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AN ENHANCED ENVIRONMENTAL MULTIMEDIA MODELLING SYSTEM (FEMMS): PART II – USER INTERFACE AND FIELD VALIDATION

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Abstract

Environmental quantitative risk assessment requires the development of multimedia modeling tools to address dynamic site conditions at field scale. This work is the second part in a two-part series. A new fuzzy-set enhanced environmental multimedia modeling system (FEMMS) has been presented in Part I. Environmental multimedia modeling often involves a sizeable amount of parameters and data. The challenges have been the difficulties to quantify the uncertainties and to manage the data and main modules. Besides the efforts of developing a new EMMS for useful functionality and engineering applicability, a user-friendly graphical user interface (GUI) has been developed in this research for the FEMMS to provide support for the processing of model input and output as well as to facilitate technology transfer. To assess the developed FEMMS and its user interface system with real case application, a larger scale application with field data is conducted to examine the performance of FEMMS in this study. The field-scale validation presented in this paper indicates that the developed FEMMS is able to (1) predict the time and space varying chemical concentrations in a multimedia environment involving air, soil, and groundwater; (2) characterize the potential risk to human health presented by contaminants released from a contaminated site; and (3) quantify the uncertainties associated with modelling systems and subsequently providing robustness and flexibility for the remediation-related decision making. It also shows that, with the aid of fuzzy-set approach and the developed GUI, FEMMS is a reliable decision making tool to address complex environmental multimedia pollution problems and to provide technical support to strategy makers in managing the contaminated environmental sites.

Key words: fuzzy-set, landfill, multimedia modeling, risk assessment, user interface, validation

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1. Introduction

Environmental quantitative risk assessment (EQRA) substantially depends on the information on chemical distribution in multiple environmental media and the chemical fluxes across their boundaries (Cohen and Cooter, 2002). One of the fundamental challenges of environmental risk assessment is to understand and characterize levels of chemical pollutants in air, water, soil, and vegetation, and to estimate chemical mass flows between these different media, and between geographical regions (Chen et al., 2017; MacLeod et al., 2010). Multimedia models provide a solution for this challenge by quantifying cumulative, multipathway exposure to pollutants that originate from contaminated air, water, and soil (McKone and MacLeod, 2003).

Over the past few decades, multimedia models have been developed at different scales with different levels of complexity (Babendreier and Castleton,

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2005; Cohen and Cooter, 2002; Hsieh and Ouimette, 1994; Lin et al., 2009; MacLeod et al., 2010; Srivastava and Singh, 2005). Such multimedia models have been applied to environmental assessment, screening of environmental problems, and creating remedial strategy for a contaminated site (Droppo et al., 1993; Hsieh and Ouimette, 1994; León et al., 2007; Mustajoki et al., 2004; Saini et al., 2009; USEPA, 1996; Voigt et al., 2010).

The linked spatial single-media model (LSSMM) is an alternative to multimedia models (Cohen and Cooter, 2002; Hsieh and Ouimette, 1994). LSSMM depicts the environment as a system of uniform media and analyses the chemical behavior in multimedia system and the inter-media transfers under the dynamic conditions (Chen et al., 2014). It can therefore provide fine spatial and temporal resolutions to evaluate risk levels of exposure to hazardous contaminants. A fuzzy-set enhanced environmental multimedia modeling system (FEMMS) has been developed to extend the previously conceptualized LSSMM in Chen et al. (2014). It includes four modules: a pollution source module, an unsaturated zone module, a saturated zone module, and an air quality dispersion module. The pollution source module is to examine the contaminant's behavior within the polluted zone (e.g., landfill) based on the advective, diffusive and degradation processes in one dimension. This chamber-type source module, through intermedia mass fluxes, links the air module from the above and to the unsaturated zone module as well as the saturated zone module below. The modules for unsaturated zone and saturated zone are introduced based on pollutant's three-dimensional (3-D) description of fate and transport in porous media. The air quality dispersion module takes volatile components emission flux and input to a modified Gaussian equation to predict the spatial and temporal profiles of chemical concentration at a receptor of interest. Dynamic intermedia mass transfers are quantified to technically link the connected multimedia environmental system for a complex contamination site. Additionally, the developed FEMMS is embedded with a fuzzy-set approach to quantify the inherent uncertainties of modeling method and the contamination site. Overall, the developed FEMMS enables quantitative analyses to obtain the temporal and spatial contaminant distributions in each environmental medium as well as the flux rates across the environmental phase boundaries (Chen et al., 2014).

Few researches have been reported on the field application of the environmental multimedia models with uncertainties being quantified (Chau, 2007). One of the major challenges is that EMMs often involves a sizeable amount of parameters and data, which are further associated with a number of uncertainties (Chen et al., 2010; MacLeod et al., 2010). For example, environmental issues of a sanitary landfill include leachate waste from the bottom of the landfill going into the surround soil and groundwater media, and the landfill gases releasing into the atmosphere. Investigation of these issues involve the installation of monitoring well, collection of site geo-hydrological data, and use of soil groundwater as well as air quality models to examine environmental impacts (Zhao and Cheng, 2006). Compared to single-medium environmental quality model, it appears that effective application of the developed FEMMS will lead to cost-effective management alternatives. Geng et al. (2001) showed that a user-friendly graphical user interface (GUI) could help to add intelligent data processing, model execution and results reporting functions, and facilitate technology transfer.

The objectives of the second part of this two-part series are: first to focus on object-oriented programming efforts needed to efficiently aggregate the developed FEMMS and its main functional modules through the development of an graphical user interface (GUI); and second to apply the developed GUI system to a field scale case study to further examine the performance and applicability of the developed FEMMS.

