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EXTENDED ENVIRONMENTAL MULTIMEDIA MODELING SYSTEM (EEMMS) AS A MORE ACCURATE RISK ASSESSMENT TOOL FOR GROUNDWATER POLLUTION

ROZBUDOWANY MULTIMEDIALNY SYSTEM MODELOWANIA ŚRODOWISKA (EEMMS) JAKO BARDZIEJ DOKŁADNE NARZĘDZIE OCENY RYZYKA W ZANIECZYSZCZENIU WÓD PODZIEMNYCH

The environmental multimedia modeling approach has been widely used for simulating contaminant transport in unsaturated and groundwater media. Yet a commonly used environmental multimedia model that has only first-order accuracy may introduce considerable numerical errors under certain circumstances. This study presents a finite element extended environmental multimedia modeling analysis system (EEMMS) for the unsaturated landfill and groundwater case studies with an incorporation of finite element numerical analysis. The developed EEMMS includes four component modules: an air module, a landfill module, an unsaturated zone module, and a groundwater zone module. The modules are solved within the EEMMS framework using Finite Element methods. Systematic model validations were implemented and tested comparing with the finite difference model and 2-D analytical model. The EEMMS was found to be more accurate that the finite difference model or 2-D analytical methods, particularly for low concentrations of groundwater pollutants. Given a large amount of uncertainties associated with EEMMS practices in porous compartments of landfill leachate media and groundwater media, non-classical uncertainty quantification techniques such as the Monte Carlo method approach are embedded into the developed EEMMS to deal with vague or imprecise model and complicated groundwater transport conditions. The risk quotient (RQ) factors combined with the present and future rates of chemical pollutant provide the spatial and temporal assessment of risk for the groundwater. The EEMMS makes the field work and groundwater treatment designs as reasonable as feasible, and is enable one to predict the probable groundwater pollution consequences.The developed EEMMS would be a useful risk assessment tool to help the subsequent management of the groundwater environmental impacts.

1. Introduction

Pollution has both short and long-term impacts on the ambient air, water, and soil environment. For example, an aged landfill may simultaneously pollute the local air, soil and groundwater. However, previous environmental pollution control has mainly focused on one environmental medium (e.g. groundwater) and relationship between all media was neglected leading to an error. Therefore, a comprehensive understanding and characterization of the natural behavior of chemical pollutants in the environment by using multimedia models are essential challenges for environmental risk assessment and management (Labieniec et al., 1996a).

Early studies on environmental multimedia modeling included the application of advective-dispersive transport equations (Harleman and Rumer, 1962). Coats and Smith (1964) incorporated a mass-transfer equation into the advective-dispersive equation and gave the analytical solutions. Analytical and numerical applications of advective-dispersive equations have been applied for single environmental media (e.g. Abdel-Salam, 1995).

More development and applications of environmental multimedia (or multimedia environmental) models (EMMs) have been reported since the early 1980s to address typical environmental pollution issues such as Superfund Sites (Mackay, 1991). Complex processes such as pollutant sorption/desorption and biochemical reactions after their release have been considered in EMMs. In summary, recent EMMs have been classified into three categories (Hsieh and Ouimetter, 1994; Cohen et al., 2002): (i) Compartmental (“well-mixed” media) models; (ii) Integrated spatial-multimedia-compartmental models (ISMCM); and (iii) Linked spatial single-media models (LSSMM). Most of the previous studies are based on one-dimensional analytical solutions (e.g. compartmental model) (Mackay, 1991). Extended EMMs have also been reported. For example, the Multimedia Environmental Pollutant Assessment System (MEPAS) is a linked spatial single-media model (LSSMM) (Droppo et al., 1989).

Recently, mathematicians, engineers, and hydrogeologists have successfully conducted researche regarding either modeling or fate of pollutants in porous media (Kindlein et al., 2006). However, all of those approaches attempt to solve the single medium’s fate and transport problem using the analytical solutions or finite difference method (FDM). Unfortunately, analytical linear equilibrium results have often ignored temporal and spatial effects; errors might also come from computation and limited considerations of boundary conditions in FDM methods.

With well-reported studies on pollutants’ fates and transport analysis (Cindoruk et al., 2008), future EMMs with numerical solutions should address pollutants' fates in an environmental multimedia system such as the decay and sorption mechanisms in the whole media. Subsequently, the present paper proposes an EEMMS, which links spatial multimedia model with numerical solutions to address landfill issues.

2. Development of the EEMMS

2.1. The Conceptual Model

Once a contaminant is released into environment from a pollution source, such as oil spill or a solid waste disposal site, it has a potential to migrate into all connected environmental media, then subsequently, humans may eventually be affected by the pollutant. Figure 1 illustrates landfill, where basic environmental media such as air, soil, and groundwater might be contaminated.

