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Application of a GIS-Based Modeling System for Effective Management of Petroleum-Contaminated Sites

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ABSTRACT

A GIS-aided simulation (GISSIM) system is developed for effective management of petroleum-contaminated sites in this study. The GISSIM contains two components: an advanced three-dimensional (3D) numerical model, and a geographical information system (GIS). The modeling component undertakes simulation for the fate of contaminants in subsurface unsaturated and saturated zones. The GIS component is used in three areas throughout the system development and implementation process: (1) managing spatial and nonspatial databases; (2) linking inputs, the model, and outputs; and (3) providing an interface between the GISSIM and its users. The system is applied to a North American case study. Concentrations of benzene, toluene, and xylenes in groundwater under a petroleum-contaminated site are dynamically simulated. Conditions of the contamination in different time stages under a variety of remediation scenarios are predicted. Reasonable outputs have been obtained and presented graphically. Implications of the modeling outputs have been analyzed based on the local environmental regulations. They provide quantitative and scientific bases for further assessment of site-contamination impacts and risks, as well as decisions of practical remediation actions. GISSIM is useful for both industrial and government sectors to make informed decisions on waste management, pollution control, site remediation, and environmental impact assessment.

Key words: petroleum waste; contamination; numerical simulation; soil; groundwater; geographical information system; decision support

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INTRODUCTION

PROBLEMS DUE TO THE CONTAMINANT LEAKAGE and spill from pipelines and storage tanks in petroleum industries have received a significant amount of attention in the past decades (Dowd, 1984; Newton, 1991). The number of underground storage tanks for petroleum products in the North America was estimated to be between 1.5 and 2 millions (Predpall *et al.* 1984). Tejada (1984) reported that as many as 23% of storage tanks leak. Soil and groundwater in thousands of sites have been contaminated by petroleum-derived contaminants. Therefore, an in-depth analysis on impacts associated with the exposed chemicals is desired for effective site management.

To evaluate the impacts, it is important to gain an insight into the fate of contaminants underground. The fate of leaked petroleum products (i.e., nonaqueous phase liquids, NAPLs) in the subsurface is related to a number of physical, chemical, and biologic processes. Upon release to the environment, NAPLs will migrate downward under the force of gravity. When significant amounts of NAPLs are released, they will transport downward until they encounter a physical barrier or are affected by buoyancy forces near the groundwater table. Once the capillary is reached, NAPLs may move laterally as a continuous, free phase layer along the upper boundary of water-saturated zone due to gravity and capillary forces. The convection, dispersion, diffusion, adsorption, volatilization, and biodegradation may govern transport of a variety of petroleum-derived chemicals in the groundwater system.

Previously, a number of studies have been undertaken for simulating the fate of NAPLs in soil and groundwater. For example, Huyakorn and Pinder (1983) discussed several formulations and solution methods for multiphase flow analysis. Abriola and Pinder (1985a, 1985b) proposed a comprehensive approach to simulate the simultaneous transport of a chemical contaminant in three physical forms: as a nonaqueous phase, as a solute component of a water phase, and as a mobile fraction of a gas phase. Kaluarachchi and Parker (1989) formulated a finite element model for simulating the multiphase flow of organic contaminants. Katyal *et al.* (1991) used a two-dimensional finite element program to simulate multiphase and multicomponent transport of NAPLs in subsurface with an assumption of the first-order decay. In general, most of the recent modeling efforts were based on multiphase, multicomponent analyses, such as MOVER, BIOF&T, and UTCHEM (Freeze *et al.*, 1995; Katyal, 1997), which can effectively reflect complexities in subsurface systems. However, extensive applications of the developed models to practical problems were limited due to the ineffectiveness in presentation and management of their inputs/outputs and the lack of dynamic and interactive systems for depicting the related spatial information graphically.

Fortunately, important progress has been made during

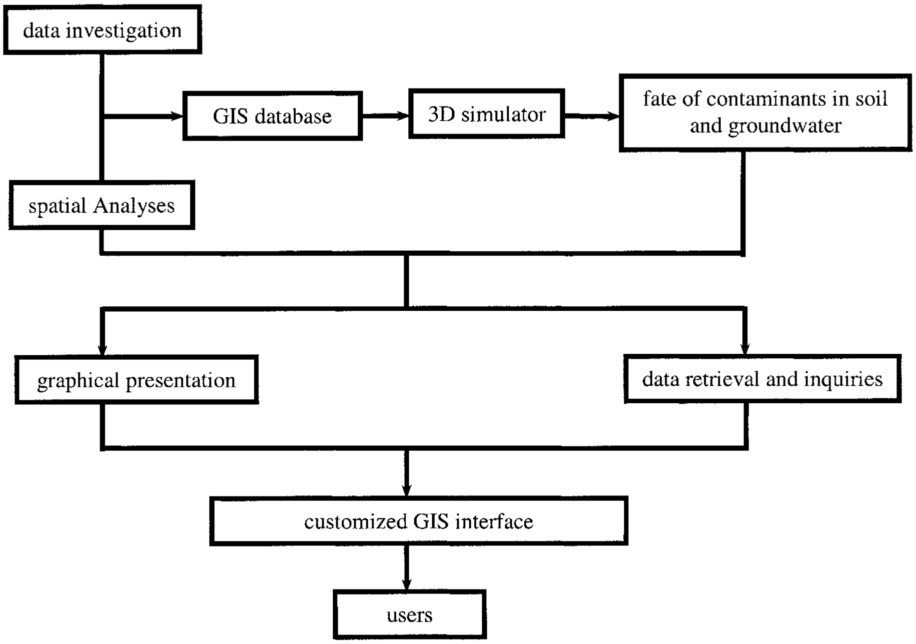


FIG. 1. Structure of the GISSIM system.

the last decade with regard to the use of a geographic information system (GIS) to deal with spatial data and present them graphically (Mattikall, 1994; Hiscock *et al.*, 1995; Wilkinson, 1996). With its powerful capacity of presenting landscape features by means of geospatially referenced data, GIS has been widely used in environmental modeling and risk assessment. For example, Schenk *et al.* (1993) studied the integration of a 3D groundwater model with a multidimensional GIS system. Batelaan *et al.* (1993) incorporated a groundwater model within a GIS system. However, most of the previous studies were limited within the scope of interactive and visual representation of modeling results (Stein *et al.*, 1995; Bober *et al.*, 1995). Only a few of them went beyond research and produced user-friendly software packages (Ehlers *et al.*, 1989; Lovertt *et al.*, 1997).

