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Recycled Material Highway Construction Environmental Assessment: Life Cycle Based Risk Assessment of Recycled Materials In Roadway Construction

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Abstract:

This paper uses a life-cycle assessment (LCA) framework to characterize comparative environmental impacts from the use of virgin aggregate and recycled materials in roadway construction. To evaluate site-specific human toxicity potential (HTP) in a more robust manner, metals release data from a demonstration site were combined with an unsaturated contaminant transport model to predict long-term impacts to groundwater. The LCA determined that there were reduced energy and water consumption, air emissions, Pb, Hg and hazardous waste generation and non-cancer HTP when bottom ash was used in lieu of virgin crushed rock. Conversely, using bottom ash instead of virgin crushed rock increased the cancer HTP risk due to potential leachate generation by the bottom ash. At this scale of analysis, the trade-offs are clearly between the cancer HTP (higher for bottom ash) and all of the other impacts listed above (lower for bottom ash). The site-specific analysis predicted that the contaminants (Cd, Cr, Se and Ag for this study) transported from the bottom ash to the groundwater resulted in very low unsaturated zone contaminant concentrations over a 200 year period due to retardation in the vadose zone. The level of contaminants predicted to reach the groundwater after 200 years was significantly less than groundwater Maximum Contaminant Levels (MCL) set by the U.S. Environmental Protection Agency (US EPA) for drinking water.

Results of the site-specific contaminant release estimates vary depending on numerous site and material specific factors. However, the combination of the LCA and the site specific analysis can provide an appropriate context for decision making. Trade-offs are inherent in making decisions about recycled versus virgin material use, and regulatory frameworks should recognize and explicitly acknowledge these trade-offs in decision processes.

Keywords: recycled materials, roadway construction, life cycle assessment, contaminant transport, risk determination.

Introduction:

There are approximately 6.4 million km of roadway in the U.S. that are being repaired every 2-5 years and replaced every 20-40 years.[1] The U.S. uses approximately 1.2 billion Mg[2] of natural aggregate every year, 58% of which is used in roadway construction. Approximately 90% of the aggregate used in roadways is virgin (636 million Mg). This equates to approximately 99 Mg of aggregate per km of roadway. While the U.S. is not currently suffering from a lack of natural aggregates, there are regions of the U.S. where natural aggregates are not as readily accessible and where the cost is higher due to transportation requirements. Furthermore, it is becoming harder to open new quarries, which increases the cost and transportation requirements for virgin aggregate.

The U.S. generates approximately 88 million Mg of coal ash (bottom and fly) of which 41% are recycled or reused in a wide variety of applications from concrete, structural fill and pavement to waste stabilization [3]. The remaining 53 millions Mg of coal ash are landfilled. Aside from the cement and concrete applications, CCP products can be used for structural fills or embankments, soil stabilization, stabilization of waste materials, flowable fill and grouting mixes, and mineral filler in asphalt paving[4]. A recent survey revealed that a primary reason that recycled material use in the US is limited is concern over environmental impacts[5]. This manuscript explores the environmental impacts from the use of coal ash, and puts these impacts in the context of other systemic impacts that result from the choice to use or not use a recycled material to replace a virgin material.

One significant aspect influencing the economic and environmental impact of high-volume material use is transportation from place of generation to application. The majority of power plants are generally located in areas of high population density, where there is an increased electricity demand. Figure 1 demonstrates that in the state of Wisconsin, the majority of the population lives in the southeastern portion of the state[6], and there is a strong correlation between population density and power plants. This suggests that the majority of coal ash will be generated in areas of higher population density and higher infrastructure demand.

Virgin aggregate, aside from being a non-renewable resource, is energy intensive to produce and has significant associated environmental impacts. The use of the industrial by-product in place of virgin aggregate, aside from reducing aggregate mining and associated environmental impacts, reduces the need to landfill industrial by-products, which can be costly due to tipping fees and utilization of landfill space. The Robinson et al. (2001) study of the Mid-Atlantic region indicated that the greatest deficiency (deficient is defined as not being able to meet 2/3 of the aggregate needs of the region) of aggregate materials occurs in high population density regions, possibly due to resulting higher infrastructure needs.[7] This results in a need to transport aggregate from a source outside that county or region equating to a significant transportation requirement. For Wisconsin, almost every county in the state has some level of sand and gravel or crushed stone production.[2] However, as the Robinson[7] study proved, the higher density regions do not have the natural aggregate production capacity to meet their needs. These aggregate needs could potentially be supplemented or replaced by recycled materials.