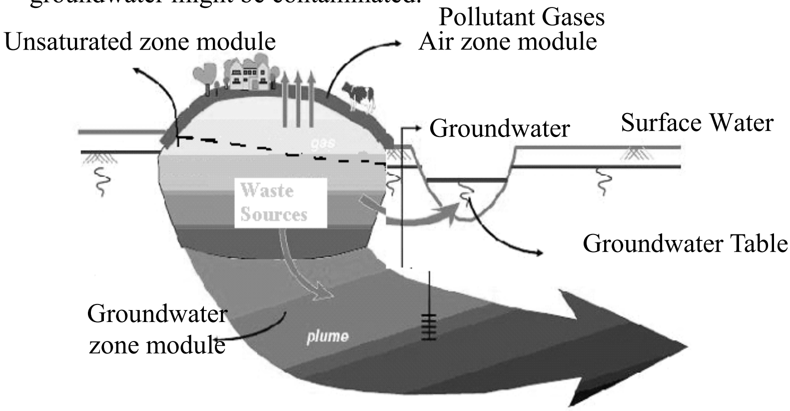

Fig. 1. EEMMS conceptual model

Based on the concept shown in Figure 1, the present study proposes a finite element environmental multimedia modeling analysis system (EEMMS) that consists of four modules: the landfill module, the unsaturated zone module, the saturated zone (groundwater) module, and the air module.

2.2. Landfill Module

The landfill module is used to simulate the pollutants' transport processes in a landfill "zone" and to compute the mass emission rate upwards into the air and the polluted leachate release rate down to the unsaturated zone. Specifically, a partial differential equation is formulated and solved to address the processes in the landfill zone and the release out of the landfill system (Parker, 1989; Lin and Hildemann, 1995):

$$\frac{\partial C_\alpha}{\partial t} = D_\alpha \frac{\partial^2 C_\alpha}{\partial x^2} - V_\alpha \frac{\partial C_\alpha}{\partial x} - \mu_\alpha C_\alpha \quad (1)$$

where,

$$D_a = \frac{a \times K_H \times D_g}{\theta \times R} + \frac{D_L}{R} \quad (2)$$

$$R = 1 + k_d \frac{\rho_b}{\theta} + \frac{\alpha K_H}{\theta} \tag{3}$$

$$\mu_\alpha = \ln 2 □ / \mathrm{t1/2} \tag{4}$$

and, a is volumetric air content ($L^3 \cdot L^{-3}$), k_d is the distribution coefficient ($L^3 \cdot M^{-1}$), C_α is the contaminant concentration in the different α components ($M \cdot L^{-3}$), D_a is the dispersion coefficient in the different α components ($L^2 \cdot T^{-1}$), D_g is the diffusion coefficient in the vapor-phase contaminant in landfill ($L^2 \cdot T^{-1}$), D_L is the diffusion/dispersion coefficient in the dissolved-phase contaminant in landfill ($L^2 \cdot T^{-1}$), K_H is the dimensionless Henry's Law Constant (dimensionless), R is the total retardation factor (dimensionless), $t_{1/2}$ is the half-life of radioactive or biodegradable materials (T), V_a is the seepage velocity of the different α components ($L \cdot T^{-1}$), θ is porosity (dimensionless), ρ_b is bulk density ($M \cdot L^{-3}$), and μ is the effective first-order decay rate constant (T^{-1}).

Both numerical and analytical solutions to Equation (1) are developed in this study. The numerical solution uses FEM (finite element methods) and FDM (finite difference methods). The analytical solution is derived below for the comparison studies introduced later:

$$C_a = \frac{C_0}{2} \exp\left(\frac{V_a \times x}{2 \times D_a}\right) \{\exp\left[-\frac{x}{2D_a}\sqrt{(V_a)^2 + 4\mu_a D_a}\right] \operatorname{erfc}\left[\frac{x - \sqrt{(V_a)^2 - 4\mu_a D_a t}}{2\sqrt{D_a t}}\right]$$

$$+\exp\left[\frac{x}{2D_a}\sqrt{(V_a)^2 + 4\mu_a D_a}\right] \operatorname{erfc}\left[\frac{x + \sqrt{(V_a)^2 - 4\mu_a D_a t}}{2\sqrt{D_a t}}\right]\} \tag{5}$$

where, erfc is the complementary error function (Vogel, 1970).

2.3. Unsaturated Zone Module

The unsaturated zone module simulates the fate and transport of leachate contaminants in the soils from the base of the landfill to the lower unsaturated/groundwater zone boundary and computes the contaminant flux as input to the saturated zone (groundwater) module. The governing three dimensional equations for the unsaturated zone soil medium are given (Carnahan and Remer, 1984) as:

$$\frac{\partial C_\alpha}{\partial t} = \frac{D_T}{R}\left(\frac{\partial^2 C_\alpha}{\partial x^2} + \frac{\partial^2 C_\alpha}{\partial y^2}\right) + \frac{D_L}{R}\frac{\partial^2 C_\alpha}{\partial z^2} - \frac{v}{R}\frac{\partial C_\alpha}{\partial z} - \mu_\alpha C_\alpha \tag{6}$$

where, D_L is the coefficient of longitudinal dispersion ($L^2 \cdot T^{-1}$), D_T is the coefficient of transverse dispersion ($L^2 \cdot T^{-1}$), v is the velocity of the flow ($L \cdot T^{-1}$), other parameters are the same as in Equation (1).

