ASSESSMENT OF THE ROADWAY MODULE IN IWEM VERSION 2 (BETA)

Final Report

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EXECUTIVE SUMMARY

This report describes an assessment of the roadway module in IWEM v2.0 (beta). This module was developed for assessing the potential for ground water impacts caused by leaching from industrial material resources (IMRs) used as pavement materials in roadway construction. A roadway is idealized as a series of “roadway-source columns” that include materials from the top of the subgrade to the ground surface and represent the paved section, the road shoulder, or a ditch. The vadose and saturated zones are below the source columns. Each roadway-source column is treated as a three-dimensional linear strip simulating a portion of the roadway. Flow and transport are simulated within each strip and in the underlying unsaturated and saturated zones. Concentrations contributed by each of the strips are aggregated to determine total impact by the system. Monte Carlo simulation is used to estimate 90th percentile concentrations at a receptor.

Comparison with field data showed that 90th percentile concentrations predicted by IWEM at a monitoring well adjacent to a highway test section constructed with IMRs were higher than measured concentrations, which suggests that the prediction by IWEM is conservative. Parametric analysis showed that concentrations at an adjacent monitoring well decrease as the depth to ground water increases and the initial leachate concentration decreases. Similar tendencies have been reported by others using physically based models. The concentration predicted at the monitoring well was also sensitive to the total (solid-phase) concentration of the IMR. This occurs because IWEM uses total concentration to define the duration of release. However, this sensitivity may not be realistic because presence of a constituent of interest in the solid phase is not necessarily indicative of the potential for leaching. Predicted concentrations were insensitive to the thickness of the IMR layer and the exposure duration. Insensitivity to layer thickness and exposure duration may be related to unrealistic assumptions used to describe the source within the pavement profile. Parametric analysis also showed that concentrations predicted by IWEM are sensitive to the aquifer hydraulic conductivity for the case that was studied, which was expected. In contrast, concentrations at the monitoring well were very sensitive to the aquifer thickness, which was not expected and should be explored.

Comparison of predictions from IWEM and WiscLEACH showed that WiscLEACH generally predicts higher concentrations because IWEM reports time-averaged concentrations over an exposure period, whereas WiscLEACH reports peak concentrations and/or concentrations at a time requested by the user. The WiscLEACH simulations also employed a lower dispersivity, which contributed to higher peak concentrations.

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1. INTRODUCTION

Many industrial material resources (IMRs) are now being used beneficially in construction applications, including roadway construction, to create long lasting and sustainable infrastructure. Because IMRs traditionally have been treated as wastes, there is concern that their presence in a roadway structure may adversely impact the environment. Ground water contamination often is the greatest concern.

Models can be used to assess the potential for ground water impacts. Models that have been developed specifically for this application include STUWMPP (Friend et al. 2004), IMPACT (Hesse et al. 2000), and WiscLEACH (Li et al. 2006). HYDRUS-2D (Simunek et al. 1999, Bin-Shafique et al. 2002, Apul et al. 2005) and the US Environmental Protection Agency's (EPA) IWEM have also been used to make assessments.

IWEM, which was developed to evaluate impacts from landfills, waste piles, and surface impoundments, employs US EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP) to simulate transport processes and ground water impacts (US EPA 2002). Melton and Gardner (2007) reviewed the applicability of IWEM for evaluating impacts from IMRs in roadways and concluded that the model was overly conservative. They recommended that the model include options that permit geometries that more realistically represent roadways, include output regarding all variables, and permit a time-varying source term. The roadway module developed for IWEM v2.0 is intended to address some of these issues.

This report describes an assessment of the roadway module in IWEM v2 (beta). The assessment consisted of comparing predictions from IWEM with field data from a site where IMRs were used in roadway construction, a sensitivity analysis to determine factors having a significant impact on predicted ground water concentrations, and a comparison between predictions made with the roadway module of IWEM v2 (beta) and

WiscLEACH. The body of this report describes the findings from the comparison with field data, WiscLEACH prediction, and the sensitivity analysis. Through this effort, a number of observations were made regarding how the roadway module can be improved. Recommendations for these improvements are included in the appendix.

2. BACKGROUND

2.1 IWEM v2 (beta)

US EPA released IWEM v2 (beta) in 2008 with the roadway module included as a new Tier 2 source type. The roadway module simulates fate and transport of constituents released from IMRs used in roadway construction. IWEM uses this information to make predictions of 90th percentile concentrations at a receptor and to make a recommendation whether the IMR application is protective of ground water. IWEM v2 (beta) relies on Version 2.2 of the EPACMTP code (RTI and HydroGeoLogic 2008). Modifications incorporated into IWEM v2 (beta) include the ability to model rectangular sources, to account for multiple roadway-source strips, to simulate a general regional flow field that may not be perpendicular to the roadway axis, and to include default pavement infiltration rates (RTI and HydroGeoLogic 2008).

The roadway module in IWEM considers a linear segment of a roadway that consists of a cross-section composed of “roadway-source columns” corresponding to the traveled way, shoulder, and a swale (Fig. 1). The traveled way includes pavement, base, sub-base, and subgrade. A shoulder includes base, sub-base, and subgrade. Each roadway-source column includes materials from the top of the subgrade to the ground surface and is underlain by a corresponding vadose zone column.

When the linear section of the roadway is considered, the roadway-source columns become roadway-source strips. Each roadway-source strip is treated as an individual source that is equivalent to the landfill source module available within

EPACMTP. The cumulative effect of these sources is determined by aggregating the impacts from each source using superposition. Monte Carlo simulation is used to account for uncertainty in the model variables. Output from the model consists of 90th percentile concentrations (RTI and HydroGeoLogic 2008).

Site-specific roadway geometric and materials parameters must be input by the user. These include length of the roadway segment, number and width of the roadway strips, number of layers in each strip, and the thickness and bulk density of each layer. For pavement layers containing IMRs, the name, initial leachate concentration, and initial total concentration must be input for each constituent. A square pulse pattern is used to describe leaching from each layer with IMRs, with the duration of the pulse computed from the total concentration of the constituent of interest. Infiltration rate for each roadway strip and the distance to the monitoring well must also be provided. The site-specific infiltration rate is assumed to be constant over time and to percolate through each roadway source strip. Regional infiltration rates can also be calculated by IWEM using a climate database based on data from 102 climatic centers and prevalent regional soil types.

When site-specific input is unavailable for subsurface hydraulic and chemical parameters, the user may select default values. The defaults include depth to the water table, aquifer thickness, hydraulic conductivity, regional hydraulic gradient, ground water pH, and 12 subsurface hydrogeological environments. The chemical parameters include chemical-specific first-order decay rate, chemical-specific organic carbon distribution coefficient, and soil-water partition coefficient for trace elements. Monte Carlo simulation is used to provide a distribution of aquifer thickness, hydraulic conductivity, regional hydraulic gradient, and soil-water partition coefficient for trace elements.

2.2 WiscLEACH Model

WiscLEACH is an analytical model for simulating leaching and transport of contaminants from roadways constructed with IMRs. WiscLEACH accounts for flow and transport in the vadose and saturated zones, and has been validated with field data collected from roadway test sections (Li et al. 2006).

WiscLEACH can simulate the two common leaching patterns for IMRs used in roadway construction: “first flush” and “lagged response” leaching (Fig. 2). The “first flush” pattern is characterized by monotonically decreasing concentrations as water flows through the material (Bin-Shafique et al. 2006), whereas the “lagged response” pattern is characterized by increasing concentration followed by decreasing concentration (Sauer et al. 2005). First-flush leaching patterns from IMRs generally correspond to adsorption-controlled release under conditions where the pH and Eh remain relatively constant and can be described mathematically by the advection-dispersion-reaction equation (ADRE) with instantaneous, linear, and reversible sorption (Bin-Shafique et al. 2006). Lagged response leaching can be attributed to a variety of geochemical processes and generally cannot be described using a single function. Thus, the lagged response pattern is input to WiscLEACH using the “user-defined” leaching pattern.

The conceptual model consists of an IMR layer in a typical roadway structure as shown in Fig. 3. The IMR layer is underlain by a subgrade and overlain by base course and pavement or shoulder material. Ground water exists at a specified depth below the IMR layer. All materials in the profile are assumed to be homogeneous and isotropic. Precipitation falling on the pavement surface, the shoulders, and surrounding ground becomes infiltration or is shed as runoff (Li et al. 2006).

As water percolates down through the profile, trace elements leach from the IMRs and migrate downward through the subgrade soils until they reach the ground water table. Flow in the IMRs and subgrade is assumed to occur only in the vertical direction. Steady 1D unit gradient flow is assumed in the pavement layers and the vadose zone, with the net infiltration rate controlled by the least conductive layer in the profile and the annual precipitation rate. Surface runoff and evaporation from the pavement surface, the shoulders, and the surrounding ground are not considered. Infiltration of runoff along the edges of the pavement structure is ignored.

