PARAMETRIC STUDY OF THE EFFECT ON GROUNDWATER QUALITY OF LEAKAGE OF BENZENE AND TOLUENE THROUGH COMPOSITE LINERS

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Abstract: Composite liners with a geomembrane and either a compacted clay or a geosynthetic clay liner are widely used to minimize leakage from landfills and other containment systems such as leachate lagoons. While much work has been done to quantify the rates of leakage, few papers assess the impact of this leakage on groundwater quality. This is particularly important for organic contaminants because of the potential for diffusion through the intact parts of the geomembrane. Building on recent developments in modeling mass-transport through leaking geomembranes as a boundary condition to the diffusion-advection boundary value problem, we report the results of a 2D finite-element parametric study of the problem using the Soil Pollution Analysis System SPAS. We assess the effect of landfill cell size, groundwater Darcy velocity and groundwater horizontal mixing, on concentrations of Benzene and Toluene, underlying a landfill with a leaking GM. We make recommendations concerning the importance of leakage and the accuracy of 1D analytical tools, namely the Rowe Equation for leakage and the POLLUTEv7 program for the prediction of contaminant transport.

Keywords: HDPE geomembrane, computer simulation, landfill liner, leak.

INTRODUCTION

Leakage through geomembranes (GMs) needs to be considered in assessing the potential performance of composite landfill liners for a particular application. Research over the last decade has developed a number of methods for assessing the likely leakage rates of various liner configurations under different hydraulic conditions and a given frequency and type of defects (e.g., Rowe, 1998; Rowe, 2005; Touze-Foltz and Giroud, 2005). These methods usually rely on 1D approximations of the hydraulic and solute transport problems and have generated leakage predictions that are widely used in landfill design practice. While leakage rates give an indication of the potential for advective transport, they do not provide any direct information regarding the potential pollutant concentration in groundwater. This is especially important for organic contaminants where diffusion through the intact parts of the geomembrane can be significant. Attempts at 2D and 3D modelling of leakage and mass transport have been made relatively recently by a number of authors (e.g., Kalbe et al., 2002; Iryo and Rowe, 2005; Saidi et al., 2006). El-Zein (2008) developed a formulation which allows the modelling of leaking geomembranes as a mass-conserving boundary condition to the coupled seepage and mass transport equations and implemented it in a finite-element computer program CONFEM (El-Zein et al., 2005), as part of the Soil Pollution Analysis System (SPAS). El-Zein and Rowe (2008) used this formulation to conduct a detailed study of the migration of dichloromethane (DCM) through compacted clay liners (CCL) and geosynthetic clay liners (GCL) for various coefficients of hydraulic conductivities of the liners, frequency of defects and transmissivities of GMs. The study found that 1D analyses reasonably replicate peak aquifer DCM concentrations, especially under conditions of reasonable mixing in the aquifer. However, in some cases, 1D analyses underestimated peak concentrations by around 40%. In addition, the study focussed exclusively on DCM and, due to space constraints, did not assess the effect of all variables of interest.

In this paper, we study the transport of benzene and toluene through leaking geomembranes and the underlying clay liner. We evaluate the effect on peak concentrations in the aquifer of two hitherto unconsidered variables, namely the base cell length parallel to the ground water flow direction and Darcy velocity of flow in the aquifer. Specifically, we conduct a set of seepage and solute transport analyses using Soil Pollution Analysis System SPAS (El-Zein and Balaam, 2008), in order to assess the effects of these variables on a) the discrepancy between of 1D and 2D solutions and b) the impact of leakage on peak concentrations.

MODEL CONSTRUCTION

Overview

A composite liner with an HDPE geomembrane over either a CCL or GCL on an attenuation layer overlying a thin aquifer was considered. A set of 100m-long, leaking wrinkles occurred regularly over the width of the geomembrane base cell, along direction x (see Figure 1). The wrinkles were assumed to be normal to the direction of water flow in the aquifer. Dimensions, material properties and other analysis data are given in Table 1. Four categories of problems were analysed, covering combinations of CCL, GCL, benzene and toluene. For each pair of liner type and pollutant, three sets of analyses were conducted. First, leakage through the geomembrane was calculated using a) the Rowe equation with hydraulic interaction between leaks (Rowe, 1998) and b) the 2D finite-element seepage component of SPAS. Second, the mass transport problem was simulated using both POLLUTEv7 in 1D (Rowe and Booker, 2005) and SPAS (El-Zein and