The use of coal ash in place of natural aggregates is common in concrete construction and is accepted as having minimal risks by regulators in this consolidated state. There are commonly used American Association of State Highway Transportation Officials (AASHTO) and Association of State and Territory Solid Waste Management Officials (ASTSWMO) specifications established for its use in concrete. The use of coal ash in unconsolidated fill is still a point of concern due to potential impacts from leaching of contaminants out of the recycled materials into the groundwater. The US EPA recommends using precautionary measures when utilizing coal combustions products (CCPs) in the unconsolidated form, to ensure that there are no adverse impacts on ground or surface water.[8]

Modeling tools have recently been developed to predict contaminant transport associated with the use of secondary materials in the highway environment[9]. Through the application of these tools in regional, state or site specific scenarios, risk analyses can be performed and put into context with other existing or occurring contaminant transfer situations that can assist regulators in making realistic determinations of the risk in using the secondary materials. Information from a life cycle assessment (LCA) can also be useful to consider how impacts differ from use of recycled materials compared to virgin materials. The combination of a life cycle impact assessment, which can be viewed as a macro-scale (regional/national) assessment of environmental costs and benefits related to recycled materials use, and a micro-scale (site-specific) risk assessment can provide a unique perspective that may be useful in considering trade-offs associated with recycled material use. The question for a regulator may then become "which impacts provide a greater risk to human health, the regional or national scale impacts or the site-specific scale impacts?" The answer can help regulators to make better informed decisions regarding the use of recycled materials and allow them to explicitly consider off-site impacts in their decisions.

LCA allows for the analysis of the environmental impacts for a product or process on a larger scale to determine environmental and economic costs and impacts from cradle to grave. While the most obvious advantage of this type of analysis is to see the most apparent cost savings over the entire life cycle of a product or process, the other advantage is that the environmental impacts of a product or process can be assessed. Based on these impacts the product or process can be modified to reduce the impacts; or a separate product can be compared to determine which has a lower cost or fewer or less severe impacts. The scope of the LCA can be defined to fit the type of analysis desired. Roth and Eklund (2003)[10] define four levels of system boundaries to define an LCA specifically for road construction: 1) the material level, 2) the road environment, 3) the road environment plus transport and pre-treatment of materials and 4) industrial system level. The industrial system level is comprehensive to include mining and production of materials, material processing, transportation, manufacturing of necessary equipment, administrative processing, product assembly, distribution, sale, use, repair, and ultimate disposal and looks at overall environmental impacts. This is a very data intensive and complex analysis. The road environment level allows the comparison of environmental performance of different materials.[10] Using LCA for analysis of materials in roadway construction, the immediate impacts may be more of concern and this will allow the user to narrow down the scope of the LCA to those aspects that have an immediate affect on the local area. This would include the road environment and transport and could be of use to local regulators who need to assess the local impacts from a particular roadway construction and the use of the recycled materials. The transport factor would be included in this assessment since it can have impacts on the surrounding community.

Modeling tools:

The purpose of this paper is to demonstrate the utility to decision makers of conducting LCA alongside site-specific risk characterization. In order to accomplish this task for a road construction scenario, two modeling tools were used. Pavement Life Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) considers materials, designs parameters, equipment and maintenance and cost inputs and provides a full life cycle costs and environmental assessment. It can be considered a semi-industrial system level analysis (it does not include the impacts from generating the recycled materials) based on the U.S. Department of Commerce census data and provides estimates of life cycle air emissions, contaminant releases, water and energy consumption and cancerous and non-cancerous human toxicity potentials.[11]

HYDRUS2D, a finite element modeling program for simulating the movement of water, heat, and multiple solutes in variably saturated media, was used to model the site-specific impacts of the use of recycled materials.[12]

Scenario:

The scenario used in this paper is based on portions of a field scale project, constructed along a highway in Lodi, WI, that used multiple industrial by-products for roadway stabilization.[13] The project constructed several sections of roadway using different recycled materials in the road sub-base as well as a control section using crushed rock. The recycled materials used in the project were coal fly ash, coal bottom ash, foundry slag and foundry sand; the physical description of the roadway scenario is described in table 1 and figure 2. This paper analyzes only the effects of using bottom ash (obtained from Alliant Energy's Columbia Power Station, Columbus, WI), since the leached metals concentrations were higher for this material than the other recycled materials. Each section of roadway had two equally sized (3.5 m X 4.75 m) lysimeters (one on the shoulder line and one at the center line) underneath the test sections to determine the quantity and concentration of leachate being generated.[13]

The scenario parameters were entered into the PaLATE and Hydrus2D programs to predict long term impacts from the use of bottom ash in the sub-base of a road. The PaLATE program evaluated the impacts from the use of bottom ash to replace crushed rock in the sub-base, and the material source distances were varied to observe the relative significance of the impacts from transportation.

The Hydrus 2D simulations used the average concentrations of Cd, Cr, Se and Ag in the leachate collected from the bottom ash section of the University of Wisconsin project for Monitoring and Analysis of Leaching from Sub-bases Constructed with Industrial Byproducts.[14] Using the Hydrus2D default parameters for silty loam, US EPA partition coefficients for metals analyzed, and the infiltration rate observed by the University of Wisconsin project team (table 2), the model predicted transport through the sub-grade to groundwater assumed to be located 5 meters below the test sections, over a range of time up to approximately 200 years. The sub-surface material was assumed to be a silty loam, based on USGS reports.

PaLATE results:

In comparing the PaLATE results for virgin material (crushed rock) with bottom ash at equivalent source distances, in almost all impact categories, bottom ash has significantly less impact than crushed rock (see table 3). The exceptions are SO_2, with negligible difference, and HTP Cancer, where crushed rock has significantly less impact than bottom ash (see figure 3). Figure 3 also presents impact ratios for the case when virgin materials have twice the haul distance; the increase in transportation has the greatest effect on HTP Non-cancer and NO_X emissions. The impact ratios for these factors decrease significantly, indicating an increase in HTP Non-cancer and NO_X emissions with the increase in transportation distances (figure 3). SO_2 emissions show negligible impact from transportation and all other factors show slight decreases in impact ratio. For this scenario, with the exception of HTP Cancer, the impacts due to bottom ash are less than the impacts from the use of virgin materials. The HTP Cancer impacts, conversely, are approximately 38% greater for bottom ash than for virgin materials. This increase is due to potential impacts from heavy metals in the bottom ash leaching into groundwater. For this specific case, the virgin material is crushed dolostone rock, which has a negligible potential risk to groundwater. The HTP cancer levels calculated by PaLATE indicate that some virgin materials, such as limestone, siliceous gravel and siliceous sand have equivalent HTP cancer levels as bottom ash. This is primarily due to the concentrations of arsenic in these materials. Arsenic is the main contributor to the HTP cancer for the water compartment and these materials contain similar concentration levels of arsenic[14].

Hydrus results:

Because of the significantly greater HTP cancer levels calculated by PaLATE, a closer examination of risks associated with this pathway was warranted. Hydrus 2D simulations were run to predict contaminant transport through the subsurface material (vadose zone) to the groundwater. The simulations indicate that Se and Cr leached from the bottom ash used in the sub-base of the road will not reach the groundwater located 5 meters below the surface even after 200 years. Figures 4 and 5 show the Hydrus2D simulations for Cr and Se transport from beneath the bottom ash layer through the vadose zone to the groundwater table located 5 meters below. The figures demonstrate that the aqueous concentrations of Cr and Se drop dramatically over time and with depth. Simulations for Cd and Ag (not shown) predicted several orders of magnitude less concentration than for Cr and Se. The simulations predict that none of the contaminants will achieve significant concentrations (relative to the US EPA MCL concentration) in the groundwater after the 200 years (see table 4). It is important to note that the significant vadose zone depth at this particular site has a significant influence on the modeling results; the impact of the groundwater table can be seen in figure 4 by observing concentrations at shallower depths.