2. Development of a User-Friendly Engineer Interface (GUI)

The developed modeling approach FEMMS contains four modules to address one contamination site releasing pollutants to the surrounding soil, groundwater, and atmosphere media. Three out of the four modules, i.e., a three-dimensional (3D) unsaturated zone advection-dispersion module, a 3D saturated zone advection-dispersion module, and a simplified 1D Gaussian plume module, are linked to the fourth module (i.e., the dynamic module addressing contaminants releasing from the landfill waste chamber) through contaminants mass fluxes from the landfill chamber upward to the atmosphere, and downward to soil and groundwater (Chen et al., 2014). The governing system emphasizes the transition of initial and boundary conditions for the four modules, which will be integrated by a user interface system.

The field-scale multimedia impacts resulting from a dynamic contaminants release involves a number of atmospheric and hydrogeological site and pollutants fate and transport model parameters, which are all associated with different layers of uncertainties. In addition to the best available deterministic information or data, the developed FEMMS includes the option of using a fuzzy-set approach to quantify field scale site and model uncertainties. Management of the data structure and input output dataset is the essential component of the GUI system.

For easy implementation of the modeling approach, a GUI has been designed using Matlab program code. The user interacts with the GUI by communicating input data into FEMMS and executing the four functional modules to obtain the expected results (Zhang, 2006). Fig. 1 presents an overview of the GUI system design for FEMMS.

The concentrations in the groundwater and the ambient air in Fig. 2 are obtained by running the

FEMMS based on the supplied input data. Alternatively, the user can enter the required input parameters through the main user interface as shown in Fig. 2 for a specific case study and the corresponding results are automatically presented in the "output window" of the GUI. The results can be also saved to ASCII format or analyzed through the chart or visualization function built in Matlab. The graphical representation of results is displayed in a series of figures after pressing the "plot now" button with an example shown in Fig. 2.

The simulation results are presented in three different ways (Zhang, 2006): [1] pollutant concentrations in the groundwater and the ambient receptors presented in the GUI "output window", i.e., the lower two sections of the main interface in Fig. 2; [2] the concentration distribution, the inter-media flux for consecutive years in text files (i.e., landfill file, unsaturated file, groundwater file, and ambient air quality file); and [3] a display of results in [1] and [2] in the form of a Matlab figure in the order of the evaluated year after pushing the "plot now" button on the GUI as shown in Fig. 2. The data managed by the developed GUI can be drawn up into six groups: chemical property; landfill module data; unsaturated zone data; saturated zone data; and other inputs. These data are related to the site layout, the environmental conditions, the meteorological conditions, and the chemical properties. The data can be input through the interface as shown in Fig. 2 to save to an input data file and or to run the model, a prepared Access or Excel data file can be also read and input into the FEMMS. Sample data for the undermentioned case study is included for illustrating the key model parameters and data structure in Table 1.

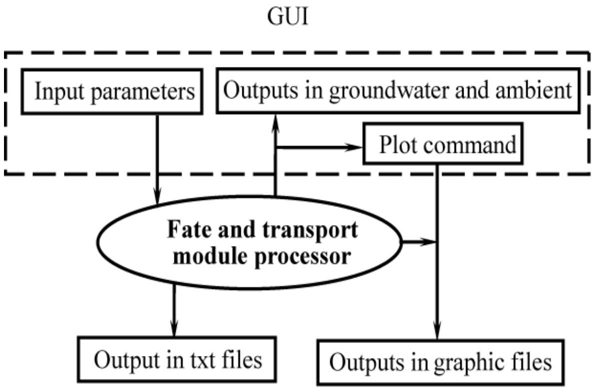

Fig. 1. The system schematic design (taken from Zhang, 2006)

Table 1. Physical properties and environmental conditions in the landfill site

Modules	***Parameters***	***Symbols***	***Inputs***	***Modules***	***Parameters***	***Symbols***	***Inputs***
Landfill module	length orthogonal to groundwater flow	A_y (m)	500	**Landfill module**	length parallel to groundwater flow	A_x (m)	800
	volumetric air content of the soil	a	0.2		volumetric water content at field capacity	θ	0.3
	organic carbon fraction	f_{oc}	0.0105		bulk density	ρ_b(kg/m^3)	600
	thickness of landfill cover	d (m)	1		landfill depth	L (m)	14
	gaseous velocity	v_G (m/d)	2.6 E-3		leachate velocity	v_L (m/d)	3.23 E-3
Un-saturated zone module	coefficient of longitudinal dispersion	D_L (m^2/d)	0.24	**Saturated zone module**	Darcy velocity	V_d (m/d)	0.576
	coefficient of transverse dispersion	D_T (m^2/d)	0.024		bulk density	ρ_{sat}	1350
	average velocity of fluid	v (m/d)	3.23 E-3		porosity	φ_s	0.3
	porosity	φ_{un}	0.365		organic carbon fraction	f_{ocsat}	0.0105
	bulk density of unsaturated zone	ρ_{unsat} (kg/m^3)	1350		half-life	τ_{sat} (d)	-
	half-life in unsaturated zone	τ_{unsat} (d)	-		dispersion coefficient in x direction	D_x (m^2/d)	1.728
	water table depth	z_{wt} (m)	10		dispersion coefficient in y direction	D_y (m^2/d)	.576
	organic carbon fraction	f_{ocun}	0.0105		dispersion coefficient in z direction	D_z (m^2/d)	0.968
Air module	annual wind speed frequency	f (φ)	0.13				
	wind speed	w (m/s)	4.3				