Leaching occurs as water percolates downward through the IMR layer. Leaching from the IMR layer can follow a first-flush pattern or any empirically defined pattern. First-flush leaching from the IMR layer is assumed to follow the ADRE with linear, instantaneous, and reversible sorption. Lagged-response leaching is defined empirically as a series of data points corresponding to concentrations and pore volumes of flow.

Transport in the vadose zone beneath the IMR layer is assumed to follow the ADRE for 1D steady state vertical flow with 2D dispersion and linear, instantaneous, and reversible sorption. Trace elements that reach the ground water table are transported horizontally and vertically, although the flow of ground water is assumed to occur predominantly in the horizontal direction. Steady saturated ground water flow is assumed, and transport is assumed to follow the ADRE with instantaneous, reversible, and linear sorption. Chemical and biological reactions that may consume or transform trace elements are assumed to be absent.

Analytical solutions to the ADRE from Leij et al. (1991, 2000) were combined in WiscLEACH to provide concentrations at specified monitoring points, the maximum concentration at a point of compliance located a specified distance from the edge of the pavement (defined by the user), and two-dimensional isochors in the vadose zone and ground water at times specified by the user. The algorithms used in WiscLEACH, verification and validation exercises, and parametric simulations illustrating sensitivity of predictions to the input variables can be found in Li et al. (2006).

2.3 Test Site at STH 60

Five test sections were constructed in 2000 along a 1.4 km stretch of Wisconsin State Highway (STH) 60 near Lodi, Wisconsin to evaluate alternative working platforms with IMRs for highway construction on soft subgrades. For three of the test sections, coarse-grained industrial byproducts (foundry sand, foundry slag, or bottom ash) were used as a working platform placed between the soft subgrade and the granular base course material. Fly-ash-stabilized subgrade (a mixture of existing subgrade and 10% fly ash by dry weight blended in situ) was used as the working platform in the fourth test section. The fifth test section is a control where crushed dolostone, a granular material commonly used in Wisconsin, was used for the working platform (Edil et al. 2002).

USGS records indicate the bedrock geology at the site is dominated by Silurian dolomite and Ordovician dolomite that is overlain by at most 15 m of calcareous till or sand and gravel outwash. Contaminating ground water in the till and outwash is the primary concern at this site.

Profiles of the test sections are shown in Fig. 4a. The IMR layer extends to the outer edges of the shoulders (13.4 m wide). Thicknesses of the byproduct layers were selected so that each test section had equal structural capacity as the control section. The pavement is 10.4 m wide and each shoulder is 1.5 m wide. Details of the structural design are described in Edil et al. (2002).

Two equal-size (3.50 m x 4.75 m) lysimeters were installed beneath each test section (Fig. 4b). One lysimeter was installed along the centerline of the pavement (“inner” lysimeter) and the other along the shoulder (“outer” lysimeter). The lysimeters were constructed with 1.5-mm-thick textured HDPE geomembrane overlain by a geocomposite drainage layer (geonet with a non-woven geotextile heat bonded to both sides). Water collected in each lysimeter drains to a 120-L tank buried adjacent to the pavement and below the frost depth. The volume of leachate collected in the tanks is measured periodically and samples are collected to determine concentrations of Cd, Cr, Se, and Ag (the four trace elements regulated in Wisconsin for applications where coal fly ash is covered with an asphalt or concrete pavement). Analysis of the lysimeter data has shown that the volumetric fluxes and concentrations are statistically similar in the inner and outer lysimeters. Thus, data from the inner and outer lysimeters have been pooled for analysis.

Ground water wells were installed 6 m from the edge of the highway shoulder to in January 2004. Continuous ground water sampling and subsequent laboratory analyses demonstrated no concentrations of Cd, Cr, Se, and Ag above the MCL at these wells 5.5 yr after construction. The field and laboratory data that were collected are compiled in Sauer et al. (2005) along with a description of the analytical methods.

3. COMPARISON OF IWEM MODEL WITH FIELD DATA

Predictions made with IWEM v2 (beta) were compared with monitoring data from the two test sections constructed with fly-ash-stabilized subgrade and bottom ash at the STH 60 site in Wisconsin (Fig. 4a). IWEM was used to predict 90th percentile concentrations at the monitoring well adjacent to each test section. The input parameters for IWEM are summarized in Table 1 for the fly ash test section and Table 2 for the bottom ash test section. The leachate concentration used in IWEM was estimated from the maximum concentration recorded in each lysimeter. The Monte Carlo simulation option was used for the aquifer hydraulic conductivity, regional hydraulic gradient, aquifer thickness, and soil-water partition coefficient because none of these parameters was measured explicitly. All simulations were conducted using a 5-yr exposure period, which corresponds to the 5-yr monitoring period at the STH 60 site.

Measured and predicted 90th percentile concentrations for Cd, Cr, Se, and Ag at the monitoring well adjacent to the fly ash test section are shown in Table 3. The reference ground water concentrations are also included in Table 3. When the median (50th percentile) volumetric flux measured on site is used as input for the infiltration rate, the predicted 90th percentile concentrations for Cd, Cr, Se, and Ag are higher than the measured concentration at the STH 60 site. However, the predicted 90th percentile concentrations for these four constituents are lower than the reference ground water concentration. Therefore, IWEM indicates that the application is “protective,” meaning that blending fly ash in the subgrade at this site will not adversely affect ground water concentrations at least within the period that was modeled. This conclusion is consistent with the data from the monitoring well in Table 3.

When the measured 90th percentile volumetric flux (0.1 m/yr) is used as the infiltration rate for the fly ash test section, the predicted 90th percentile concentrations for Cd, Cr, Se, and Ag increase by nearly two times (Table 3). Higher infiltration rate causes more advection through the vadose zone and therefore greater mass loading to ground water. However, the predicted 90th percentile concentrations for the four constituents at the fly ash test section are still lower than the reference ground water concentration. Therefore, IWEM reports that the application is “protective” for the four constituents, which is consistent with the monitoring well data.

Predicted 90th percentile concentrations for the four trace elements are lower than the reference ground water concentration when the median infiltration rate is used as input for the bottom ash test section (Table 3). However, the predicted concentrations exceed concentrations measured at the monitoring well. In contrast, when the measured 90th percentile volumetric flux is used as the infiltration rate, the predicted 90th percentile concentrations for Cd and Se exceed the reference ground water concentration. Thus, IWEM indicates that the application is “protective” using the median infiltration rate and “not protective” using the 90th percentile infiltration rate.

These findings are consistent (median infiltration rate) or conservative (90th percentile infiltration rate) when compared to the monitoring well data.

4. PARAMETRIC STUDY OF IWEM MODEL

A series of parametric simulations was conducted with the roadway module in IWEM v2.0 (beta) to evaluate how system variables (e.g., layer thicknesses, depth to ground water table, initial concentration, exposure duration, receptor location, hydraulics of aquifer, etc.) affect predictions made by the model. The analyses were conducted using the same inputs used to simulate the fly ash test section at STH 60 (Table 1) with a site-specific infiltration rate of 0.042 m/yr.

The parametric analysis was conducted by varying each input variable systematically from the base case (parameters in Table 1), while holding all other input variables constant. Sensitivity was evaluated with the sensitivity coefficient (Zheng and Bennett 2002), $S = (\Delta\zeta/\zeta)/(\Delta b/b)$, where ζ is the response variable and b is the independent variable (site geometric variables). For this analysis, the response variable was the 90th percentile concentration for Cd at the monitoring well. When the sensitivity coefficient has a large magnitude ($|S|$), the independent variable has a large effect on the response variable, indicating sensitivity. When the sensitivity coefficient is zero, the independent variable has no effect on the response variable. For this analysis, parameters were considered significant if the magnitude of the sensitivity coefficient exceeded 0.1.

4.1 Depth to Ground Water

Sensitivity coefficients are shown in Table 4 for depth to ground water. The sensitivity coefficients are higher than 0.1, indicating that concentration at the monitoring well is sensitive to depth to ground water. Depth to ground water affects the amount of dispersion and dilution that occurs between the pavement and the monitoring well, and therefore should impact concentrations at the monitoring well significantly (Li et al. 2006).

4.2 Thickness of IMR Layer

Sensitivity coefficients for thickness of the IMR layer are shown in Table 5. Thickness of the layer containing IMRs should affect concentrations at the monitoring well because the thickness affects the total mass available for leaching and the surface area available for reactions (Li et al. 2006). However, predictions made by IWEM are insensitive to thickness of the IMR layer (sensitivity coefficient is zero in Table 5), at least for the thicknesses that were considered. This may be related to the mechanism used by IWEM to release constituents from the layer containing IMRs.

4.3 Initial Concentration

Sensitivity coefficients are shown in Table 6 for analyses where the initial leachate concentration was varied. Concentrations at the monitoring well are very sensitive to the initial leachate concentration (sensitivity coefficients near 1.0), which is expected. Release of constituents at higher concentrations for the IMR will result in higher concentrations in the vadose zone and ground water.