This research provides an extended integration of a subsurface model and GIS with a focus on the following two objectives:

1. To develop a GIS-based simulation (GISSIM) system for petroleum waste management. This system will contain an advanced 3D numerical model for simulating the fate of contaminants in soil and groundwater, as well as a data management system based on GIS for supporting the simulation process and presenting the modeling inputs and outputs graphically.
2. To apply the developed system to a North American case study. Concentrations of benzene, toluene, and xylenes in groundwater under a petroleum-contaminated site will be dynamically simulated. The impact of the contamination in different time intervals under a variety of remediation scenarios will be predicted through interactive handling the modeling database in a desktop GIS environment.

THE GIS-BASED SIMULATION (GISSIM) SYSTEM

Multicomponent transport model

One of the key components in the GISSIM system is a multicomponent simulation model. It can be used for simulating the transport and biodegradation of multiple contaminants in subsurface media under various site conditions and remediation scenarios. A typical subsurface transport media has five regions: (1) voids filled with air, (2) mobile water located inside the larger interaggregate pores or fractures, (3) immobile water located mainly in the intraaggregate pores or in the porous media sur-

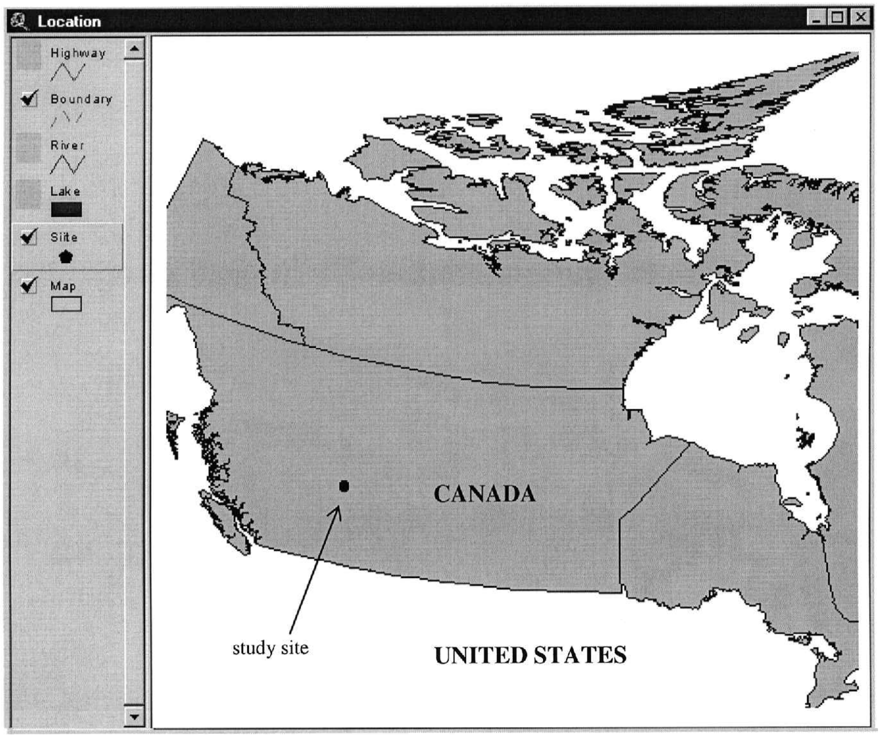


FIG. 2. The study site.

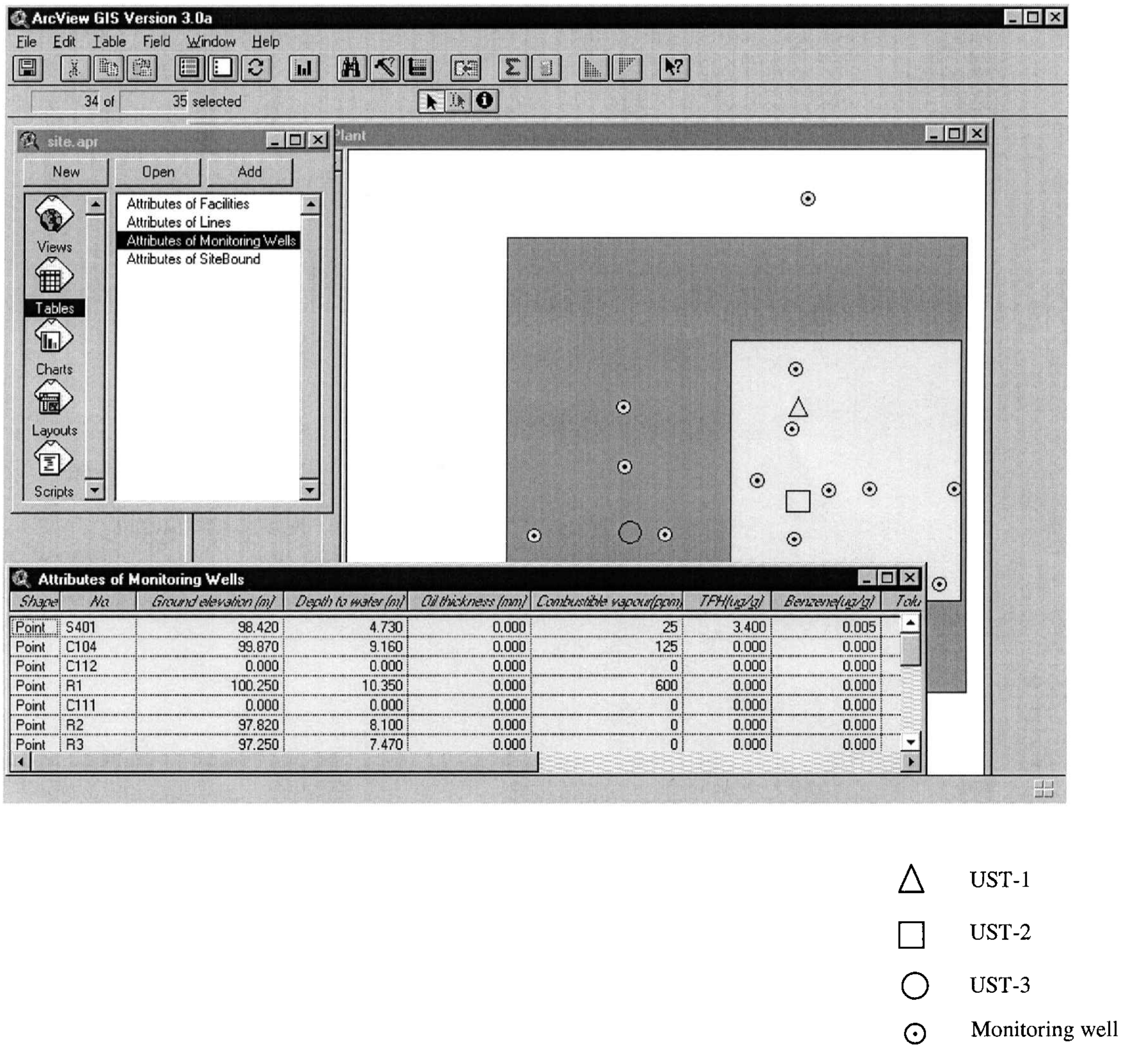
rounding fractures, (4) a dynamic soil region in equilibrium with the mobile phase, and (5) a stagnant soil region where mass transfer is diffusion limited. The general transport equation can be expressed as (Van Genuchten and Wierenga 1976):