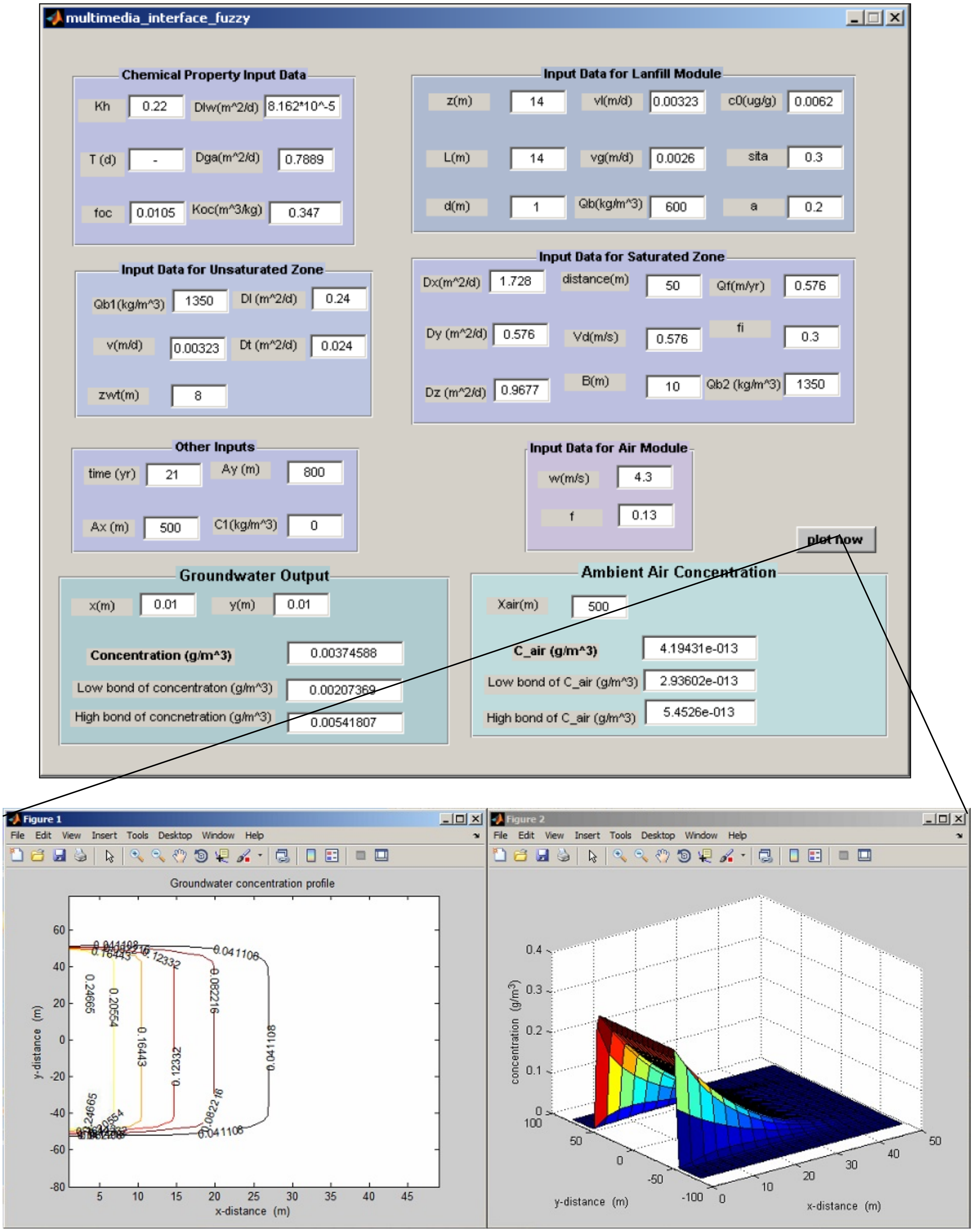

Fig. 2. An illustration of the main user interface (Adapted upon Zhang, 2006)

3. Field validation of FEMMS

The FEMMS was developed and evaluated in the part I of this series (Chen et al., 2014). However, the effectiveness of applying the FEMMS to a large scale field contamination site is yet to be examined. A large amount of landfill site information are obtained from the Trail Road Sanitary Landfill in the Region of Ottawa-Carleton to conduct a field validation of the developed FEMMS in this study (TRNL, 1995, 2002).

3.1. Overview of the landfill site

The Trail Road Sanitary Landfill site is in the Region of Ottawa-Carleton, Canada (Abbey et al., 1998; Dillon Consulting Limited, 2008; Ziad, 2007). The site of approximately 2.023 km^2 (Shaker and Yan, 2010). The closest residence is 0.85 km from the landfill site boundary. The closest residential subdivision is Barrhaven, which is about 2 km away (Fig. 3). Approximately 500 meters from the northern boundary of the Trail Road Landfill is a large de-watering pond used for storing the local groundwater discharge. Jock River is located approximately 1 km from the north of the pond, water of which eventually discharges into it. Southwest of the Trail Road Landfill is the Nepean Landfill.

The Trail Road Sanitary Landfill site including the Nepean and Trail Road landfills has been operated in stages. The Nepean Landfill began operation in the early 1960s and received waste until the early 1980s when it was considered nearly full. The Nepean Landfill was capped with a polyethylene liner and soil in 1993 (Dillon Consulting Limited, 2008). After the Nepean Landfill closing, the Trail Road Landfill was opened in 1980.

It is difficult to obtain the detailed annual disposal rate of Nepean Landfill and Trail Landfill for the year 1960 to the year 1992 due to the lack of historical operation information. Therefore, based on the data from the Trail Road and Nepean Landfill (TRNL) (1995, 2002), the rate of refuse annually disposed in the landfill is estimated at 287,000 t/yr.