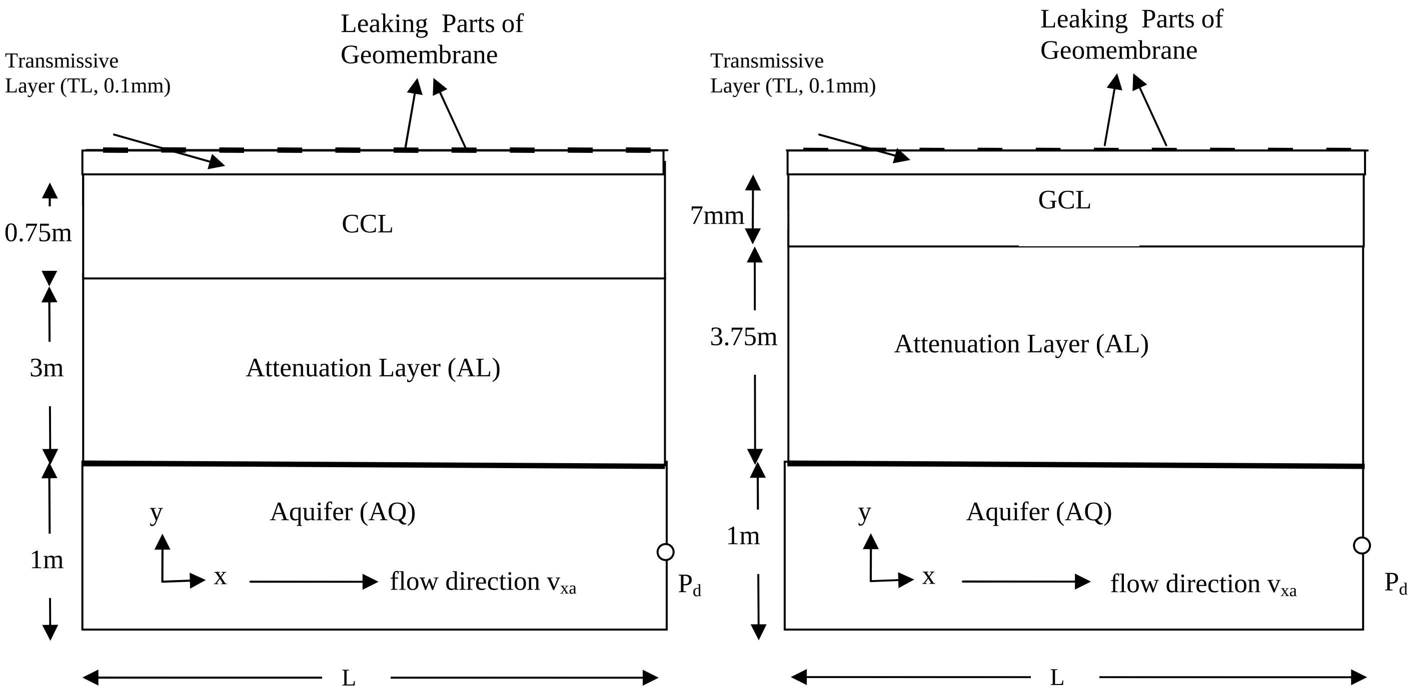


Figure 1. CCL and GCL systems with Leaking Geomembranes (not to scale)

Table 1. Problem dimensions, material properties and other parameters*

				Benzene		Toluene	
Layer	**Entity**	**Symbol**	**Units**	**CCL Sys**	**GCL Sys**	**CCL Sys**	**GCL Sys**
Waste	length of base cell	L	m	variable	variable	variable	Variable
	waste per unit area	d_w	t/m2	25	25	25	25
	proportion in the waste	p	mg/kg	0.014	0.014	0.7	0.7
	initial concentration	C_0	μg/l	20	20	1000	1000
	equivalent height	H_r	m	17.5	17.5	17.5	17.5
	decay half-life	$t_{\frac{1}{2}g}$	years	25	25	15	15
Geomembrane	thickness	h	mm	1.5	1.5	1.5	1.5
	diffusion coefficient	D_g	m^2/s	$2.4x10^{-13}$	$2.4x10^{-13}$	$2x10^{-13}$	$2x10^{-13}$
	partition coefficient	S_{gf}	DL	55	55	125	125
	transmissivity	θ	m^2/s	$1.6x10^{-8}$	10^{-10}	$1.6x10^{-8}$	10^{-10}
	decay half-life	$t_{\frac{1}{2}g}$	years	no decay	no decay	no decay	no decay
	wrinkle width	2b	m	0.3	0.3	0.3	0.3
	wrinkles frequency	F	wr/ha	2.5	2.5	2.5	2.5
Clay Liner	thickness	H	mm	750	7	750	7
	Porosity	N	DL	0.4	0.7	0.4	0.7
	hydraulic conductivity	K_{xx}, K_{yy}	m/s	10^{-9}	10^{-10}	10^{-9}	10^{-10}
	diffusion coefficient	D_0	m^2/s	$3x10^{-10}$	$1.5x10^{-10}$	$3x10^{-10}$	$2x10^{-10}$
	decay half-life	$t_{\frac{1}{2}}$	years	100	100	60	60
Attenuation Layer	thickness	H	m	3	3.75	3	3.75
	Porosity	N	DL	0.3	0.3	0.3	0.3
	hydraulic conductivity	K_{xx}, K_{yy}	m/s	10^{-7}	10^{-7}	10^{-7}	10^{-7}
	diffusion coefficient	D_0	m^2/s	$5x10^{-10}$	$5x10^{-10}$	$6x10^{-10}$	$6x10^{-10}$
	decay half-life	$t_{\frac{1}{2}}$	years	100	100	60	60
Aquifer	thickness	H	m	1	1	1	1
	Porosity	N	DL	0.3	0.3	0.3	0.3
	hydrodynamic dispersion	D_{xa}	$m^2/year$	variable	variable	variable	variable
	hydrodynamic dispersion	D_{ya}	$m^2/year$	∞	∞	∞	∞
	Darcy velocity	v_{xa}	m/s	variable	variable	variable	variable
	decay half-life	$t_{\frac{1}{2}}$	years	100	100	60	60

*DL: dimensionless; entities specified as variable are given in individual figures for specific simulations; wr/ha: wrinkles per hectare

Balaam, 2008) in 2D and the results were compared in order to assess the accuracy of 1D approaches in modelling the impact of leakage on groundwater quality. Finally, a parametric analysis was conducted using SPAS to quantify the effect of base cell width and Darcy velocity of fluid flow in the aquifer on peak concentrations in the aquifer. In the parametric study, base width values of 40m, 200m and 600m, and Darcy velocities in the aquifer of 0.5, 1 and 2 m/a were used. Predictions were compared to the baseline of an intact geomembrane, in order to quantify the impact of leakage on groundwater quality. In both SPAS and POLLUTEv7, mass-conserving boundary conditions in the waste were used to account for the decline in time of concentration in the waste, as a result of decay and migration by advection and diffusion into the underlying liner. All analyses were performed on a laptop PC.

