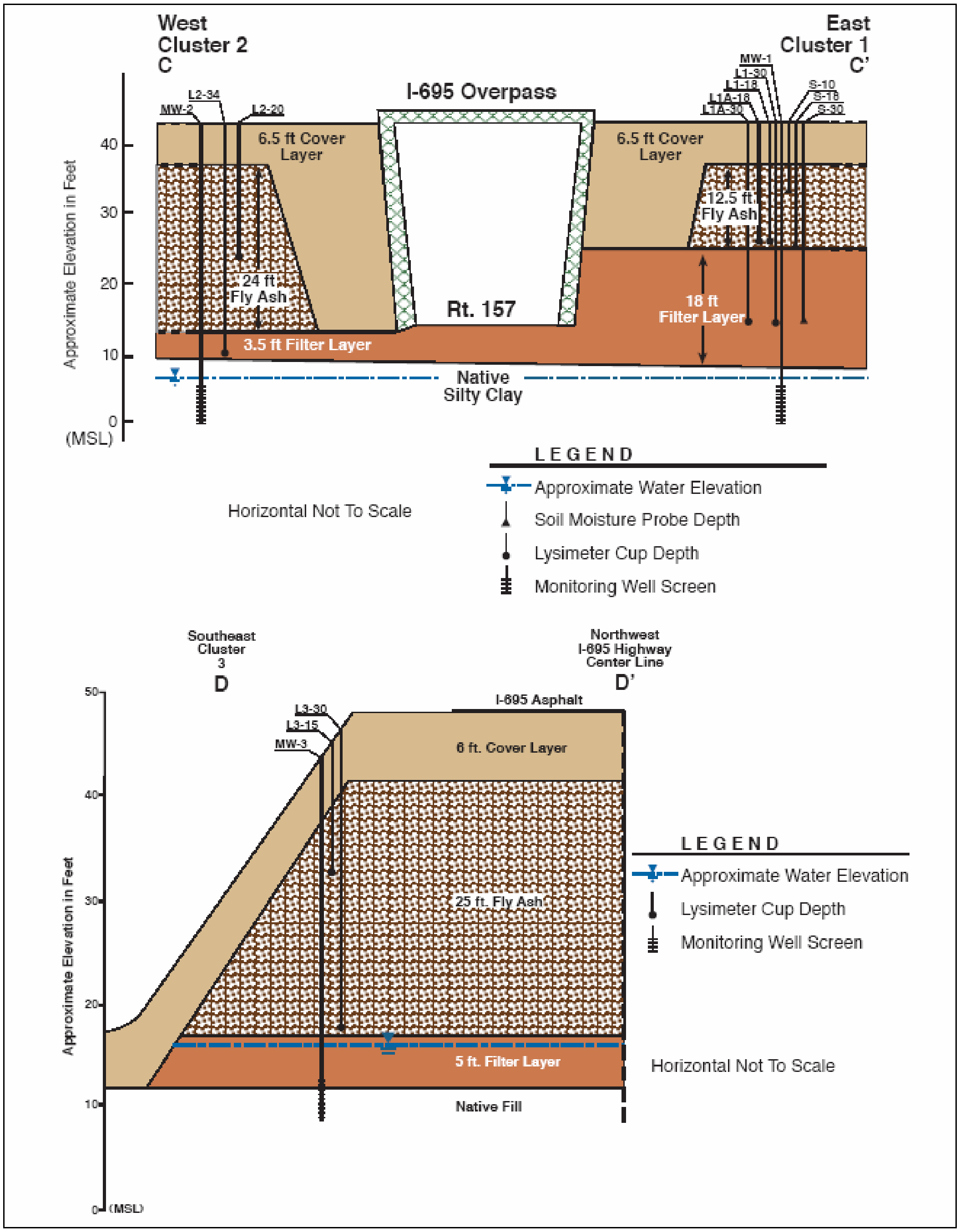


Figure 9. Schematic cross-sections of I-695 site (ERM, 2004).

Between 1999 and 2003, samples were collected from the wells and lysimeters at both overpass sites and analyzed by Lancaster Laboratories for the following constituents:

- Trace elements (e.g. arsenic, barium, beryllium, cadmium, chromium, copper, lead, manganese, nickel, selenium);
- Major cation elements (e.g. aluminum, calcium, iron, magnesium, potassium, sodium) and;
- Major anions (e.g. chloride, fluoride, sulfate, nitrite, and alkalinity) (ERM, 2004).

For the purpose of this research, only trace elements were considered as IWEM cannot model the other constituents.

With the exception of manganese (Mn), none of the trace elements detected in the lysimeters and wells ever exceeded MD regulatory MCLs. Because Mn often showed up in the groundwater and not the lysimeter data, it is assumed that Mn preexists in the groundwater, thus is not a result of the CCP leachate. However, several detections of arsenic and barium, did appear in both the lysimeter and well data implying there may be some connections between CCP leachate and groundwater concentrations. As with the North Carolina data, this scenario provided another opportunity to evaluate if IWEM could have successfully predicted groundwater concentrations resulting from secondary material leaching, regardless of MCL exceedences. Details of this modeling are presented in the next chapter.

A detailed description of this site, including environmental setting and construction details can be viewed in Environmental Resources Management, Inc.'s (ERM) 2004 technical report where the preceding data was obtained.

2. METHODS

2.0 Overview

Data from the study areas outlined in Section 1.2 were used for input into IWEM and various other solute transport models to validate IWEM's groundwater concentration predictive capabilities with respect to secondary material reuse. A two-step systematic approach was taken to accomplish this task. First, this involved running numerous (400+) simulations with IWEM to obtain groundwater concentrations at various points down gradient from the leachate source over a time distribution ranging from 1 to 200 years (maximum time allowed by IWEM). Secondly, using the same input, simulations were performed with HYDRUS-2D. The results of the two models were compared to determine IWEM's accuracy. In addition to other models, IWEM outputs were compared to actual groundwater field data. After analyzing data comparisons between models and field studies, informative conclusions were made regarding IWEM's ability to accurately predict groundwater concentrations resulting from secondary material leaching, particularly focused on the highway environment.

2.1 Study Data

The study described here uses data collected from the three areas presented in Section 1.2 as well as arbitrarily chosen values. Data used for model input can be divided into four categories: 1. WMU parameters, 2. site-specific geologic/hydrogeologic data, 3. infiltration data and 4. constituent parameters (e.g. metal distribution coefficients).

2.1.1 WMU parameters (IWEM modeling specifically)

For the purpose of this research, all IWEM modeling was performed using waste piles (WPs) as the representative WMU. It is felt a waste pile best exemplifies a real-life application of secondary materials in a roadway setting. IWEM considers a WP to be a temporary source with an average operational life of 40 years which is similar to fill used for structural support in a road.

In addition to the WMU type, IWEM requires several WMU parameters. The following are parameters required for WPs:

- distance to well (m)
- area (m^2)
- depth of base of WP below ground surface (m)
- operational life

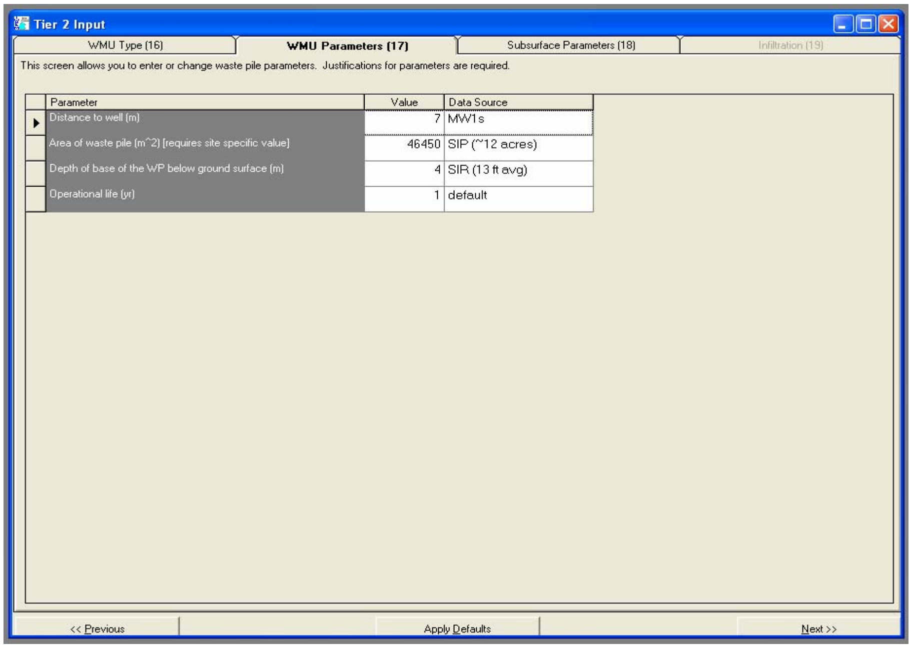
WP parameters were varied extensively throughout the course of IWEM modeling for each study area (especially distance to well and operational life). In most cases, distance to well and operational life values were arbitrarily chosen. An exception to this is when actual field data presented a monitoring well specified a certain distance from the material source where groundwater sampling results are available for a known time after implementation of the structural fill. In this case, IWEM simulations were performed using these known time and distances to evaluate whether the model would have predicted the concentrations detected in the well. As an example, data from the NC site shows elevated levels of As and Pb in a monitoring well located approximately 7 meters from the edge of the coal ash source. These concentrations were detected 10 years after the application of the fill. Thus, IWEM was run with a well located 7 meters from the waste pile for ten years. The final output concentrations for As and Pb from the model were then compared to the field data.

For each site, the reported WP areas were used for modeling (Table 2). Using these values helps mimic real-life scenarios, ensuring outputs are as realistic as possible. An exception to this relates to various IWEM modeling with the WisDOT data. Many simulations were performed where WP areas for all four secondary material sections were arbitrarily chosen to be 200 m^2. This was used to provide a level ground for comparison purposes between the sections. However, runs were performed using the actual area of the bottom ash section (790 m^2) in addition to an area representative of a one mile stretch of highway (8367 m^2) and one ten times that. Additional information on this is provided in Section 2.2.

Table 2. Waste pile areas per study site used for IWEM input.

Study Sites	**Area (m^2)**
Wisconsin (bottom ash)	790.4
North Carolina	46450
Maryland (Rts. 213/301)	2160
Maryland (I-695))	2000

Lastly, the depth of the WP below the ground surface is required for input into IWEM. This value for this parameter is generally zero because the secondary material usually applied over the top of the ground surface. However, for the NC study area, the depth was specified at 4 feet below the surface because the fill was overlain by earthen material (Sherrill, 2003). Figure 10 displays a sample WMU parameter input screen from IWEM.



This screen allows you to enter or change waste pile parameters. Justifications for parameters are required.

Parameter	Value	Data Source
Distance to well (m)	7	MW1s
Area of waste pile (m^2) [requires site specific value]	46450	SIP (~12 acres)
Depth of base of the WP below ground surface (m)	4	SIR (13 ft avg)
Operational life (yr)	1	default

Figure 10. Sample WMU parameter input screen from IWEM.

2.1.2 Site-specific geologic/hydrogeologic data

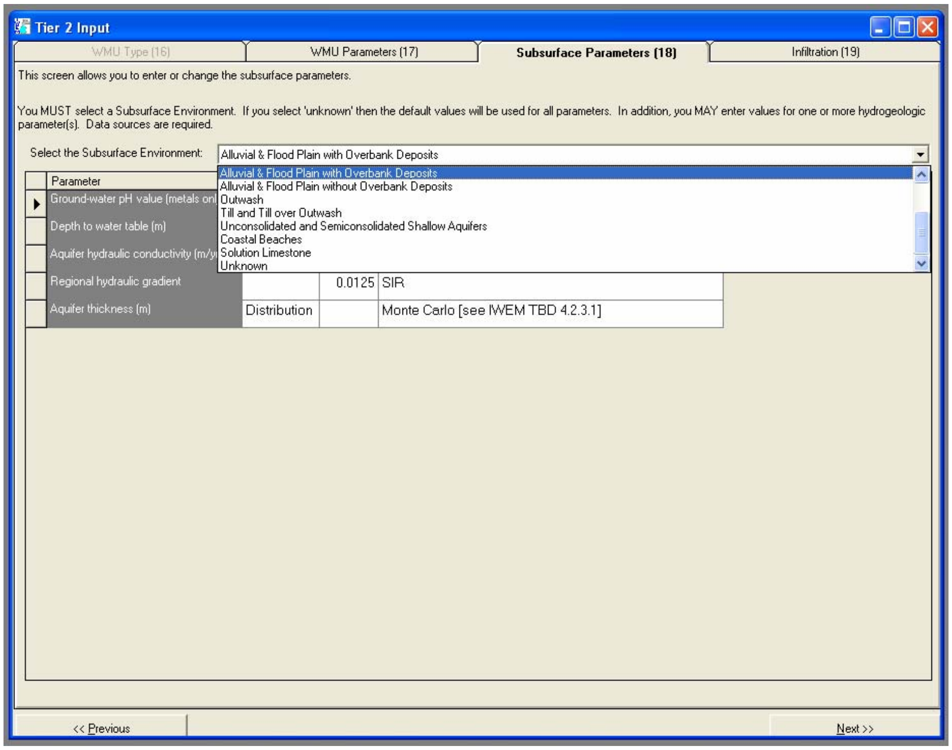
In addition to WMU parameters, data pertaining to a site's geologic and hydrogeologic makeup is crucial when modeling groundwater and solute transport. How groundwater and constituents behave in the subsurface is largely dictated by the material through which it travels.

IWEM, as well as most other groundwater models, requires geologic information which includes the type of subsurface environment (e.g. till over sedimentary rock, sand and gravel, alluvial and floodplain with overbank deposits, etc.) and soil type (e.g. sandy loam, silty clay loam, etc.). Additionally, the user is prompted to input various hydrogeologic parameters including:

- groundwater pH
- depth to water table (m)
- hydraulic conductivity (m/yr)
- hydraulic gradient
- aquifer thickness (m)

For some study areas (e.g. WisDOT), not all site-specific geologic/hydrogeologic data was available. To compensate for these unknown parameters, IWEM relies upon the EPACMTP Monte Carlo module to derive the data, allowing the model to perform probabilistic analyses of constituent fate and transport. A Monte Carlo simulation "is a statistical technique by which a quantity is calculated repeatedly, using randomly selected parameter values for each calculation" (EPA, 2002). Simply speaking, based on the site's subsurface environment, a Monte Carlo simulation is able to approximate the full range of possible outcomes for a particular unknown parameter, and its likelihood. Additionally, the Monte Carlo module in EPACMTP "makes it possible to incorporate variability into the subsurface pathway modeling analysis and to quantify the impact of parameter variability on well concentrations" (EPA, 2002). More detailed information pertaining to the Monte Carlo module is described in the *EPACMTP Technical Background Document (U.S. EPA, 2002a).*

All available geologic/hydrogeologic data was either obtained through the reports described in Chapter 1 or the USGS. Additionally, information was kept consistent between all models to ensure accurate comparisons between them. A summary of geologic/hydrogeologic input data for each study area in presented in Table 3.



This screen allows you to enter or change the subsurface parameters.

You MUST select a Subsurface Environment. If you select 'unknown' then the default values will be used for all parameters. In addition, you MAY enter values for one or more hydrogeologic parameter(s). Data sources are required.