Comparison of results:

HTP results from PaLATE are derived from leaching potential of materials and average heavy metal concentrations.[11] Table 4 provides tabulated data for the metal concentrations used in the

PaLATE program calculations, data collected by the University of Wisconsin project, the US EPA MCLs and the concentrations predicated by the Hydrus2D simulations. The data used in the PaLATE program came from a study by Morse et al(2001)[15] using materials collected in southern United States (NM, TX, OK, and LA). The Morse study metal concentrations were determined by synthetic precipitation leaching procedure (SPLP) (EPA SW-846 Method 1312). Data collected by the University of Wisconsin and used in the Hydrus 2D simulations are greater than the data collected by Morse et al., and furthermore, simulations were conducted with a constant flux boundary condition, meaning that leachate concentrations were assumed to be constant over the 200-year period. Both of these indicate a certain level of conservatism, as studies have shown decreases in leachate concentrations over time[14].

HTP values are based on the potential leaching concentration of the metals in the materials and does not account for the retardation of contaminants in the sub-surface materials, which acts to prevent significant transport to the groundwater over very long time frames and which reduces peak concentrations reaching the groundwater. The Hydrus 2D simulations do account for transport through the sub-surface and the chemical and physical reactions that occur to reduce contaminant flux, the resulting degradation of groundwater resources and associated human health risks.

The predictions for contaminant concentrations in the groundwater below a 5 m vadose zone after 200 years are shown in Table 4. The maximum concentration just above the groundwater table after 200 years is 0.171 ppb for Cr and 0.002 ppb for Se, both significantly below the groundwater MCLs for those metals (table 4)[16].

Discussion:

The two simulations combined indicate that using bottom ash in place of crushed rock, on a regional or national scale, would result in a reduced energy and water consumption, reduced CO, CO_2, NO_X, SO_2 emissions, reduced mercury and lead emissions and a reduced non-cancer HTP. It would, however, result in an increased cancer HTP due to contaminants that leach from the bottom ash into the groundwater.

HTP is a normalized risk factor reflecting the potential harm that a chemical can cause when released into the water or air environment, based on its toxicity and the potential dose.[17] The HTPs calculated by PaLATE for this scenario are a summation of risk factors for all the contaminants in a material in water and the potential harm that can be caused when all of the contaminants leached from a recycled material reach the groundwater. The Hydrus2D simulations, however, indicate that the contaminants leached from the recycled material might never reach the groundwater at any significant level, suggesting the risk associated with this particular use is quite small from this exposure pathway.

In the United States, a regulatory body currently is likely to only consider the potential impact to the groundwater. However, in the case study provided, trade-offs associated with coal ash use are significant, particularly in comparison with predicted groundwater impact. National or regional level regulators may use this type of analysis to encourage the use of bottom ash; in the case study shown, an increase in cancer HTP could be considered a reasonable trade-off for a reduction in energy and water consumption, air emissions, mercury and lead emissions and non-cancer HTP. The Hydrus 2D results reveal that the HTP impacts, which are specific to the locality, would not be realized for well over 200 years, and at levels that would still be significantly below groundwater MCLs.

There are additional factors that may be considered important to consider in this type of analysis that were not considered here. For example, using the recycled materials saves non-renewable resources and disposal of recycled materials in landfills has real environmental and economic costs, additional trade-offs not considered in this analysis.

The analysis conducted here demonstrates the importance of considering a broad range of environmental and economic impacts when establishing policies and regulations. Regulations in the US are segmented, sometimes referred to as "stove-pipes" for their lack of ability to mix with other types of regulations. Explicit consideration of environmental and economic trade-offs associated with a policy or decision requires the ability to consider how a decision or policy may influence other, perhaps seemingly disconnected, areas of the environment or economy. Environmental regulations may be broadly described as being designed to protect the environment. The analysis provided in this paper shows that a more holistic and multi-scale analysis may be most appropriate for determining whether decisions or policies accomplish that. In the case study described, it is clear that significant environmental trade-offs and small risk reduction rewards would result from a decision prohibiting recycled materials use in favor of virgin aggregate.