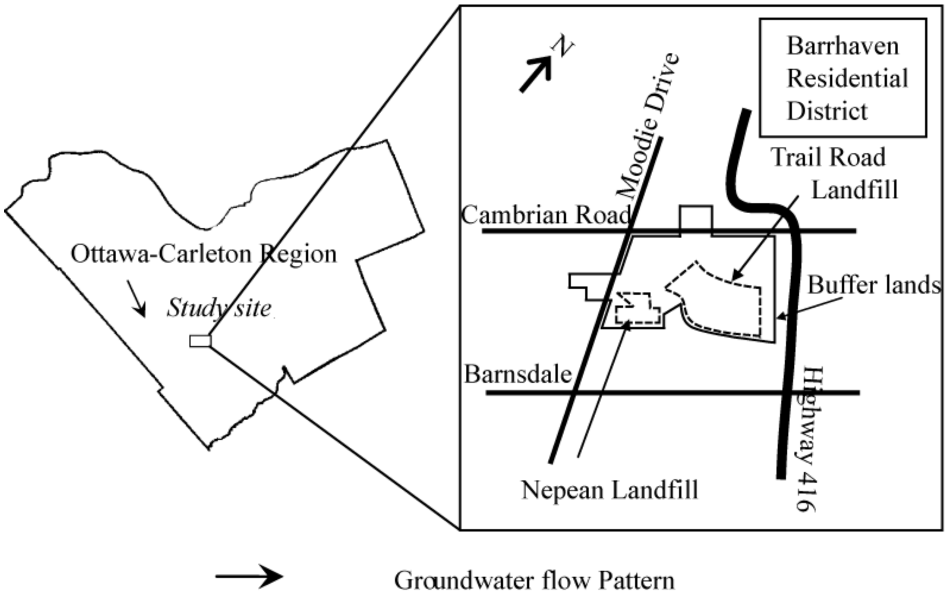

Fig. 3. Trail Road Sanitary Landfill (TRNL, 2002)

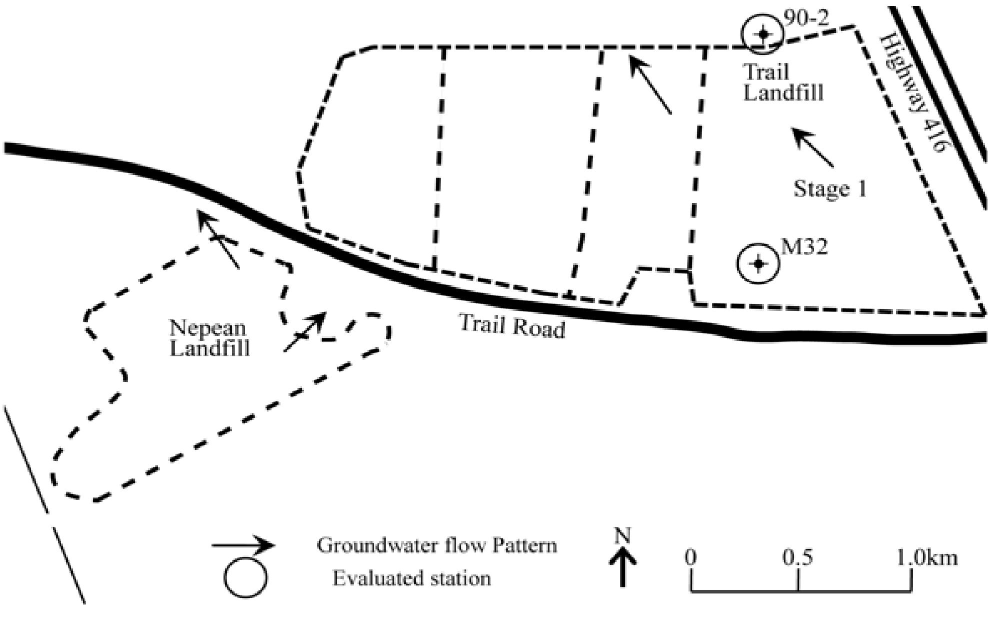

Fig. 4. Location of monitoring station (TRNL, 2002)

Table 2. Input parameters related to chemical properties

Parameters	*Symbols*	*Benzene*	*Ethylbenzene*	*Toluene*
Gaseous diffusion coefficient in air	D_g^a (m^2/d)	0.756	0.635	0.706
Liquid diffusion coefficient in water	D_l^w (m^2/d)	8.81×10^{-5}	6.7×10^{-5}	7.33×10^{-5}
Organic carbon partition coefficient	K_{oc} (m^3/kg)	0.347	0.305	0.25
Henry's law constant, dimensionless	K_H	0.225	0.322	0.25
Half-life in landfill	τ (d)	-	-	-

3.2. Collection and preparation of model data

Following the approach outlined by the International Atomic Energy Agency (IAEA) (1989), important parameters that have relatively great potential influences on the modeling outputs are selected or estimated. The input parameters associated with environmental conditions and the physical properties of the site are summarized in Table 1 (Zhang, 2006). Other parameters related to chemical properties are given in Table 2.

Although a large amount of site information is obtained, data collected from the monitoring stations M32 and M90 of which locations are shown in Fig. 4 can be used for all the functions of FEMMS. All the input parameters are entered into the multimedia modeling system, and then they are utilized by the modules in accordance with the internal order of the model execution.

Imprecise and inaccurate input parameters are the primary source of modeling error for the environmental risk assessment. Some observed data can also be flawed due to sampling and analysis errors (Howard et al., 1991). For example, so far as the half-life of a chemical is concerned, there may be significant discrepancy between its value measured in the laboratory and the actual value on a site (Hazardous Substances Data Bank (HSDB), 2005). On the other hand, determination of a parameter value itself carries inherent uncertainty since the processes simulated by the model have a large natural variability in time and space.

Moreover, such values are often derived from the experimental data that refer to only a few discrete points in time and space (USEPA, 1996). In this context, a fuzzy-set approach as described in Part I of this two-part series is employed to quantify various uncertain information associated with input parameters and the subsequent results besides the maximum effort on data collection. Therefore, there will be high and low bounds of modeling results in comparison with the observed data for the study contaminant.

3.3. Simulation results and comparison with field observation data

Detailed modeling results for the contaminants of ethylbenzene at M32 in the Trail Road landfill are given in Table 3. The simulated concentration of ethylbenzene in the groundwater at x = 0 gradually decreased from 29.5 mg/m^3 in 1999 to 27.2 mg/m^3 in 2002 due to spreading via dispersion in soil and groundwater, and a little loss via volatilization from the landfill cover; the low bound concentration decreased correspondingly from 16.2 mg/m^3 to 15.0 mg/m^3; and the high bound concentrations show the same trend from 42.8 mg/m^3 to 39.4 mg/m^3. Decrease in the concentration is achieved partly due to the infiltration into the landfill cover and the chemical properties. Ethylbenzene is not a highly volatile compound, implying that volatilization is not a significant loss pathway for this compound; instead, it migrates downward with infiltration and enters into the groundwater. Compared with the observed concentration in the groundwater beneath the Trail Road Landfill, the first two calculated mean concentrations agree with the field monitoring data, which get 0.88 and 0.87 of grade of membership in the fuzzy set outputs.