1D Models

Leakage was estimated using the Rowe Equation which accounts for hydraulic interaction between leaks in adjacent wrinkles. The equation had been derived based on an idealization of the flow equation in the case of a clay liner and an underlying attenuation layer. POLLUTEv7, a mass transport analysis program in 1D, was used to derive contaminant concentrations in the aquifer. Leakage rates, calculated from the Rowe Equation, were used to calculate the vertical Darcy velocities used in POLLUTEv7 as input data. Where discrepancies in leakage calculations were found between the Rowe Equation and the seepage SPAS analysis, the mass transport problem in POLLUTEv7 was solved using both leakage values separately, in order to identify distinct sources of divergence between 1D and 2D results. Diffusion through the GM was modelled by assigning the value of the permeation coefficient, $P_g = S_{gf}D_g$ as the diffusion coefficient input for this layer.

2D Models

SPAS, a Laplace-transform finite-element program with special tools for landfill modelling, was used to conduct 2D analyses. Landfill features, such as layers and leaks, were generated automatically, subject to user-defined control parameters. An equivalent boundary condition was specified to simulate the leaking geomembrane, with a mass-limited source of waste on top. Separate diffusion D_g and surface partitioning S_{gf} coefficients were used for the geomembrane. However, in one scenario, results were compared to the case when a permeation coefficient P_g is used instead, and were found to yield identical aquifer peak concentration curves. Discharge by advection was assumed at the downstream face of the aquifer, while no discharge was taken at the upstream face. The horizontal coefficient of hydrodynamic dispersion in the aquifer D_{xa} was taken as 100m^2/year in the SPAS analyses. However, given that POLLUTEv7 makes the assumption of perfect horizontal mixing in the aquifer ($D_{xa}=\infty$), additional SPAS analyses with $D_{xa}=\infty$ were conducted in some cases to elicit the effect of mixing. Default parameters of meshing and refinements around leaks were used. Convergence analyses were conducted to assess the quality of numerical results. The steady-state seepage problem was first solved to determine the spatial distribution of seepage velocities. SPAS calculated leakage rates across the top surface of the clay liner by integrating seepage velocities along this line. Seepage velocities at finite-element nodes were then used as input data for a solute transport analysis, through an automated procedure. Peak concentrations were taken to occur at the downstream point P_d shown in Figure 1. This assumption was regularly checked and found to be correct.

RESULTS

Leakage Calculations: Rowe Equation with Interaction versus SPAS

A comparison of leakage predictions in 1D and 2D is shown in Table 2. Clearly, predictions of the Rowe Equation with hydraulic interaction for CCL systems are highly accurate for most cases, within a few percents of 2D results. At the high end of leakage rates, the discrepancy is larger but predictions from the Rowe Equation are conservative. In GCL systems, leakage predictions of the Rowe Equation are 23% smaller than the SPAS seepage results. This is consistent with earlier findings by El-Zein and Rowe (2008). The discrepancy is within an acceptable range since it is likely to be smaller than the sensitivity of concentration to uncertainties in data. In any case, it appears from these results that a correction factor of 1.3 can be applied to 1D predictions to close the discrepancy.

Contaminant Transport: 1D versus 2D Approches

Figures 2 and 3 show the change in time of concentration of benzene and toluene, respectively, at point P_d, and compare predictions of POLLUTEv7 and SPAS, for leaking and non-leaking cases. Results have been derived for L=200m as well as L=600m because, as shown in the following section, the latter case yield higher peaks of concentration. Three comments can be made concerning a) leaking versus non-leaking peaks; b) 1D versus 2D predictions for non-leaking cases and c) 1D versus 2D predictions for leaking cases.

The peak impact considering leakage is around three times that for diffusion alone for the CCL systems (leakage rate=61 lpdh) and about twice that for the GCL systems (leakage rate=41 lpdh) for 2.5 holed-wrinkles per hectare.

In the absence of leakage, under perfect mixing in the aquifer, 1D and 2D predictions coincide as expected, since the problem becomes perfectly one-dimensional. When $D_{xa}=100\text{m}^2$/year is used in SPAS under non-leaking conditions, the peak concentration increases. This is due to the fact that, despite the uniform contaminant loading in the waste, SPAS does reflect the asymmetry in boundary conditions between the upstream and downstream faces of the aquifer, with higher concentrations occurring downstream.