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Table 1: Physical description of roadway scenario.[13]

Length	305 m
Pavement width	10.4 m
Shoulder width	1.5 m
Base and stabilized subgrade width	13.4 m
Depth of vadose zone	6 m

Table 2: Hydrus2D model parameters

Infiltration rate	0.026 cm/day
Cd K_d	501.2
Cr K_d	6.3
Se K_d	20
Ag K_d	398.1
Depth of vadose zone	5 m

Table 3: LCA material production and transportation impacts for use of bottom ash (source distance = 80 km) and virgin materials (source distance = 80 and 160 km).

	Bottom Ash (80km)		**Virgin Material (80km)**		**Virgin Material(160km)**	
	Mat Prod	Trans	Mat Prod	Trans	Mat Prod	Trans
Energy [MJ]	1,298,710	605,840	2,683,791	685,778	2,683,791	1,315,351
Water [kg]	234	103	427	117	427	224
CO_2 [Mg]	56	45	154	51	154	98
NO_X [kg]	581	2,413	778	2,731	778	5,239
PM_{10} [kg]	409	470	1,815	532	1,815	1,021
SO_2 [kg]	36,269	145	36,365	164	36,365	314
CO [kg]	139	201	268	228	268	437
Hg [g]	1	0	1	0	1	1
Pb [g]	43	20	72	23	72	44
RCRA HazW Gen [kg]	8,087	4,365	9,696	4,941	9,696	9,478
HTP (Cancer)	258,980	12,987	154,493	14,700	154,493	28,195
HTP (Non-cancer)	580,639	15,932,615	146,394	18,034,833	146,394	34,591,585

Table 4: Metal leaching concentrations from bottom ash.

Metal	PaLATE (Morse, 2001)[15]	UWisc data (2005)[14]	MCL for groundwater[16]	Hydrus 2D prediction - 200 yrs
Cd	< 1.0 ppb	21.2 ppb	5 ppb	2.60e-10 ppb
Cr	10.60 ppb (sd 4.34)	15.1 ppb	100 ppb	0.171 ppb
Se	<25.0 ppb	41.2 ppb	50 ppb	2.24e-3 ppb
Ag	None	11.8 ppb	100 ppb*	2.60e-10 ppb

* Secondary MCL standard.[16]

Figure 1: Location of power plants with respect to population densities in Wisconsin.[6]

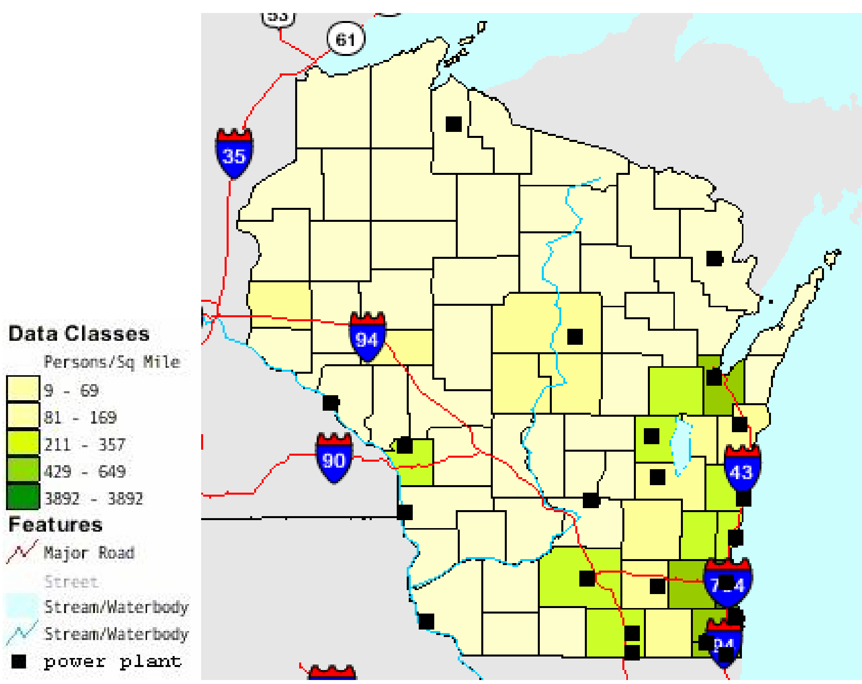

Figure 2: Physical description of roadway scenario.[13]