Table 3. Comparison of modeling results and observed ethylbenzene concentrations at the monitoring well M32

Year	*Low bound of concentration* (mg/m^3)	*Modeled concentration at M32* (mg/m^3)	*High bound of concentrations* (mg/m^3)	*Observed concentration* (mg/m^3)	*Fuzzy possibility grade*
1999	16.2	29.5	42.8	31.1	0.88
2000	15.9	28.8	41.8	30.5	0.87
2001	15.4	28.1	40.7	1.8	-
2002	15.0	27.2	39.4	15.6	0.05

Table 4. Comparison of modeling results and observed toluene concentrations at the monitoring well M32

Year	*Low bound of concentration* (mg/m^3)	*Modeled concentration at M32* (mg/m^3)	*High bound of concentration* (mg/m^3)	*Observed concentration at M32* (mg/m^3)	*Possibility*
1999	58.3	106	153.7	92	0.71
2000	56.9	103.4	149.9	108	0.90
2001	55.2	100.3	145.4	21.6	-
2002	53.2	96.8	140.3	54.5	0.03

The monitoring data in 2001 it sharply decreased to 1.8 mg/m^3 and then rose to 15.6 mg/m^3 and is out of the range of the fuzzy set output. The reason includes that the precipitation rate in 2001 was smaller than that in 1999 and 2000 (e.g., the total precipitation in the Ottawa region was 987.4 mm in 2000, remarkably dropped to 753.6 mm in 2001, and increased again to 867.9 mm in 2002. Precipitation data are from the Historical Climate Database of the Government of Canada); more contaminants thus remained in the soil in that year than in the previous two years. After the infiltration rate rose again, the retarded contaminant was solved, and then along with the newly arriving pollutant leachate from the landfill was carried to the groundwater. As a result, the concentration at this location went up from 1.8 mg/m^3 to 15.6 mg/m^3. Errors in sampling and chemical analysis and complexities in the site conditions could also have contributed to the noted discrepancies.

The simulated toluene concentration in the groundwater at M32 is shown in Table 4. Table 5 shows the predicted concentration in the groundwater for benzene at M90. The concentration of benzene decreased slowly from 6.1 mg/m^3 in 1999 to 5.7 mg/m^3 in 2002; the low bound was 3.4 mg/m^3 in 1999 and 3.1 mg/m^3 in 2002; and the high bound was from 8.8 mg/m^3 to 8.3 mg/m^3 during these 4 years. Dispersion could explain the main pathway loss, while volatilization of the benzene is limited due to its modest Henry's law constant and the protection of the landfill cover. The modeling results are very close to the observed concentration at the monitoring station in 1999 and 2000. However, the monitoring data oscillates in the following years and shows a trend that is different from those of the toluene and ethylbenzene at station M32. The big change in the monitoring data from 2000 to 2001 reflects the significant change of climate condition, e.g., change of precipitation as discussed earlier.

The discrepancy between that modeling results and monitoring data is also due to the diverse geological conditions under the landfill site. A greater amount of pollutant was carried to this point but could not be swept away due to the low groundwater flow and the retardation of the soil. Various errors in collecting and analyzing leachate samples and complexities of the landfill site mainly lead to the disagreement in the validation of FEMMS using the field-scale data. However, the validation results still demonstrates that FEMMS is capable of providing reasonable prediction of time and space varying pollutant concentration in media.

4. Prediction and assessment of the landfill contamination using the user-friendly FEMMS with uncertainty analysis

Following the validation of FEMMS using 1999 to 2002 field-scale data, the user-friendly FEMMS is applied to the Trail Road Landfill for an extended evaluation period. The evaluation locations for the groundwater are M32 and M90 unchanged, while it is assumed that there is a receptor positioned 500 meters away from the landfill site boundary in a southwest direction. The modelling input parameters in Table 1 and Table 2 are used. The simulation results contain the contaminant concentration distribution in the environmental media and the inter-media fluxes, and the concentrations at the receptors in the groundwater and atmosphere for each contaminant: benzene, ethylbenzene and toluene (BET). However, for the comparison of variation of the contaminants in the groundwater or the ambient air, the outputs are discussed as two groups: the outputs for ambient groundwater and air quality.

4.1. Evolution of groundwater contaminant in the Tail Road Landfill site for 2003-2011

For assessing benzene contamination in the site, the fuzzy set approach is used (Chen et al., 2014). The fuzzy approach outputs of benzene concentrations at M90 are presented in Fig. 5. The high bound of concentration decreases from 8.0 mg/m^3 to 5.6 mg/m^3, and the low bound decreases from 3.0 mg/m^3 to 2.1 mg/m^3 during the 9-year prediction period. This difference between high and low bounds indicates that the benzene concentration at the end of the evaluation period will fall into the range of 2.1 mg/m^3 to 5.6 mg/m^3 given that there are fluctuations in the environmental conditions or modeling errors. The ethylbenzene concentration predictions are presented in Fig. 6.

The high bound of concentration decreases from 38.1 mg/m^3 to 25.2 mg/m^3, while the low bound decreases from 14.4 mg/m^3 to 9.6 mg/m^3. At the end point of the evaluation period, the ethylbenzene concentration is between the range of 9.6 mg/m^3 and 25.2 mg/m^3. It is interpreted as the fluctuation of environmental conditions and the discrepancy in the estimates of parameters. According to the predictions, the low bound of predicted concentration is much greater than the Ontario Drinking Water Standards (ODWS) at 2.4 mg/m^3 indicating that the M90 location under study will still be contaminated in 9 years.