Select the Subsurface Environment: Alluvial & Flood Plain with Overbank Deposits

Parameter			
Ground-water pH value (metals onl			
Depth to water table (m)			
Aquifer hydraulic conductivity (m/y			
Regional hydraulic gradient		0.0125	SIR
Aquifer thickness (m)	Distribution		Monte Carlo [see IWEM TBD 4.2.3.1]

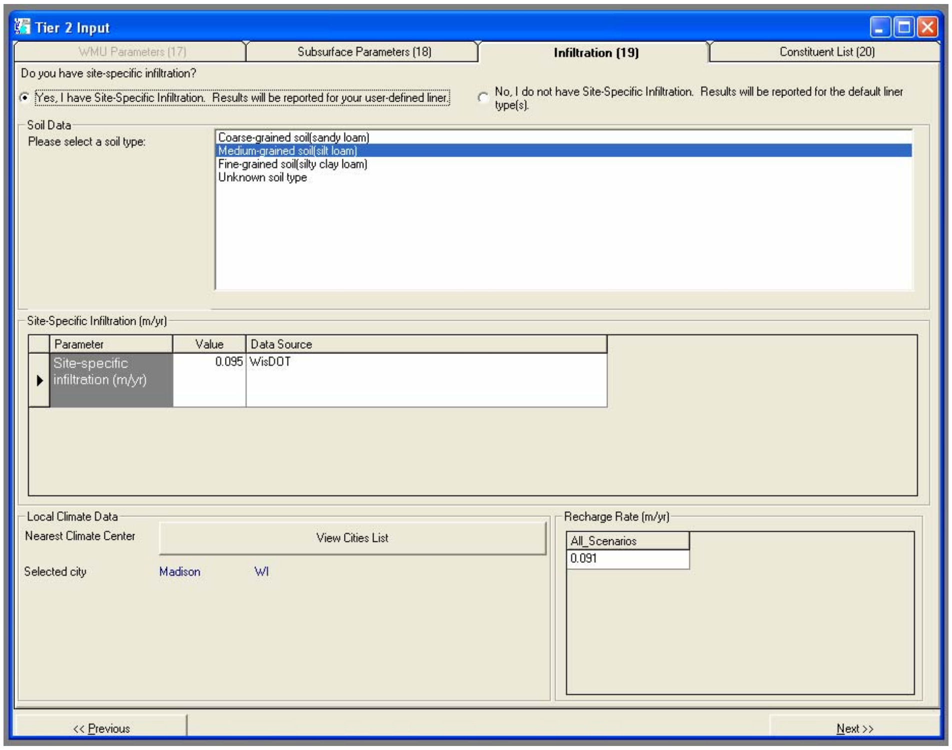
Figure 11. Sample geologic/hydrogeologic data input screen from IWEM.

Table 3. Geologic/hydrogeologic model input parameters for each study area (b = aquifer thickness; dh/dl = hydraulic conductivity; GW = groundwater; K = hydraulic conductivity; MC = Monte Carlo; WT = water table).

Study Area	**Subsurface Environment**	**Soil Type**	**GW pH**	**Depth to WT (m)**	**K (m/yr)**	**dh/dl**	**b (m)**
Wisconsin	till over sedimentary rock	silt loam	6.5	5	MC	MC	MC
North Carolina	alluvial & flood plain with overbank deposits	silty clay loam	MC	4	0.022	0.0125	MC
Maryland (Rts 213/301)	unconsolidated/ semiconsolidated shallow aquifer	sandy loam	5	6.1	MC	MC	18.3
Maryland (I-695)	unconsolidated/ semiconsolidated shallow aquifer	silty clay loam	6.5	0.75	MC	MC	36.6

2.1.3 Infiltration data

In order for a constituent to be leached from a source and carried down through the subsurface, an aqueous mechanism must exist to promote its mobility. In most cases, when considering WMUs, this mechanism refers to rainfall, or recharge. IWEM has a separate input screen which requires the user to specify the average annual recharge rate (m/yr) for the study area of interest, as well as the infiltration (flux) of the leachate through the bottom of the WMU (m/yr). Additionally, the type of soil that the leachate will encounter through the bottom of the WMU is required (e.g. silty loam). Figure 12 is a sample infiltration input screen for the WisDOT study area.



Do you have site-specific infiltration?

● Yes, I have Site-Specific Infiltration. Results will be reported for your user-defined liner.

○ No, I do not have Site-Specific Infiltration. Results will be reported for the default liner type(s).

Soil Data

Please select a soil type:

- Coarse-grained soil(sandy loam)
- Medium-grained soil(silt loam)
- Fine-grained soil(silty clay loam)
- Unknown soil type

Site-Specific Infiltration (m/yr)

Parameter	Value	Data Source
Site-specific infiltration (m/yr)	0.095	WisDOT

Local Climate Data

Nearest Climate Center

Selected city Madison WI

Recharge Rate (m/yr)

All_Scenarios
0.091

Figure 12. Sample infiltration data input screen from IWEM.

User-specified recharge rates are not allowed in IWEM. However, using the HELP model version 3.03, the IWEM database contains a list of average annual recharge rates for 97 climate stations in the lower 48 contiguous states, representing 25 climate regions (EOA, 2002). Table 4 lists the climate station and corresponding recharge rate used for each study area. For continuity purposes, these values were used for all models.

Table 4. Recharge rates by study area obtained from IWEM. Rates were used in all simulations for all models.

Study Area	**Climate Station**	**Recharge Rate (m/yr)**
Wisconsin	Madison, WI	0.091
North Carolina	Greensboro, NC	0.326
MD: Rt.213/I-695	Seabrook, NJ	0.243/0.143

IWEM does allow the user to specify site-specific infiltration data. Infiltration values were provided by The University of Wisconsin-Madison for the WisDOT study area for each test section. Additionally, infiltration rates for the coal ash used for construction of the routes 213/301 and I-695 overpasses in Maryland were provided by *Environmental Resources Management, Inc.* of Annapolis, MD. These values were used in all simulations for all models (Table 5).

Site-specific infiltration rates for the North Carolina study area were not available. Instead, pre-defined infiltration rates from the IWEM database were used. Based on the recycled material's permeability (e.g. low, medium, high), IWEM provides a numerical value for infiltration. For North Carolina, the low permeability designation was chosen for coal fly ash due its poor water transmitting properties. This corresponded to an infiltration rate of 0.243 m/yr.

Table 5. Site-specific infiltration data for WisDOT and Maryland sites.

Test-Section Material	**WisDOT Infltr. (m/yr)**	**MD Infltr. Rts. 213/301 (m/yr)**	**MD Infltr. I-695 (m/yr)**
Bottom Ash	0.0949	---	---
Fly Ash	0.0584	0.178	0.131
Foundry Sand	0.0110	---	---
Foundry Slag	0.0803	---	---

2.1.4 Constituent data

For the purpose of this project, only the fate and transport of metals (e.g. Cd and Pb) were modeled as they are the primary constituents related to secondary materials. Constituent data such as initial concentrations and distribution coefficients (K_ds) are essential information required to perform accurate and successful groundwater modeling of metals.

Site investigations from each study area yielded the types of metals detected in the reused materials as well as initial concentrations of each via laboratory testing. For the WisDOT and Maryland study areas, initial concentrations were measured from the leachate collected in lysimeters located directly below the fills (see Chapter 1). For the North Carolina data, initial concentrations were measured via TCLP testing. Metals detected and corresponding concentrations are listed in Tables 7a – c for each area. All concentrations are listed in parts per million (ppm).

Table 6a. Metals and corresponding initial concentrations detected in each secondary material for the WisDOT study area (Edil et al., 2003).

Material	Cadmium	Chromium	Selenium	Silver
Bottom Ash	0.0212	0.0151	0.0412	0.0118
Fly Ash	0.0032	0.0143	0.0263	0.0038
Foundry Sand	0.0118	--	--	--
Foundry Slag	0.0166	0.0319	0.0178	0.0039

Table 6b. Metals and corresponding initial concentrations detected in each secondary material for the North Carolina study area (Sherrill, 2003).

Material	Arsenic	Lead
Coal fly ash	0.11	0.353

Table 6c. Metals and corresponding initial concentrations detected in each secondary material for the Maryland study areas (ERM, 2004).

Material	Location	Arsenic	Barium
Coal fly ash	Routes 213/301	---	0.052
Coal fly ash	I-695	0 .037	---

The above data was used for input in all modeling scenarios and simulations. Detailed procedures for each model are described in the next sections.

In addition to initial concentrations, K_d values for each metal are required to perform accurate modeling simulations. The K_d is a constituent-specific parameter which is a measure of how strongly the leached constituent will bind to soil in the subsurface. The greater the K_d value, the more strongly a metal will attach itself to the soil, thus limiting its mobility through the subsurface and into the groundwater.

In IWEM, the modeler can either specify a user-defined K_d or rely upon the built-in USEPA developed chemical speciation model MINTEQA2 to derive a value if not known. IWEM modeling was performed both with using user-defined and MINTEQA2 values. User-defined numbers were obtained from a 1999 USEPA document which reported average K_d values for a variety of metals based on an extensive literature search. Mean values for metals considered in the research are presented in Table 7. These K_ds were used for modeling with HYDRUS-2D.

Table 7. EPA tabulated K_d values based on literature search (EPA, 1999).

Metal	**K_d (L/Kg)**
Ag (I)	398.1
As	1584.9
Ba (II)	100
Cd (II)	501.2
Cr (VI)	6.3
Pb (II)	5011.9
Se (IV)	20

2.2 IWEM Modeling

Comprehensive modeling (400+simulations) has been performed with IWEM to determine how the model responds when simulating water and contaminant transport from heavy metal bearing secondary materials into the subsurface. The objective of this work is to evaluate whether IWEM can be used as a predictive tool to accurately determine whether leaching from materials will result in significant changes in groundwater concentrations when the materials are reused as a base or sub-base in a roadway.

Several steps were taken to accomplish the aforementioned objective. First, modeling was performed to evaluate how IWEM responds to varying input parameters. This included observing the model's behavior while treating heavy metal transport as a function of:

1. time/WMU operational life;
2. receptor well distance secondary material source;
3. varying distribution coefficient values (K_d);
4. waste management unit (WMU) areas.

Variable parameters 1, 2 and 4 were simulated primarily using WisDOT data for model input, largely because only information from this study area was available earlier on in the validation process when this modeling occurred. Additionally, the WisDOT project provides the greatest amount of data due to the use of four recycled materials at the study area (only fly ash is used at the North Carolina and Maryland sites). Input data from all three study areas was used to evaluate IWEM's response to varying metal K_d values.

2.2.1 Variable WMU operational life with fixed receptor well distance

To evaluate how IWEM treats heavy metal transport as a function of leaching time, thirteen simulations were run for each test section at the WisDOT study area (52 total), where the operational life of the secondary material application was varied. Each simulation was performed with a receptor well located an arbitrarily fixed 50 meters from the leachate source.

The thirteen simulations spanned a range from 1 to 200 years (max input value for IWEM) which included: 1, 5, 10, 15, and 20 to 200 years at 20 year intervals. All other input values were held constant for each run. Distribution coefficient values derived from

MINTEQA2 were applied. For the first 20 years, the model was run at 5 year intervals in order to determine when IWEM would recognize the presence of the constituent at the receptor well.

2.2.2 Variable receptor well distance from source with fixed WMU operational life

The objective of this portion of research was to evaluate how IWEM predicts constituent mobility in the subsurface as a function of leaching distance from the source. Again, the WisDOT information was used as model input for the same reasons discussed earlier.

Nine simulations were run for each section (36 total) varying the distance of the groundwater receptor well from the leachate source. The nine simulations spanned a range of distances from 10 to 500 meters which included: 10, 25, 75, 100, 150, 200, 300, 400, and 500 meters. All other input values were held constant for each run and K_d values were again derived using MINTEQA2. For the purpose of this series of simulations, IWEM's default operational life for a waste pile (40 years) was used as the fixed time.

2.2.3 Variable K_d values

A series of simulations were run where user-define K_ds were varied to evaluate how IWEM responds to such changes. Twelve runs were executed using different K_d values for cadmium in bottom ash from the WisDOT data. IWEM's default operational life of 40 years for a WP was chosen as the run time. The arbitrarily chosen K_d values used ranged from 0 to 8 which included: 0, .001, .01, .05, .1, .5, .75, 1, 2, 3, 5, and 8. All other input values (e.g. hydrogeologic and infiltration parameters) were held constant for each run. For the purpose of these series of simulations, an arbitrary well distance of 50 meters from the leachate source was selected. Simulations were not performed for the other test sections under the assumption they would yield the same trends.

Upon initial evaluation of the IWEM modeling results where MINTEQA2 was used to derive K_d values, it appeared the final concentrations were higher than expected. It was felt that attenuating factors such as dispersion and dilution would have played a greater role in reducing concentrations over the transport distance specified. A hypothesis was made that the K_d values being used were smaller (possibly by several orders of magnitude) than those reported in the literature. However, IWEM does not produce an output file listing which K_d values were selected by MINTEQA2, thus these numbers were not known. To investigate this observation further, several simulations (using WisDOT data) were taken and used to back-calculate K_ds. This was accomplished by randomly selecting user-defined K_d values and running simulations until final concentrations matched those produced by the MINTEQA2 K_d derived runs.

The results and conclusions from the work above (presented in Section 2.0.3) prompted the running of time-dependent IWEM simulations using the EPA reported K_d data listed in Section 2.1.4. The purpose of this was to determine what difference, if any, the low K_d values selected by MINTEQA2 had on the final groundwater concentrations observed at the receptor well by comparing them to the simulations using EPA reported K_d values. Based on comparisons of the EPA reported K_ds with other literature values, confidence in the accuracy of these numbers is strong. Thus, it stands to reason that if MINTEQA2 is drawing upon unrealistically low K_d values, then IWEM may be viewed as being too conservative and over predicting final groundwater output concentrations.

Runs were executed using input data from all three study areas. Using the WisDOT data, nine simulations were run for each test section (40 total). The simulations spanned a range from

1 to 200 years which included: 1, 5, 10, 15, 20, 50, 100, 150 and 200 years. For all runs, a fixed receptor well distance of 50 meters from the source was used keeping all other input values constant for each run. IWEM modeling using the North Carolina and Maryland data are discussed in Sections 3.2.5 and 3.2.6 respectively.

2.2.4 Variable WMU areas

Lastly, to evaluate IWEM's response to changing input parameters, multiple simulations were run while varying the area of the WMU of interest (waste pile in this research). As discussed earlier in this chapter, data from WisDOT was used for this portion of the research. In particular, metals were simulated leaching from the bottom ash section of the site. The other three materials were not modeled based on the assumption they would yield the same trends. All other input values were held constant.

Areas modeled include the arbitrarily chosen 200 m^2 section discussed in Section 2.1.1, a one mile stretch of highway covering 8367 m^2, and the 790 m^2 bottom ash from the WisDOT site. Five simulations were run for each area using varying WP operational lives: 20, 60, 100, 160, 200 years. A receptor well was located a fixed distance of 50 meters from the source.

2.2.5 Additional Modeling with WisDOT Data

As described in Chapter 1, two monitoring wells were installed adjacent to the bottom ash and fly ash test sections, 6 meters from the Wisconsin State Highway 60 shoulder. Continuous groundwater sampling and subsequent laboratory analyses have demonstrated no concentrations of Ag, Cd, Cr and Se above the MDL at these wells 5.5 years after the application of the materials.

Additional modeling was performed for both test sections to evaluate if IWEM predicts similar observations. The model was run for 1, 2, 3, 4, 5, and 5.5 years using the actual material areas for each test section (790 m^2 and 395 m^2 for bottom and fly ash respectively) with fixed receptor well distances of 6 meters. All other input data (e.g. initial metal concentrations and leachate fluxes) was held constant. Additionally, distribution coefficients were derived using MINTEQA2.

2.2.6 Modeling with North Carolina data

Data from the Highway 301 at Swift Creek project near Battleboro, NC (discussed in Chapter 1) was introduced midway through the research portion of this project. Unlike the WisDOT data where no elevated groundwater concentrations had been observed, this study area presented a situation where the secondary material (coal fly ash) applied at the site caused groundwater concentrations to exceed regulatory standards (As and Pb in this case). Because of these exceedances, this data provided the perfect opportunity to model with IWEM in order to determine if the model would have predicted the contamination prior to coal ash reuse.