$$\begin{aligned}\partial(\theta_m C_{\mathrm{wm}})/\partial t &+ \partial(\theta_{\mathrm{im}} C_{\mathrm{wim}})/\partial t + \partial(f\,\rho P_{\mathrm{wm}})/\partial t \\ &+ \partial[(1-f)\rho P_{\mathrm{wim}}]/\partial t = \partial(\theta_{\mathrm{m}} D_{ij} \partial C_{\mathrm{wm}}/\partial x_j)/\partial x_i \\ &- \partial(q_i C_{\mathrm{wm}})/\partial x_i - q_s C_{\mathrm{ws}}\end{aligned} \quad (1)$$

where C_{wim} is the concentration of contaminant w in immobile water [ML^{-3}]; C_{wm} is the concentration of contaminant w in mobile water [ML^{-3}]; C_{ws} is the concentration of contaminant w in injected fluid [ML^{-3}]; D_{ij} is the hydrodynamic dispersion tensor corresponding to a direction defined by i, j [$L^2\,T^{-1}$]; f is the fraction of sorption site that is in direct contact with mobile liquid; i is the direction i in a Cartesian coordinate system; j is the direction j in a Cartesian coordinate system; P_{wim} is the adsorbed phase concentration of contaminant w in immobile phase [MM^{-1}]; P_{wm} is the adsorbed phase concentration of contaminant w in mobile phase [MM^{-1}]; q_i is the Darcy velocity in direction i [LT^{-1}]; q_s is the volumetric flow rate of fluid injection (or withdrawal) per unit volume of porous medium [$L^3\,L^{-3}\,T^{-1}$]; t is the time [T]; x_i is the distance in direction i [L]; x_j is the distance in direction j [L]; ρ is the soil bulk density [ML^{-3}]; θ_{im} is the fraction of soil filled with immobile water; and θ_m is the fraction of soil filled with mobile water.

The value of D_{ij} is defined as follows (Bear, 1972):

$$\theta_m D_{ij} = d_L|q|\delta_{ij} + (d_L - d_T)\; q_i q_j/|q| + \theta_m \tau D_c \delta_{ij} \quad (2)$$



Attributes of Monitoring Wells

Shape	No	Ground elevation (m)	Depth to water (m)	Oil thickness (mm)	Combustible vapour(ppm)	TPH(ug/g)	Benzene(ug/g)	Tolu
Point	S401	98.420	4.730	0.000	25	3.400	0.005	
Point	C104	99.870	9.160	0.000	125	0.000	0.000	
Point	C112	0.000	0.000	0.000	0	0.000	0.000	
Point	R1	100.250	10.350	0.000	600	0.000	0.000	
Point	C111	0.000	0.000	0.000	0	0.000	0.000	
Point	R2	97.820	8.100	0.000	0	0.000	0.000	
Point	R3	97.250	7.470	0.000	0	0.000	0.000	

FIG. 3. Site location of three USTs displayed by GISSIM. Δ, UST-1; □, UST-2; ○, UST-3; ⊙, Monotoring well.

where d_L is the longitudinal dispersivity [L]; d_T is the transverse dispersivity [L]; D_c is the molecular diffusion coefficient [L^2T^{-1}]; $|q|$ is the absolute value of Darcy velocity [LT^{-1}], $|q|$ is the $(|q_i|^2 + |q_j|^2)^{1/2}$; q_j is the Darcy velocity in direction j [LT^{-1}]; δ_{ij} is the Kronecker delta; and τ is the tortuosity.

Using the following continuity equation for water flow:

$$-\partial(q_i)/\partial x_i = \partial(\theta_m)/\partial t - q_s \tag{3}$$

and assuming a linear sorption isotherm ($P_m = K_d C_m$ and $P_{im} = K_d C_{im}$), Equation (1) can be written as:

$$\begin{aligned}\partial C_{\mathrm{wm}}/\partial t[\theta_m + f\rho k_d] + \partial C_{\mathrm{wim}}/\partial t\ [\theta_{\mathrm{im}} + (1-f)\rho k_d] \\ = \partial(\theta_m D_{ij}\partial C_{\mathrm{wm}}/\partial x_j)/\partial x_i - q_i \partial C_{\mathrm{wm}}/\partial x_i \\ - q_s(C_{\mathrm{ws}} - C_{\mathrm{wm}})\end{aligned} \tag{4}$$

The concentrations of contaminants in mobile and immobile phases have the following relation (Kaluarachchi and Parker, 1990):

$$\partial C_{\mathrm{wim}}/\partial t\ [\theta_{\mathrm{im}} + (1-f)\rho k_d] = X\,(C_{\mathrm{wm}} - C_{\mathrm{wim}}) \tag{5}$$

where X is a mass transfer coefficient for diffusive mass exchange between the mobile and immobile phases [T^{-1}].