Table 2. Comparison of calculated leakage rates from 1D and 2D approaches

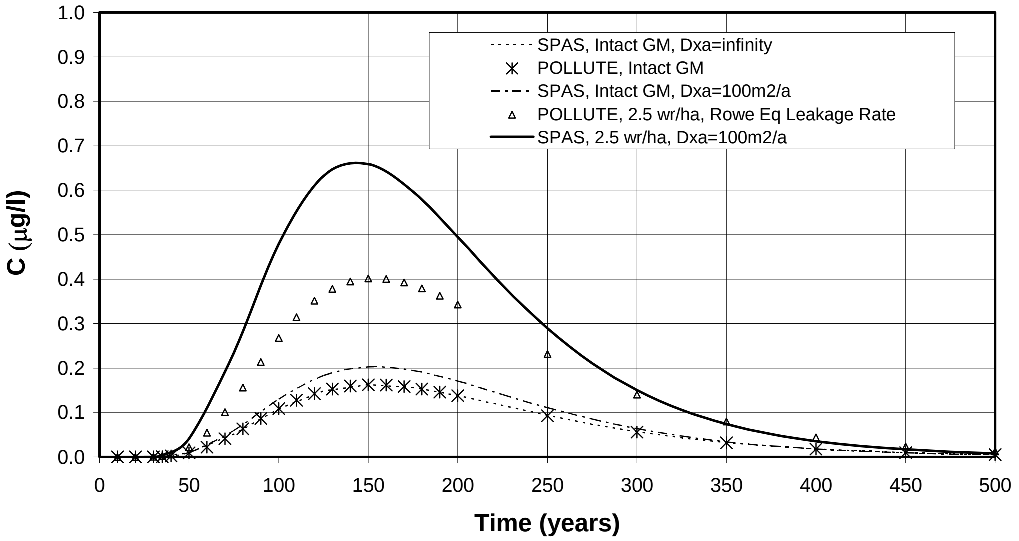
system	Width (m)	Wrinkles	wrinkles per hectare	SPAS (2D)		Rowe Equation with Interaction (1D)		% DIFFERENCE
				m/a	lphd	m/a	lphd	
CCL	600	1	0.167	1.50E-04	4.11	1.48E-04	4.05	-1%
CCL	600	6	1	9.14E-04	25.04	8.86E-04	24.27	-3%
CCL	600	15	2.5	2.29E-03	62.74	2.22E-03	60.82	-3%
CCL	200	5	2.5	2.28E-03	62.47	2.22E-03	60.82	-3%
CCL	200	10	5	4.49E-03	123.01	4.43E-03	121.37	-1%
CCL	100	5	5	4.49E-03	123.01	4.43E-03	121.37	-1%
CCL	100	7	7	6.09E-03	166.85	6.20E-03	169.86	2%
CCL	80	7	8.75	7.25E-03	198.63	7.75E-03	212.33	7%
CCL	80	10	12.5	9.03E-03	247.40	1.11E-02	304.11	23%
CCL	40	5	12.5	9.03E-03	247.40	1.11E-02	304.11	23%
GCL	600	1	0.167	1.00E-04	2.74	7.58E-05	2.08	-24%
GCL	600	6	1	5.92E-04	16.22	4.55E-04	12.47	-23%
GCL	600	15	2.5	1.48E-03	40.55	1.14E-03	31.23	-23%
GCL	200	5	2.5	1.48E-03	40.55	1.14E-03	31.23	-23%
GCL	200	10	5	2.96E-03	81.10	2.27E-03	62.19	-23%
GCL	100	5	5	2.96E-03	81.10	2.27E-03	62.19	-23%
GCL	100	7	7	4.14E-03	113.42	3.18E-03	87.12	-23%
GCL	80	7	8.75	5.17E-03	141.64	3.98E-03	109.04	-23%
GCL	80	10	12.5	7.37E-03	201.92	5.68E-03	155.62	-23%
GCL	40	5	12.5	7.37E-03	201.92	5.68E-03	155.62	-23%

2D peak concentrations for benzene are around 0.6ppb compared to 1D predictions of 0.4ppb in CCL systems, using POLLUTEv7. For toluene the peaks were about 0.8 and 0.5ppb respectively. In both cases the difference in predicted concentration is of no practical significance since (a) they are both well below the typical maximum acceptable concentration of 5ppb, and (b) the uncertainty regarding the source concentration and other parameters is far greater than the difference in the predictions. Likewise for toluene the calculated values are below the recommended maximum concentration of 24ppb. The difference in the leakage rates calculated from the Rowe Eq. versus the full 2D SPAS analysis contributes to the discrepancy between the SPAS and POLLUTE results. Hence, the POLLUTE results can be improved by using the SPAS flow rate or, in the absence of this, by multiplying the flow derived from the Rowe equation by 1.3, as stated earlier, before using it in the mass-transport analysis.

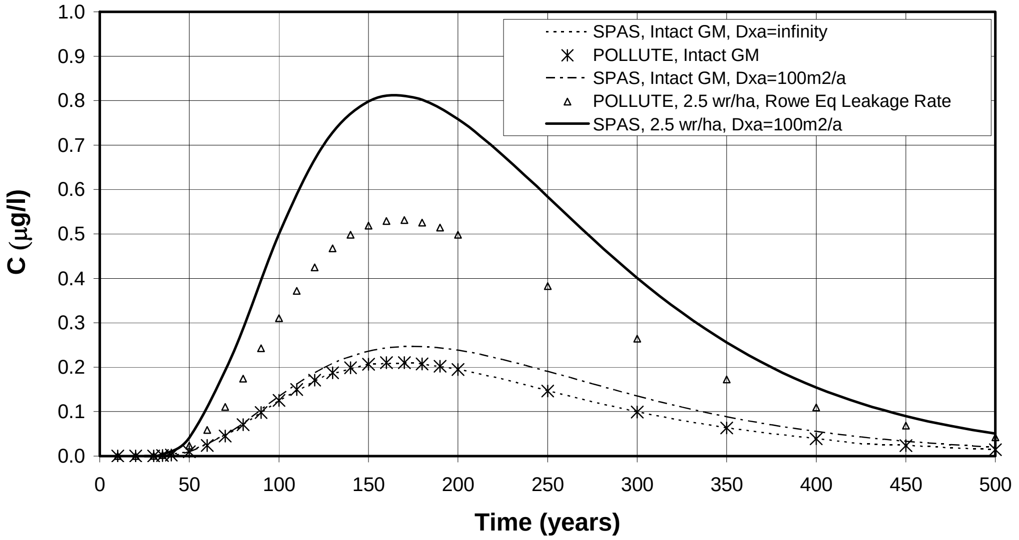
Irrespective of whether a 1D (POLLUTE) or 2D (SPAS) analysis is used these results show that to assess impact it is necessary to go beyond the estimation of hydraulic leakage rates and calculate the effect of leakage on groundwater quality. These results also show that, for the landfill considered, the impact on the aquifer would be acceptable based on common limits on the allowable concentrations of benzene or toluene in groundwater. Since the objective of transport analyses such as those performed here is to identify whether or not it is likely that the concentration will be above or below allowable levels, it is generally adequate to perform a simple analysis (e.g. using Rowe Eq., with the flow multiplied by 1.3 to adjust for the approximations in the analysis) and establish whether (a) the concentration is well below the allowable levels, (b) well above allowable levels or (c) close to allowable levels. In cases (a) the design can be considered adequate. In case (b) the design is not adequate and needs to be revised. In case (c) more investigation is needed. This investigation might include doing a more rigorous 2D analysis (e.g., using SPAS). Nevertheless, designers must keep in mind that an examination of the uncertainty in input parameters, such as the initial concentration, sorption and half-lives might have a greater influence on any final conclusion as to whether the proposed design is adequate.