In a June 2004 groundwater investigation, As and Pb exceedances (0.028 and 0.068 ppm respectively) were detected in monitoring well MW1s located approximately 7 meters from the east edge of the reused coal ash. Using the input data described earlier in this section, IWEM simulations were set up to replicate actual conditions at the site in order to model the transport of As and Pb to MW1s. Two sets of time-dependent runs were executed using: 1. MINTEQA2 derived K_ds and 2. EPA reported K_ds listed in Table 7. Seven simulations were performed for each K_d scenario at 1, 5, 10 (time between coal ash reuse and investigation), 20, 50, 150 and 200 years. Following the modeling, observations were made to determine if IWEM was able to predict the groundwater contamination reported from field data, and if so, to what accuracy.

Additionally, modeling described in the previous paragraph was applied to MW2s at the site located approximately 48 meters east from the edge of the coal ash fill and 41 meters downgradient of MW1s. No As or Pb contamination was detected at this well. Modeling was performed to evaluate IWEM's ability to account for attenuation factors (e.g. dispersion and adsorption) which would be responsible for the absence of As and Pb at MW2s after 10 years. Furthermore, observations were made beyond 10 years to analyze if As and Pb would eventually be introduced into MW2s.

2.2.7 Modeling with Maryland data

As with the North Carolina data, leaching information from the Maryland sites was used for modeling with IWEM to further evaluate the model's predictive accuracy with respect to secondary materials. While no metal MCL exceedances were found in the groundwater at the site, detections of As, Ba and Se were encountered in several areas of the Routes 213/301 and I-695 overpasses.

Only the southern area of the Routes 213/301 overpass was modeled under the assumption that the north cluster would yield similar trends/results. Here MW-102 was installed in a pre-existing exploratory borehole through the coal ash and extended 10 feet below the water table with a 5-foot screened interval. Additionally, lysimeter L102-9 was installed to the base of the coal ash to monitor groundwater solute concentrations entering the subsurface (ERM, 2004). The concentrations detected here were used as initial input concentrations into IWEM.

From 1999 to 2003, field sampling of MW-102 revealed detections of Ba which was used as the solute of concern for IWEM modeling. The last round of sampling in 2003 indicated Ba at 0.06 ppm. In 1999, Ba was detected at 0.052 ppm in L102-9 which was used as the initial input concentration (ERM, 2004). Using input parameters described earlier in this chapter, simulations were run with both MINTEQA2 derived and EPA tabulated distribution coefficients with a coal ash operational life of 10 years (reflective of the time between coal ash application and Ba detection in MW-102 in 2003). Once modeling was complete IWEM results were compared to the Ba concentrations detected in MW-102.

For the I-695 overpass, transport of As and Se in the groundwater to MW-3 (in cluster 3) was modeled. Again, only one area was taken into account under the assumption that the other clusters would yield similar trends/results. Additionally, the highest concentrations of As and Se were found in this vicinity. As with MW-102, MW-3 was installed in a pre-existing exploratory borehole through the coal ash and extended 10 feet below the water table with a 5-foot screened interval. Adjacent to the well, lysimeter L3-30 was installed to the base of the coal ash to monitor groundwater solute concentrations entering the subsurface (ERM, 2004).

From 2000 to 2003, field sampling of MW-3 and L3-30 continuously showed detections of As and Se in the groundwater (although never exceeding the MCL). Concentrations of As and Se (0.037 and 0.029 ppm respectively) detected in L3-30 during the first sampling event in 2000 were used for initial concentrations in IWEM. With the input parameters described earlier in this chapter, simulations were run with both MINTEQA2 derived and EPA tabulated distribution coefficients with a coal ash operational life of 5 years (reflective of the time between coal ash application and As/Se detection in MW-3 in 2003). Once modeling was complete IWEM results were compared to the As and Se concentrations of 0.01 and 0.023 ppm respectively detected in MW-3 in 2003. These results are reported in Chapter 3.

2.3 HYDRUS-2D Modeling

Following IWEM modeling, the next phase of research involved comparing IWEM's results to those of other solute transport groundwater models using the same input. Doing so allowed for the analysis of whether IWEM can accurately predict groundwater concentrations at a point down gradient from a secondary material source. IWEM simulates 1-D flow in the unsaturated zone and 3-D flow in the saturated zone. A situation such as this requires the use of two models in order to effectively mimic the secondary material leaching scenario modeled by IWEM.

HYDRUS-2D was used to simulate one dimensional (1D) vertical solute transport from the secondary material source through the unsaturated zone down to the water table. Not only can HYDRUS provide 1D flow to mimic that modeled by IWEM, but it can do so through variably saturated media representative of the unsaturated zone. Input including initial metal concentrations and fluxes from the secondary material source, soil type, recharge rates, and hydrogeologic parameters (e.g. conductivity) remained unchanged from those used for IWEM simulations. Upon running HYDRUS, output concentrations and fluxes were read from the lower boundary of the modeled domain which is representative of the top of the water table (i.e. 0 pressure head).

Two scenarios were run with HYDRUS using the WisDOT data for input: 1. with a cross-sectional length of 14 meters (m) to mimic the arbitrarily chosen 200 m^2 WMU area ($(14\ m)^2 \sim 200\ m^2$) used for most of the previous IWEM simulations; and 2. with a cross-section length of 1000 m to represent a real life application of secondary materials along a stretch of highway. The purpose of using these extreme lengths is to compare the output concentrations from both and determine if increasing the cross-sectional horizon has any dramatic effect on the concentration observed at the water table along the plume centerline. In previous IWEM work, it was observed that increasing the WMU area had an almost linear effect on the output groundwater concentrations. It was thought that this is an unrealistic result that may be attributed to IWEM assuming its WMUs to be square which is not representative of roadway geometry (rectangular). Chapter 3 discusses this topic in greater detail. Both scenarios were run using the average EPA tabulated K_d values from Table 7.

Additionally, the 14 m cross-sectional scenario was run using a K_d value of zero for each solute (Ag, Cd, Cr, and Se). The majority of the IWEM simulations run to date have relied upon K_d values drawn from the MINTEQA2 database incorporated into the software. Earlier work has demonstrated that these values are relatively low (on the order of magnitude of one or less) and comparison to the HYDRUS-2D results using a K_d value of zero (i.e. low K_d) should help confirm this observation . Moreover, as discussed earlier, IWEM had been run as a function of time using the tabulated EPA values allowing once again for effective comparisons.

All HYDRUS simulations were run for 200 years using bottom ash data, which yielded the highest leachate concentrations. No runs were performed for the other materials in the research (e.g. foundry slag) under the assumption that these would yield identical trends. The unsaturated zone was represented by a simple rectangular geometry. The boundary conditions (BC) of the modeled domain were set up such that the top was defined by a daily *constant flux BC* representing the incoming water leaching from the secondary material as reported by Sauer et. al (2005); the bottom as a *constant pressure head BC* set equal to zero which is characteristic of the water table; and the vertical sides as *no-flow BCs*. Additionally, five observation nodes were set along the center of the domain extending from the surface to the water table. Solute concentrations and fluxes, as well as water fluxes could be read from these nodes. Figures 13 and 14 display graphical representations of the boundary conditions and nodal arrangements for the 14 m cross-section respectively.

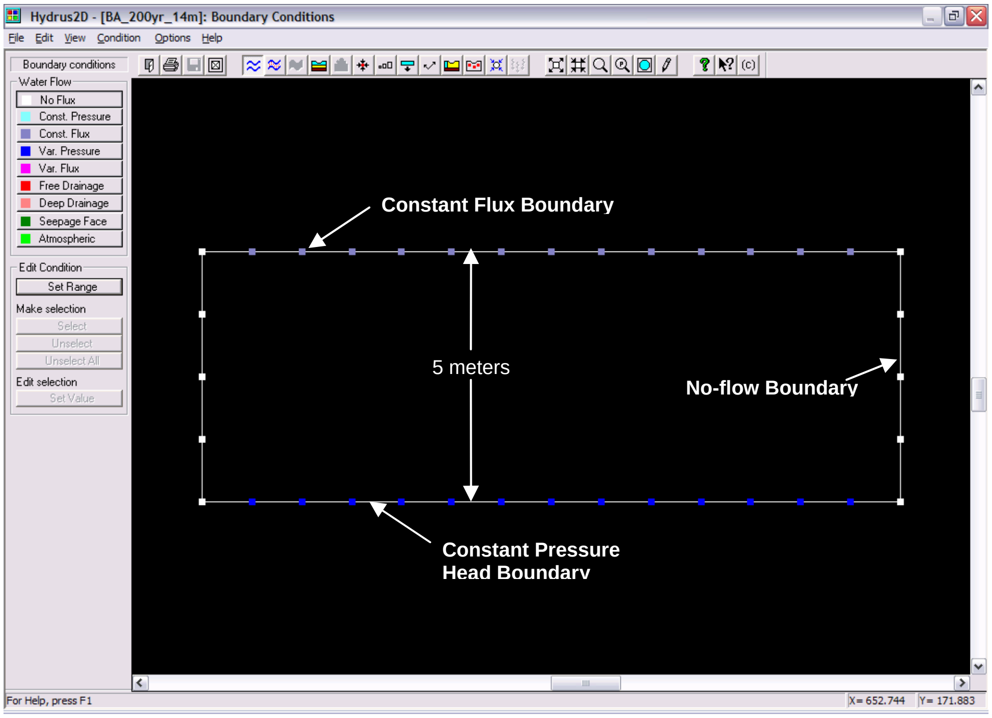


Figure 13. Graphical display of boundary conditions used for 14 m cross-section in HYDRUS-2D.

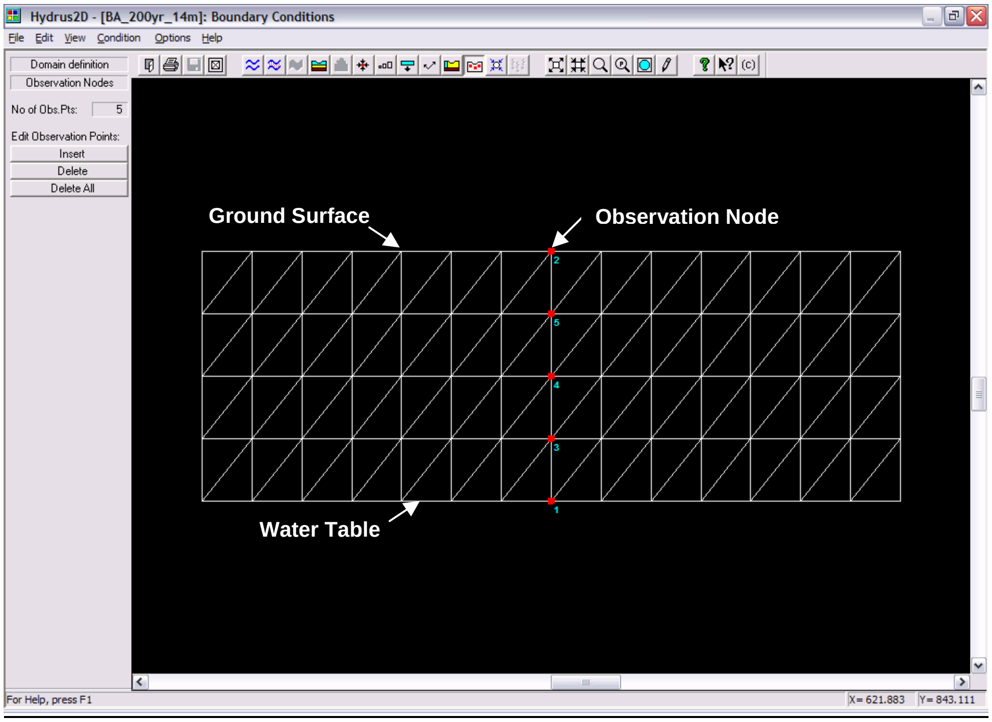


Figure 14. Graphical display of observation nodes used for 14 m cross-section in HYDRUS-2.

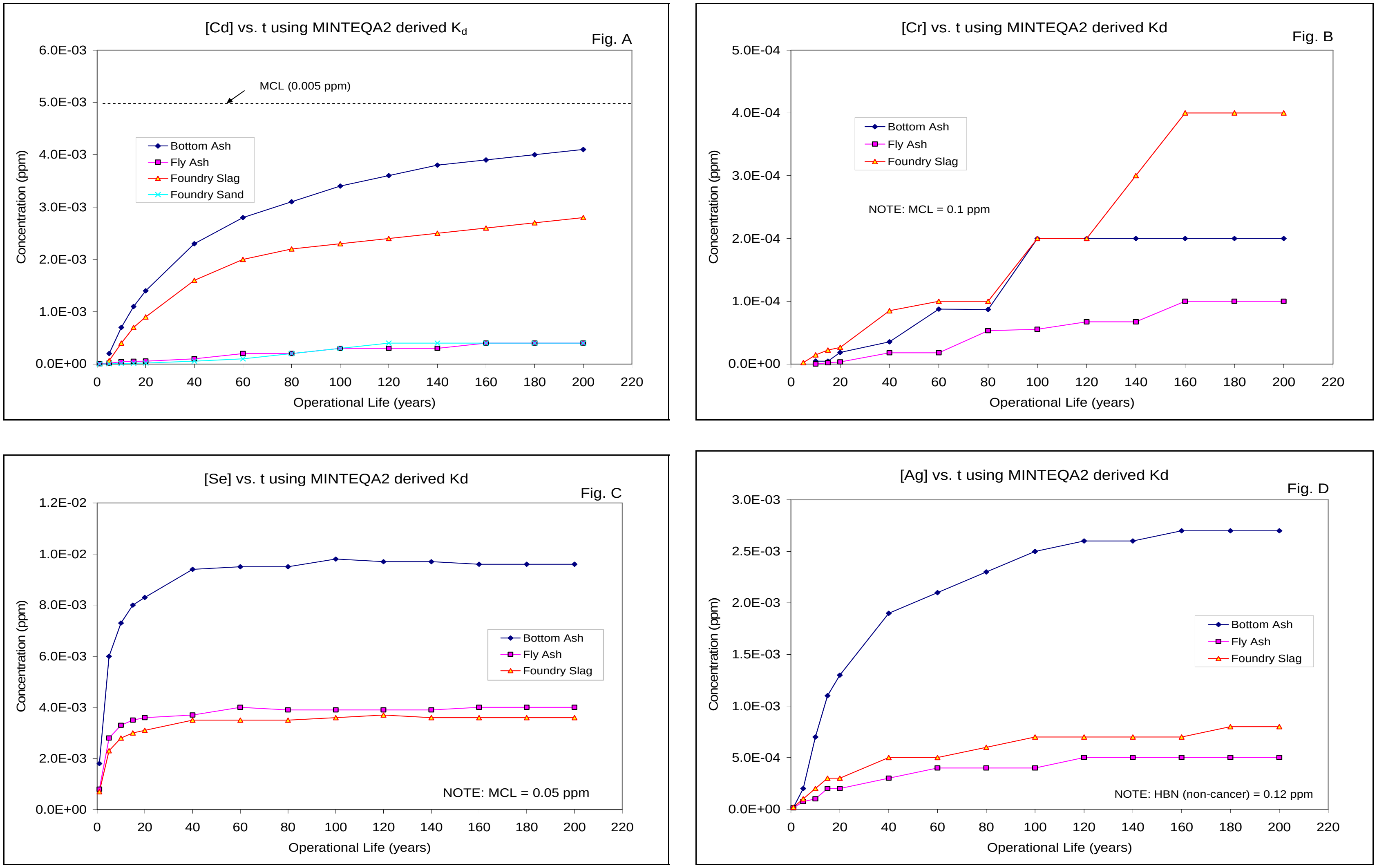
3. RESULTS AND DISCUSSION

3.0 IWEM Modeling

After running 400+ simulations with IWEM, using various input data provided by select study areas, results were analyzed to help evaluate and form conclusions regarding IWEM's performance as a fate-and-transport model with respect to the beneficial use of secondary materials in a road environment. Initial modeling was performed to observe how IWEM responded to varying input parameters, primarily using data from the WisDOT study area. Next, using input data from sites with elevated groundwater concentrations caused by secondary material leaching, the model was tested to determine if IWEM would have predicted such concentrations. Finally, comparisons were made between IWEM and HYDRUS-2D to evaluate agreement between the two models.