Incorporating decay losses λ_{wm} and contaminant loading from a hydrocarbon source to the mobile phase H_w in Equations (4) and (5), yields (Kaluarachchi and Parker, 1990):

$$\begin{aligned}[\theta_m + f\rho k_d]\ \partial C_{\mathrm{wm}}/\partial t + [\theta_{\mathrm{im}} + (1-f)\rho k_d]\ \partial C_{\mathrm{wim}}/\partial t \\ = \partial(\theta_m D_{ij}\partial C_{\mathrm{wm}}/\partial x_j)/\partial x_i - q_i\partial C_{\mathrm{wm}}/\partial x_i \\ - q_s(C_{\mathrm{ws}} - C_{\mathrm{wm}}) - \lambda_{\mathrm{wm}} + H_{\mathrm{w}}\end{aligned} \tag{6}$$

$$[\theta_{\mathrm{im}} + (1-f)\rho k_d]\ \partial C_{\mathrm{wim}}/\partial t = X\,(C_{\mathrm{wm}} - C_{\mathrm{wim}}) - \lambda_{\mathrm{wm}} \tag{7}$$

More detailed formulation and solution process for the multiphase and multicomponent transport model in porous media were provided by Kaluarachchi and Parker (1990), Katyal and Parker (1992), and Katyal (1997).

Generally, the above model has the capability to model complex heterogeneous and anisotropic hydrogeology. Through this modeling system, concentrations of up to five contaminants in a 3D domain can be predicted at a prescribed time horizon. The modeling outputs will provide important bases for decisions of site remediation actions.

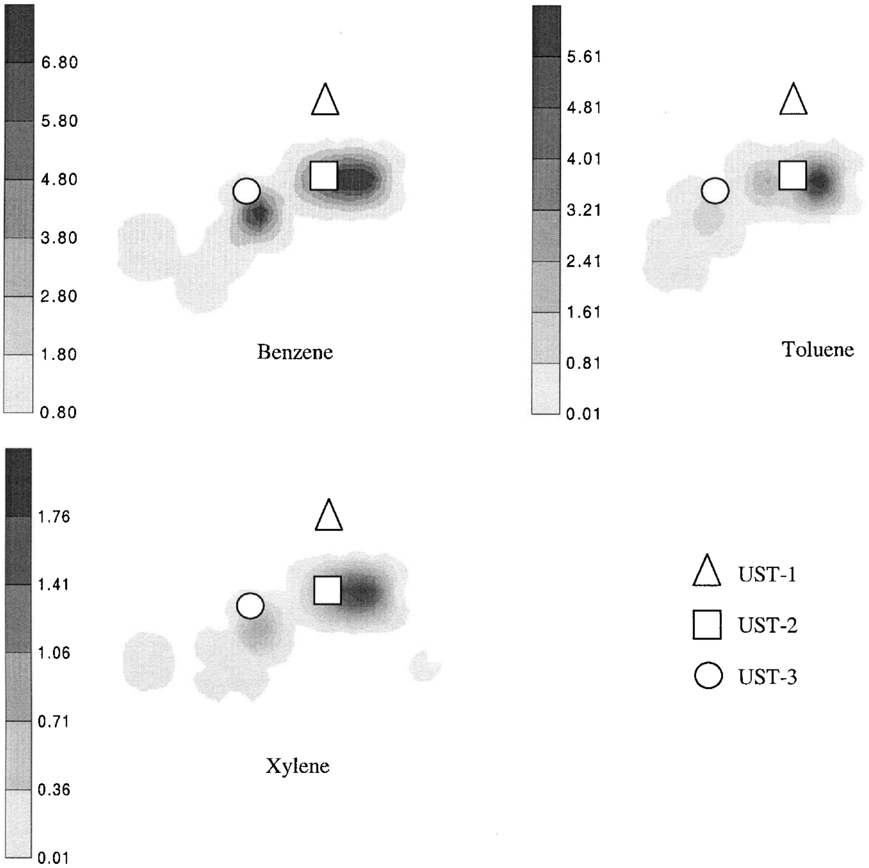
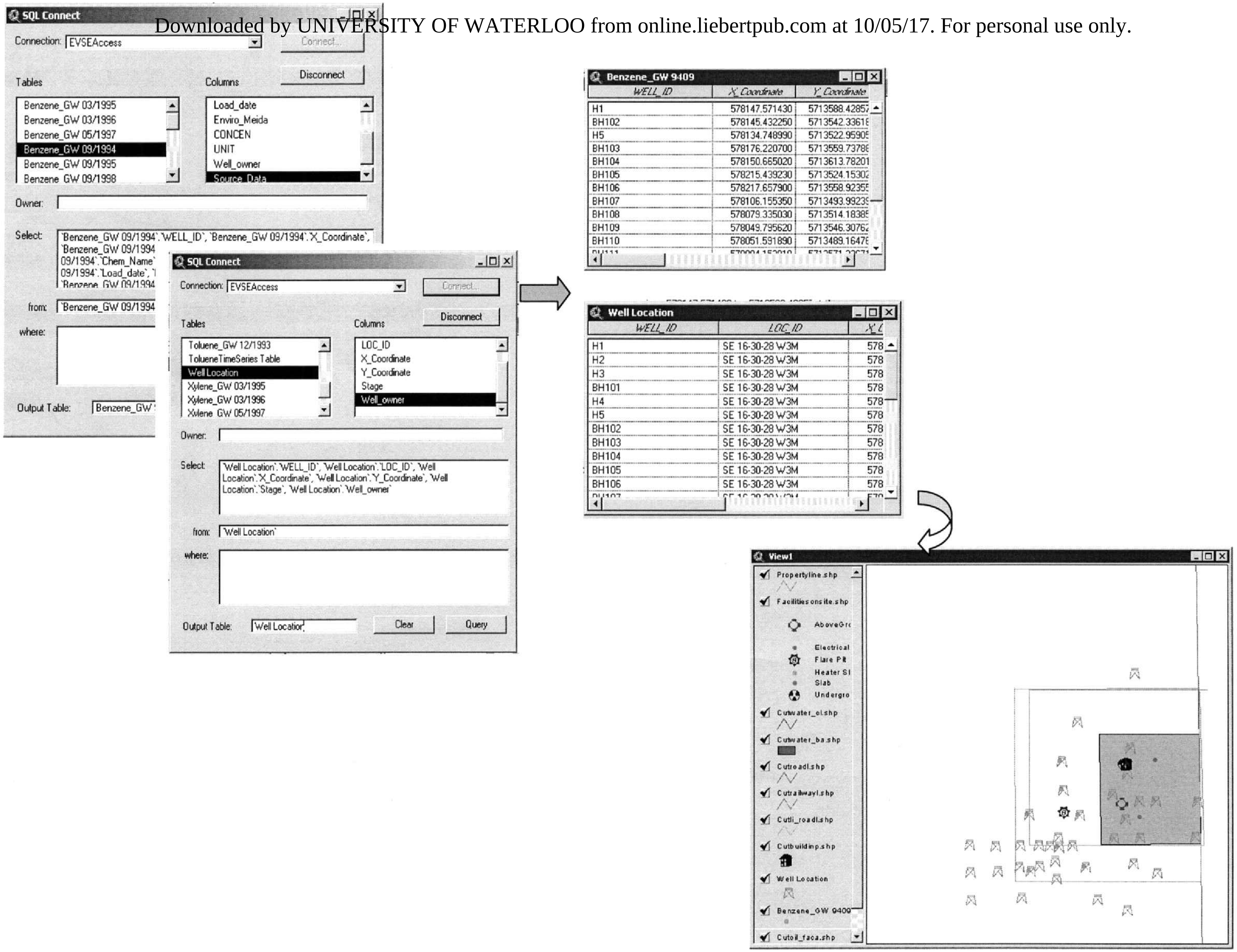