The analytical solution to Equation (6) is given by Carnahan and Remer (1984):

$$C_\alpha = \frac{m_0 \exp[-(\gamma + \mu_t)t]}{4\pi\eta D_T D_L^{1/2}} \exp\left(\frac{vz}{2D_L}\right) erfc\left[0.5\eta\left(\frac{R}{t}\right)^{1/2}\right] \tag{7}$$

where, m_0 is the rate of release of the solute from the point source at time zero ($M \cdot T^{-1}$), and

$$\eta = \left(\frac{r^2}{D_T} + \frac{z^2}{D_L} \right)^{1/2} \tag{8}$$

$$r^2 = x^2 + y^2 \tag{9}$$

$$\gamma = \frac{v^2}{4D_L R} \tag{10}$$

2.4. Saturated Zone (Groundwater) Module

The governing equation for the saturated zone groundwater is given as follows (Carnahan and Remer, 1984):

$$\frac{\partial C_\alpha}{\partial t} = \frac{1}{R}\left[D_x \frac{\partial^2 C_\alpha}{\partial x^2} + D_y \frac{\partial^2 C_\alpha}{\partial y^2} + D_z \frac{\partial^2 C_\alpha}{\partial z^2} - V_x \frac{\partial C_\alpha}{\partial x} - V_y \frac{\partial C_\alpha}{\partial y} - V_z \frac{\partial C_\alpha}{\partial z} \right] - \mu_\alpha C_\alpha \tag{11}$$

where, C_a is the contaminant concentration, equal to the mass of contaminant per unit volume of ground water ($M \cdot L^{-3}$), V_x, V_y, V_z are the components of the seepage velocity ($L \cdot T^{-1}$), D_x, D_y, D_z are the components of the dispersion coefficient ($L^2 \cdot T^{-1}$), other parameters are similar to those in Equation (1).

The analytical solution to Equation (11) can be obtained to comparison analysis introduced later (Domenico, 1987).

$$C_\alpha(x,y,t) = \frac{C_{\alpha 0}}{8} \exp\left(\frac{x}{2\alpha_x}\left[1 - \left(1 + \frac{4\mu_{sat}\alpha_x}{V_d / R} \right)^{1/2} \right] \right) erfc\left(\frac{x - (V_d t / R)(1 + 4\mu_a \alpha_x R / V_d)^{1/2}}{2(\alpha_x V_d t / R)^{1/2}} \right)$$
$$\left\{ erf\left[\frac{y + A_y / 2}{2(\alpha_y x)^{1/2}} \right] - erf\left[\frac{y - A_y / 2}{2(\alpha_y x)^{1/2}} \right] \right\} \left\{ erf\left[\frac{z + H}{2(\alpha_z x)^{1/2}} \right] - erf\left[\frac{z - H}{2(\alpha_z x)^{1/2}} \right] \right\} \tag{12}$$

where, H is the aquifer-mixing zone thickness (L). It is the vertical thickness of this plume within the aquifer at the point where the plume passes beneath the contamination site (Solhotra et al., 1995), and V_d is the seepage velocity ($L \cdot T^{-1}$), and α_x, α_y, α_z are the dispersivity in the coordinate directions, and are defined as the dispersion coefficient divided by the mean seepage velocity:

$$\alpha_x = \frac{D_x}{V_d}, \alpha_y = \frac{D_y}{V_d}, \alpha_z = \frac{D_z}{V_d} \tag{13}$$

where, D_x, D_y and D_z are the dispersion coefficients in *x, y,* and *z* directions, respectively ($L^2 \cdot T^{-1}$). Other parameters are similar to those in the Equation (1).

2.5. Air Module

The air module zone is one of the principal pollutant transport ways through which volatile organic compounds (VOCs) and other toxic chemicals volatilising from waste disposal sites may reach living organisms. This air module simulates the transport and diffusion of constituents in the form of volatilized gases emitted from area sources into the air. The governing equation for the air zone is given as follows:

$$\frac{\partial C}{\partial t} = D_a \frac{\partial^2 C}{\partial^2 Z} \tag{14}$$

where, t is time (T), C is the concentration (mg m^{-3}) in dimensions of Z (L), D_a is the diffusion coefficient in dimensions of ($L^2 \cdot T^{-1}$), and Z is the length along the study direction (L). The resulting flux can be derived from Fick's First Law:

$$F_a = AD_a \frac{\partial C}{\partial Z} \tag{15}$$

where, A is the area of plane of diffusion (L^2), D_a is the diffusion or turbulent coefficient of molecular ($L^2 \cdot T^{-1}$), and F_a is the mass flux ($M \cdot L^{-2} \cdot T^{-1}$).