Fig. 7 shows the outputs of uncertainty analysis for the toluene concentrations beneath the Trail Road Landfill site. The high bound of toluene concentration decreases from 134.5 mg/m^3 to 81.2 mg/m^3, while the low bound decreases from 51 mg/m^3 to 30.8 mg/m^3 during the evaluation period. Since the toluene is present in high initial concentration compared to the other two contaminants, it still ranges between 30.8 mg/m^3 and 81.2 mg/m^3 after 9 years. The low bound of computed concentration is slightly over the ODWS at 24 mg/m^3; thus an action should be taken to protect the downstream groundwater.

4.2. Evolution of ambient air quality in the Trail Road Landfill site for 2003-2011

The computed yearly variance of the benzene concentration at the receptor is given in the form of a defuzzified output in Fig. 8.

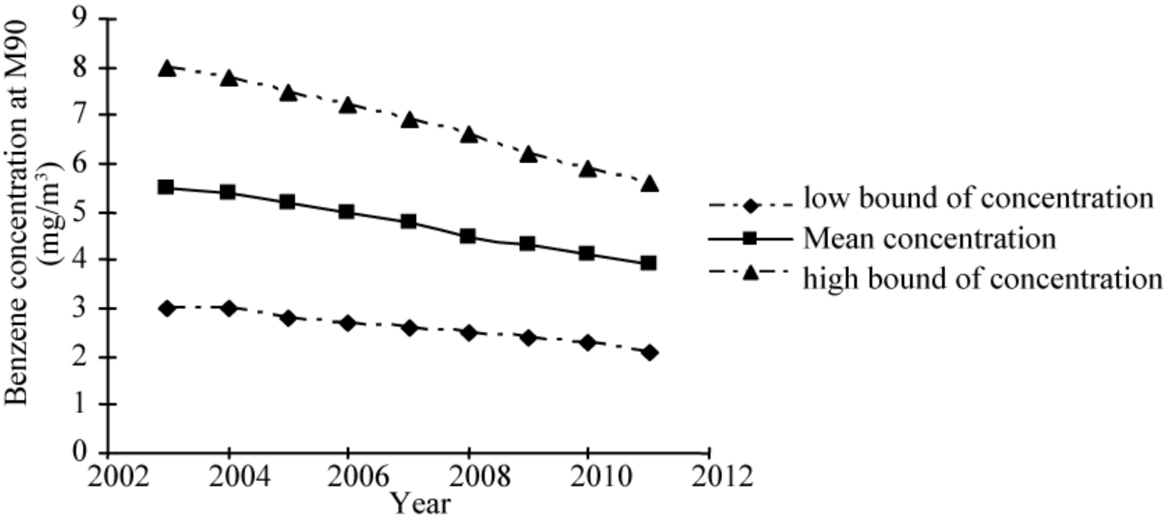

Fig. 5. Benzene concentrations at the monitoring well M90 for 2003-2011

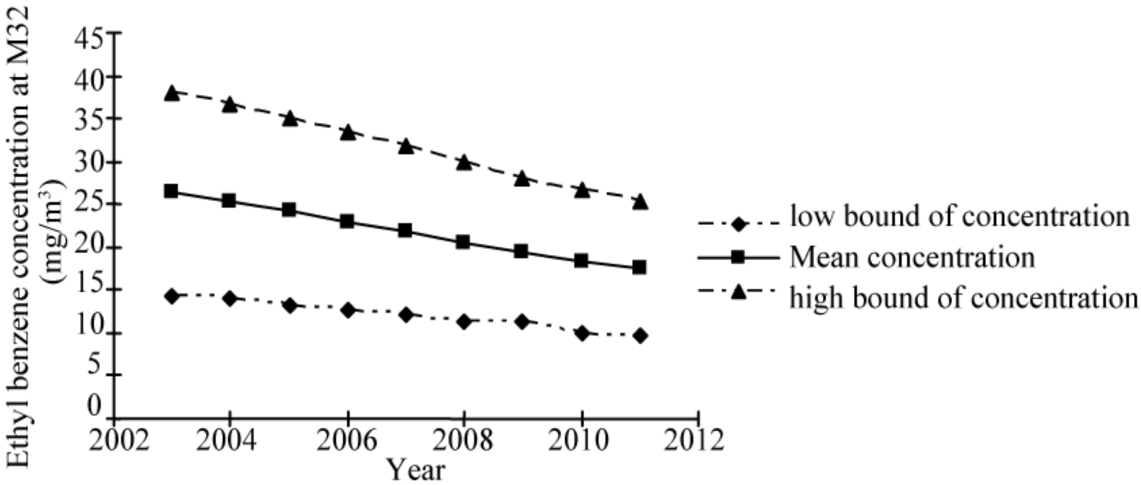

Fig. 6. Ethylbenzene concentrations at the monitoring well M32 for 2003-2011

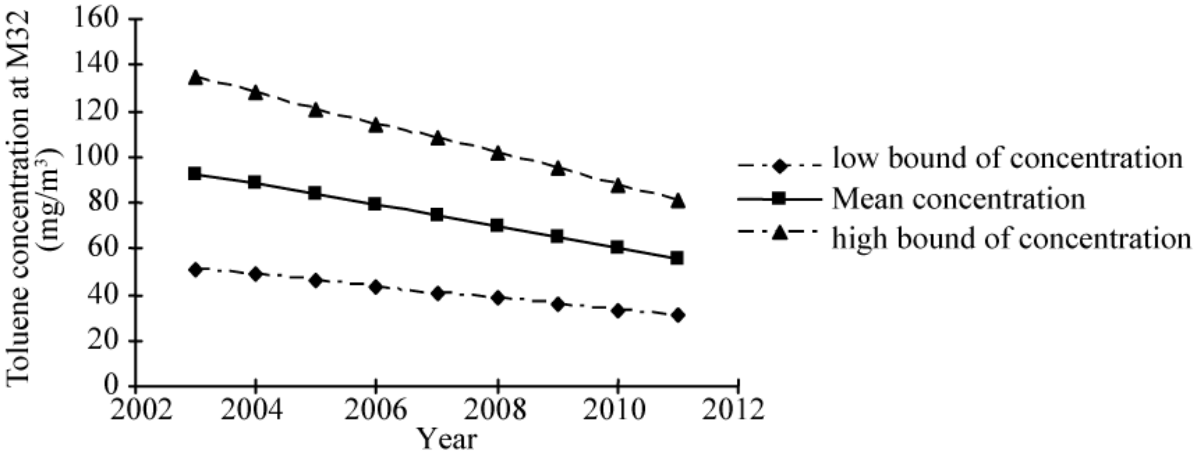

Fig. 7. Toluene concentrations at the monitoring well M32 for 2003-2011

Table 5. Comparison of modeling results and observed benzene concentrations at the monitoring well M90