Sensitivity coefficients for initial total concentration are shown in Table 7. The sensitivity coefficients are higher than 0.1, indicating that 90th percentile concentration at the monitoring well is sensitive to the initial total concentration. This was expected because IWEM defines the duration of release based on the initial total concentration. As shown in Table 7, the pulse duration for cadmium leaching in IMRs layer ranges from 29.7 yrs to 2973 yr depending on the total concentration of cadmium used as input. However, presence of cadmium (or any constituent of interest) in the solid phase is not indicative of potential for leaching. Thus, the sensitivity to total concentration may not be realistic.

4.4 Exposure Duration

Sensitivity coefficients for the exposure duration are shown in Table 8. IWEM allows the user to provide a user-defined exposure duration up to 100 years. There is no sensitivity to the exposure duration (sensitivity coefficient is zero). Insensitivity could be expected if constituents did not reach the monitoring well over the 99-yr duration considered in the analysis, or if the concentration at the monitoring well was relatively constant over time. Constituents did reach the monitoring well during this 99-yr period, however, and sensitivity to related variables that affect concentration over time was observed (e.g., initial leachate concentration and depth to ground water). Thus, the insensitivity to exposure duration was unexpected.

4.5 Location of Monitoring Well

Sensitivity coefficients are shown in Table 9 for location of the monitoring well. The sensitivity coefficients are higher than 0.1, indicating that concentration at the monitoring well is sensitive to location of the monitoring well. Locating the monitoring well further from the roadway results in lower concentration because of additional dispersion and dilution.

4.6 Hydraulic Conductivity of the Aquifer

Sensitivity coefficients for hydraulic conductivity of aquifer are shown in Table 10. The sensitivity coefficients are much higher than 0.1, indicating that concentration at the monitoring well is sensitive to hydraulic conductivity of aquifer. Hydraulic conductivity of the aquifer controls advection in ground water, which affects dispersion and dilution.

Thus, concentration at the monitoring well should be sensitive to hydraulic conductivity of aquifer (Li et al. 2006).

4.7 Aquifer Thickness

Sensitivity coefficients for aquifer thickness are shown in Table 11. The sensitivity coefficients are much higher than 0.1, indicating that concentration at the monitoring well is very sensitive to aquifer thickness. This finding was unexpected, as dispersion and dilution in close proximity to the source should not be affected significantly by thickness of the aquifer.

4.8 Summary Remarks on Sensitivity Analysis

Some of the unexpected findings from the sensitivity analysis (e.g., insensitivity to IMR layer thickness or exposure duration) may be related to assumptions made in the source term used in the roadway module. The square pulse used as the source is convenient numerically, but is not realistic. Most constituents released from IMRs (including trace elements) do not exhibit a pulse release pattern. In addition, relating the duration of the pulse to the total concentration of the constituent of interest is not logical, because presence of a constituent in the solid phase is not indicative of potential for leaching. These assumptions are intended to result in conservative predictions (i.e., over-prediction of concentrations at a receptor). Whether these assumptions actually result in a conservative prediction is unknown. However, none of the cases evaluated in this study resulted in an unconservative prediction (i.e., predicted concentration < field measured concentration).

The sensitivity to aquifer thickness was not anticipated. This condition may be an artifact of the conditions evaluated in this study, but should be explored further.

5. COMPARISON OF PREDICTIONS FROM IWEM AND WISCLEACH

Simulations were conducted with IWEM and WiscLEACH to compare predictions from both models under similar circumstances. Concentrations were predicted at a monitoring well adjacent to each test section (6 m downstream from pavement edge). WiscLEACH was run for a period of 100 yr. IWEM simulations considered exposure periods as long as 100 yr. Data summarized in Table 1 were used as input to IWEM. Total concentrations in the IMRs at STH 60 were not available. Thus, the total concentration for each element considered in the analysis was assumed to be same (Table 1).

For WiscLEACH, concentrations in the lysimeters reported by Sauer et al. (2005) (Fig. 5) were input as leachate concentrations in the IMR layer using the user-defined leaching pattern. For times outside the data set in Fig. 5 (i.e., 5-100 yr), the concentration was assumed to vary linearly between the last measured concentration and zero concentration at 100 yr. The maximum concentration in the lysimeter data set for each trace element was used as the initial leachate concentration in IWEM. These lysimeter concentrations reasonably represent leachate concentrations for each of the IMRs because the lysimeters were located directly beneath the IMR layer in each test section.

Two different cases were considered with IWEM. In one case, Monte Carlo simulation was used for the aquifer hydraulic properties and the partition coefficient (referred to as “Full Monte Carlo” in results). In the other case, the aquifer properties were specified (hydraulic conductivity of 3650 m/yr, regional hydraulic gradient of 0.001, and thickness of 20 m) and the partition coefficient was defined using Monte Carlo simulation (referred to as “Monte Carlo for Partition Coefficients” in results).

The same aquifer hydraulic properties were used as input to WiscLEACH. Retardation factors in the vadose zone and in the aquifer were assumed to be 1.0, the porosity of the vadose zone was assumed to be 0.33, and the porosity of aquifer was assumed to be 0.30. Vertical dispersivity in vadose zone was set at 0.042 m and the horizontal dispersivity in ground water was set at 0.021 m. The ratio of lateral dispersivity to longitudinal dispersivity was specified as 1:10. Molecular diffusion coefficients were set at 0.006 m^2/yr for Cd, 0.004 m^2/yr for Cr, 0.006 m^2/yr for Se, and 0.011 m^2/yr for Ag in WiscLEACH (Li et al. 2006).

Predictions made for each of the STH 60 test sections are summarized in Tables 12-15. In general, higher concentrations were predicted by WiscLEACH than by IWEM when the aquifer properties were specified in both models. Closer agreement between predicted and measured concentrations was obtained when the hydraulic properties and partition coefficient were specified in IWEM using Monte Carlo simulation. This occurs because the distribution of possible concentrations has greater range when Monte Carlo simulation is used for both aquifer hydraulic properties and the partition coefficient in the analysis. As a result, the 90th percentile concentration is higher and closer to the prediction made with WiscLEACH.

Differences between the predictions can be attributed to several factors, the most important of which are the reporting of peak vs. time-averaged concentrations and the different dispersivities used as input to WiscLEACH and IWEM. The effect of time-averaging over an exposure period is evident when a concentration record is considered. For example, Fig. 6 shows the temporal variation in concentration predicted at the monitoring well by WiscLEACH. The concentration varies temporally, increasing from zero initially to the peak concentration at 35.6 yr, and then rapidly diminishing. A time-averaged concentration represents an average of the concentrations in the record, with the magnitude depending on the duration of the average. Because the actual concentration varies with time, the time-averaged concentration must be lower than the peak concentration.

To evaluate the importance of the exposure period, the aforementioned IWEM simulations were conducted using exposure period of 0.1, 5, and 100 yr. Each analysis resulted in the same concentration, as shown in Table 16. This was not expected, as the cadmium concentration at the monitoring well varies over time (Fig. 6). This issue should be explored further.

Differences in the dispersivities used in IWEM and WiscLEACH cause differences in predicted concentrations because the dispersivity affects spreading of the contaminant in ground water (higher dispersivity results in lower concentration). In IWEM, the longitudinal dispersivity in aquifer is scaled based on distance to the well and is assigned via Monte Carlo simulation (US EPA 2002). In this study, the longitudinal dispersivity assigned by IWEM ranged from 0.02 to 20 m, whereas the longitudinal dispersivity in WiscLEACH was set at 0.02 m. As a result, WiscLEACH reported higher concentrations at the monitoring well.

Other factors that contribute to differences in concentration reported by WiscLEACH and IWEM include differences in the monitoring well depth and the partition coefficients assigned in WiscLEACH and IWEM. As shown in the WiscLEACH predictions in Fig. 6, the concentration at the monitoring location varies with depth. IWEM assigns the monitoring well depth between 0 and 10 m using Monte Carlo simulation (US EPA 2007). As a result, the concentration reported by IWEM will vary depending on the depth assigned in a particular realization, and this depth may not be coincident with the peak concentration.

To assess the effect of the partition coefficient, additional simulations were conducted using essentially the same partition coefficients in both models. Partition coefficients near zero were assigned to IWEM (a non-zero partition coefficient must be input to IWEM) and partition coefficients equal to zero were assigned to WiscLEACH. As shown in Table 12, using a partition coefficient near zero increased the difference between the concentrations predicted by IWEM and WiscLEACH modestly. Thus, the differences in the partition coefficients employed in IWEM and WiscLEACH is not a controlling factor affecting differences between the predictions from the models.

6. CONCLUSIONS AND RECOMMENDATIONS

This report has described an assessment of the roadway module in IWEM v2.0 (beta), which was created for evaluating impacts to ground water caused by leaching from industrial material resources (IMRs) used in roadway construction. The assessment consisted of three parts:

(i) comparison between predictions made using the roadway module and concentrations measured at monitoring wells adjacent to highway test sections constructed using fly ash and bottom,

(ii) a parametric analysis evaluating the sensitivity of predictions from IWEM v2.0 (beta) to key input variables, and

(iii) comparison between predictions made using the IWEM roadway module and the WiscLEACH model.