2.6. Integrated Model Development

Governing equations are proposed with derived analytical solutions have been given for the four modules of the EEMMS. The similarities among the four governing equations serve as the basis that introduces the integrated development of the new EEMMS with the numerical analysis. Such integration is based on the consideration of mass balance, box model concept, and numerical analysis techniques (Mackay, 1991). Equations (1), (6), (11), and (14) for the four media zones share the same general fate and transport mechanisms. They all concern the pollutants penetrating not only with the advection and transformation inside a particular medium, but also with the inter-media mass transfers. Furthermore, reactions for sink, sorption, radioactive decay and biodegradation are included in those equations. Whereas integrating the entire system consisting of four zones, non-uniform and non-steady conditions should be considered. The following equations give integrated boundaries and initial conditions for solving Equations (1), (6), (11), and (14) within an EEMMS framework using FDM and FEM. The follows gives the solution algorithm for the EEMMS at one-dimensional conditions:

$$C(z,0) = C_0 \quad if \ 0 < z < L \tag{16}$$

$$if \quad z > L, \text{ t=0, } C_1\text{=0, } C_2\text{=0; t=}+\infty\text{, } C_1\text{=0, } C_2\text{=0} \tag{17}$$

$$C_\alpha(x,t)\Big|_{t=0} = C_0(x) \tag{18}$$

$$-D_a \frac{\partial C_a}{\partial X} + V_a C_a \bigg|_{t>0, X=0} = kC_0 \tag{19}$$

$$-D_a \frac{\partial C_a}{\partial X} + V_a C_a \bigg|_{t>0, X=L} = kC_{out} \tag{20}$$

where, L is the length of the simulated landfill depth (L), in which C_0 is the background concentration in landfill. The upper boundary condition is shown as Equation (21):

$$F_t(0,t) = -kC_G(0,t) \tag{21}$$

where, k is the overall mass transfer coefficient through the top cover ($L \cdot T^{-1}$) as estimated by (Zhang et al., 2003):

$$\frac{1}{k} = \frac{d}{D_g} + \frac{1}{k_t} \tag{22}$$

in which k_t is the mass transfer coefficient in the air-soil boundary layer ($L \cdot T^{-1}$), D_g is the gaseous diffusion coefficients (($L^2 \cdot T^{-1}$)) in the soil (Millington and Quirl, 1961), and d is the thickness of landfill cover (L). The chemical flux F_t ($M \cdot L^{-2} \cdot T^{-1}$) is the sum of the vapor flux and the flux of dissolved solute. The total mass flux is the sum of the flux above, calculated by:

$$F_t(z,t) = F_g(z,t) + F_l(z,t) + F_a(z,t) \tag{23}$$

where, F_g is the gas phase diffusive flux, F_l is the aqueous phase diffusive flux, and F_a is the gaseous phase advective flux.

The analyses above made it possible for the governing equations of all four modules to be solved within one scheme and to generate coherent simulation results for air, landfill, unsaturated, and saturated media modules. Both steady and unsteady flow effects are considered in the proposed EEMMS. The outputs of the EEMMS include (i) gaseous emission flux out of landfill cover, (ii) a spatial concentration distribution profile of the source in a landfill chamber, the surrounding soil media, and the adjacent groundwater system. Both finite difference and finite element methods are examined to give numerical solutions for the developed EEMMS.

3. Model Testing

The developed EEMMS is applied to a representative multimedia environment with a landfill as shown in Figure 1 in this section. It is intended to assess the impact of landfill on its surrounding air, soil and groundwater resulted from landfill emissions of benzene. The site data are modified from Lin and Hildemann (1995), Domenico (1987) and Carnahan and Remer (1984). Both numerical and analytical solutions are obtained based on Equations (1) to (23).

The input parameters include the landfill data, the chemical properties, and the soil properties under landfill. Characteristics, chemical properties of unsaturated zone and saturated zone are summarized in Tables 1 through 4.