Contaminant Transport: Parametric Analyses using SPAS

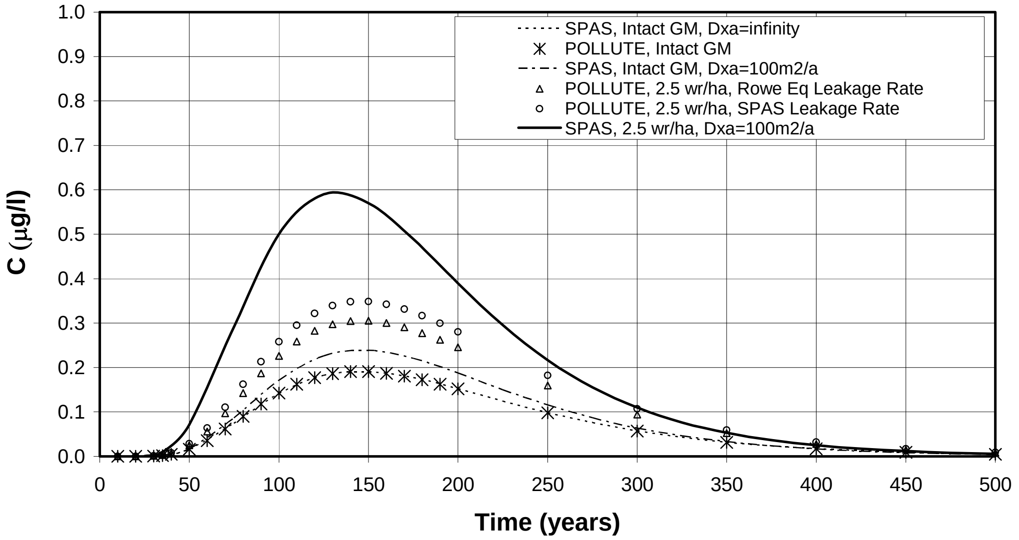
The sensitivity of peak aquifer concentrations to the length of landfill in the direction of groundwater flow and Darcy velocity in the aquifer is shown in Figures 4 and 5. A number of observations can be made. First, larger Darcy velocities in the groundwater lead to smaller concentration peaks as a result of greater dilution in the aquifer. However, at high values of L, the effect of change in Darcy velocity is substantially reduced. This is likely due, in part, to reduced dilution (the fluid added by leakage is larger because of the longer portion of the landfill, L, in the direction of groundwater flow). Second, larger landfill base widths lead to larger peaks at P_d because of the higher overall intake of contaminants being washed downstream. Third, the peak concentration varies with L and v_{xa} between 0.1 and 0.8ppb for benzene and 3 and 17ppb for toluene as one moves from L=40m, v_{xa}=2m/a to L=600m, v_{xa}=0.5m/a.



i. CCL system; L=200m (2.5 wr/ha: SPAS leakage rate= 62 lpdh; Rowe Eq leakage rate= 61 lpdh)

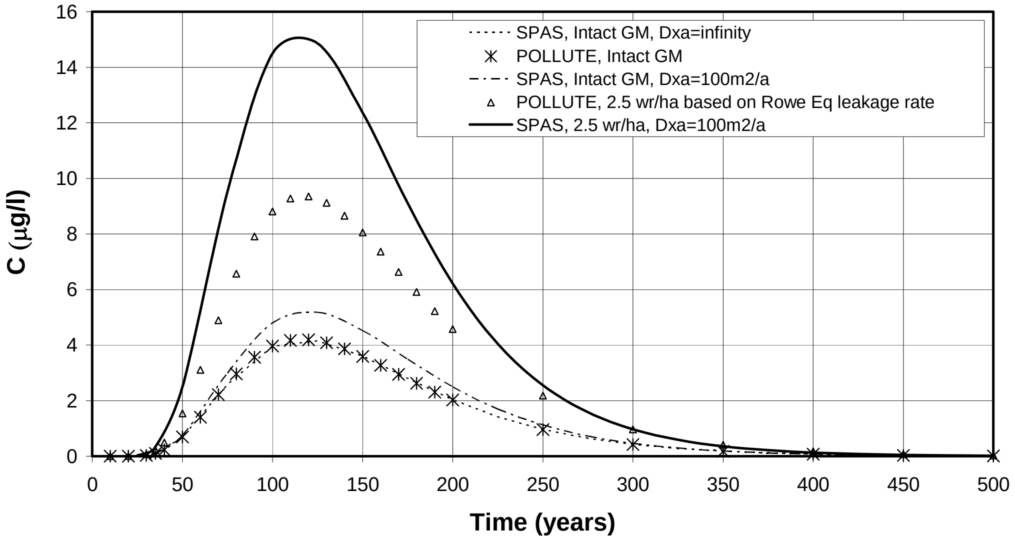


ii. CCL system; L=600m (2.5wr/ha: SPAS leakage rate= 63 lpdh; Rowe Eq leakage rate= 61 lpdh)



iii. GCL system; L=200m (2.5 wr/ha: SPAS leakage rate= 41 lpdh; Rowe Eq leakage rate= 31 lpdh)