The comparison with field data showed that concentrations predicted by IWEM are higher than concentrations measured in the field, which suggests that IWEM is conservative. Melton and Gardner (2007) report a similar finding. IWEM also indicated that test sections employing fly ash and bottom ash were ‘protective’ when median infiltration rates were used as input, which is consistent with the field data (i.e., no impacts to ground water have been observed at the field site). However, a general inference regarding the degree of conservatism inherent in IWEM cannot be drawn from these findings. Assessing the degree of conservatism will require a more thorough analysis.

The parametric analysis showed that the concentration predicted at a monitoring well increases as the depth to ground water table decreases and the initial leachate concentration increases. This sensitivity is logical and has been reported by others. Sensitivity to the initial total concentration was also observed. This sensitivity occurs because the release period in IWEM is based on the total concentration. However, similar behavior is unlikely to occur in the field because presence of a constituent of interest in the solid phase is not indicative of potential for leaching.

Concentrations predicted at the monitoring well were insensitive to the thickness of the layer containing IMRs and the exposure duration. The insensitivity to thickness may be related to unrealistic assumptions made in the source term. These assumptions, and how they affect predictions, need further study.

Concentrations at the monitoring well decreased as the distance to the monitoring well increased or hydraulic conductivity of aquifer increased, which was expected. In contrast, concentration at the monitoring well decreased as the thickness of the aquifer increased. Sensitivity to aquifer thickness was not expected and should be explored.

Comparison of predictions from IWEM and WiscLEACH for conditions at four highway test sections constructed with IMRs showed that WiscLEACH generally predicted higher concentrations than IWEM. Higher concentrations were predicted by WiscLEACH because of differences in the type of concentrations reported (e.g., peak vs. time averaged), the dispersivities used in each model, and the depth in ground water considered. Future versions of IWEM should consider reporting the peak concentration as well as the concentration a function of time and depth at the monitoring location.

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U.S. EPA, 2002, EPACMTP Technical Background Document. Office of Solid Waste, Washington, DC.

U.S. EPA, 1999, Partition Coefficients for Metals in Surface Water, Soil, and Waste. Office of Solid Waste, Washington, DC.

Zheng C. and Bennett G.D. *Applied contaminant transport modeling* (2nd edition), Wiley-Interscience, New York, 2002.

TABLES

Table 1. IWEM input parameters for fly ash test section at STH 60.

<table>
<tr><th>Category</th><th>Input Parameters for Fly ash Test Section at STH 60, Wisconsin</th></tr>
<tr><td>Source Type</td><td>Select “Roadway” with facility identification information</td></tr>
<tr><td>Source Parameters</td><td>

Number of roadway strips = 3
Roadway segment length (m) = 1
Table of roadway geometry

<table>
<tr><th>Strip #</th><th>Strip type</th><th>Width (m)</th><th># of layers</th></tr>
<tr><td>1</td><td>Shoulder</td><td>1.5</td><td>3</td></tr>
<tr><td>2</td><td>Paved Area</td><td>10.4</td><td>4</td></tr>
<tr><td>3</td><td>Shoulder</td><td>1.5</td><td>3</td></tr>
</table>

Table of Layer Properties

<table>
<tr><th>Strip #</th><th>Layer #</th><th>Thickness (m)</th><th>Bulk density (g/cm^3)</th></tr>
<tr><td>1</td><td>1</td><td>4.32</td><td>1.50</td></tr>
<tr><td>1</td><td>2</td><td>0.30</td><td>1.67</td></tr>
<tr><td>1</td><td>3</td><td>0.38</td><td>1.00</td></tr>
<tr><td>2</td><td>1</td><td>4.32</td><td>1.50</td></tr>
<tr><td>2</td><td>2</td><td>0.30</td><td>1.67</td></tr>
<tr><td>2</td><td>3</td><td>0.26</td><td>1.00</td></tr>
<tr><td>2</td><td>4</td><td>0.12</td><td>1.00</td></tr>
<tr><td>3</td><td>1</td><td>4.32</td><td>1.50</td></tr>
<tr><td>3</td><td>2</td><td>0.30</td><td>1.67</td></tr>
<tr><td>3</td><td>3</td><td>0.38</td><td>1.00</td></tr>
</table>

Shortest distance between the roadway edge and the monitoring well = 6 m
Distance along roadway from the point at which measurement was made to the midpoint of the roadway segment = 0 m
Angle between roadway and ground water flow = 90^0

</td></tr>
<tr><td>Subsurface Parameters</td><td>

Subsurface environment is till over sedimentary rock
Ground water pH = 6.5
Depth to water table = 5 m
Aquifer hydraulic conductivity, regional hydraulic gradient, and aquifer thickness are calculated with Monte Carlo simulation
Aquifer hydraulic conductivity = 3650 m/yr (base case only)
Aquifer thickness = 20 m (base case only).

</td></tr>
</table>

Table 1. IWEM input parameters for fly ash test section at STH 60 (continued).

<table>
<tr><th>Category</th><th>Input Parameters for Fly ash Test Section at STH 60, Wisconsin</th></tr>
<tr><td>Infiltration</td><td>

The predominate soil type surrounding the roadway is medium-grained soil (silt loam)
The nearest climate center is at Madison, Wisconsin. The recharge rate is specified 0.091 m/yr by IWEM.
User specified infiltration rates

<table>
<tr><th>Strip #</th><th>Type</th><th>Infiltration rate[*](m/yr)</th><th>Infiltration rate[#](m/yr)</th></tr>
<tr><td>1</td><td>Shoulder</td><td>0.042</td><td>0.1</td></tr>
<tr><td>2</td><td>Paved</td><td>0.042</td><td>0.1</td></tr>
<tr><td>3</td><td>Shoulder</td><td>0.042</td><td>0.1</td></tr>
</table>
[*,#] are estimated from the 50th and 90th percentile of measured infiltration rate in the lysimeters installed at the STH 60 site, respectively.
</td></tr>
<tr><td>Constituent List</td><td>

Table of Constituent Initial Concentration (for Layer 2 - fly ash layer only, there are no leachate from other layers)

<table>
<tr><th>Constituent</th><th>Strip 1 leachate conc.[+] (mg/L)</th><th>Strip 2 leachate conc.[+] (mg/L)</th><th>Strip 2 total conc.[#] (mg/kg)</th><th>Strip 3 leachate conc.[+] (mg/L)</th></tr>
<tr><td>Cadmium</td><td>0.0321</td><td>0.0321</td><td>8.0</td><td>0.0321</td></tr>
<tr><td>Chromium (VI)</td><td>0.0202</td><td>0.0202</td><td>7.0</td><td>0.0202</td></tr>
<tr><td>Selenium</td><td>0.089</td><td>0.089</td><td>10.0</td><td>0.089</td></tr>
<tr><td>Silver</td><td>0.113</td><td>0.113</td><td>12.0</td><td>0.113</td></tr>
</table>
[+] are from measured leachate concentration in the lysimeters installed at the STH 60 site; [#] are user-input but without measured data.
</td></tr>
<tr><td>Constituent Properties</td><td>

Partitioning coefficient K_d (L/kg) for Cd, Cr, Se, and Ag are calculated by MINTEQA2 using Monte-Carlo method.

</td></tr>
<tr><td>Reference GW Conc.:</td><td>

Table of Reference Ground Water Concentration

<table>
<tr><th>Chemicals</th><th>Reference ground water concentration (mg/L)</th><th>Exposure duration (yr)</th></tr>
<tr><td>Cadmium</td><td>0.004</td><td>5</td></tr>
<tr><td>Chromium (VI)</td><td>0.10</td><td>5</td></tr>
<tr><td>Selenium</td><td>0.03</td><td>5</td></tr>
<tr><td>Silver</td><td>0.03</td><td>5</td></tr>
</table>
</td></tr>
<tr><td>Run Manager</td><td>

Number of Monte Carlo to run for each constituent for each layer of each strip = 10,000.

</td></tr>
</table>

Table 2. Additional IWEM input parameters for other test sections at the STH 60 site.

Parameters		Bottom ash section	Foundry slag section	Foundry sand section
Thickness of IMR layer (m)		0.6	0.84	0.84
Infiltration rate[1](m/yr)		0.053	0.049	0.014
Infiltration rate[2] (m/yr)		0.169	0.145	0.054
Leachate concentration[3] (mg/L)	Cadmium	0.0212	0.032	0.00278
	Chromium (VI)	0.0321	0.0496	0.006
	Selenium	0.141	0.151	0.105
	Silver	0.0152	0.0082	0.00255

[1] Median measured infiltration rate from lysimeters installed at STH 60 site
[2] 90% percentile infiltration rate from lysimeters at STH 60 site
[3] Maximum measured leachate concentration in the lysimeters at STH 60 site

Table 3. Comparison of measured and IWEM predicted concentrations for the fly ash and bottom ash test sections at the STH 60 site[1].