FIG. 4. Observed BTX concentrations at groundwater table layer in 1997.



SQL Connect

Connection: EVSEAccess

Owner:

Select: `Benzene_GW 09/1994`.`WELL_ID`, `Benzene_GW 09/1994`.`X_Coordinate`, `Benzene_GW 09/1994 09/1994`.`Chem_Name` 09/1994`.`Load_date`, `I `Benzene_GW 09/1994

from: `Benzene_GW 09/1994

where:

Output Table: Benzene_GW

SQL Connect

Connection: EVSEAccess

Owner:

Select: `Well Location`.`WELL_ID`, `Well Location`.`LOC_ID`, `Well Location`.`X_Coordinate`, `Well Location`.`Y_Coordinate`, `Well Location`.`Stage`, `Well Location`.`Well_owner`

from: `Well Location`

where:

Output Table: Well Location

Benzene_GW 9409

WELL_ID	X_Coordinate	Y_Coordinate
H1	578147.571430	5713588.4285
BH102	578145.432250	5713542.3361
H5	578134.748990	5713522.9590
BH103	578176.220700	5713559.7378
BH104	578150.665020	5713613.78201
BH105	578215.439230	5713524.1530
BH106	578217.657900	5713558.9235
BH107	578106.155350	5713493.9923
BH108	578079.335030	5713514.1838
BH109	578049.795620	5713546.3076
BH110	578051.591890	5713489.1647

Well Location

WELL_ID	LOC_ID	X_
H1	SE 16-30-28 W3M	578
H2	SE 16-30-28 W3M	578
H3	SE 16-30-28 W3M	578
BH101	SE 16-30-28 W3M	578
H4	SE 16-30-28 W3M	578
H5	SE 16-30-28 W3M	578
BH102	SE 16-30-28 W3M	578
BH103	SE 16-30-28 W3M	578
BH104	SE 16-30-28 W3M	578
BH105	SE 16-30-28 W3M	578
BH106	SE 16-30-28 W3M	578

FIG. 5. Construction of a GIS database.