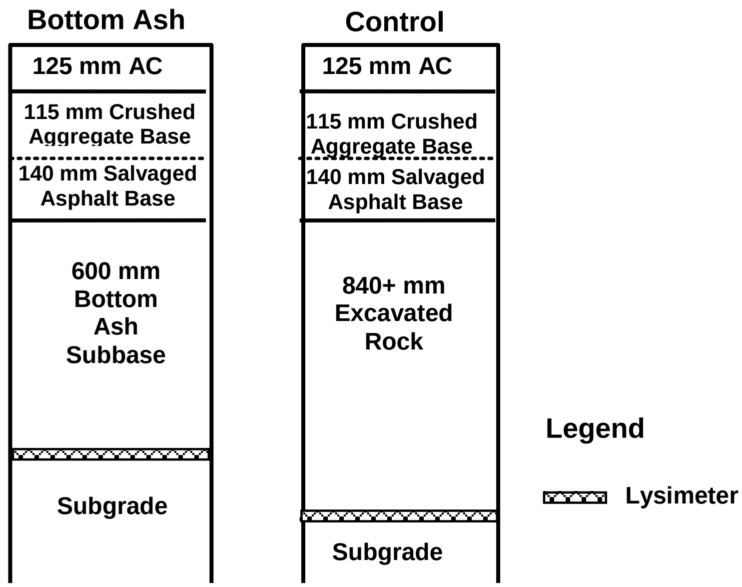

Figure 3: Ratio of impacts from use of bottom ash (BA) in roadway construction compared to virgin materials (VM): BA source at 80 km, VM source at 80 and 160 km. Ratios less than 1.0 indicate that impacts due to virgin material are greater than impacts due to bottom ash. The black bar indicates the ratio of impacts for materials sources at equal distances. The grey bar indicates the ratio of impacts for materials with the source for virgin materials being twice that of the bottom ash.