Figure 2. Comparison of 1D and 2D predictions of the change in time of benzene concentrations at P_d; v_{xa}=1m/a (wr/ha: wrinkles per hectare)



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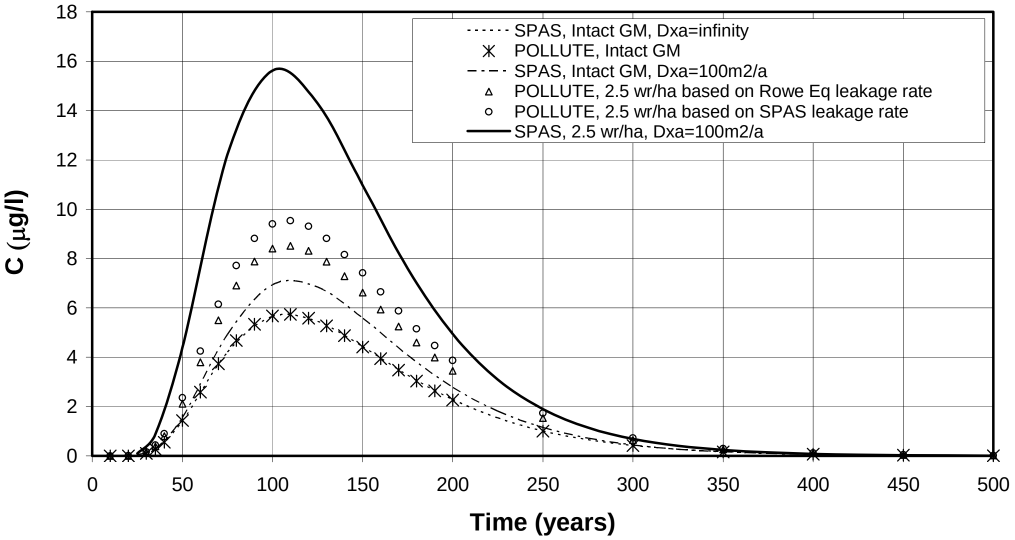

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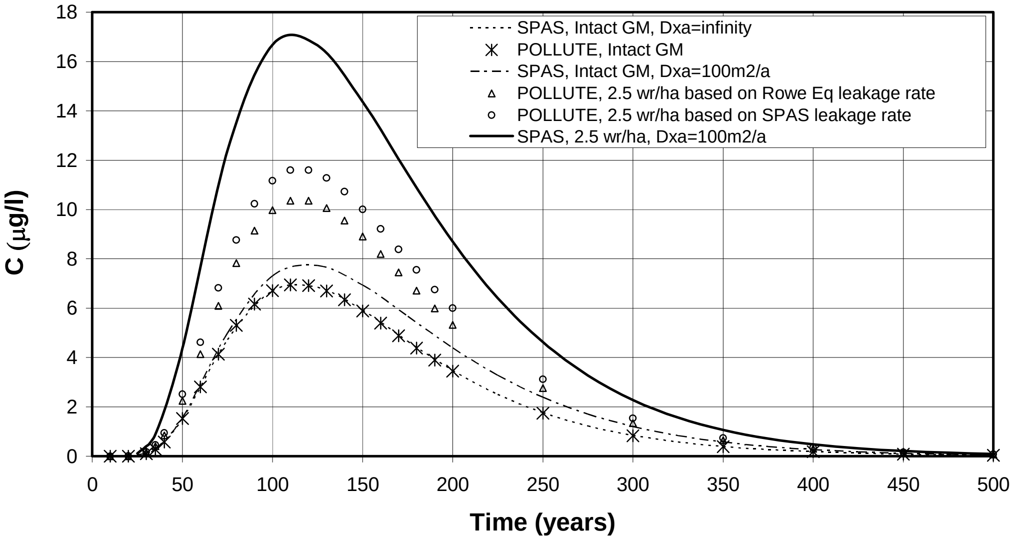
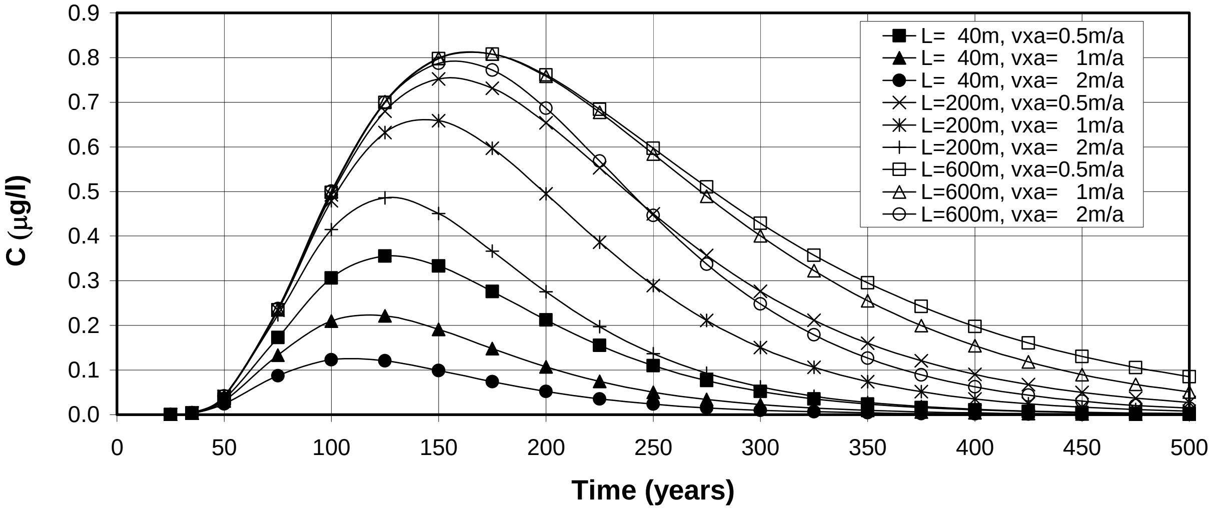
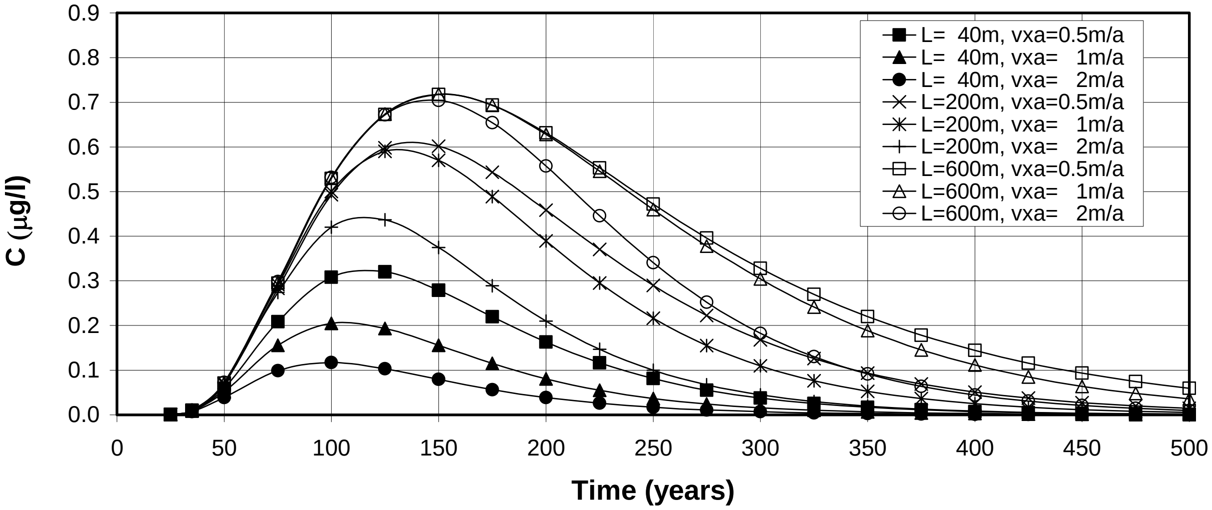