3.0.1 Variable WMU operational life with fixed receptor well distance

To evaluate how IWEM treats heavy metal transport as a function of leaching time, thirteen simulations (spanning 1 to 200 years) were run for each test at the WisDOT study area (52 total), where the operational life of the secondary material application was varied. The metals simulated were Ag, Cd, Cr, and Se. Each simulation was performed with a receptor well located an arbitrarily fixed 50 meters from the leachate source. Once all the runs were complete, output concentrations of each constituent for each test section were plotted verse time (Figures 15A through 15D).



Figures 15A-D. Groundwater concentration vs. time predicted by IWEM for metals leaching from recycled materials.

The plots in Figure 15 depict similar trends for the transport of metals in the subsurface. Initially, as leaching time increases, metal concentrations increase quickly in the receptor well down gradient. However, as time progresses, concentration increases diminish resulting in steady state behavior caused by dilution. In some cases (e.g. Cr and Se), the concentrations eventually plateau indicating no net sorption is taking place, where the difference between the input concentration and the plateau concentration demonstrates the magnitude of dilution that has occurred in the system. This shows that new contaminant entering the system is no longer increasing apparent groundwater concentrations as a result of dilution by surrounding freshwater.

Furthermore, in the cases of Cr for all four materials and Cd for bottom ash and foundry slag, detectable groundwater concentrations do not appear in the receptor well until approximately five years after the material is applied. This phenomenon illustrates that, in addition to dilution, IWEM is effectively accounting for metal adsorption onto aquifer materials as the constituents travel through the unsaturated zone. Once breakthrough is achieved, the constituents eventually enter the saturated zone where they mix with the groundwater and flow to the receptor well. If adsorption occurs, then one would theoretically expect to observe this delayed response.

Normally, after a certain period of time, it would be expected for the concentration of a particular constituent to decrease with dilution as a result of a source being finite. In an actual field situation, waste within a finite source (as with secondary material applications) would eventually be depleted and, thus, would no longer contribute to the formation of leachate into the subsurface. IWEM does not depict such a scenario here because a waste pile (selected WMU) is assumed to be a continuous-type source where leaching occurs at a constant leachate concentration equal to the initial input. In other words, leachate is continually being introduced into the unsaturated and saturated zones with no depletion of the constituent of concern (COC) occurring within the waste pile material (e.g. bottom ash). This assumption is acceptable however, because IWEM considers a waste pile to be a temporary source with an average operational life of 40 years (even though model simulations were run for 200 years). The leaching of metals over 40 years is not considered to be a significant amount of time due to their slow moving nature within the subsurface. Although the average operational life of a waste pile is 40 years, the model was run for 200 years to simply gage its response to achieving equilibrium conditions.

Based on the discussion in the preceding paragraphs, it appears that IWEM is accurately portraying the movement of metals within the subsurface as a function of time. Thus, keeping the MCL of a particular metal in mind, it seems one can determine, at least to a first approximation, if a certain material will contribute an appreciable concentration to groundwater a particular distance from the source. An informed decision can then be made whether the material of interest is safe enough for beneficial use or not. In the case of all the metals modeled here, it would appear that each secondary material would be safe enough to reuse for 200+ years under this scenario (i.e. fixed receptor well 50 meters from source) and using the MCL as criterion.

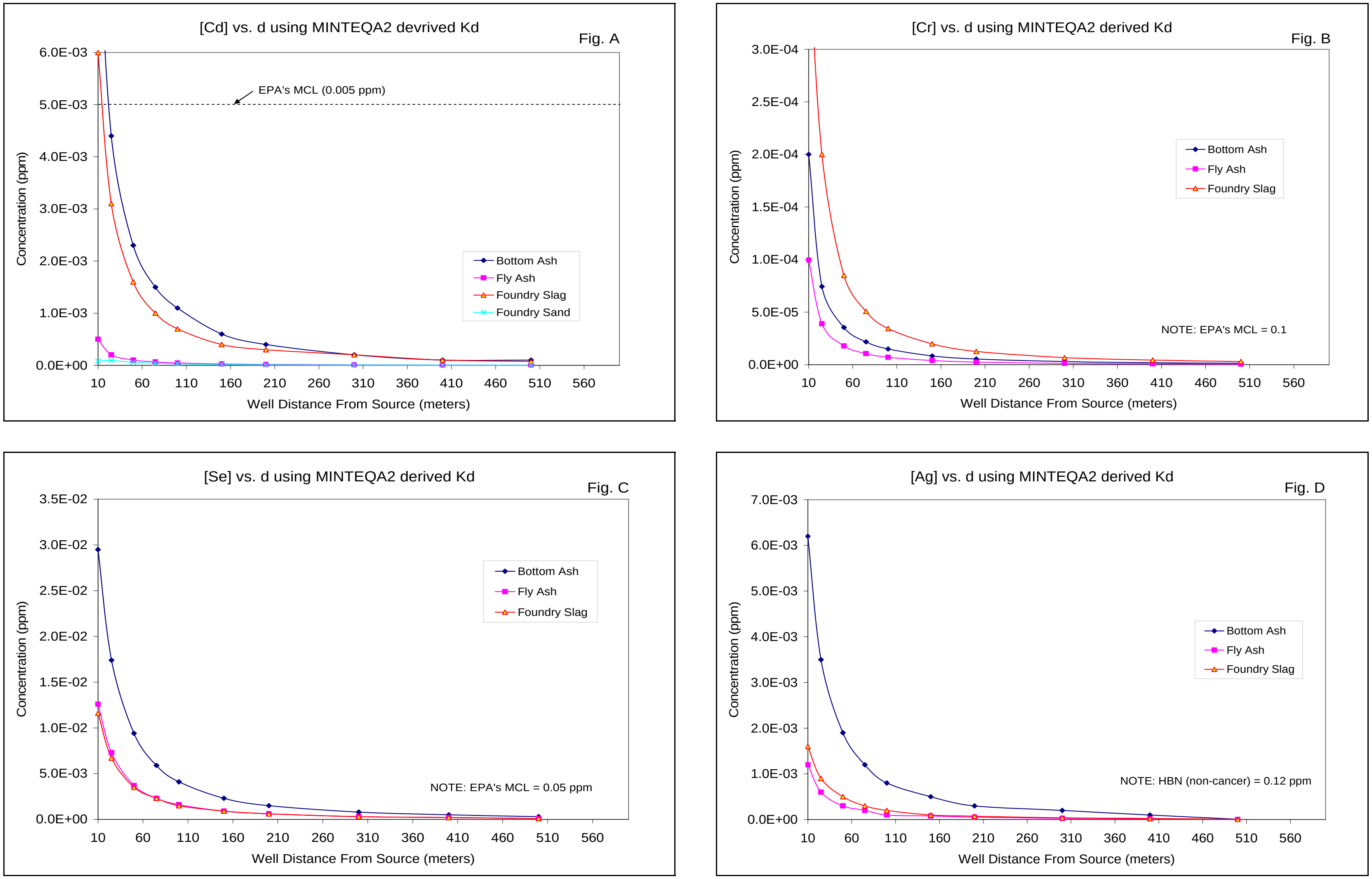
It should also be noted that while Cr displays an unusual step-like behavior with increasing time (for reasons unknown), the overall trend is similar to the other metals, thus it is viewed as acceptable data for this research. All simulations performed for Cr throughout this research exhibited the same trend regardless of input concentration, therefore it reasonable to attribute the strange behavior to IWEM performance and not input parameter uncertainty.

3.0.2 Variable receptor well distance from source with fixed WMU operational life

To evaluate IWEM's heavy metal transport capabilities as a function of receptor well distance from the source, nine simulations were run for each test section at the WisDOT study area (36 total), where the well distance was varied from 10 to 500 meters. The metals simulated were Ag, Cd, Cr, and Se. Each simulation was performed for a fixed leaching time (WMU operational life) of 40 years (average operational life for waste piles). Once all the runs were complete, output concentrations of each constituent for each test section were plotted versus well distance (Figures 16A through 16D).

An evaluation of Figures 16A through 16D clearly illustrates IWEM's ability to show the inverse relationship between increasing well distance and decreasing concentration along the plume centerline, as would be expected. With increasing transport distance (i.e. increased well distance) attenuation and dilution factors dominate in the subsurface and act to reduce the metal concentrations in the groundwater. IWEM successfully accounts for these factors via solving the advection-dispersion equation within the unsaturated and saturated zones (see Chapter 2).

Based on the work presented here, it appears the IWEM is accurately portraying the movement of metals within the subsurface as a function of receptor well distance from the leachate source. Keeping the MCL of a particular metal in mind, it seems one can determine, at least to a first order degree, if a certain recycled material will contribute an appreciable concentration to groundwater for a particular operational life. Thus, an



Figures 16A-D. Groundwater concentration vs. receptor well distance for metals leaching from recycled materials after 40 years.

informed decision can be made whether the material of interest is safe enough for beneficial use in a particular area based on the source/location for regional groundwater use (e.g. drinking water). In the case of all the metals modeled here, it would appear that each secondary material would be safe enough to reuse over a 40 year period if kept at least 35 meters from the nearest source of usable groundwater (as determined from Figure 16A. However, peak concentrations may occur beyond 40 years, thus a time dependent simulation (Section 3.0.1) would become necessary to run in conjunction with this data to truly determine the usability of the material.

3.0.3 Variable K_d values

As detailed in Section 2.2.3, twelve runs were executed using arbitrary user-defined K_d values for cadmium in bottom ash from the WisDOT data to evaluate how IWEM responds to such changes. After the twelve simulations were complete, the output concentrations were plotted as a function of the corresponding K_d used as depicted in Figure 17.

Analysis of Figure 17 clearly shows that IWEM accurately portrays the inverse relationship between K_d and concentration. This result establishes user confidence in IWEM's ability to account for adsorption of metals onto aquifer materials in order to help provide an accurate output concentration. However, it should be noted that over a longer period of time, after breakthrough has been achieved, concentrations would eventually become independent of the distribution coefficient. As a result, deviation from the trend depicted in Figure 17 would occur.

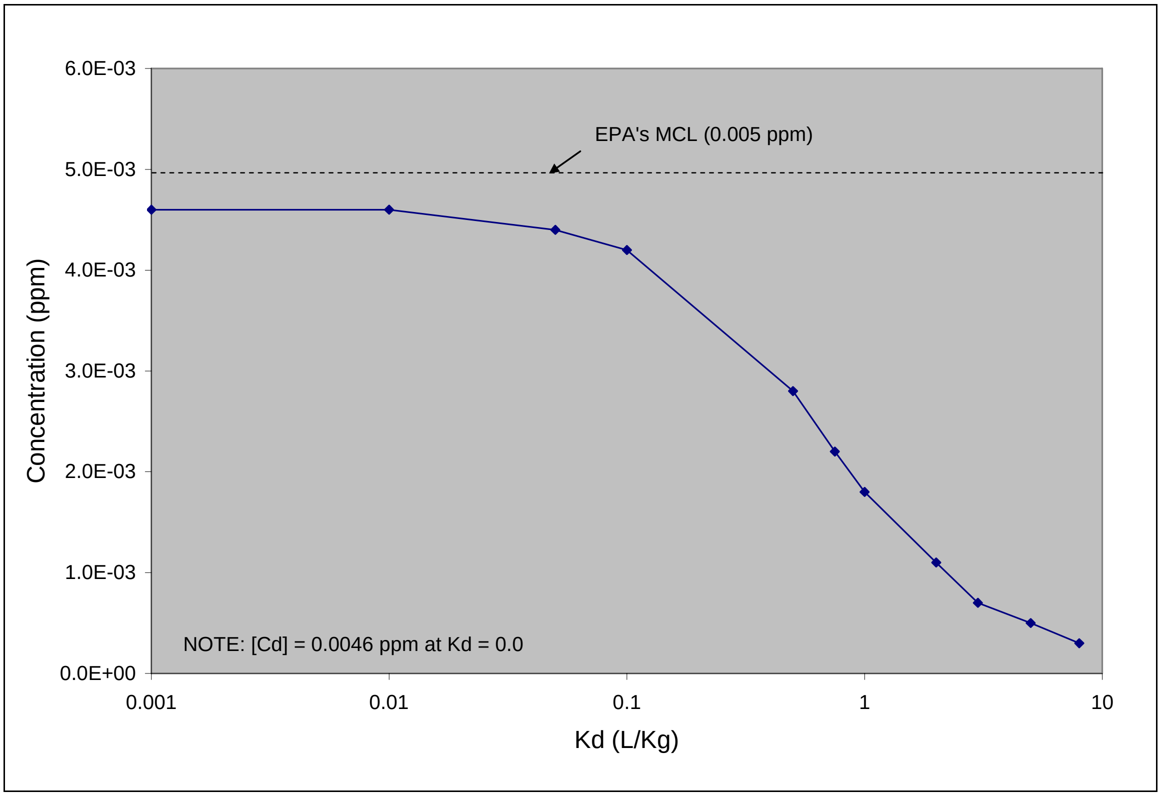


Figure 17. Cadmium concentrations as a function of variable K_d values. The simulation was run for bottom ash from the WisDOT data with a receptor well located 50 meters from the source over a leaching period of 40 years. Initial Cd concentration equal to 0.0212 ppm.

While Figure 17 depicts the proper concentration/K_d relationship for early time, the arbitrarily chosen K_d values are noticeably smaller (by several orders of magnitude) than distribution coefficient values normally reported in the literature for cadmium (as well as other heavy metals). For example, the average K_d for Cd reported by USEPA earlier in Chapter 3 is 598 L/Kg. The coefficients presented in the above figure suggest that when MINTEQA2 is used to derive K_ds, the values chosen are unrealistically small compared to reported literature values. Recalling from Section 2.2.3, an attempt to back -calculate K_d values was performed to investigate the magnitude of the MINTEQA2 derived distribution coefficients. Results of this procedure did in fact show that MINTEQA2 was selecting K_d values much smaller than those reported in the literature (especially those reported by the EPA). It was determined that K_d

values used were on an order of magnitude of 1 (and often less than that). Thus, if K_d values used are lower than they should be, then IWEM is likely producing higher than expected output concentrations which would label the model as being conservative (over predicting concentrations in groundwater).

However, it should be noted by the user that peak concentrations (regardless of the K_d value used) may not occur until beyond that maximum allowed modeling time (even if the material has been removed). This could result in a situation where the user is mislead into believing a certain material is safe for reuse after a particular time, when in fact unacceptable concentrations in groundwater could result some time beyond the realm of modeling. For example, IWEM may determine that after 50 years an application of coal fly ash will not result in As levels above the MCL in groundwater. Thus the user may be confident to apply the ash unaware that an element could potentially cause adverse conditions beyond 200 years (IWEM maximum allowed modeling time) and affect future generations.

Conversely, if IWEM determines a material is clean enough for reuse, this conservatism can be viewed as a confirmation, knowing that the groundwater concentration will be actually less than predicted.

As discussed in Section 2.2.3, to investigate IWEM's conservatism further, the bottom ash simulations presented in Section 3.0.1 were rerun using USEPA K_d values. Simulations were not run for Cr because IWEM does not allow user specified K_d values for this particular metal. Table 8 shows comparisons between the output concentrations (ppm) generated using MINTEQA2 derived and EPA tabulated distribution coefficients.

An analysis of Table 8 shows that for each metal, the concentrations produced using MINTEQA2 derived K_ds are larger than those calculated with the EPA tabulated values.

Often, these numbers are higher by several orders of magnitude. Based on the inverse relationship between distribution coefficient and concentration, Table 8 clearly demonstrates that MINTEQA2 is drawing upon coefficients smaller than reported by the EPA which explains why final concentrations are higher due to less attenuation of the constituents by soil particles.