Constituent	Measured concentration at monitoring well at STH 60 site (mg/L)[4]	IWEM 90th percentile exposure level under median infiltration rate[2] (mg/L)		IWEM 90th percentile exposure level under 90% infiltration rate[3] (mg/L)		Reference ground water concentration (mg/L)
		Fly ash section	Bottom ash section	Fly ash section	Bottom ash section	
Cadmium	Below detection limit, < 0.0001	0.0017	0.0015	0.003	0.0045	0.004
Chromium (VI)	Below detection limit, < 0.002	0.0009	6×10^{-5}	0.0017	0.0028	0.10
Selenium	Below detection limit, < 0.002	0.0045	0.0098	0.0083	0.0301	0.03
Silver	Below detection limit, < 0.0002	0.0057	0.0011	0.0104	0.0032	0.03

[1] Monte Carlo simulation of aquifer hydraulics and partition coefficients
[2] Median measured infiltration rate in the lysimeters installed at STH 60 site
[3] 90% percentile of measured infiltration rate in the lysimeters installed at STH 60 site
[4] Measured concentration at monitoring wells between September 2000 and June 2005 adjacent to the fly ash and bottom ash test sections.

Table 4. Parametric analysis for depth to ground water table[+]

Depth of ground water (m)	IWEM 90th percentile exposure level for Cadmium (mg/L)	Sensitivity[#]
5 (base case)	0.0017	-
6	0.0018	0.30
7	0.0016	0.15

[+]only the depth of ground water was changed from the base case, other input parameters the same as base case (Table 1).

[#]defined as $S = (\Delta\zeta/\zeta)/(\Delta b/b)$, where ζ is 90th percentile exposure level for cadmium at the monitoring well and b is the depth to the ground water table.

Table 5. Parametric analysis for thickness of fly ash layer[+]

Thickness of fly ash layer (m)	IWEM 90th percentile exposure level for Cadmium (mg/L)	Sensitivity
0.3 (base case)	0.0017	-
0.4	0.0017	0.0
0.5	0.0017	0.0

[+]only thickness of fly ash layer was changed from base case, other input parameters remained the same as the base case (Table 1).

Table 6. Parametric analysis for initial leachate concentration[+]

Initial leachate concentration of Cadmium (mg/L)	IWEM 90th percentile exposure level for Cadmium (mg/L)	Sensitivity
0.0321 (base case)	0.0017	-
0.06	0.0032	1.05
0.12	0.0063	0.49

[+]only initial leachate concentration of cadmium changed from base case, other input parameters the same as base case (Table 1).

Table 7. Parametric analysis for initial total concentration+

Initial total concentration of Cadmium (mg/kg)	IWEM 90th percentile exposure level for Cadmium (mg/L)	Sensitivity	Pulse duration for cadmium leaching in IMR layer (yr)
8.0(base case)	0.0017	-	2,973
0.8	0.0016	0.07	297
0.08	7.09×10^{-4}	0.59	29.7

+only initial total concentration of cadmium was changed from base case, other input parameters the same as base case (Table 1).

Table 8. Parametric analysis for the exposure duration+

Exposure duration of Cadmium (yr)	IWEM 90th percentile exposure level for Cadmium (mg/L)	Sensitivity
5 (base case)	0.0017	-
4	0.0017	0.0
20	0.0017	0.0
99	0.0017	0.0

+only exposure duration was changed from base case, other input parameters the same as base case (Table 1).

Table 9. Parametric analysis for location of monitoring well+

Location of monitoring well from edge of pavement (m)	IWEM 90th percentile exposure level for Cadmium (mg/L)	Sensitivity
5	0.0018	0.30
6 (base case)	0.0017	-
7	0.0016	0.15
8	0.0015	0.20

+only the location of monitoring well was changed from base case, other input parameters the same as base case (Table 1).

Table 10. Parametric analysis for hydraulic conductivity of aquifer+

Hydraulic conductivity of aquifer (m/yr)	IWEM 90th percentile exposure level for Cadmium (mg/L)	Sensitivity
1825	9.04×10^{-5}	1.72
3650 (base case)	4.86×10^{-5}	-
7300	2.46×10^{-5}	0.49
8760	2.10×10^{-5}	0.41

+only hydraulic conductivity of aquifer was changed from base case, other input parameters the same as base case (Table 1).

Table 11. Parametric analysis for thickness of aquifer+

Thickness of aquifer (m)	IWEM 90th percentile exposure level for Cadmium (mg/L)	Sensitivity
15	7.31×10^{-4}	1.14
20 (base case)	5.69×10^{-4}	-
25	4.82×10^{-4}	0.61
30	2.74×10^{-4}	1.03

+only the thickness of aquifer was changed from base case, other input parameters the same as base case (Table 1).

Table 12. Comparison of concentrations predicted by IWEM and WiscLEACH at the monitoring well in the fly ash test section at STH 60 site.

Constituent	Measured Concentration at STH 60 site (mg/L)	Predicted concentration (mg/L) at 50% leaching flux			
		IWEM – Monte Carlo for Partition Coefficients	IWEM – Full Monte Carlo	IWEM – No Partitioning	WiscLEACH
Cadmium	BDL, < 0.0001	4.77×10^{-5}	0.0017	1.01×10^{-5}	0.001
Chromium (VI)	BDL, < 0.002	7.47×10^{-9}	0.0009	1.43×10^{-11}	0.002
Selenium	BDL, < 0.002	1.38×10^{-4}	0.0045	1.79×10^{-5}	0.07
Silver	BDL, <0.0002	1.68×10^{-4}	0.0057	3.51×10^{-5}	0.06

Table 13. Comparison of concentrations predicted by IWEM and WiscLEACH at the monitoring well in the bottom ash test section at the STH 60 site.

Constituent	Measured Concentration at STH 60 site (mg/L)	Predicted Concentration at 50% leaching flux (mg/L)		
		IWEM – Monte Carlo for Partition Coefficients	IWEM – Full Monte Carlo	WiscLEACH
Cadmium	BDL, < 0.0001	3.07×10^{-5}	0.0015	0.0017
Chromium (VI)	BDL, < 0.002	3.1×10^{-8}	6×10^{-5}	0.0064
Selenium	BDL, < 0.002	2.29×10^{-4}	0.0098	0.085
Silver	BDL, <0.0002	2.43×10^{-5}	0.0011	0.001

Table 14. Comparison of concentrations predicted by IWEM and WiscLEACH at the monitoring well adjacent to the foundry slag test section at the STH 60 site.

Constituent	Predicted Concentration at 50% leaching flux (mg/L)		
	IWEM – Monte Carlo for Partition Coefficients	IWEM – Full Monte Carlo	WiscLEACH
Cadmium	4.54×10^{-5}	0.002	0.0025
Chromium (VI)	4.31×10^{-8}	9×10^{-5}	0.0054
Selenium	2.35×10^{-4}	0.0098	0.087
Silver	1.23×10^{-5}	0.0005	0.0026

Table 15. Comparison of concentrations predicted by IWEM and WiscLEACH at the monitoring well in the foundry sand test section at STH 60 site

Constituent	Predicted concentration at 50% leaching flux (mg/L)		
	IWEM – Monte Carlo for Partition Coefficients	IWEM – Monte Carlo for Partition Coefficients	WiscLEACH
Cadmium	4.73×10^{-7}	1.28×10^{-6}	0.001
Chromium (VI)	1.42×10^{-18}	2.5×10^{-15}	0.002
Selenium	2.46×10^{-5}	5.1×10^{-5}	0.037
Silver	3.33×10^{-17}	3.3×10^{-16}	0.0006

Table 16. Comparison of measured and predicted concentrations at the monitoring well adjacent to the fly ash test section at STH 60 site

Constituent	Measured concentration at STH 60[1] (mg/l)	Predicted concentration at median infiltration rate = 0.042 m/yr (mg/l)				Reference ground water concentration (mg/l)
		IWEM prediction for exposure periods of 0.1, 5, and 100 yr			Wisc-LEACH[6]	
		0.1 yr	5 yr	100 yr		
Cadmium	BDL[2], < 0.0001	0.0017	0.0017	0.0017	0.001	0.004
Chromium (VI)	BDL, < 0.002	2.7×10^{-5}	2.7×10^{-5}	2.7×10^{-5}	0.002	0.10
Selenium	BDL, < 0.002	0.0048	0.0048	0.0048	0.07[7]	0.03
Silver	BDL, <0.0002	0.0060	0.0060	0.0060	0.06	0.03

[1] Measured concentration at monitoring wells during the period of September 2000 to June 2005.

[2] BDL is below detection limit, from Sauer et al. (2005).