iii. GCL system; L=600m (2.5 wr/ha: SPAS leakage rate= 41 lpdh; Rowe Eq leakage rate= 31 lpdh)

Figure 3. Comparison of 1D and 2D predictions of the change in time of toluene concentrations at P_d; v_{xa}=1m/a (wr/ha: wrinkles per hectare)



i. CCL system (leakage rate=61 lpdh)



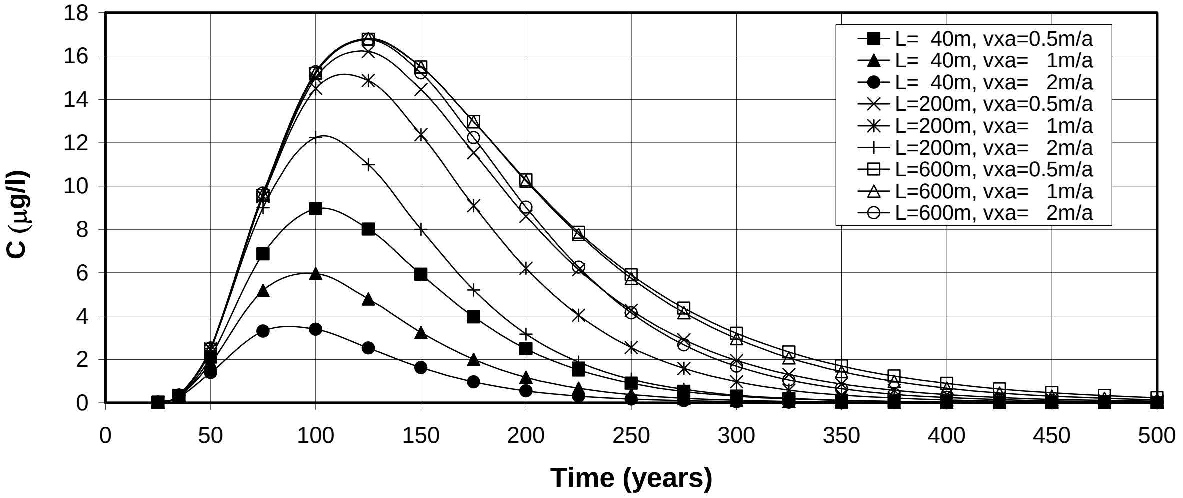
ii. GCL system (leakage rate=41 lpdh)

Figure 4. Change in time of concentration of benzene at P_d; D_{xa}=100m^2/a; 2.5 wrinkles per hectare: effects of cell length and Darcy velocity of flow in aquifer (leakage rate:

However, all values are below typical allowable values (5 and 24ppb respectively). This type of sensitivity analyses can be used to assess the effect of uncertainty regarding input parameters such as the length of the landfill in the direction of groundwater flow (this uncertainty can arise from the variable geometry of the landfill and the uncertainty regarding flow direction which in some cases can change seasonally) and the Darcy velocity in the aquifer. In the cases considered here, if the range of values examined represented uncertainty regarding the parameters, the design would be considered adequate although, in the worst case for toluene, is getting close to the allowable limit. Therefore, careful examination of the assumptions regarding initial concentration would be appropriate in a real case.