Table 8. Comparison between output concentrations (ppm), as a function of time, generated using MINTEQA2 and EPA K_ds with WisDOT data.

	Cd		**Se**		**Ag**	
Time (yrs)	MINTEQA2	EPA	MINTEQA2	EPA	MINTEQA2	EPA
1	0	0	1.80E-03	5.65E-06	1.67E-05	0
5	2.00E-04	0	6.00E-03	2.82E-05	2.00E-04	0
10	7.00E-04	0	7.30E-03	5.65E-05	7.00E-04	0
15	1.10E-03	0	8.00E-03	8.47E-05	1.10E-03	0
20	1.40E-03	0	8.30E-03	1.00E-04	1.30E-03	0
50	2.50E-03	0	9.40E-03	3.00E-04	2.00E-03	0
100	3.40E-03	0	9.80E-03	6.00E-04	2.50E-03	0
150	3.80E-03	0	9.70E-03	8.00E-04	2.60E-03	0
200	4.10E-03	0	9.60E-03	1.10E-03	2.70E-03	0

Again, the values of these K_ds are not known because IWEM lacks the production of an output file stating the selected values. The distribution coefficients could be back-calculated based on the iteration procedure described earlier. However, while this approach seems to yield accurate results, the procedure is very time consuming and can easily be avoided with the generation of an output file after each run.

Additionally, with the coal fly ash data from the North Carolina study area, a series of IWEM simulations were performed using MINTEQA2 derived and EPA tabulated K_ds. Results from these runs are presented in Table 9 and again it can be seen that the concentrations generated using MINTEQA2 are significantly larger than those produced with the EPA distribution coefficients. In fact, the MINTEQA2 outputs quickly reach the level at which the concentrations are equal to the initial model input concentrations (0.11 and 0.353 ppm for As and Pb respectively). These results are further confirmation that MINTEQA2 is using K_ds smaller than those normally expected from the literature.

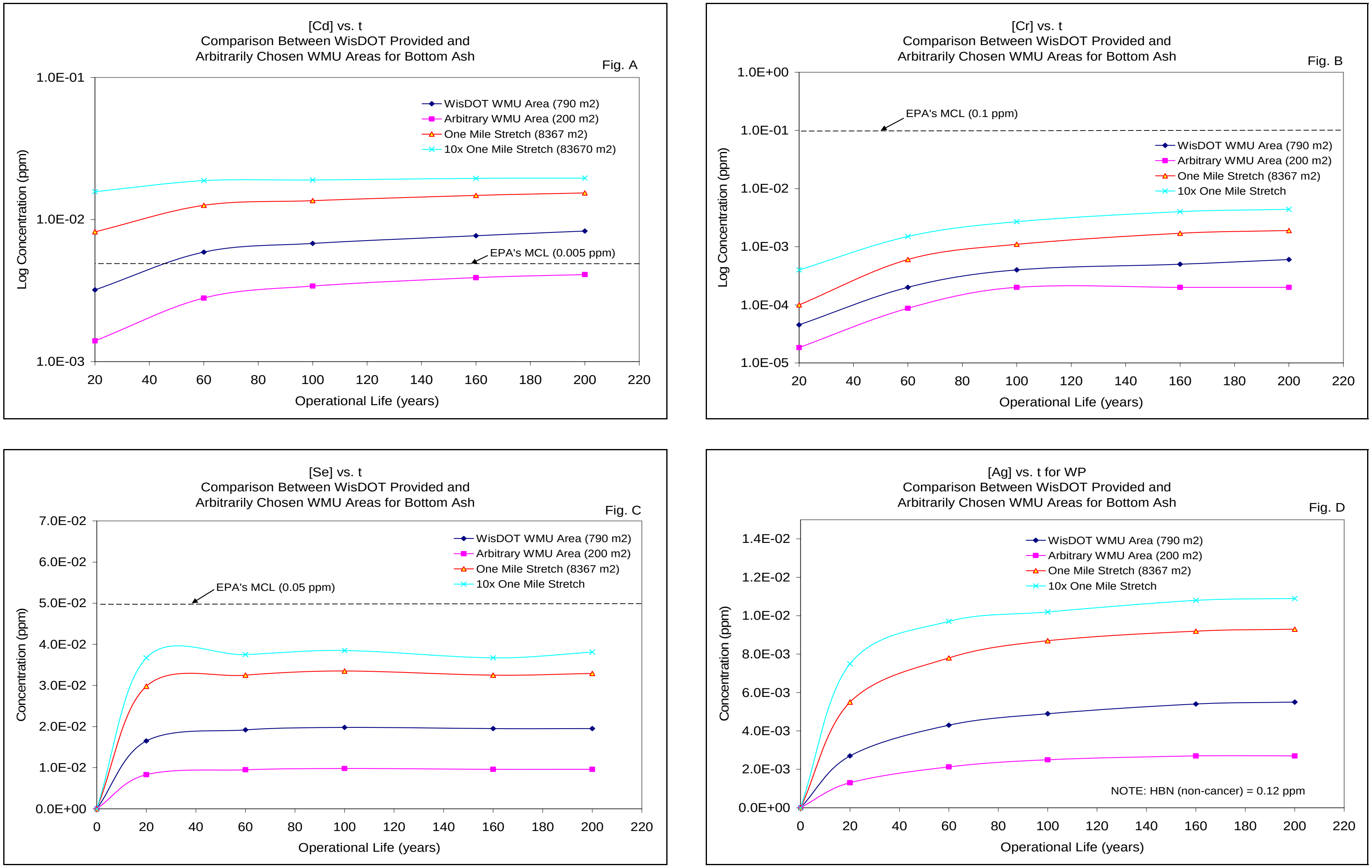
Table 9. Comparison between output concentrations (ppm), as a function of time, generated using MINTEQA2 and EPA K_ds with North Carolina data.

	As		Pb	
Time (yrs)	MINTEQA2	EPA	MINTEQA2	EPA
1	5.11E-02	0	3.52E-02	0
5	1.10E-01	0	1.18E-01	0
10	1.10E-01	0	1.50E-01	0
20	1.10E-01	0	3.53E-01	0
50	1.10E-01	0	3.53E-01	0
100	1.10E-01	0	3.53E-01	0
150	1.10E-01	0	3.53E-01	0
200	1.10E-01	0	3.53E-01	0

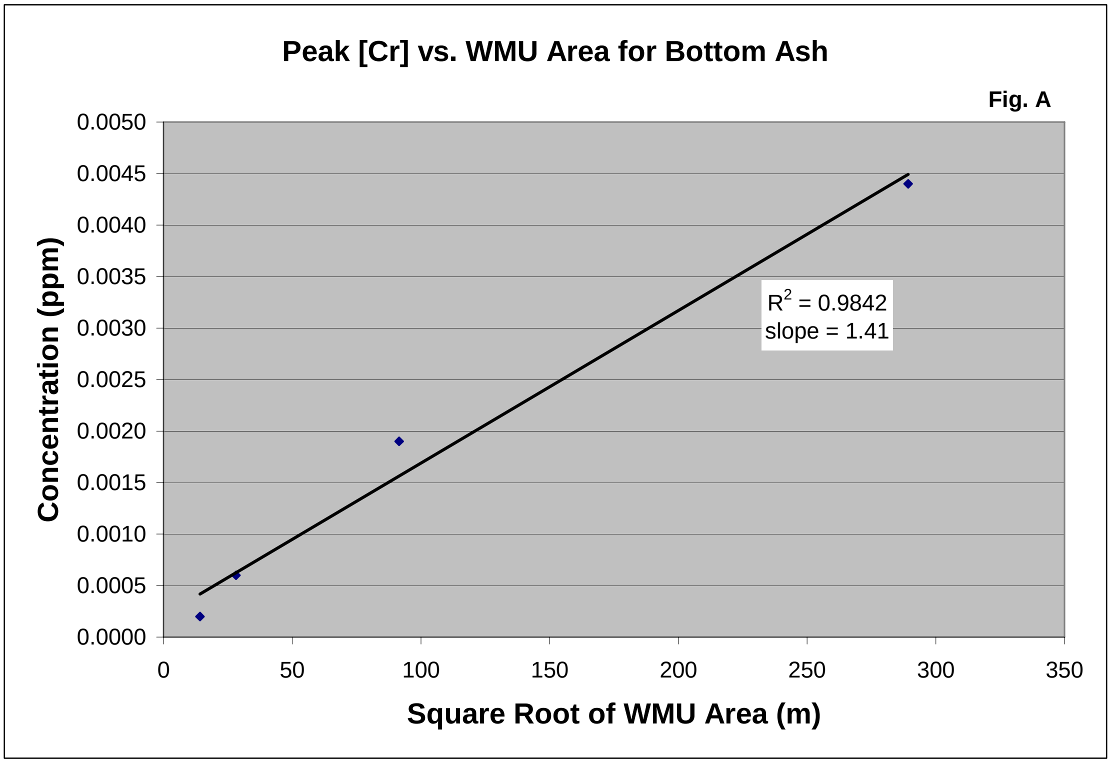
3.0.4 Variable WMU areas

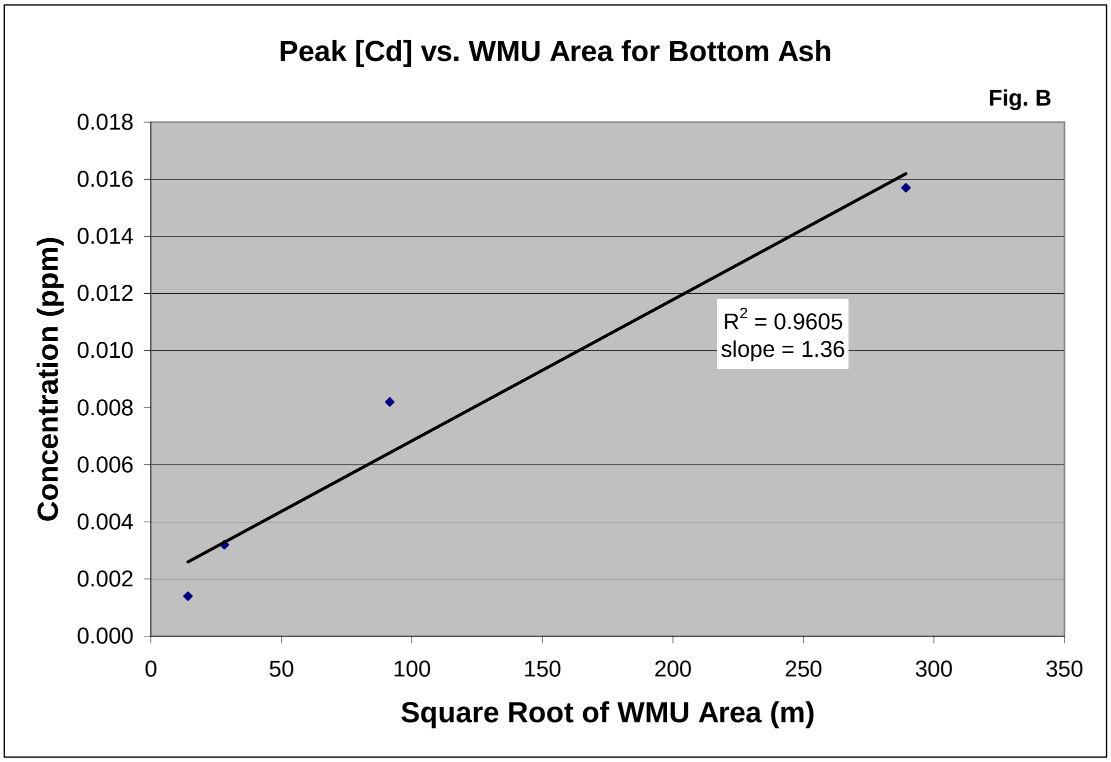
As discussed in Section 2.2.4, multiple simulations were run while varying the area of the WMU of interest (waste pile in this research) using the WisDOT data. Again, the purpose of this was to gain a better understanding of how IWEM responds to varying input parameters. After all simulations were complete, metal concentrations were plotted as a function of time for each area (Figures 22A to 22D).

Analysis of each figure clearly shows a distinct increase in concentration as WMU area increases for each metal of concern. This apparent linear trend between output concentration and WMU footprint area is most likely the result of IWEM assuming WMUs to be square (EPA, 2002). To investigate this observation further, peak Cr and Cd concentrations were plotted as a function of the square root of the WMU area (Figures 23A & B). As indicated by their r^2 values and slopes of approximately 1.4, both figures display a relatively high function of linearity, as seen in Figure 18, especially with larger areas. These figures suggest that IWEM, theoretically, is displaying the proper relationship between contaminant load and area for a square geometry. Analysis of Figures 19A & B shows that doubling the area of a square geometry results in approximately a 1.4x factor increase in concentration which is the expected outcome. In theory, doubling the area of a square increases the length/width dimensions by a factor of 1.4 which should increase the mass loading, and thus groundwater concentrations, by the same factor. Again, Figures 19A & B demonstrate that IWEM is properly calculating concentrations as a function of area for square geometries. However, because square geometries are always assumed, the model does not allow the user to portray the true rectangular shape of a roadway which is desired in order to produce the most accurate results.



Figures 18A-D. Groundwater concentration vs. varying WMU area for metals leaching from recycled material.





Figures 19A-B. Peak Cr and Cd concentrations vs. WMU area. Results depict relative linear trends between contaminant load and area for square geometries.

This inability to account for varying geometries may greatly limit IWEM's usefulness for modeling secondary material leaching from roadway settings, especially if a high degree of accuracy is desired. Assuming only a square geometry appears to be another key factor contributing to IWEM's over predicting of output concentrations in relation to secondary material reuse in a roadway setting.

Based on the above discussion, a recommendation for the appropriate use of IWEM may be to use the model for simulating water and solute transport from only representative squares of roadways. For instance, given secondary materials beneath a 6 m wide roadway, it may be useful to apply IWEM for modeling a 36 m^2 (6m x 6m) section of the road. This appears to be a case where IWEM's conservatism could be minimized. If a larger portion of the roadway were to be simulated, then factoring out mass loading factors may need to be considered in order to produce more accurate predictions. In other words, each time the area is doubled, then a factor of 1.4 needs to be subtracted from the output groundwater concentration to account for the additional loading produced with a square geometry that, in actuality, does not contribute to the groundwater.

3.0.5 Additional Modeling with WisDOT Data

As discussed in Section 2.2.5, additional modeling was performed with IWEM using the WisDot groundwater data. The purpose was to determine if IWEM would predict metal groundwater concentrations below the MDLs as observed at the site during the first five years following secondary material applications of bottom and coal fly ash. Once modeling was completed, groundwater concentrations (or absence of) resulting from secondary material leaching were plotted as a function of time and compared to the MDLs of the corresponding metal of concern (Figures 20A-C).

Analysis for Figures 20A-C shows that after five years, concentrations of Cd for bottom ash and Se for both bottom and fly ash exceeding the MDLs. However, Cd concentrations for fly ash and Ag for bottom and fly ash remained below the MDLs as observed at the study area. Additionally, IWEM predicted 0 ppm of Cr in groundwater after five years for both materials which corresponds to the field measurements.

Although IWEM predicted concentrations above the MDLs in several cases, MINTEQA2 derived distribution coefficients were used (because actual field K_ds have not been measured at the site) which, as previously discussed in this chapter, appear to be considerably lower than what actual field values may be when compared to the literature. Use of low K_ds would effectively result in higher predicted concentrations which could explain the reason why some of the values are shown to exceed the MDLs.

Based on the exceedences, it can be assumed that this is merely a case where IWEM is over predicting concentrations as a result of using low K_d values, poor geometry considerations, or a combination of both. However, without knowledge of the actual K_d values, establishing confidence in this assumption becomes difficult. However, because several scenarios predicted metal concentrations above MDLs, for the time being, IWEM still needs to be considered conservative at least until MINTEQA2 and/or actual field K_ds are known to perform further evaluations. Still, these simulations can be viewed as worst-case scenarios due to the apparent low K_d values selected by MINTEQA2. As a result, predicted concentrations are likely higher than actual conditions.