Year	*Low bound of concentration (mg/m³)*	*Modeled concentration at M90 (mg/m³)*	*High bound of concentration (mg/m³)*	*Observed concentration at M90 (mg/m³)*	*The possibility*
1999	3.4	6.1	8.8	6.3	0.93
2000	3.3	6.0	8.7	6.2	0.93
2001	3.2	5.8	8.5	9.8	-
2002	3.1	5.7	8.3	3.5	0.15

The high bound decreases from 3.889 E-11 mg/m^3 to 1.07 E-11 mg/m^3, and also the low bound decreases from 2.049 E-11 mg/m^3 to 5.76 E-12 mg/m^3 for 2003-2011. Even the high bound of simulated benzene concentration for every evaluated year at the exposure site is far less than the 8.0 E-2 mg/m^3 of the risk assessment reference concentration (USEPA, 1999, 2002). Thus it can be concluded that the risk resulting from the inhalation of benzene for human beings at the exposure site can be neglected.

The modeling results of yearly ethylbenzene concentration are shown in Fig. 9. The defuzzified outputs in 2003 are 2.036E-10 mg/m^3 and 3.872E-10 mg/m^3, and those in 2011 are 6.37E-11 mg/m^3 and 1.183E-10 mg/m^3 for low and high bounds, respectively. According to the 1.0 mg/m^3 of the reference concentration (USEPA, 1999), the ethylbenzene concentration has no adverse impact on human health at the exposure site.

The toluene concentrations for each evaluated year are shown in Fig. 10. They indicate that the low bound of estimated concentration decreases considerably from 2.641 E-10 mg/m^3 to 6.11 E-11 mg/m^3 and the upper limit decreases from 4.905 E-10 mg/m^3 to 1.135 E-10 mg/m^3 during the evaluation period. The toluene concentrations at the assessment receptor are much lower than 5 mg/m^3 of the reference concentration (USEPA, 2005). Hence, the risk impact of toluene on human health is negligible.

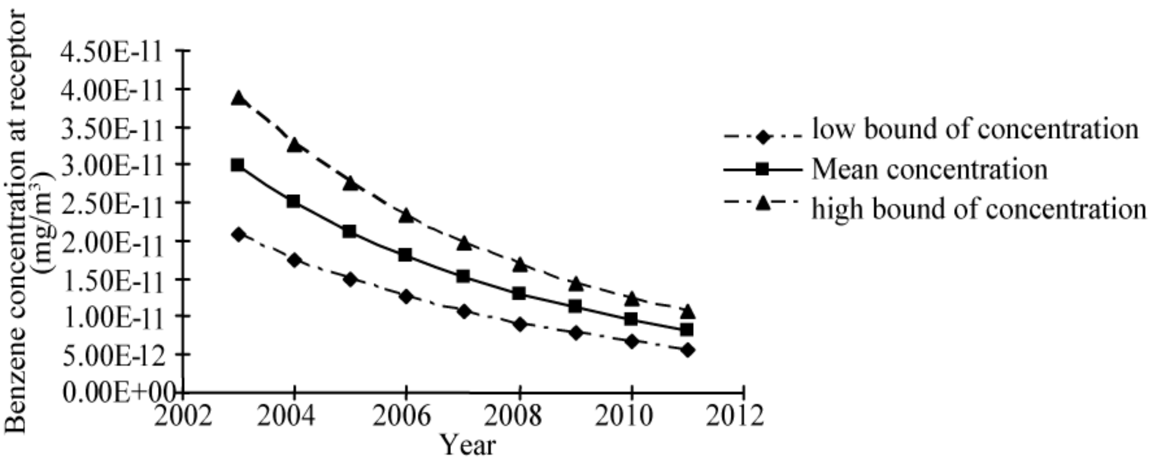

Fig. 8. Yearly benzene concentration profile at ground surface receptor for 2003-2011