FIGURES

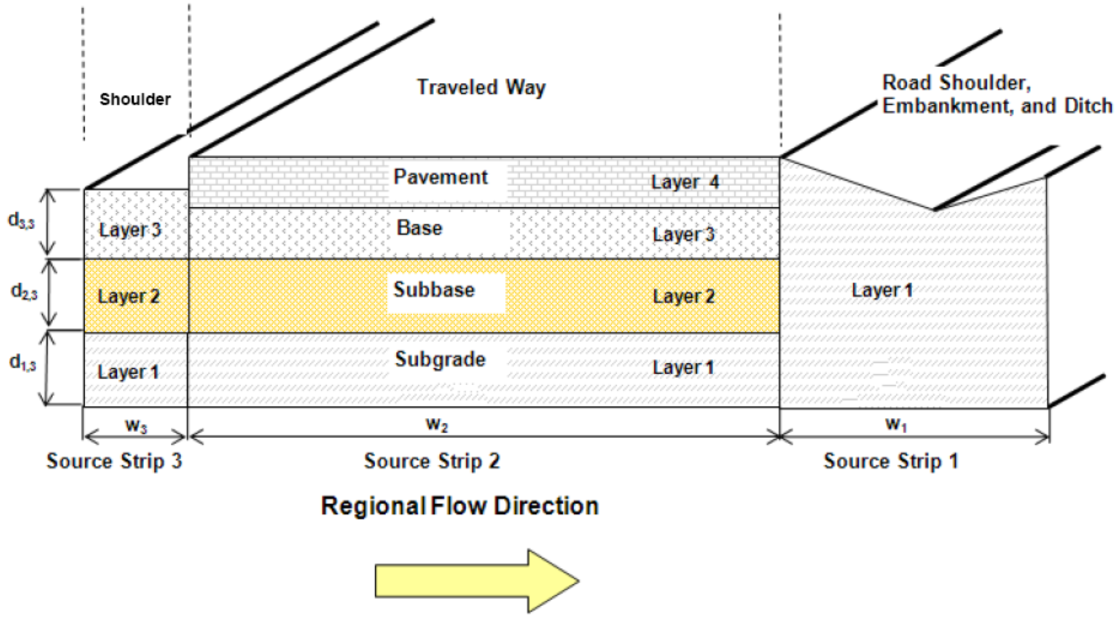

Fig. 1. Example of columns and-source strips used in the roadway module.

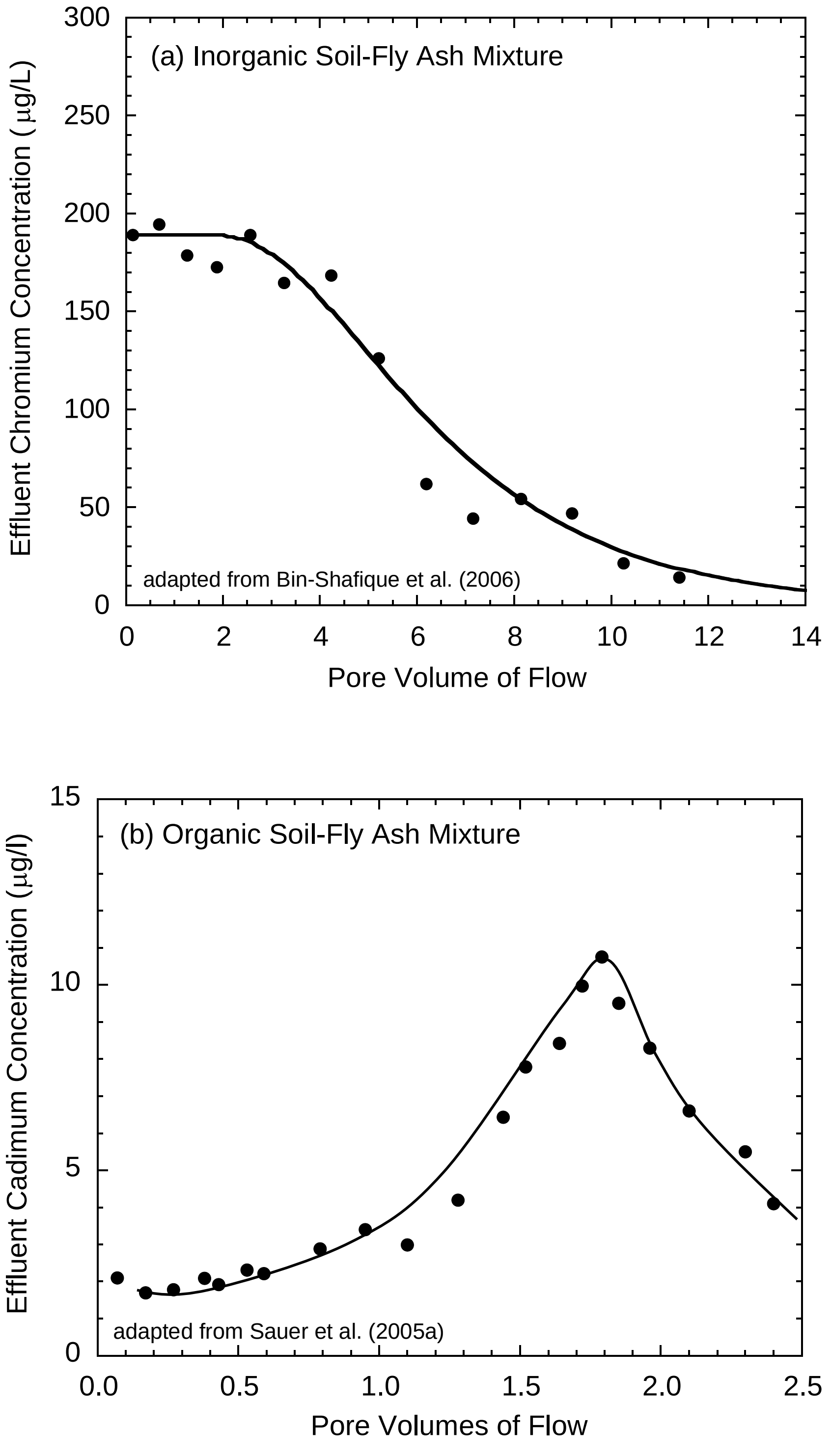

Fig. 2. Examples of first-flush (a) and lagged response (b) leaching patterns. The smooth lines in (a) correspond to predictions made with the advection-dispersion-reaction equation with linear, instantaneous, and reversible sorption. Graphs adapted from Bin-Shafique et al. (2006) and Sauer et al. (2005).

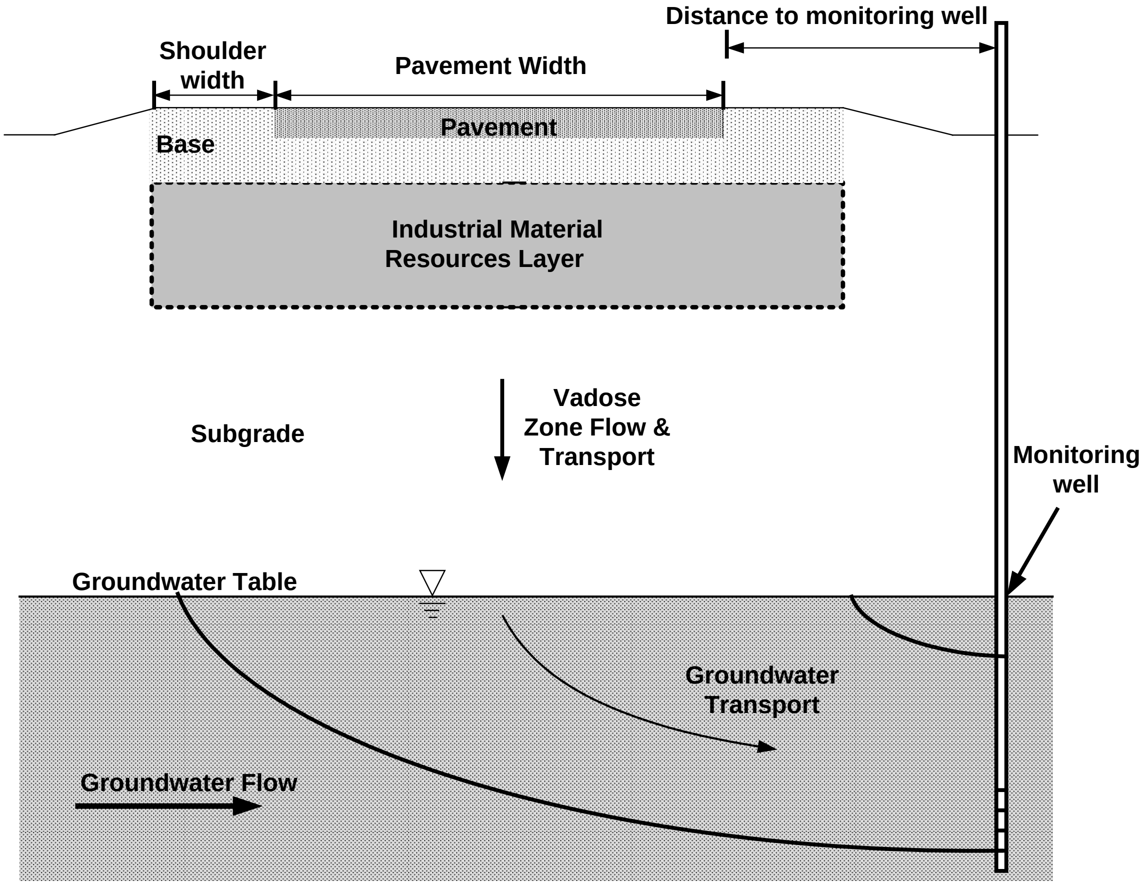

Fig. 3. Conceptual model in WiscLEACH for predicting impacts to the vadose zone and ground water caused by leaching from a pavement structure with an IMR layer.