Tab. 1 Input parameters for air module

Parameters	Symbol (units)	Value
Coefficient of transverse dispersion	D_T (m^2/day)	1E-6
Half-life	$t_{1/2}$ (day)	365
Retardation (dimensionless)	R	1
Air zone height	Z (m)	5

Tab. 2 Input parameters for landfill module (adapted from Lin and Hildemann, 1995)

Parameters	Symbol (units)	Value
The gaseous diffusion coefficient in air	D_g (m^2/day)	0.752
Henry's law constant (dimensionless) of benzene	K_H	0.22
Half-life of benzene	$t_{1/2}$ (day)	365
The liquid diffusion coefficient in water	D_l (m^2/day)	0.0000881
Bulk density	ρ_b (kg/m^3)	1350
Landfill depth	Z (m)	1
The volumetric air content of the soil	a	0.2
Volumetric water content at field capacity	θ	0.3

Tab. 3 Input parameters of unsaturated zone module (adapted from Domenico, 1987)

Parameters	Symbol (units)	Value
Coefficient of transverse dispersion of benzene	D_T (m^2/d)	0.0027
Average velocity of fluid	v (m/d)	0.005
Porosity	φ_{un}	0.4
Bulk density of unsaturated zone	ρ_{unsat} (kg/m^3)	1590
Half-life in unsaturated zone	$t_{1/2unsat}$ (d)	365
Water table depth	z_{wt} (m)	3.5

Tab. 4 Input parameters of saturated groundwater module (Carnahan and Remer, 1984)

Parameters	Symbol (units)	Value
Bulk density	ρ_{sat} (kg/m^3)	1590
Porosity	φ_s (dimensionless)	0.4
Organic carbon fraction	f_{ocsat} (dimensionless)	0.0125
Half-life	$T_{1/2SAT}$ (D)	365

Both numerical and analytical results are obtained and compared in Figure 2. This figure shows that pollutant concentration profiles along the depth are well simulated by using both analytical and numerical methods for this case. They are in accordance with other analytical solutions given for similar examples in Lin and Hildemann (1995), Domenico (1987), and Carnahan and Remer (1984).

To examine the accuracy of the above model, simulation results from the landfill zone are compared with literature data presented by Lin and Hildemann (1995). Also, analytical solutions based on Equation (5), the Gauss equation, FEM, and FDM are provided as shown in Figure 3 for a comprehensive model testing. It demonstrates an impact of time to the benzene emissions fluxes. As time increased, the expansion of benzene flux decreased. It also can be concluded from Figure 3 that the more contaminants are carried with the leachate, less volatilization occurs early on. It shows that the numerical model results are in very good agreement with the analytical model outputs. Figure 3 shows the relationship between the distance and the predicted benzene concentration distribution in the groundwater. It shows that the predicted concentration at groundwater is 6.5E-4 g·m^{-3} at the end of the evaluation period. The concentration slowly decreases in the down gradient of the groundwater flow due to the contaminant transport and decay in the groundwater.

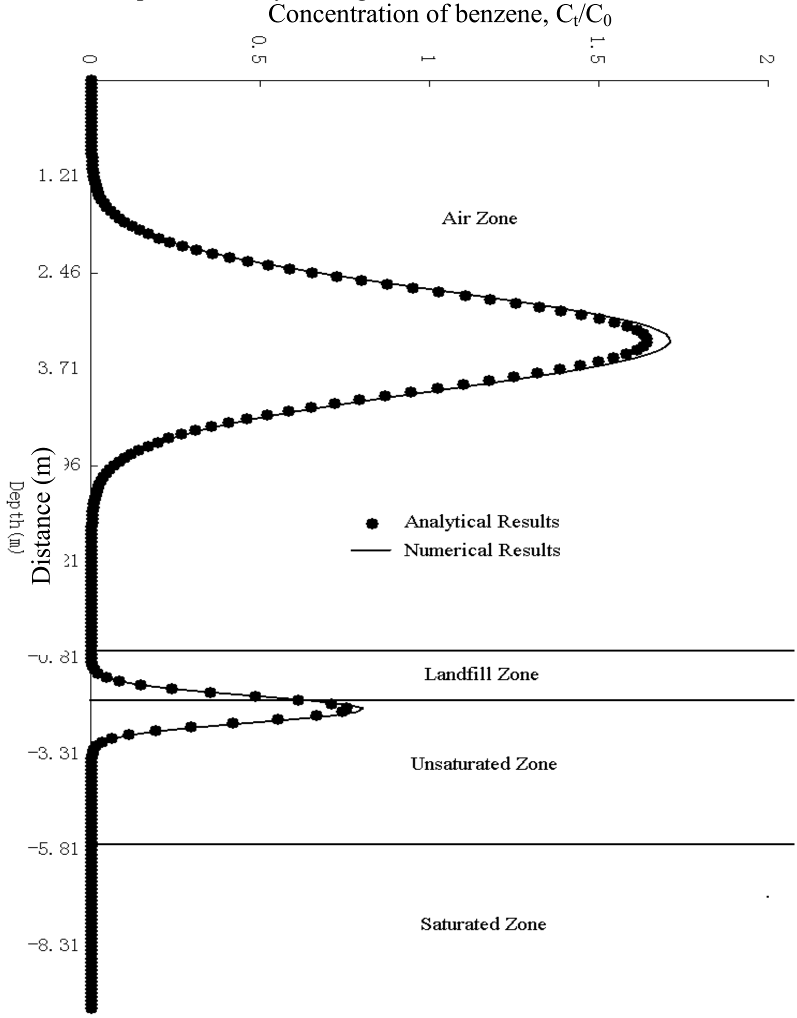

Fig.2. EEMMS numerical and analytical solution profiles for the testing case which includes air, landfill, unsaturated and saturated (groundwater) modules.