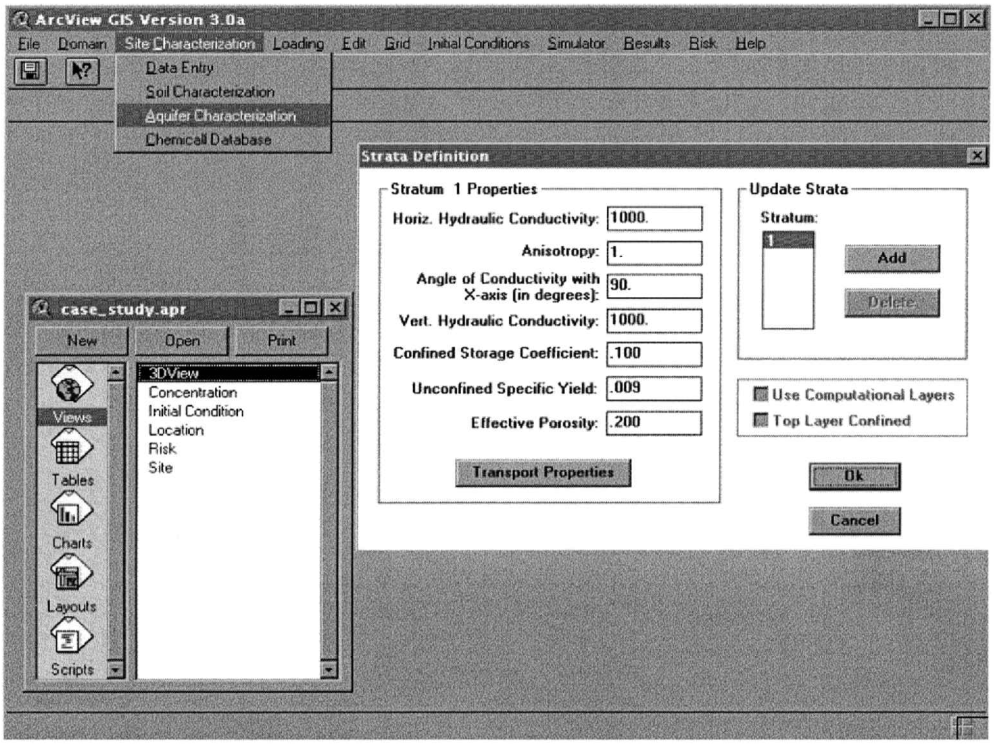
GIS system

A desktop GIS is chosen as a basic tool throughout the modeling processes due to its ability to clearly expose complex environmental conditions in the subsurface. In general, GIS is used in three areas throughout the system development and implementation process: (1) managing spatial and nonspatial databases; (2) linking inputs, model, and outputs; and (3) providing an interface between the GISSIM and its users. The goal is to couple a GIS with the model to allow smooth communication between the modeling system and its users. Figure 1 shows structure of the proposed GISSIM system. Microsoft Excel and Access are used for the spreadsheet and relational database components. Special user-defined Graphic User Interfaces are created through programming Microsoft Visual Basic and the Avenue language, which provide tools for preparation of model input data set, data retrieval and inquiries, visual presentation of modeling results, and site spatial characterization.

Database management. A GIS is used to enter data, compare data from different sources and in different formats, assess data availability and quality (e.g., accuracy and scale), and identify potential data errors (Grossmann and Eberhardt, 1993). A centralized database with a structure that allows efficient storage and retrieval of spatially referenced time-series data is developed before the simulation process. The database assures the integrity of data and makes it possible to analyze related information comprehensively.

Generally, spatially referenced physical data for the groundwater model can be divided into two categories, one value per location (or one-for-one), and many values per location (or many-for-one). Examples of the one-for-one data include area of a polygon, and elevation of a point. Time-series data belong to the many-for-one category, such as temporal variations of pollutant concentrations and groundwater flows. To store and retrieve these two types of data efficiently during a modeling process, different data structures and retrieval methods are required. It is assumed that features of a location (e.g., monitoring wells, and pollution sources) can be uniquely identified through a location identifier (ID).

The one-for-one data can be stored as location attributes attached to a GIS coverage. In this type of database, the location ID is used as a key for data storage and retrieval. The many-for-one data can be stored in separate databases with one file for each attribute at each physical location. In this type of databases, a file name should



Stratum 1 Properties

Horiz. Hydraulic Conductivity: 1000.
Anisotropy: 1.
Angle of Conductivity with X-axis (in degrees): 90.
Vert. Hydraulic Conductivity: 1000.
Confined Storage Coefficient: .100
Unconfined Specific Yield: .009
Effective Porosity: .200

Update Strata

Stratum: 1

☐ Use Computational Layers
☐ Top Layer Confined

FIG. 6. Database preparation.

reflect both the location ID and the name of physical attribute it stores. In this study, a number of locations are considered, with each of them referring to a group of attribute data. This leads to a large amount of files corresponding to inputs and outputs of the simulation model. To enhance management of these files, a communication channel between Microsoft Access database and the ArcView GIS database is built through Visual Basic programming.

Model interface. This study considers both hydrogeologic characteristics and contaminant features in evaluating the impact of contamination sources on subsurface water quality. The proposed GISSIM system links digital data, model, and computational outputs together. Its interface generates proper input data files automatically for the model, serving as a bridge between the input data and the simulation model. The GISSIM's retrieval and presentation function allows users to retrieve and analyze information of site conditions and modeling results dynamically. A geographic "hot link" is created as a hypermedia function to communicate spatially referenced information into various types of data. For example, a contaminant's concentration at a spatial location can be retrieved through clicking on that location at the screen referring to a subsurface layer. In addition, the model interface connects the simulation results to a graphic display supported by GIS.