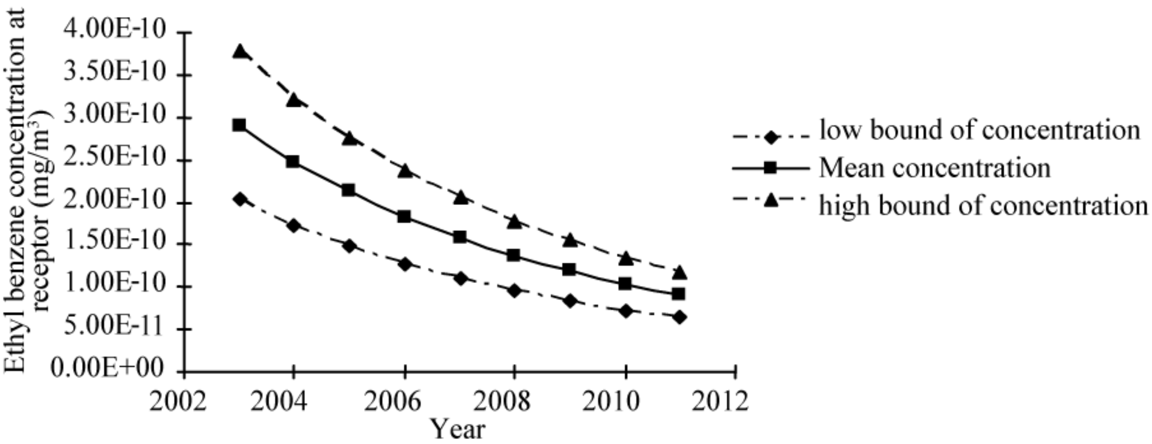

Fig. 9. Yearly ethylbenzene profile at ground surface receptor for 2003-2011

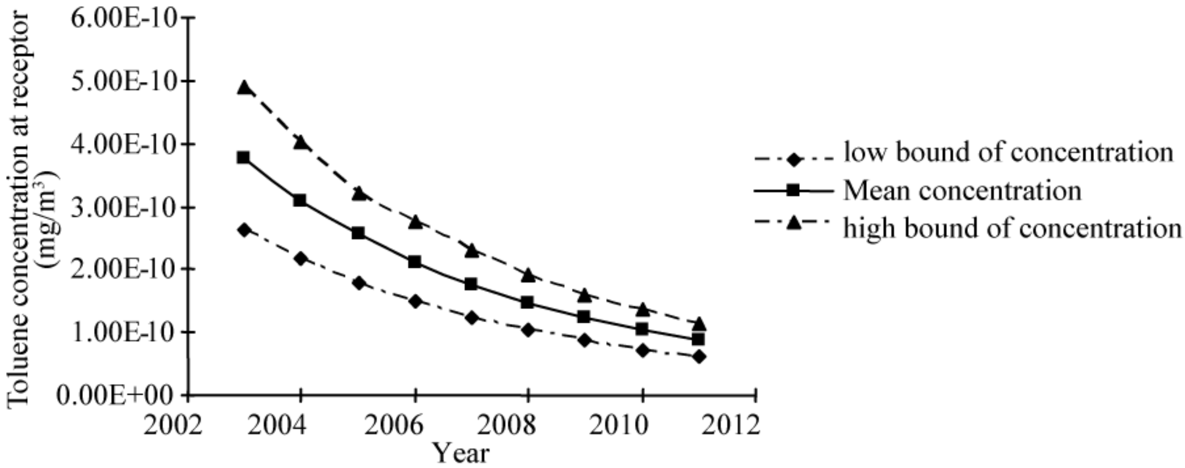

Fig. 10. Yearly toluene profiles at ground surface receptor for 2003-2011

5. Discussion

The model validation and application using field scale data show that FEMMS, enhanced with the aid of quantified uncertainties, can be applied to investigate large-scale site contamination with multimedia characteristics. Landfill is selected in this study as it involves a typical complex environmental multimedia, i.e., a landfill waste zone, the surrounding unsaturated zone, the atmosphere above the landfill, and the groundwater below the landfill. In such case, landfill waste zone evolves in releasing different contaminants at different rate into the regional three media, soil, ground water, and air.

The developed FEMMS is capable of simulating an unsteady state pollutants fate and transport within the landfill waste chamber, which result in dynamic emission sources into the connected atmosphere, soil, and groundwater. Subsequently, the dynamic emission sources are taken by three different modules to quantify multi-dimensional concentration profile in the unsaturated zone, saturated zone, and atmosphere zone above the landfill. This improves the spatial and temporal resolution of previous environmental multimedia models (e.g., McKone and MacLeod, 2003). Particularly, the developed FEMMS has been enhanced by a fuzzy-set approach to quantify different uncertainties associated with the modeling process and the complex site multimedia environmental conditions; this provides more quantitative details to support for the related site management decision making (e.g., Chen et al., 2010).

Like other models, the developed model is based on several assumptions such as initial uniform contaminant concentration in the landfill chamber and moderate climate change, which could be improved with more sampling analyses when possible. Such assumptions may limit the applicability of the model. Hence, engineer and decision-makers should be fully aware the assumptions to apply the model. Discrepancy in the model validation based on the obtained deterministic data information could be traced to the combined effect of several contributing factors. Choosing proper input parameters to represent the site condition is important, since the parameters are site dependent. The input data for the model from the collected and analyzed samples may have errors, and they can also influence the outcome of model significantly. Consideration must be taken to reduce the combined effect of such factors to improve the accuracy of model prediction. The developed GUI effectively manages the major modeling processes including data analysis, communicating input data to functional modules, and results presentation.

In parallel to using a fuzzy-set approach to quantify model and site uncertainties and to overcome the possible field data availability issue during the simulation process, future work can further extend the developed FEMMS by: (1) considering numerical solution with irregular computational mesh for the governing equations in the FEMMS at higher computational cost; (2) improving modeling accuracy by improving numerical analysis algorithm for better addressing the site anisotropic and heterogenetic conditions; and (3) including hydrological and climate change inputs into the modeling system to examine the effects of changing climatic conditions such as precipitation and temperature on the site contamination.

6. Conclusions

The developed user-friendly environmental multimedia modeling system (FEMMS) includes extended LSSMM-type fate and transport modules, a system GUI, a system input processing unit, and a system output processing function. The application of FEMMS to a complex landfill site in Canada demonstrate that it is functional, computational efficient, and user-friendly. FEMMS also quantify system uncertainties associated with modeling processes and site dynamics providing reliable risk or impact assessment to support remediation decision making.

Data are obtained for the Trail Road Landfill in the years of 1999 to 2002, which have been applied to the field validation of the developed FEMMS in this study. The field validation and predication indicate that the soil and groundwater in the landfill area are under risks. Several major programs have been implemented by the City of Ottawa in recent years to manage the landfill site including waste to energy, composting, and facility optimization projects.

Full numerical analysis or computational fluid dynamics (CFD) can be employed in the next to generate numerical results of the FEMMS to examine non-equilibrium unsteady state environmental flow conditions and the anisotropic heterogenetic characteristics of the environmental media. It is also becoming more important to consider climate change and its effects on the dynamics of site contamination. Lastly, latest computer technology can help to build model based software interface.

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