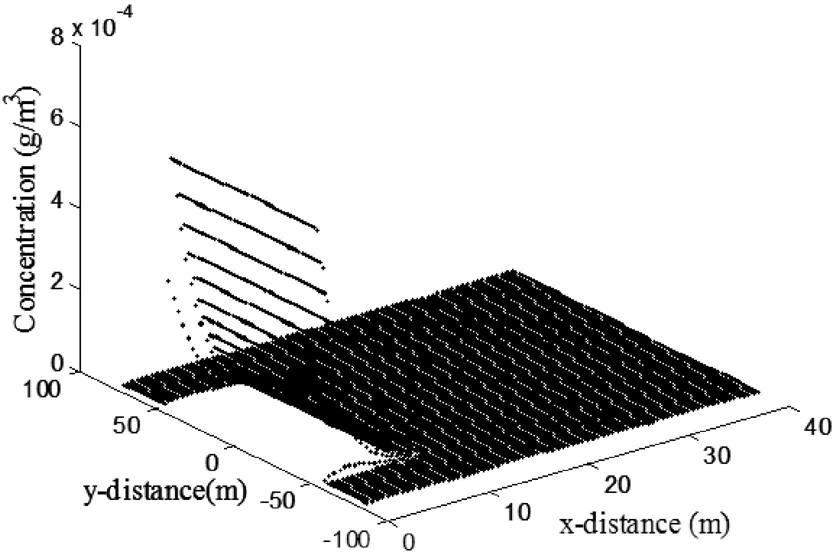

Fig. 3. Benzene concentration profile in the groundwater zone

4. Preliminary Model Validation

A preliminary validation of the EEMMS focuses on the landfill system. Data were adapted from Rickabaugh (1990), who described an experimental landfill study where the emission mass flux of gaseous benzene out of a landfill impacted the multimedia environment (surrounding soil, water and air). The landfill waste was divided into twelve categories to ensure that the waste was "typical municipal refuse". The waste was shredded and loaded into a landfill cell lift-by-lift and finally compacted to a density of 474 $kg \cdot m^{-3}$ (wet weight). The landfill configuration and operational parameters are presented in Table 5. The data in that table are used to validate the mass emission flux of gaseous benzene out of the landfill cover simulated using EMMS. The leachate, gas production, and gas composition were monitored for five years. The initial concentration of benzene in the landfill was 83 $mg \cdot kg^{-1}$ (wet refuse weight).

Tab. 5 Input parameters for modeling the mass flux of benzene (Rickabaugh, 1990)

The gaseous diffusion coefficient in air	D_g^a (m^2/d)	0.752	Length Orthogonal to groundwater flow	L_y (m)	1.435
Organic carbon partition coefficient	K_{oc} (m^3/kg)	0.083	Length parallel to groundwater flow	L_x (m)	0.457
Henry's law constant, dimensionless	K_H	0.22	The volumetric air content of the soil	a	0.15
Half-life	$t_{1/2}$ (d)	300	The volumetric water content at field capacity	θ	0.4
Organic carbon fraction	f_{oc}	0.0125	Bulk density	ρ_b (kg/m^3)	474
Cover thickness	d (m)	0.305	Landfill depth	L (m)	1.22
Gaseous velocity	v_G (m/d)	0.0005	Liquid velocity	v_L (m/d)	0.0005
The liquid diffusion coefficient in water	D_l^w(m^2/d)	8.81×10^{-5}	-	-	-

Both analytical and numerical (FDM and FEM) approaches were used to analyze the experimental input data reported in Rickabaugh (1990). The analytical solutions for the gaseous benzene flux were based on Equation (5) and on the numerical solution of Equations. Particularly, unsteady flow effects are addressed in the numerical models. Table 6 shows the results that we obtained using the three approaches shown in Figure 4, together with the experimental results reported by Rickabaugh (1990).