CONCLUSIONS

We conducted a set of analyses to assess the effect of leakage through geomembranes on peak concentrations of benzene and toluene in groundwater. Larger landfill base widths and smaller Darcy velocities in the groundwater yield higher peak concentrations, although the sensitivity to Darcy velocities declines at larger base widths. Using modeling to assess the suitability of a barrier system design (for a hypothetical case) is illustrated using both a simple, commonly used, 1D analysis (POLLUTE) and a full 2D analysis (SPAS). It was shown that the Rowe equation generally provides a very good estimate of leakage. However, it is recommend that leakages calculated from the Rowe equation be increased by 30%, especially when applied to GCL calculations. Although the 2D analysis gives higher peak concentrations, the difference in predictions is of no practical significance in the cases studied here since the peaks remain below the typical maximum acceptable concentrations. Hence, it is generally adequate to start with a simple 1D analysis (e.g. using Rowe Eq., and POLLUTE). If the concentration is well below the allowable levels, the design can be deemed safe. If it is well above, the design needs to be reviewed. If concentration is close to allowable levels, more investigation is needed. This investigation might include doing a more rigorous 2D analysis (e.g. using SPAS) and/or assessing the sensitivity of concentrations to uncertainty in some input parameters.



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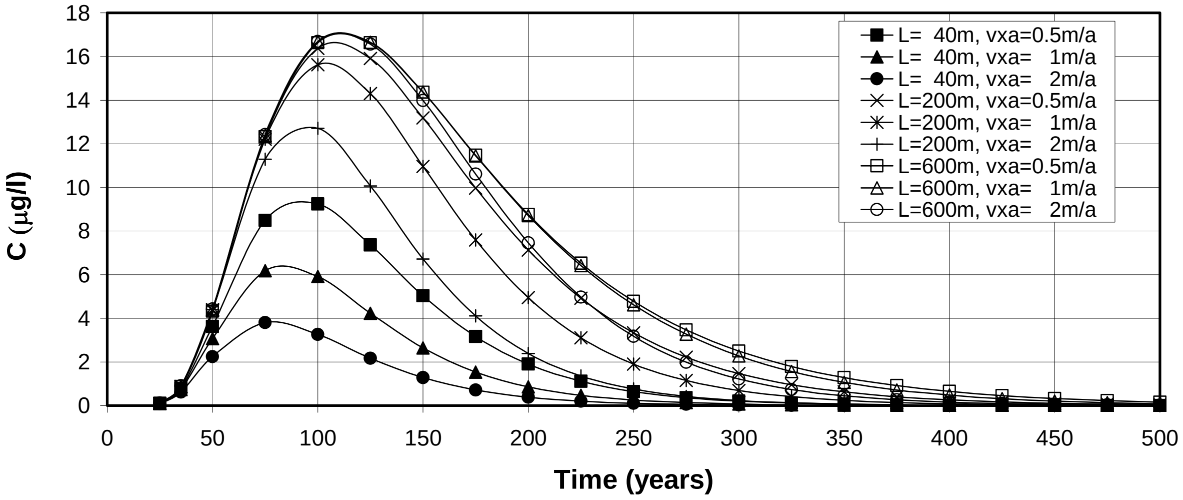

ii. GCL system (leakage rate=41 lpdh)

Figure 5. Change in time of concentration of toluene at P_d; D_{xa}=100m^2/a; 2.5 wrinkles per hectare: effects of cell length and Darcy velocity of flow in aquifer

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REFERENCES

El-Zein A, Carter JP and Airey DW. 2005. Multiple-porosity contaminant migration by finite-elements. *International Journal of Geomechanics ASCE,* 5(1):24-36.

El-Zein A. 2008. A general approach to the modeling of contaminant transport through composite landfill liners with intact or leaking geomembranes. *Int J Numerical Analytical Methods Geomechanics*, 32(3):265-287.

El-Zein A and Balaam N. 2008. SPAS: A new finite-element tool for modelling transport through single or double composite liners, with advanced global boundary conditions. *4th European Geosynthetics Conference*, Sep 08.

El-Zein A and Rowe R.K. 2008. Impact on groundwater of concurrent leakage and diffusion of dichloromethane through geomembranes in landfill liners. *Geosynth Intern*, 15(1):55-71.

Iryo T & Rowe RK. 2005. Hydraulic behaviour of soil-geocomposite layers in slopes, *Geosynt Intern,* 12(3): 145-155.

Kalbe U et al. 2002. Transport of organic contaminants within composite liner systems. *Applied Clay Sci* 21:67-76.

Rowe RK. 1998. Geosynthetics and the Minimization of Contaminant Migration through Barrier Systems Beneath Solid Waste. *Sixth International Conference on Geosynthetics*, Keynote Lecture, 27-102.

Rowe RK. 2005. Long-term performance of contaminant barrier systems, *Geotechnique* 65(9):631-678,

Rowe RK and Booker JR. 2005. POLLUTEv7 Pollutant migration through a nonhomogeneous soil, ©1983-2005, Distributed by GAEA Environm Eng Ltd 87 Garden Street, Whitby, Ontario, Canada, support@gaea.ca.

Saidi F, Touze-Foltz N & Goblet G. 2006. 2D and 3D numerical modelling through composite liners involving partially saturated GCLs. *Geosynthetics Intern*, 13(6): 265-276.

Touze-Foltz, N & Giroud JP. 2005. Empirical equations for calculating the rate of liquid flow through composite liners due to large circular defects in the geomembrane, *Geosynth Intern*, 12(4): 205-207.