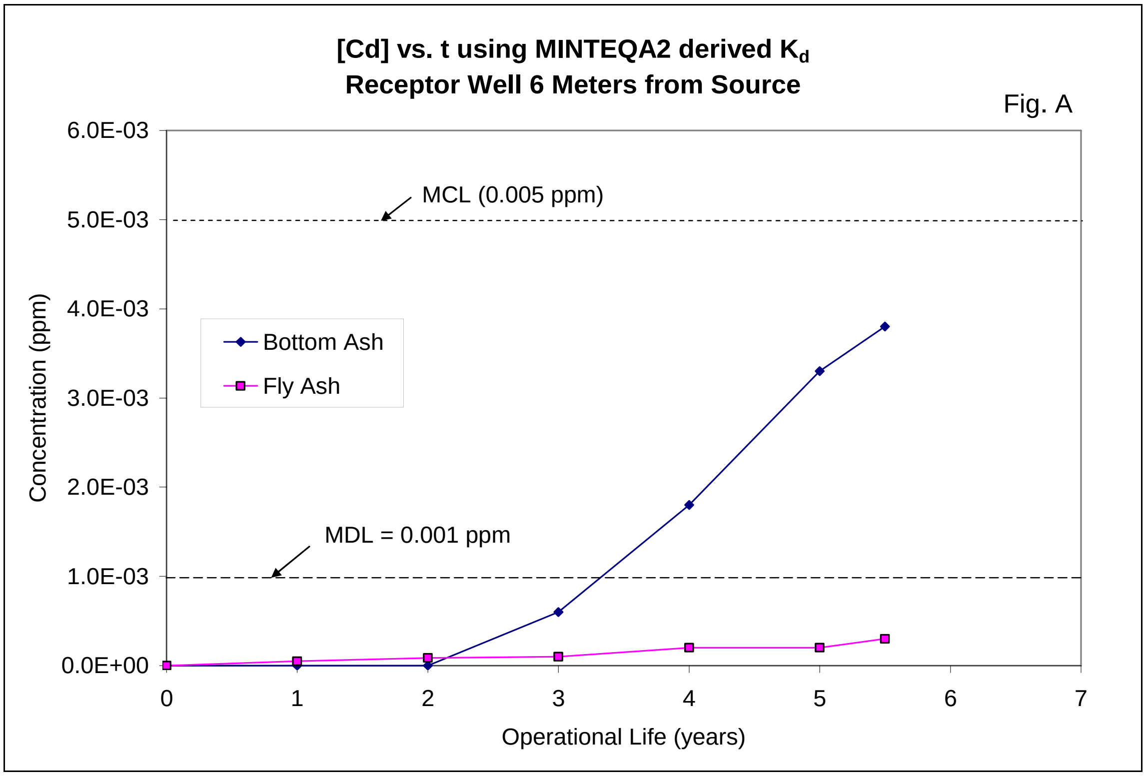


Fig. A

[Cd] vs. t using MINTEQA2 derived K_d
Receptor Well 6 Meters from Source

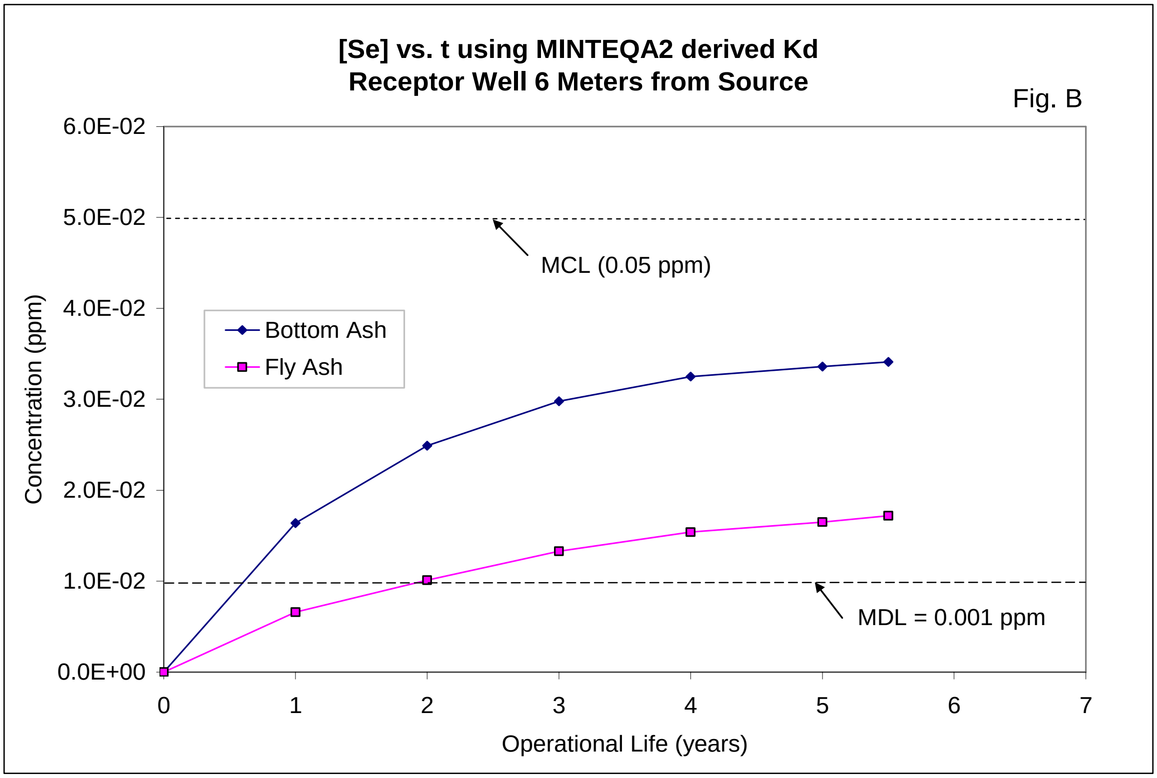
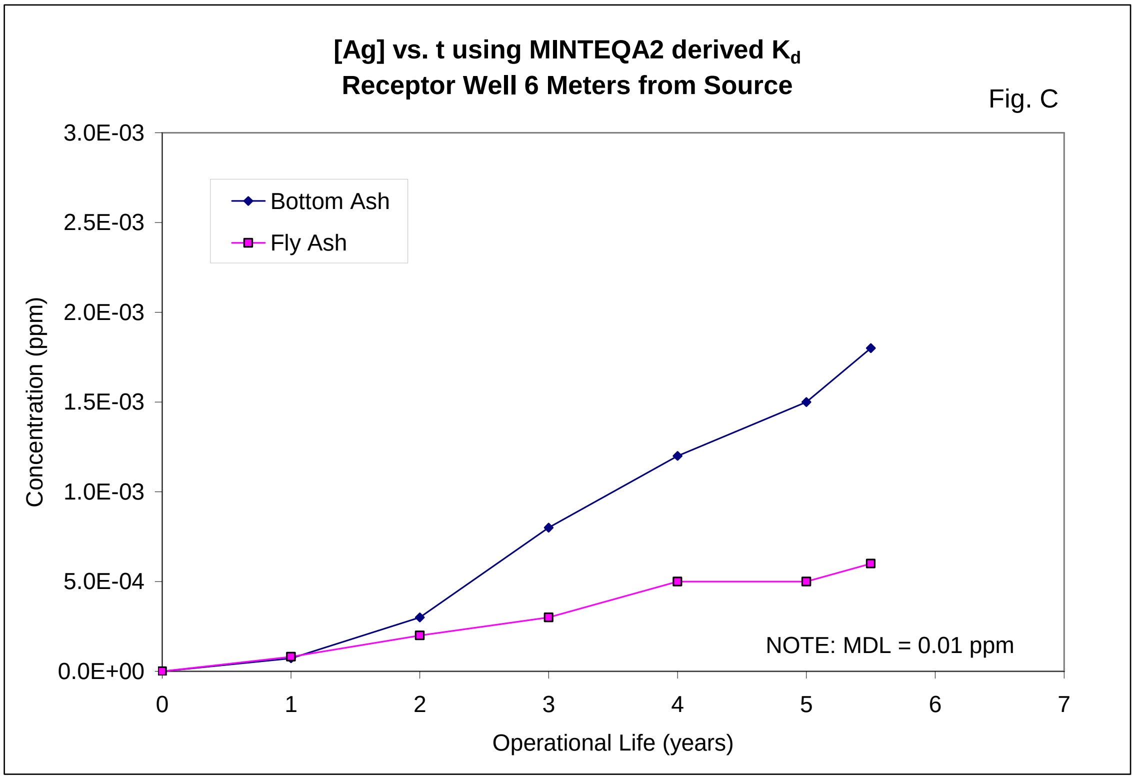


Fig. B

[Se] vs. t using MINTEQA2 derived Kd
Receptor Well 6 Meters from Source



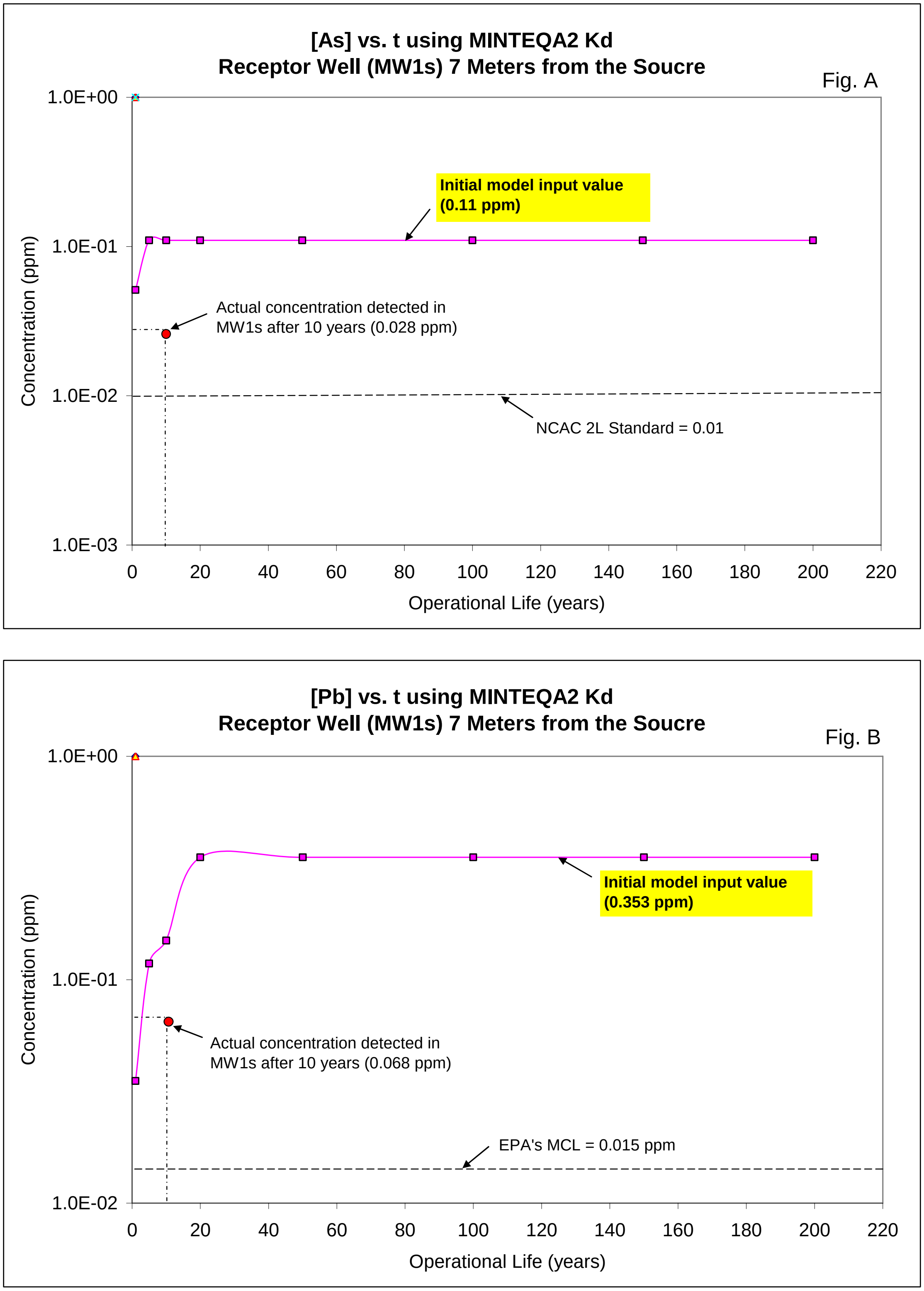
Figures 20 A-C. IWEM predicted metal concentrations over five years for bottom ash and coal fly ash at the WisDOT study area. Concentrations measured in actual monitoring wells at the study area located 6 meters down gradient of each secondary material.

3.0.6 Modeling with North Carolina data

As outlined in Section 2.2.5, IWEM modeling was performed to simulate the transport of As and Pb (leaching from coal fly ash) into monitoring well MW1s where field sampling has detected exceedances of these metals at 0.028 and 0.068 ppm respectively. Again, modeling was performed using both MINTEQA2 and EPA tabulated distribution coefficients.

Figures 21 A and B depict time-dependent modeling after 200 years using K_ds selected by MINTEQA2. Analyses of these figures show that within the first year, IWEM is predicting As and Pb well above their respective MCLs in MW1s. In fact, for As, concentrations reach the initial model input value of 0.11 ppm within 5 operational years. Similarly, the initial model input value of 0.353 ppm for Pb is predicting to occur before 20 years. These results imply that no dilution is occurring indicating that IWEM may not be properly solving the advection-dispersion equation for this particular situation where the water table is present at the bottom of the fill.

Conversely, using average EPA tabulated distribution coefficients of 1,585 and 5,012 L/Kg for As and Pb respectively, IWEM predicts zero impact to groundwater in MW1s after 200 years. With MINTEQA2 specified K_ds, IWEM was clearly able to predict the exceedances reported by field/laboratory testing. While the magnitude of these predicted values appears to be another case of IWEM's conservatism when compared to test results, something positive can be taken from the fact that the model was able to show groundwater contamination would result in conjunction with the reuse of the coal fly ash as indicated from field studies. However, as shown with the WisDOT data, the stark contrast between MINTEQA2 and EPA K_d produced concentrations remains unexplained and is thus, worrisome. These results demonstrate the importance of selecting the appropriate K_d to represent a site when modeling and, thus, must be considered extremely carefully when using IWEM in order to produce the most accurate predictions.



[As] vs. t using MINTEQA2 Kd
Receptor Well (MW1s) 7 Meters from the Soucre

Fig. A

Initial model input value (0.11 ppm)

Actual concentration detected in MW1s after 10 years (0.028 ppm)

NCAC 2L Standard = 0.01

[Pb] vs. t using MINTEQA2 Kd
Receptor Well (MW1s) 7 Meters from the Soucre

Fig. B

Initial model input value (0.353 ppm)

Actual concentration detected in MW1s after 10 years (0.068 ppm)

EPA's MCL = 0.015 ppm

Figures 21A-B. As and Pb concentrations with time at MW1s using MINTEQA2 derived K_ds.

The two scenarios presented above appeared to be extreme cases with respect to the magnitude of K_d values used. For this reason, an attempt was made to estimate the actual soil K_d values for the site based on the concentrations of As and Pb detected in MW1s to get an estimate of IWEM's conservatism. An iteration procedure was performed where user-defined K_d values were repeatedly changed in order to produce an output concentration which matched the field concentrations of As and Pb. Results from this procedure produced K_d values of approximately 21 L/Kg and 28 L/Kg for As and Pb respectively (Figure 22). While these values are several orders of magnitude lower than the average EPA tabulated numbers (which is not unusual considering the wide range of K_ds metals can have based on varying site conditions), they still in fact are within the literature ranges reported, (albeit on the lower end). It can be inferred that they must also be several orders of magnitude higher than the MINTEQA2 derived K_ds since field concentrations are still considerably lower than those produced using MINTEQA2 (see Figure 21A & B).