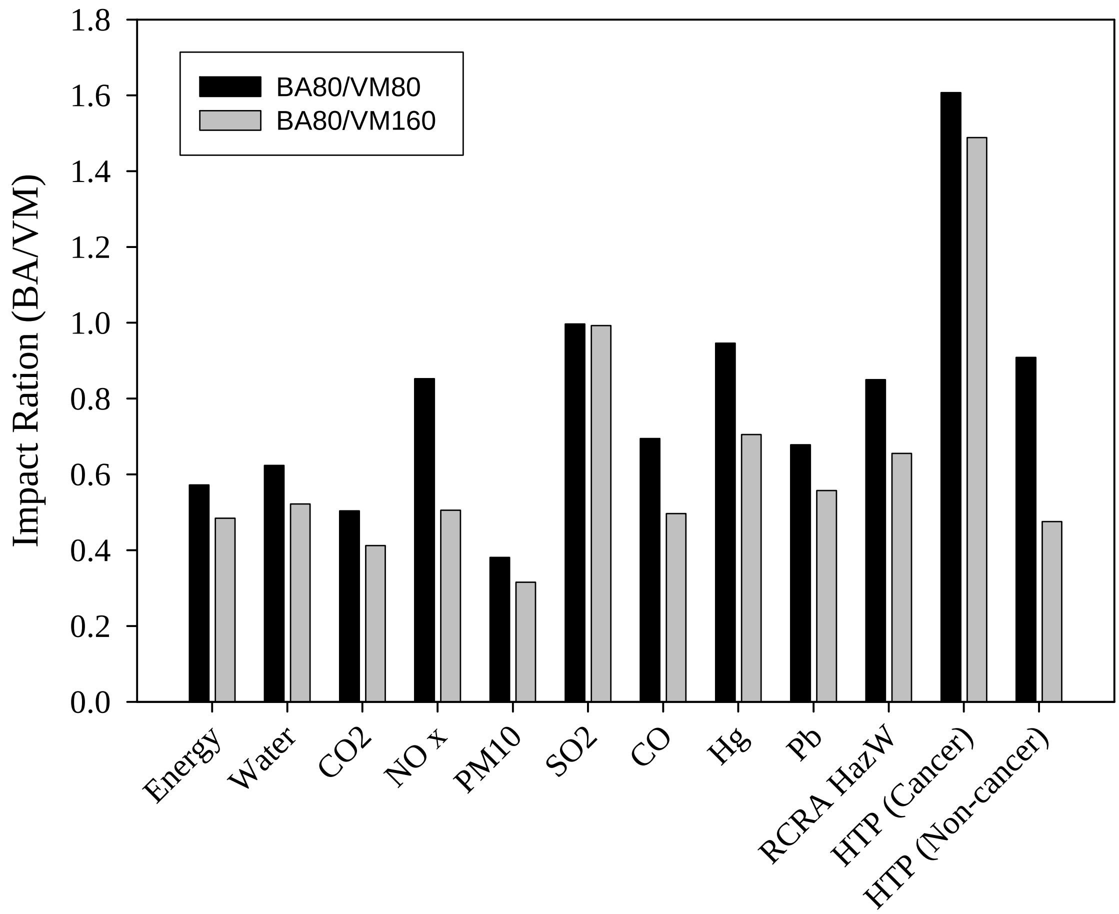

Figure 4: Hydrus2D simulation for transport of Cr from beneath the recycled materials layer in the road sub-base to groundwater (5 meters below the recycled materials layer) over 200 years.

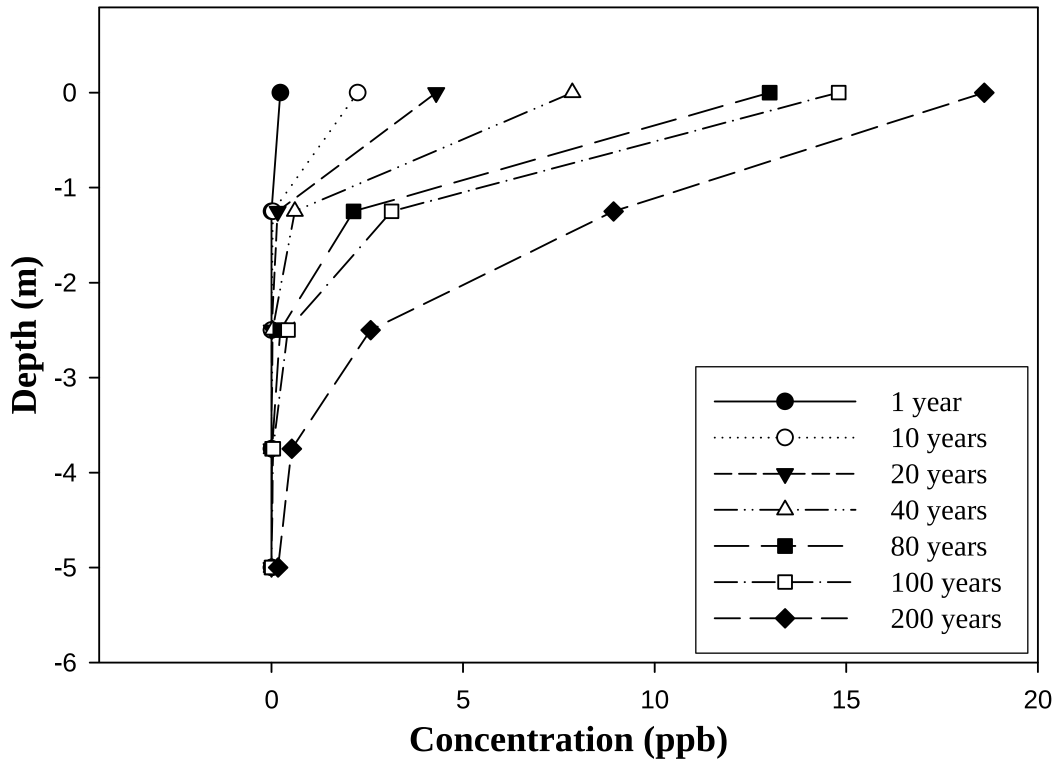

Figure 5: Hydrus2D simulation for transport of Se from beneath the recycled materials layer in the road sub-base to groundwater (5 meters below the recycled materials layer) over 200 years.