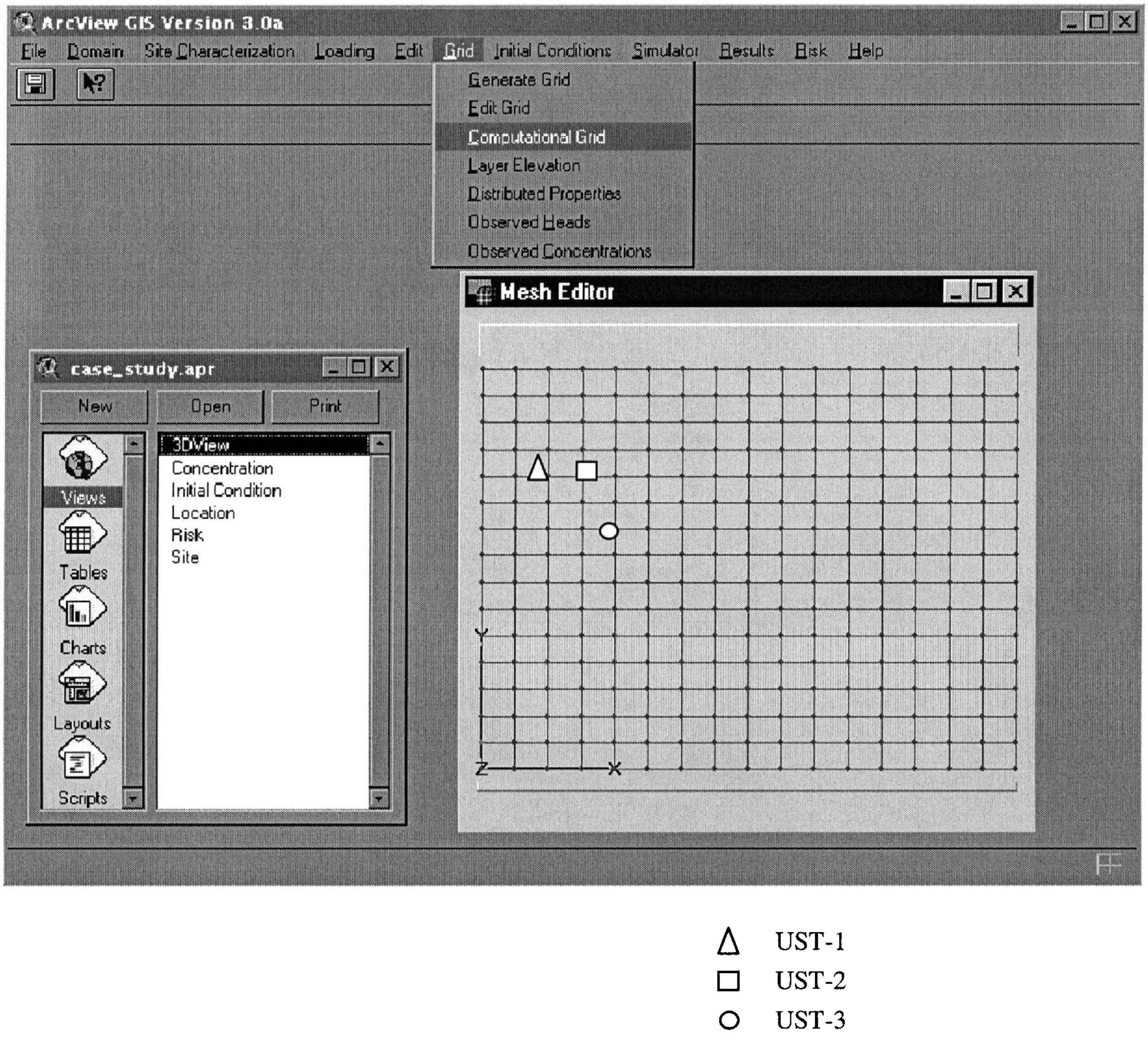


FIG. 7. The grid system. Δ, UST-1; □, UST-2; ○, UST-3.

User interface. The user interface makes the implementation of the GISSIM a robust and user-friendly process. This component provides a two-way communication between the system and its users (Faust *et al.*, 1991). On the one hand, the user may interactively delineate an area of concern, identify contamination sources to be considered, add additional data, or specify a particular planning objective. On the other hand, the system can explain to the user about each step in the modeling process and display results from running the simulation model. The system can also provide its user an evaluation of the quality of data, accuracy of the result, and level of uncertainty. If the user is not satisfied with the results from available data, the system can recommend to what data are needed to improve the modeling performance.

The display of data is the final stage in the modeling process, providing a link between the data and the user. The most powerful medium for this communication is the graphics, usually in the form of maps, charts, or tables. In this study, ArcView is used for managing and displaying modeling results. The user can use ArcView's statistical and spatial query functions to select output information. Avenue scripts were developed to create a customized user interface. Distribution of pollutant concentrations in the subsurface at a prescribed time can thus be displayed dynamically through contours and 3D surfaces within the GISSIM system.

CASE STUDY

Overview of the study site

The study site is located in western Saskatchewan, Canada (Fig. 2). It was operated as a natural gas processing plant from mid-1960s to early 1990s. The plant was utilized to remove naphtha condensate from the natural gas stream prior to transport to a regional transmission line. Throughout the history of the site, the condensate was disposed of in three perforated underground storage tanks (USTs) (Fig. 3), which then leaked into the soil and finally into the groundwater following seepage. Two contaminant concentrated zones were formed in the subsurface capillary fringe (at the interface between unsaturated and saturated zones).

The site is bounded in all directions by agricultural land. There are several farm residences located within a 1.5-km radius of the site all with domestic water wells. In recent years, agricultural land in the southeast has been used for livestock husbandry (for cows and horses).

Groundwater was encountered between 5 and 10 m below the surface. The general groundwater flow direction is towards the south, with the gradient of the water table being slightly from the northeast to the southwest. The groundwater table is located predominantly within a clay-till soil layer.

Figure 4 shows the observed concentrations of benzene, toluene, and xylene at the study site. Two highly concentrated zones exist around underground storage tank 2 (UST-2) and under UST-3. The highest benzene concentration (7.58 mg/L) was observed at a monitoring well located at the east of UST-3. The peak concentrations of toluene and xylene (5.92 and 1.87 mg/L, respectively) were observed at a well located at 20 m east of UST-2. If the local Non-Potable Groundwater Quality Guidelines are applicable to the study site, the peak concentration of benzene will be over four times the regulated 1.9 mg/L, and that of toluene will be over three times the regulated 1.9 mg/L. In comparison, the xylene concentrations are generally lower than the regulated values.

The site conditions and modeling outputs can be conveniently represented through the developed GISSIM system. For instance, facilities and emission sources on the site can be presented graphically through the GIS. The observed and predicted contaminant concentrations, as well as information about the groundwater table, can be displayed as 2D contour lines or 3D surfaces. The stratigraphy in the subsurface can be visualized with sufficient data on the distribution of soil types at different elevations and cross-sections. In addition, many modeling parameters at a spatial location, such as hydraulic conductivity, soil density, water saturation level, and air pressure, are grouped into a many-for-one data category in the GIS. The above information can be retrieved by clicking the related features (point, lines, and polygons) in the GISSIM system.

GISSIM modeling process

The GISSIM modeling process involves the following four steps:

Step 1: Digitization and GIS database development. This step is to provide a GIS database of pollution-related parameters at the site. The GIS database addressed here is a special component hosting all the information related to site contamination and hydrological conditions such as soil types, pollution source distributions, contamination levels, and surrounding environmental features (e.g., residential zones, river, and lakes). The database has two components: ARC coverages for geographic features and unique feature IDs; and Microsoft Access tables for attribute items, with the feature ID as a unique key. The connection between the two is built on the Data-