Additionally, the same simulations executed for MW 1s were replicated for MW2s located 48 meters downgradient from the edge of the fly ash (41 meters from MW1s). At this location, field sampling and subsequent laboratory testing showed no detection of As and Pb over regulatory standards. It should be noted that field samples were collected 10 years following the application of the fly ash.

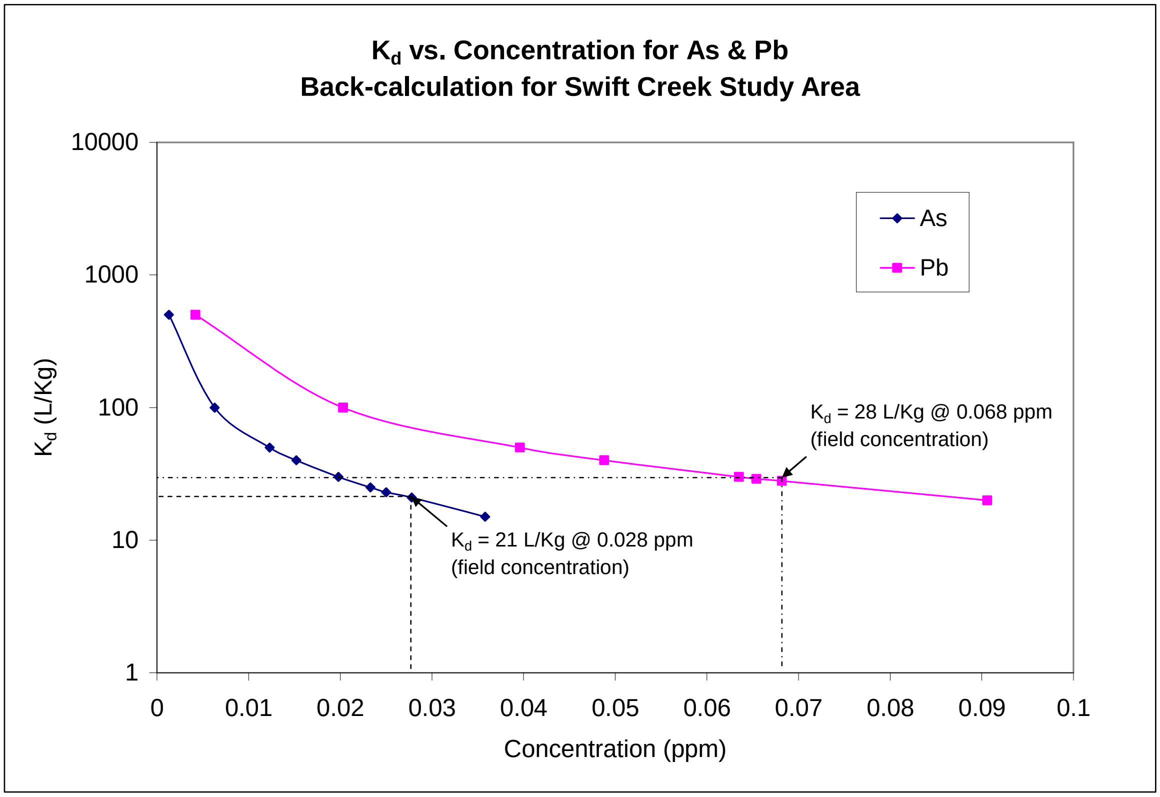
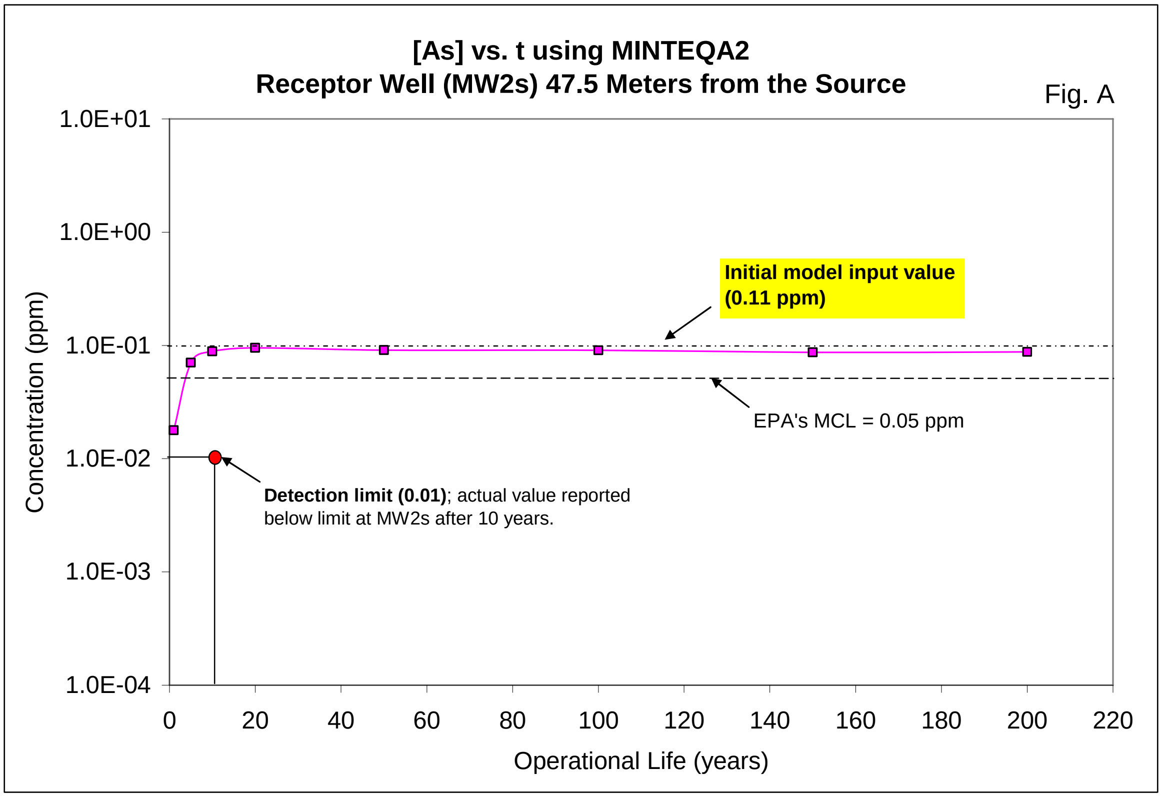


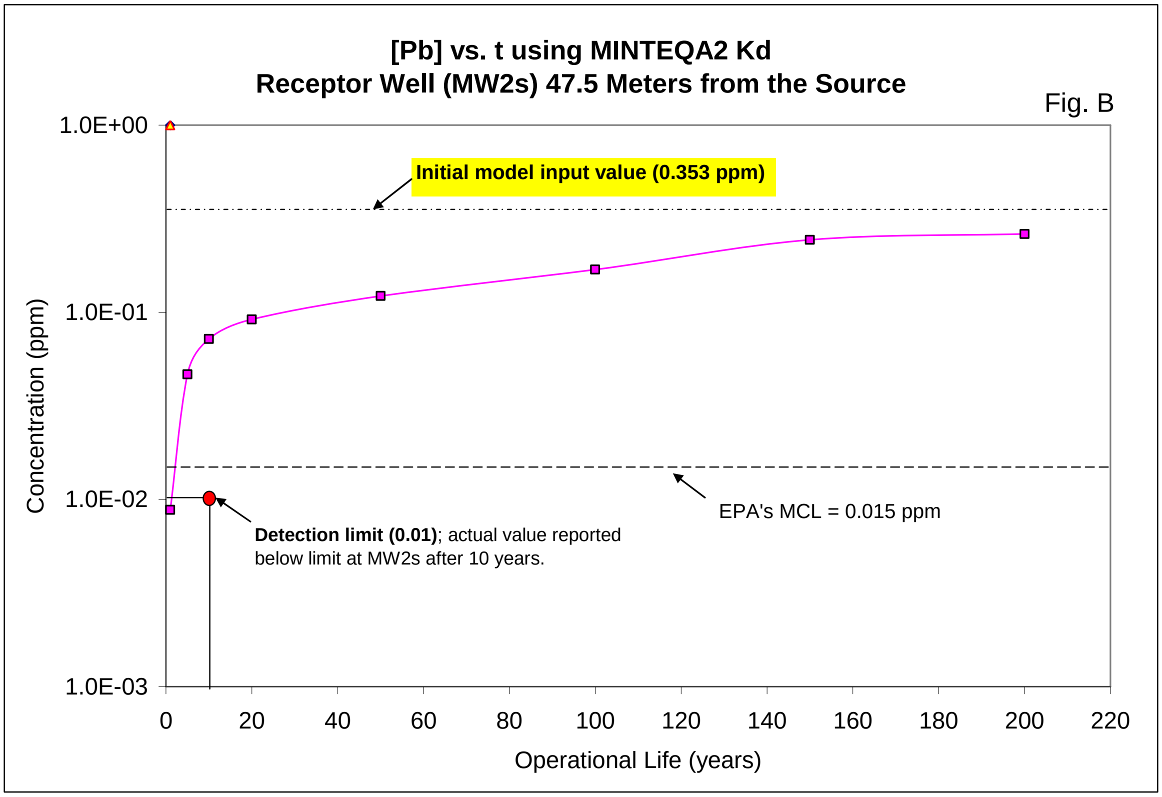
Figure 22. Back-calculated field K_ds (L/Kg) estimated for As and Pb at the Swift Creek study area.

Figures 23A and B again show levels of As and Pb quickly (within 5 years) rising above their respective MCLs in MW2s, although never achieving their initial input concentrations over 200 years as seen in MW1s. After ten years (time between construction and the data collection), IWEM predicts concentrations of 0.088 and 0.0721 ppm for As and Pb respectively in MW2s. These values are a stark contrast to the non- detections reported by the field data and again illustrate another case were IWEM appears to be over predicting. A scenario such as this would lead the user to believe the coal ash (at least in the short term) poses a threat to subsurface conditions and may result in abandoning the reuse of a seemingly non-threatening material. Instead, the user may just opt to landfill the coal ash where it is of no use.

To justify the preceding statements, the estimated site-specific K_d values for As and Pb (21 and 28 L/Kg respectively) were used to simulate transport to MW2s. Results from this simulation demonstrated no detectable As or Pb concentrations in MW2s which is consistent with the field data. This result further demonstrates the importance of using the appropriate Kd for a given situation.



Figures 23A-B. As and Pb concentrations with time at MW2s using MINTEQA2 derived K_ds.



Figures 23A-B continued

Actual site conditions considered by IWEM may also explain why the model is over predicting by such a large magnitude for the North Carolina study area. Recall from Section 1.2.2 that the coal ash is underlined by a highly impermeable layer of Altavista soil (hydraulic conductivity ~ 7x10^{-8} cm/sec). Additionally, Figure 24 shows that groundwater levels in MW1s and MW2s are located above this material (up into the coal ash) indicated that pooling of rain water and water used for dust control is occurring because the soil is acting as a barrier to vertical migration of groundwater. Due to the impermeability of the soil and IWEM's apparent conservative nature, it makes sense to assume IWEM is allowing very little of the water to penetrate through the confining bed. This situation, coupled with the moderate regional hydraulic gradient, may be resulting in the lateral migration of the dissolved metal carrying groundwater over the Altavista soil and directly into the down gradient shallow wells. In fact, the well screen for MW1s is located well above the Altavista soil which acts as a direct receptor for the lateral moving groundwater into the well.

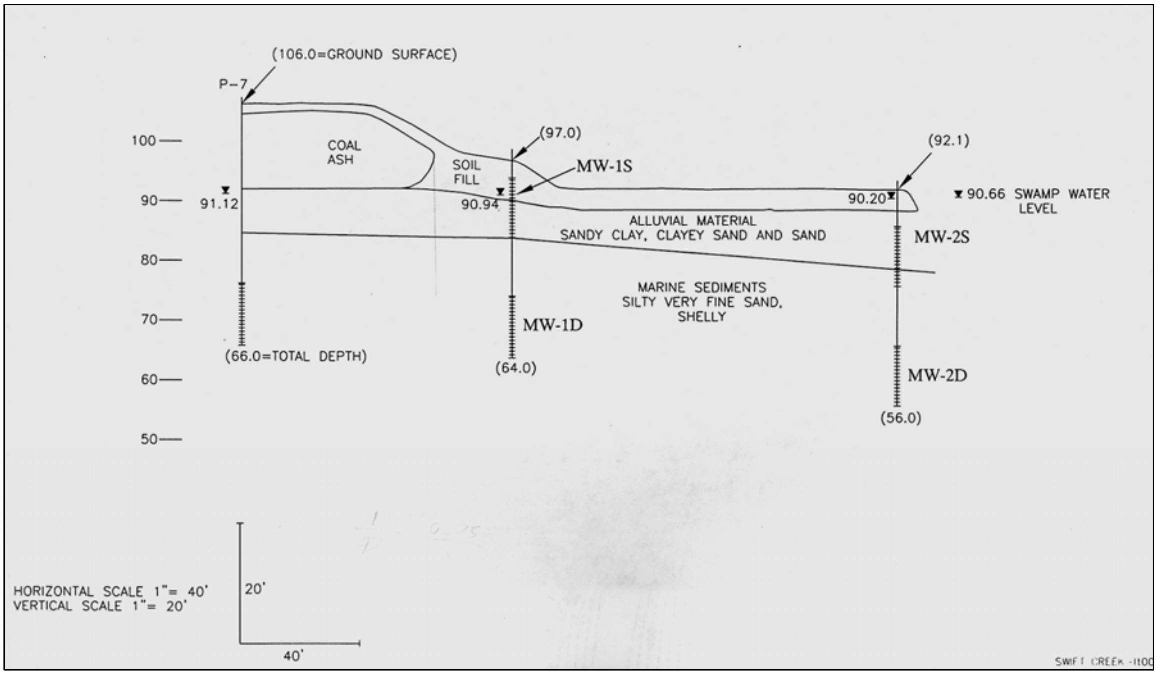


Figure 24. Hydrogeologic cross-section of Swift Creek study area (Sherrill, 2004).

3.0.7 Modeling with Maryland data

3.0.7.1 Routes 213/301 Overpass

IWEM modeling of the Routes 213/301 overpass (south cluster) produced Ba output concentrations of 0.0515 and 0.0002 ppm for the MINTEQA2 derived and EPA tabulated K_d simulations respectively. These values are in comparison to the analytical detection of 0.06 ppm at MW-102 ten years after the coal fly ash application at the site. Analysis of these results clearly shows that the MINTEQA2 results are most comparable to the actual field data while the EPA concentration is several orders of magnitude less. This is another demonstration of how

MINTEQA2 uses K_d values much smaller than those normally reported in the literature. In this case, 100 L/Kg was the user-defined distribution coefficient chosen for Ba. Thus MINTEQA2 must have selected a much lower K_d for Ba in order to predict a concentration two orders of magnitude greater.

Based on these results, the first impression would be to rely on MINTEQA2 in order to predict concentrations similar to those seen in reality. However, one can make the argument that using 100 L/Kg provides the most realistic situation because the value lies within the range reported from the literature K_ds, thus the output concentration associated with it is most likely closer to the truth. Additionally, the input concentration used for these simulations was measured six years after the coal ash implementation. The material contains a finite amount of Ba and over the years, some of the Ba most likely was leached away from the ash thus lowering its concentration observed in the lysimeter. In other words, the true initial input concentration would be higher which in turn would produce a greater output. Because it is not known how much higher the initial concentration would have been in the ash, it is difficult to predict what the model output would produce. However, based on results in the preceding sections, one can infer that the model output would be higher than actual site conditions would likely show, which again demonstrates IWEM's over predictive nature.