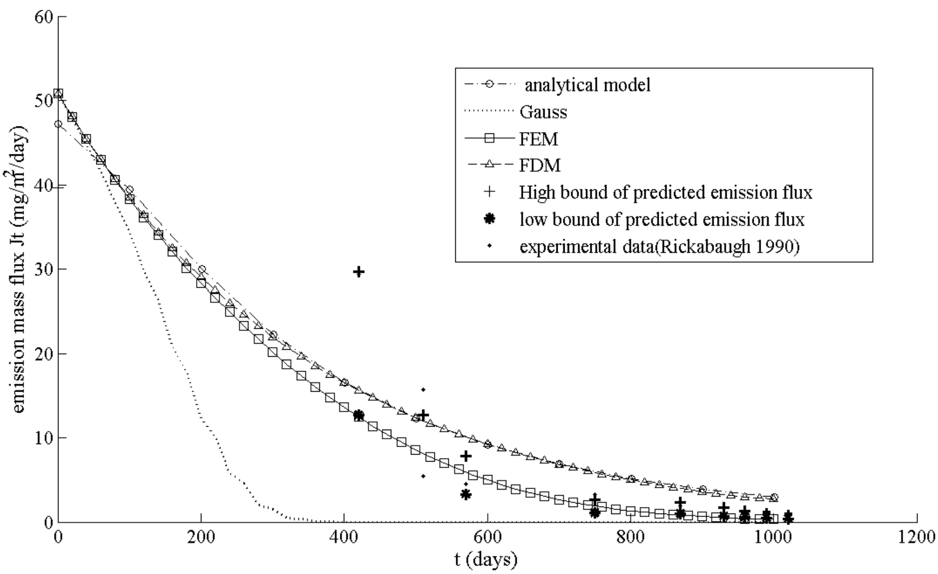

Fig.4. Comparisons between FEM, FDM, Gauss, analytical results and Rickabaugh's (1990) experimental results

As shown in Table 6, except for the Gauss results, analytical and numerical results based on EEMMS provide good simulations compared to the experimental results. Furthermore, as shown in Figure 4, all the FEM predictions were in the range (between the high and low boundaries) of the experimental results. In contrast, the majority of the FDM and analytical predictions (shown in italic font) were too high and fell outside the high boundary of the experimental results, particularly at the later times tested (570-1020 days). The outputs from the FEM method are in the best agreement with the experimental results. In conclusion, as shown in Table 6 and Figure 4, the FEM results of the developed EEMMS provided the more accurate prediction of the complex unsteady landfill gas mass flux.

Tab. 6 Comparison of the flux generated from the EEMMS model using the numerical (FEM and FDM) and analytical approaches as well as Rickabough's (1990) experimental results

	DATA FROM RICKABAUGH (1990)			
Time (days)	**Lower boundary experimental results ($mg\cdot m^{-2}\cdot d^{-1}$)**	**Mean experimental results ($mg\cdot m^{-2}\cdot d^{-1}$)**	**Upper boundary experimental results ($mg\cdot m^{-2}\cdot d^{-1}$)**	**FEM Model results ($mg\cdot m^{-2}\cdot d^{-1}$)**
420	12.7	29.34	29.7	15.7
510	5.4	15.7	12.7	14.9
570	3.3	4.5	7.8	4.4
750	1.1	3.3	2.6	3.2
870	1.0	1.89	2.3	1.7
930	0.7	1.0	1.7	1.0
960	0.6	1.1	1.3	0.9
990	0.5	1.03	1.2	0.8
1020	0.4	0.6	1.0	0.5

5. Intergrated Risk Assessment

Once the input data are entered using the Monte Carlo simulation, parameters probability density functions (PDFs) are generated and simulated results are provided in a Monte Carlo simulation output. The Figure 5(a) and 5(b) show the impact of landfill emissions of benzene on its surrounding air, soil and groundwater resulted from modeling test modified from Lin and Hildemann (1995), Domenico (1987) and Carnahan and Remer (1984) after 10 years. About 60% of the predicted concentrations fall in the range of 0.05 to 0.15 mg/m^3. The maximum concentration is only 0.247 mg/m^3. The percentiles of 5% and 95% of benzene point concentration are 0.248 and 0.021 mg/m^3 respectively. According to the the groundwater quality standard, 0.01mg/L, concentration of the benzene contaminants don't exceed standard after 10 years.