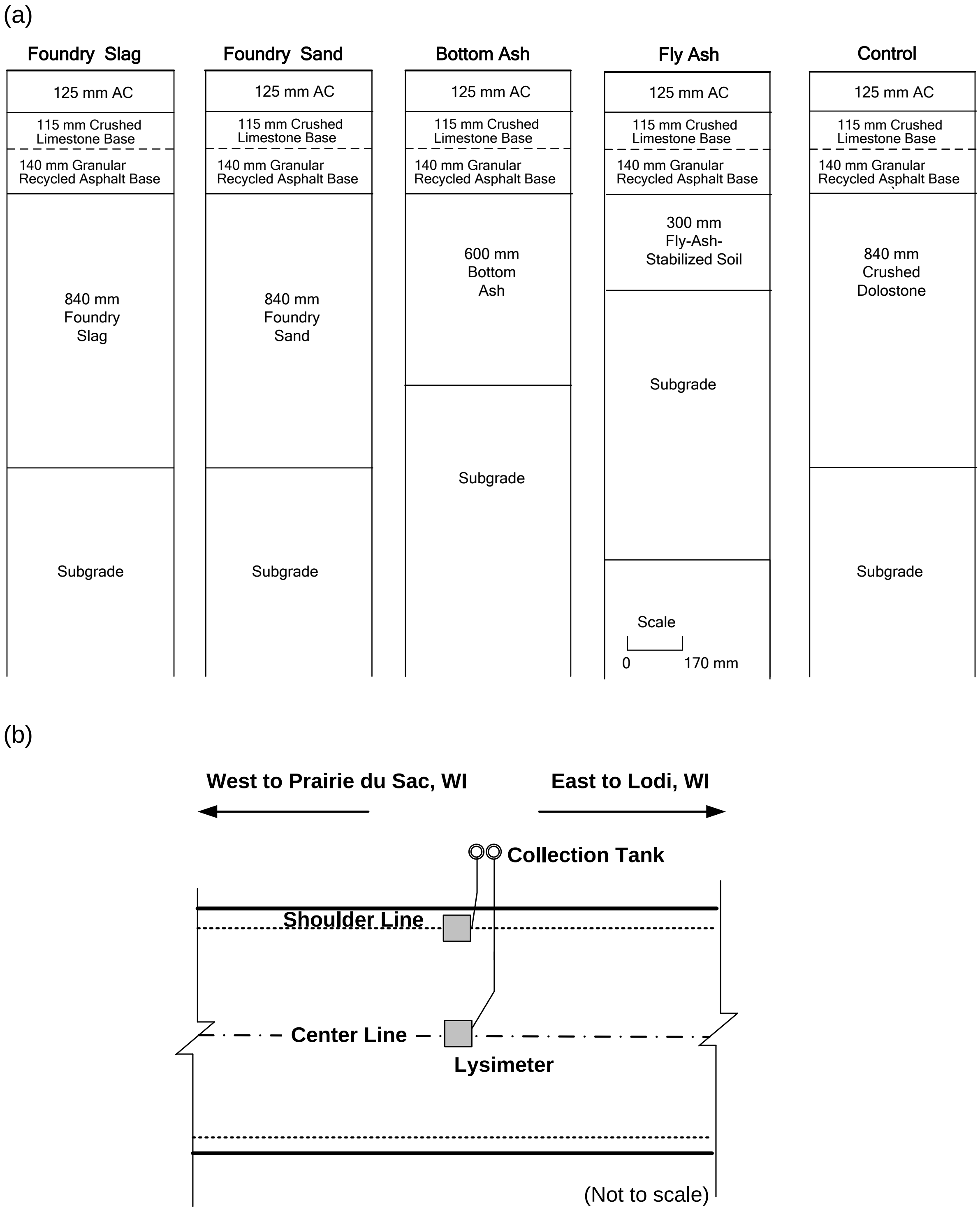

Fig. 4. Profiles of the test sections constructed using foundry slag, foundry sand, bottom ash, fly ash, and crushed rock (control) at STH 60 near Lodi, WI: (a) profile of pavement structures and (b) layout of lysimeters. (AC = asphalt concrete).

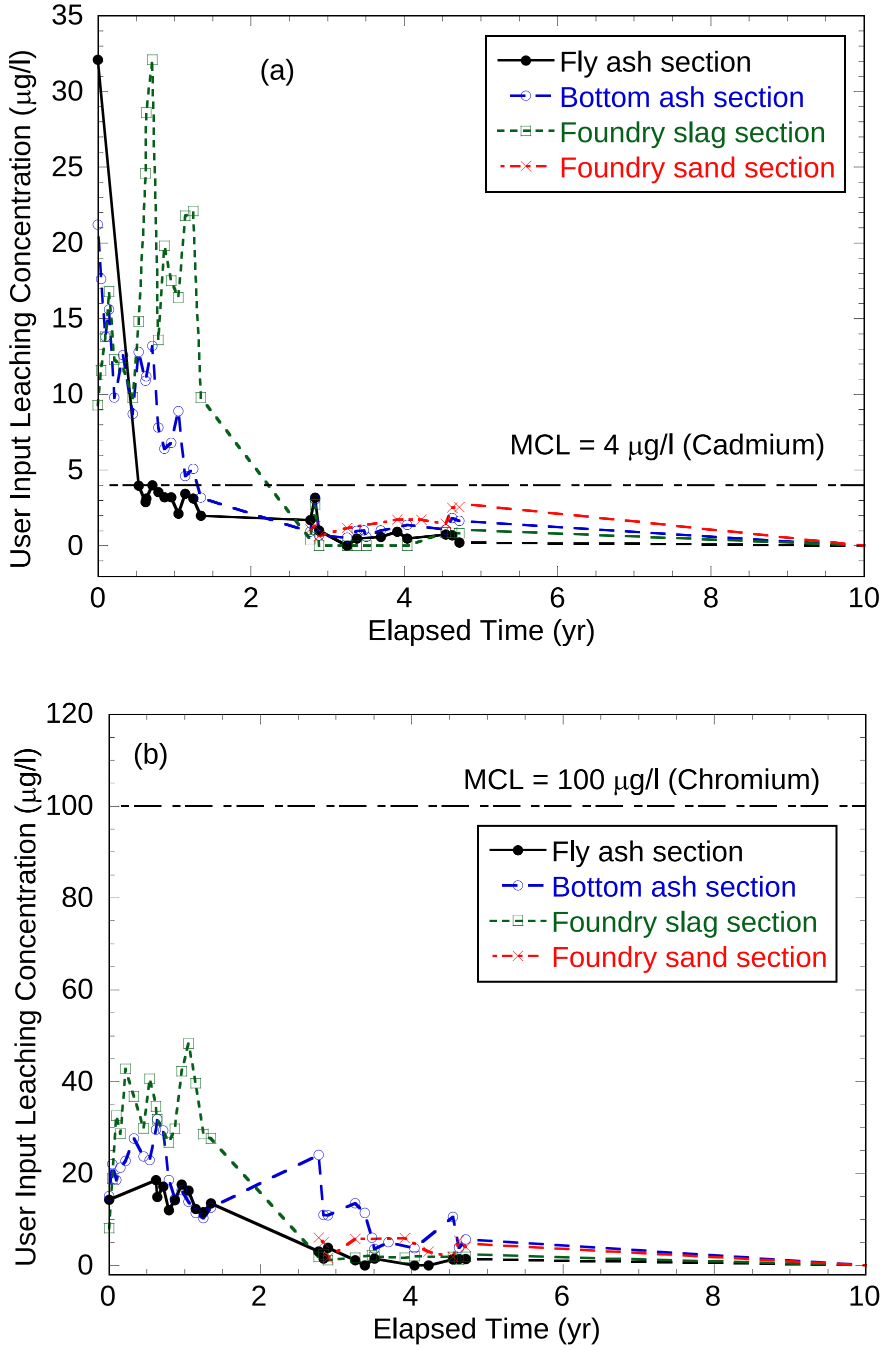

Fig. 5. Leachate concentrations in lysimeters at four test sections at STH 60 site: (a) cadmium, (b) chromium, (c) selenium, and (d) silver. The solid symbol represents data collected from September 2000 to June 2005. The dashed line represents a linear extrapolation from last measured concentration to zero at 10 years from leaching.