3.0.7.2 I-695 Overpass

Table 10 contains the I-695 overpass modeling results in comparison to the As and Se concentrations detected in MW-3. Trends in the data are very similar to those observed in the Routes 213/303 groundwater. Again, MINTEQA2 results are comparable to the field data. Conversely, the EPA results are substantially lower. However, as with the Routes 213/303 data, the input concentration used for these simulations was measured several years (five) after the coal ash implementation, thus concentrations are most likely greater than what the actual values would have been for the same reasons discussed in the previous section. Additionally, the MINTEQA2 results are most likely greater than actual conditions due to apparent low K_d selections which, again, makes the case for IWEM being overpredictive.

Table 10. IWEM modeling results for I-695 overpass.

	MW-2	**MINTEQA2**	**EPA**
As (ppm)	0.01	0.0085	0
Se (ppm)	0.023	0.0285	0.0002

3.1 HYDRUS-2D Modeling

As described in Section 2.3, the objective of modeling with HYDRUS-2D was to validate IWEM's one dimensional (1D) vertical solute transport from the secondary material source through the unsaturated zone down to the water table. Again, simulations were performed using bottom ash data from the WisDOT study area for 14 and 1000 m cross-sectional length scenarios.

Solute concentrations from the five nodes for the 14 and 1000 m scenarios, using USEPA K_ds, were compared for 200 years. Table 11 shows the concentrations of Cd, Cr, Se, and Ag at node 5 (bottom boundary/water table) for select years.

Table 11. HYDRUS-2D metal concentrations at node 5 (bottom boundary/water table).

	Cd		**Cr**	
Time (yrs)	14m	1000m	14m	1000m
1	0	0	8.35E-15	9.12E-15
10	4.70E-20	5.07E-20	1.04E-10	1.12E-10
40	4.78E-17	5.21E-17	9.58E-08	1.04E-07
100	4.64E-15	5.09E-15	7.60E-06	8.25E-06
150	3.53E-14	3.86E-14	4.87E-05	5.25E-05
200	2.60E-13	1.62E-13	1.71E-04	1.84E-04
	Se		**Ag**	
Time (yrs)	14m	1000m	14m	1000m
1	7.38E-17	8.01E-17	0	0
10	8.48E-13	9.15E-13	8.27E-20	8.92E-20
40	8.38E-10	9.14E-10	8.40E-17	9.17E-17
100	7.69E-08	8.43E-08	8.15E-15	8.95E-15
150	5.58E-07	6.09E-07	6.19E-14	6.78E-14
200	2.24E-06	2.43E-06	2.60E-13	2.84E-13

Analysis of Table 11 clearly shows that increasing the cross-sectional length of the domain (while keeping the width component fixed) has minimal effect on the solute output concentrations along the centerline. This is in contrast to the large increases in concentration as a function of WMU area observed with IWEM as shown in Figure 20. These results support the notion discussed in Section 3.0.4 that IWEM can not accurately portray the true geometry of a roadway since the footprint of the waste piles are treated as square. Thus, increases in output concentrations with WMU area are overly exaggerated which may lead to false determinations of whether a secondary material is appropriate for reuse.

Theoretically, a longer source will have a greater impact on groundwater concentrations for a square geometry. For instance, doubling the area of a square will increase the cross-sectional length by a factor of 1.4, thus the groundwater impact should be approximately 1.4

times greater. To illustrate this point, an IWEM simulation was performed with the WISDOT data bottom ash data for a 400 m^2 WMU area (two times the 200 m^2 arbitrary area reported earlier) for a period of 100 years with a receptor well 50 m down gradient. Metal output concentrations for each area and corresponding factor increases are reported in Table 12.

Results presented in Table 12 illustrate IWEM's ability to account for the 1.4 factor increase in groundwater concentrations when the foot print area of a square geometry is doubled. However, the question remains whether IWEM can accurately calculate groundwater concentrations for a different geometry (e.g. a road).

Table 12. Metal output concentrations for each area and corresponding factor increases.

	Concentration (ppm)		**Factor Increase**
Metal	*200 m^2*	*400 m^2*	
Cd	2.30E-03	3.60E-03	1.6
Cr	3.54E-05	5.69E-05	1.6
Se	9.40E-03	1.40E-02	1.5
Ag	1.90E-03	2.80E-03	1.5

Next, comparisons between HYDRUS-2D and IWEM results were performed using USEPA reported K_d values. Again, concentrations of interest from HYDRUS were taken from the bottom node. Results are presented in Table 13.

Analysis of Table 13 shows that the models predict similar concentrations for Cd and Ag. Because HYDRUS is only simulating transport through the unsaturated zone, it is likely the concentrations presented here would decrease due to dispersion and further retardation in the saturated zone, bringing them closer to the zero values reported by IWEM.

However, for Cr and Se, concentrations predicted by HYDRUS are considerably lower than those of IWEM (especially in early time). This raises concern because, again, HYDRUS is only representing transport through the vadose zone (while IWEM simulates transport through both unsaturated and saturated zones) and one would expect the concentrations to be larger because the solutes have not yet been subject to further transport, dilution and attenuation through the saturated zone. This provides clear evidence that IWEM is over predicting concentrations and because equal user-defined K_d values were used between the models, this conservatism is likely the result of differing geometry considerations (i.e. square vs. rectangle).

Table 13. Comparison between HYDRUS-2D and IWEM results for bottom ash concentrations (mg/l) with time using USEPA tabulated K_d values for both models.

	Cd		Cr	
Time (yrs)	**IWEM**	**Hydrus**	**IWEM**	**Hydrus**
1	0	0	0	8.35E-15
10	0	4.70E-20	6.55E-04	1.04E-10
20	0	1.50E-18	1.00E-03	3.21E-09
40	0	4.78E-17	2.50E-03	9.58E-08
80	0	1.52E-15	2.82E-03	2.67E-06
100	0	4.64E-15	3.00E-03	7.60E-06
150	0	3.53E-14	9.00E-03	4.87E-05
200	0	2.60E-13	1.20E-02	1.71E-04
	Se		Ag	
Time (yrs)	**IWEM**	**Hydrus**	**IWEM**	**Hydrus**
1	5.65E-06	7.38E-17	0	0
10	5.65E-05	8.48E-13	0	8.27E-20
20	1.00E-04	2.68E-11	0	2.64E-18
40	3.22E-04	8.38E-10	0	8.40E-17
80	5.06E-04	2.58E-08	0	2.68E-15
100	6.00E-04	7.69E-08	0	8.15E-15
150	8.00E-04	5.58E-07	0	6.19E-14
200	1.10E-03	2.24E-06	0	2.60E-13

Finally, a comparison was made with IWEM results using MINTEQA2 K_d values and HYDRUS results using values equal to zero (Table 14).

Observations from Table 14 show similar results in magnitude between the models for each solute and time. This appears to confirm the notion that IWEM is drawing upon very low K_d values (less than or equal to 1 L/Kg) from MINTEQA2 since HYDRUS is using a value of zero in this situation.

Table 14. Comparison between HYDRUS-2D and IWEM results for bottom ash concentrations (mg/l) with time. Results based on using K_d values of zero and MINTEQA2 derived for HYDRUS and IWEM respectively.

	Cd		Cr	
Time (yrs)	**IWEM**	**Hydrus**	**IWEM**	**Hydrus**
1	0	1.24E-07	0	9.70E-08
10	7.00E-04	1.07E-03	4.53E-05	8.40E-04
20	1.40E-03	1.12E-02	1.84E-04	8.17E-03
40	2.30E-03	2.29E-02	3.54E-04	1.61E-02
80	3.10E-03	2.11E-02	8.68E-04	1.52E-02
100	3.40E-03	2.15E-02	2.00E-03	1.50E-02
150	3.90E-03	2.08E-02	2.00E-03	1.51E-02
200	4.10E-03	2.09E-02	2.00E-03	1.51E-02
	Se		Ag	
Time (yrs)	**IWEM**	**Hydrus**	**IWEM**	**Hydrus**
1	1.80E-03	2.41E-07	1.67E-05	6.90E-08
10	7.30E-03	2.10E-03	7.00E-04	6.01E-04
20	8.30E-03	2.18E-02	1.30E-03	6.24E-03
40	9.40E-03	4.45E-02	1.90E-03	1.28E-02
80	9.50E-03	4.11E-02	2.30E-03	1.18E-02
100	9.80E-03	4.17E-02	2.50E-03	1.19E-02
150	9.70E-03	4.04E-02	2.60E-03	1.16E-02
200	9.60E-03	4.06E-02	2.70E-03	1.16E-02

4. CONCLUSIONS AND RECOMMENDATIONS

4.0 Objectives

The objectives of this study were to:

- Evaluate IWEM's basic performance as a groundwater model by observing how it responds to varying input parameters;
- Evaluate IWEM's groundwater modeling capabilities with respect to heavy metal leaching from reused secondary materials in comparison to other model results and actual field data and;
- Form a conclusion as to whether IWEM is suitable for predicting groundwater concentrations resulting from secondary material leaching.

In addition, this section provides recommendations for changes to IWEM that would improve its utility as a model to evaluate groundwater impacts associated with recycled materials use in roadways.

4.1 Basic Groundwater Modeling Performance

Overall, IWEM performed satisfactorily as a tool for predicting groundwater and solute flow at points down gradient from a source. With respect to varying WMU operational life, it was clearly able to demonstrate the non-linear relationship between increasing leaching time and solute concentration. However, the majority of the WMUs modeled in IWEM (e.g. waste pile) are treated as continuous-type sources where leachate is continually being introduced into the subsurface with no depletion of the constituent of concern occurring within the waste material (e.g. bottom ash). Because of this, concentrations never peak and appear to keep increasing or plateau with time. In reality, materials provide finite sources of leachate and leached metals concentrations decrease over time. With this said, modeling over long time periods (100+ years) may not produce accurate/realistic results. Modeling particular WMUs is better left to the short term during which it is unlikely that metals within the subsurface will reach their peak concentrations. If IWEM is adapted to allow representation of recycled materials applications as finite sources, rather than continuous-type sources, it should be feasible to run the model for longer time periods.

IWEM's ability to successfully solve the advection-dispersion equation allows it to accurately portray the movement of metals within the subsurface as a function of receptor well distance from the leachate source (an exception to this may occur when the water table is present at or above the bottom of a particular material as is the case for the North Carolina study area (Section 4.0.5)). Accounting for various attenuation factors, IWEM shows the inverse relationship between concentration and well distance along the plume centerline, as would be expected. Using this, one can determine, at least to a first order degree, if a certain recycled material will contribute an appreciable mass to groundwater for a particular operational life.

As with varying well distance from leaching source, IWEM accurately portrays the inverse relationship between the K_d of a constituent and its predicted concentration. This result establishes user confidence in IWEM's ability to account for adsorption of metals onto aquifer materials in order to help provide an accurate output concentration and makes it clear that K_d is a critical parameter for predicting contaminant movement.

One area of concern with respect to K_d values lies in the magnitude of the values derived by MINTEQA2 when user-defined values are unknown. Extensive modeling with various input data continually demonstrated that MINTEQA2-derived values appear to be much smaller than expected when compared to the literature. As a result, it is thought that IWEM may be too conservative in nature and will over predict output concentrations. This could result in a situation where the user is mislead into believing a certain material is not safe for reuse, when no groundwater contamination is likely to occur. As a result, the material may be unnecessarily landfilled. Conversely, if IWEM determines a material is clean enough for reuse, this conservatism can be viewed positively, providing confidence that the output concentration will be less than predicted. The major problem with this, however, is that parameter output files are not provided so it is not known what values are selected by MINTEQA2; comparisons to other values cannot be made in order to asses the integrity of the distribution coefficient chosen and the degree of conservatism is unknown.

4.2 Modeling Performance of Secondary Material Reuse

For the purposes of evaluating IWEM's performance with respect to leaching from reused secondary materials in a roadway setting, waste piles were used as the representative WMU. In addition to the parameters described in the preceding section, WMU (waste pile) areas were varied with fixed operational lives and well distances. An apparent linear relationship was observed between increasing output concentration and increasing WMU footprint area.

As discussed in Chapter 3, this situation is the result of an assumed square waste pile area by IWEM, which may not allow the modeler to accurately portray the true geometry of a roadway section. As demonstrated with HYDRUS-2D modeling, increasing the cross-sectional length of an area should have a negligible effect on groundwater concentrations down gradient along a plume center line due to various attenuation factors. In this case the restrictions of the model may not allow accurate representation of a roadway section in relation to the underlying groundwater flow direction.

A recommendation for the appropriate use of IWEM may be to use the model for simulating water and solute transport from only representative squares of roadways. For instance, given secondary materials beneath a 6 m wide roadway, it may be useful to apply IWEM for modeling a 36 m^2 (6m x 6m) section of the road. This appears to be a case where IWEM's conservatism could be minimized. If a larger portion of the roadway were to be simulated, then factoring out mass loading factors may need to be considered in order to produce more accurate predictions.

4.3 Conclusions on IWEM's Suitability for Determining Secondary Material Reuse

Based on the information collected in this study, it would be appropriate to use IWEM as a first-order approximation in determining whether secondary materials are safe for reuse in a roadway setting. However, factors including the model's over predictive nature and inability to accurately represent the true geometry of a roadway may make it a liability for producing a final determination. As mentioned in Section 4.1, IWEM may be useful in a situation where the model predicts that, after long times (100+ years), adverse groundwater impacts will not result from secondary material leaching.

On the other hand, completely relying on IWEM may result in the unnecessary disposal of materials and prohibit safe and effective recycled materials use. To the extent that the model is overly conservative, the user may opt to use virgin materials which not only depletes natural resources but has many other environmental impacts associated with mining, processing and transportation. Over-conservatism in assessing environmental risk from leaching can have many consequences related to human health risks, environmental degradation and ecosystem risks that should be recognized during any continued development of use of the IWEM model.

Additionally, other factors were observed throughout this research which may hinder IWEM's suitability for determining secondary material reuse. One factor of concern is IWEM's lack of output files listing the non-user specified parameters selected by the model. Monte Carlo selected parameters (e.g. hydraulic conductivity, infiltration, etc.) as well as MINTEQA2 derived distribution coefficients are unknown to the modeler at the completion of a simulation. Having knowledge of these unknown values would allow the user to compare them to other sources to determine their credibility. For instance, if a Monte Carlo simulation produced a hydraulic conductivity of 10^{-6} cm/s for a well-sorted sand and gravel aquifer, the user could make the determination that this value is inaccurate and more representative of an aquifer composed of silt and clay (glacial till) instead (Fetter, 2001). This would allow the user to decide it would be more plausible to enter his/her own conductivity more reflective of a sand and gravel aquifer (10^{-3} – 10^{-1} cm/s) in order to produce a more accurate output concentration (even though the true hydraulic conductivity value may still not be known).

Throughout this research, IWEM's conservative nature has been repeatedly stated. But how conservative is IWEM? As of now, the answer to this is not clearly known but knowledge of such information could prove to be very beneficial when assessing whether a certain material is safe enough for reuse. Having an idea of how much IWEM over predicts may allow the modeler to formulate calculations which could give a better indication of actual conditions.

It should also be noted that IWEM is an extremely user-friendly program. Little to no groundwater modeling experience is required to execute the program. Ease of use make the model very accessible to sectors of the industry that may not be particularly proficient in modeling.

4.4 Recommendations

Users seeking first-order approximations on materials may find the program to be beneficial in the form evaluated in this research. However, in order to promote IWEM as a tool that can be relied upon to justify the use or limitation of secondary applications, some changes should be made to the model.

- The model should allow representation of more complex geometries with variation of the angle of incidence of groundwater flow.
- K_d values, and all other parameters determined by IWEM through the Monte-Carlo procedures, should be clearly output in files.
- The model should allow for time-variant input (leachate) concentrations. This could take the form of mathematical functions or raw data (leachate concentrations could vary by month or year, and could represent data collected from the field or from laboratory experiments).
- The model should output distributions rather than single values, particularly when the model is conducting a Monte-Carlo analysis. This information would improve the utility of the model and allow the user or decision maker to understand the uncertainty associated with the predictions.

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