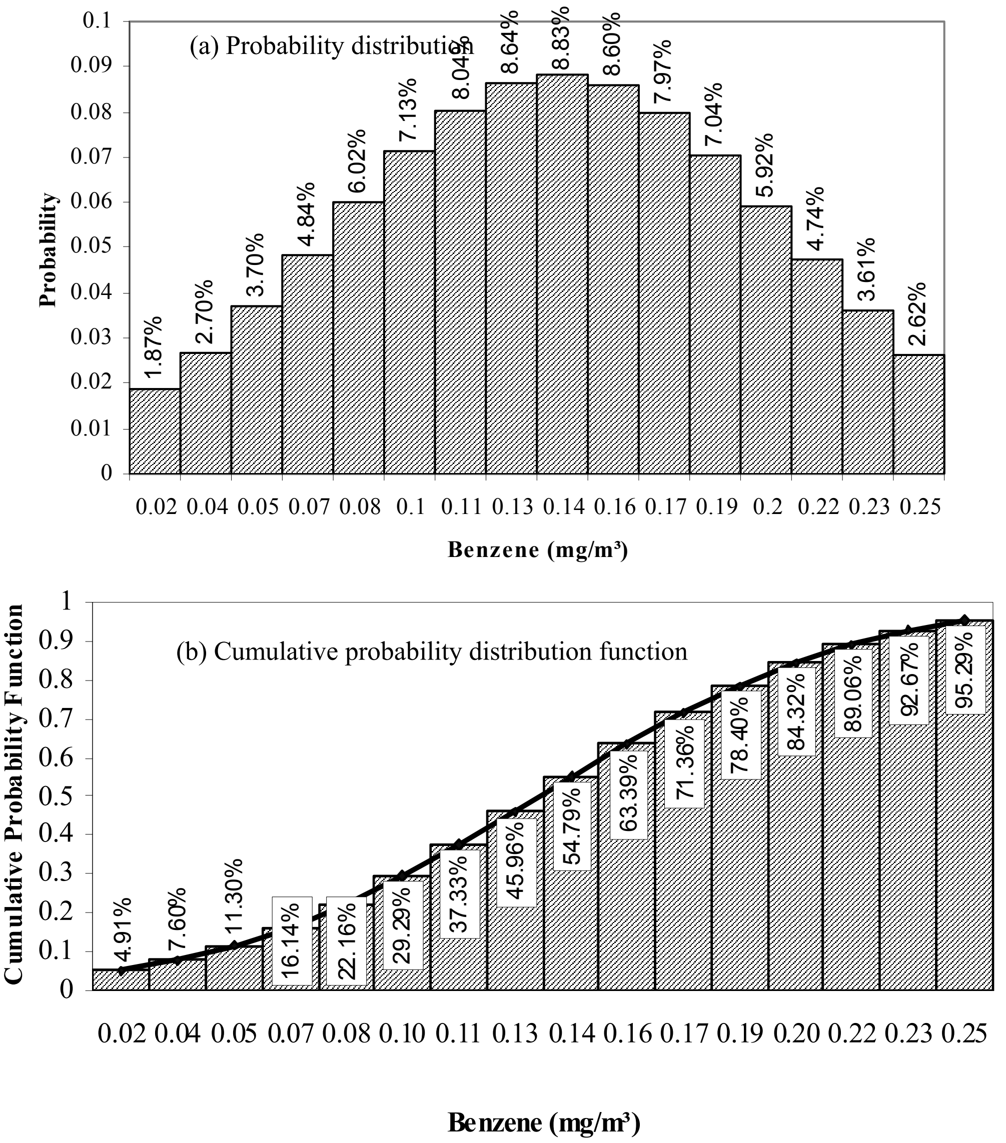

Fig.5. Benzene concentrations after 10 years: (a) probability distribution and (b) cumulative probability distribution

6. Discussion

Case studies show that numerical analysis not only gets the better simulation results for EEMMS improvement, but also it is effective in the environmental assessment of the complex multimedia system. A numerical model developed within the EEMMS framework handles both steady and unsteady flows, and provides predictions of spatial and temporal concentration profiles.

Both FEM and FDM are implemented to predict concentration profiles and mass fluxes out and into the interconnected multimedia environment using nonreflecting boundary and interface conditions with hexahedral grids. It was found that analytical solutions and finite difference methods (FDM) approaches to multimedia environment problems are limited due to the complexity of the problems, the sophistication of the mathematical formulas, as well as difficulty in their implementation.

When the steady and unsteady effects were considered for the same grid size, the computing time required for an unsteady flow simulation was approximately 20 times longer than that of the steady flow analysis. A multi-layer numerical solution was examined in the present study for the developed EEMMS. If developing the one-dimensional solution into full three-dimensional (3D), it is noted that solving EEMMS models will impose demanding computational requirements than the one-dimensional solution.

7. Conclusion

An extended environmental multimedia modeling system (EEMMS) has been developed in this study. It improves previous EMMS (1) by considering the unsteady flow effects of landfill gas and leachate emissions; (2) by integrating air, landfill, unsaturated, and groundwater modules within an EMMS framework based on mass conservation, mass flux, and transient non-uniform initial and boundary conditions; and (3) by introducing numerical solutions based on FEM and FDM. The model is first developed to address multi-dimensional environmental multimedia pollution problems. It is believed that FEM eliminates the geometric constraints (i.e. complex problem domain or boundary) that are usually approximated by FDM. In addition, numerical dispersion is expected to be reduced due to the reduced discretization error.

Preliminary validation has been conducted for the developed EEMMS. It is found that both analytical and numerical models provide well-simulated results compared with observation data in a temporal and spatial scheme. Under the same condition, FEM gives the best results compared to FDM, analytical, and Gauss equation outputs. The integrated risk assessment shows that the developed EEMMS can be used as a risk assessment tool, and a useful tool for field tests, and landfill designing works, control of emission and management of groundwater as well as assessing degree of impacts.

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