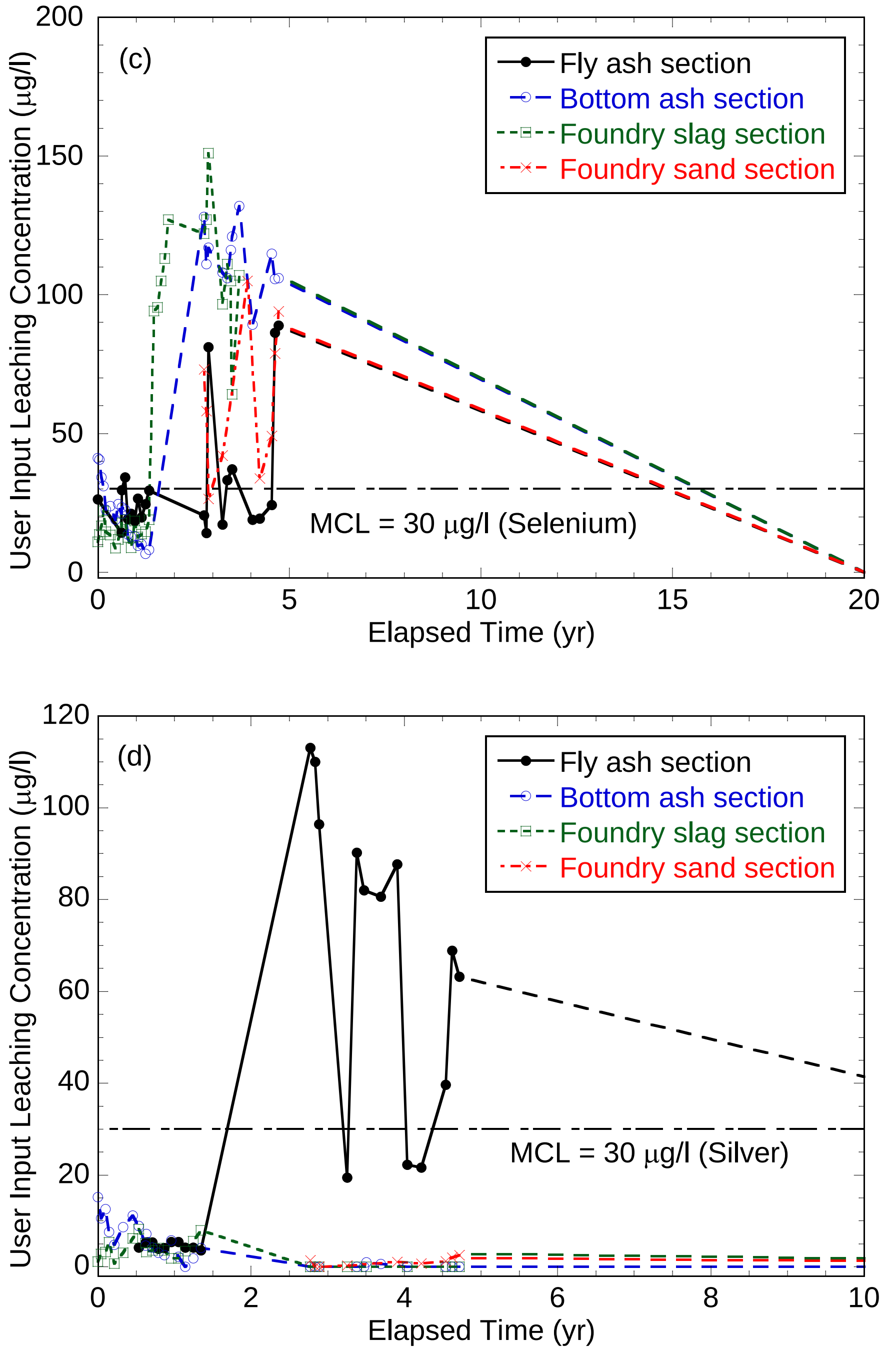

Fig. 5. Leachate concentrations in lysimeters at four test sections at STH 60 site: (a) cadmium, (b) chromium, (c) selenium, and (d) silver. The solid symbol represents data collected from September 2000 to June 2005. The dashed line represents a linear extrapolation from last measured concentration to zero at 10 years from leaching.

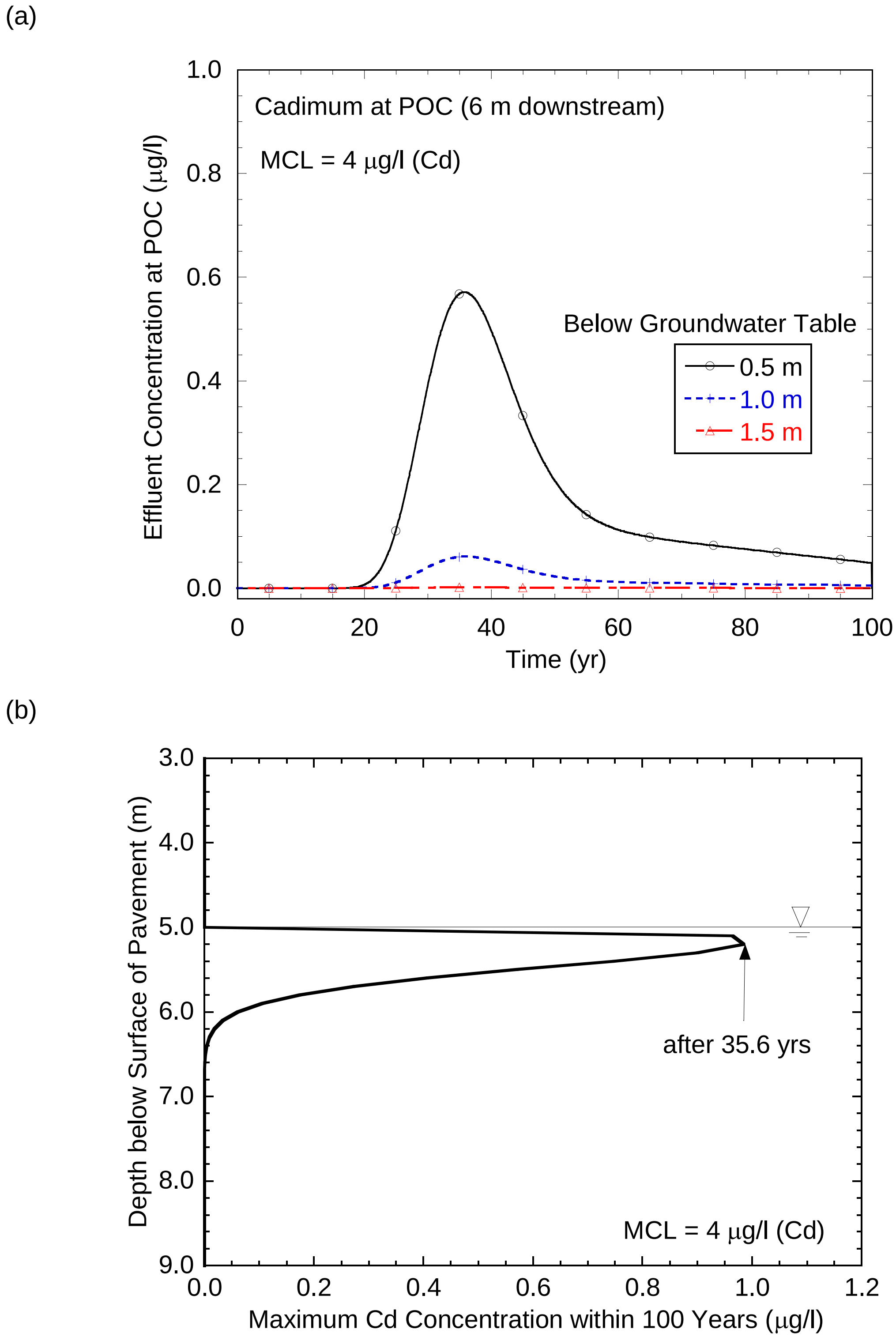

Fig. 6. Predicted concentration at a monitoring well located 6 m downstream from the pavement edge of the fly ash test section at STH 60: (a) concentration vs. time and (b) peak concentration predicted over a 100-yr period as a function of depth below ground surface. The median measured leaching flux (0.042 m/yr) was used as input.

APPENDIX

ADDITIONAL OBSERVATIONS AND RECOMMENDATIONS FOR IMPROVING IWEM

- Pulse releases are not common. A user-defined leaching pattern could be added to permit time-varying leachate concentrations in the IMR layer. 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 field or laboratory experiments).
- The user cannot enter the diffusion coefficient, which can be important for transport in the vadose zone or in a saturated zone comprised of fine-grained soils. An option to enter the diffusion coefficient, or an illustration of how IWEM selects the diffusion coefficient, could be added.
- The user cannot enter the upper and lower bound of Monte Carlo simulations in the aquifer hydraulics, dispersivity, and partition coefficients.
- There is no output information for the maximum concentration profile in the monitoring well as a function of depth, and there is no time reported when the peak concentration occurs at the monitoring well. Providing more detailed output information would help the user understand the predictions being made by IWEM.
- The output is overly simplistic. Additional information should be provided in addition to a conclusion regarding whether the application is "protective" and the 90th percentile concentration. An advanced user option could be included that includes output from the Monte-Carlo simulations. This information would improve the utility of the model and allow the user or decision maker to understand the uncertainty associated with the predictions.
- The Windows interface is easy to use, but crashes frequently with "Run time error '9'" during the data input. A more reliable Windows interface is recommended.

- The current roadway module interface does not allow user to save the input parameters before running IWEM. Allowing the user to save the input parameters before running IWEM is recommended.