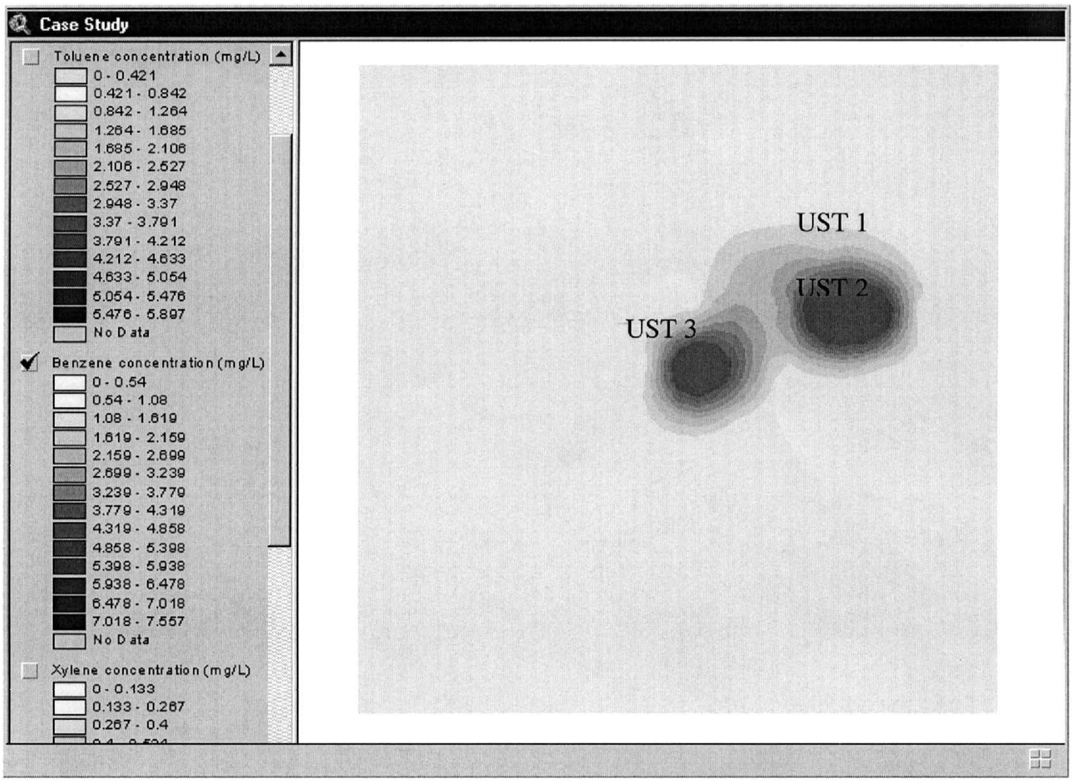


FIG. 8. Predicted benzene concentrations.

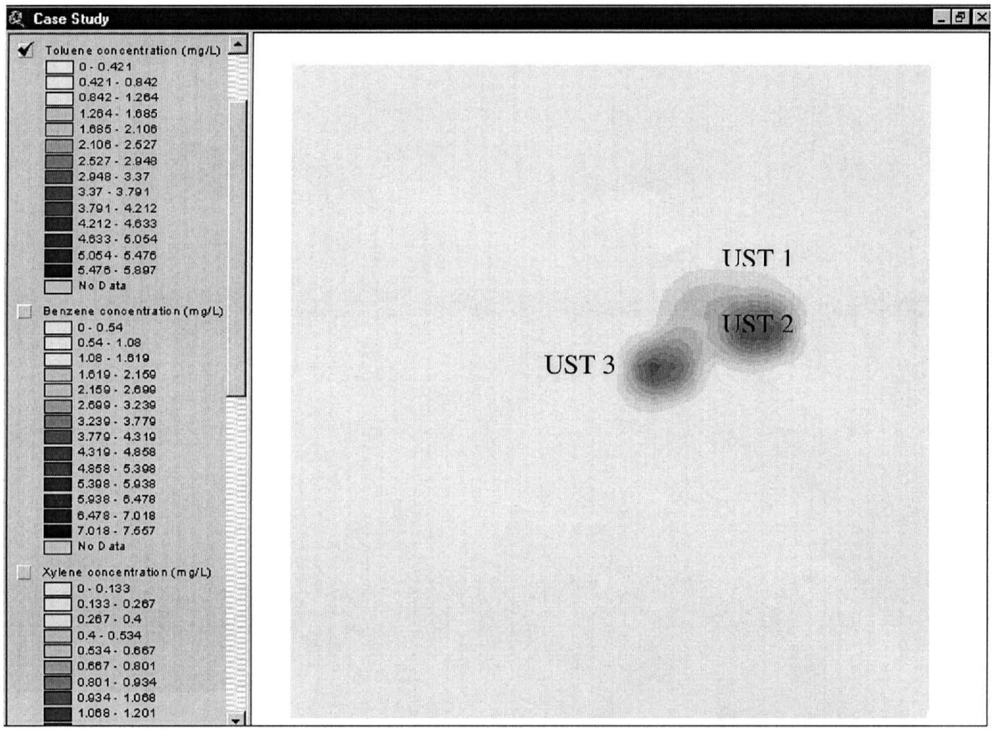


FIG. 9. Predicted toluene concentrations.

base Integrator in ARC/INFO and ARCVIEW3. Figure 5 shows the details of the construction of a spatial GIS database. The database is useful for further modeling work. For example, user could build up the input data for the multicomponent transport simulator by using the interface as shown in Fig. 6.

Step 2: Grid system development. The multicomponent transport model is implemented through a computational grid system. Normally, 2D grid systems can be directly generated in the GIS. Because this study requires a 3D mesh, an external mesh editor is launched to create and edit 3D finite element meshes at 16 × 17-m resolution. This editor allows generation of irregular quadrilateral meshes in two or three dimensions, as well as analysis of soil and groundwater properties in the study domain. Figure 7 shows the top slice of the generated 3D mesh.

Step 3: Contaminant transport modeling. The multicomponent transport simulator can be launched through the proposed event-driven interface. After the modeling inputs are prepared in the GIS database, the simulator can be used for predicting the fate of benzene, toluene, and xylenes (BTXs) in the aquifer.

Step 4: Results representation. The simulation outputs are transformed into a GIS acceptable format. They can be presented in several ways, such as statistical charts, contour lines, and 3D surfaces. Figures 8 to 10 present the simulated concentration of BTXs through contour lines.

Model evaluation and testing

Calibration and verification are important steps for the modeling study with a focus on groundwater. They were undertaken using data obtained during 1993 to 1997 from five monitoring wells. Information of site conditions and contamination sources in 1993 was used for estimating model parameters. The monitoring data of 1997 were then used to verify the model. The absolute errors between simulated and observed benzene concentrations range from 0.023 to 0.532 mg/L, with a mean relative error of 44.4%. The mean relative errors for toluene and xylenes are 71.0% and 56.2%, respectively. The results indicated that existence of the three contaminants in most of the monitoring wells is well simulated by the model. A few exceptions exist due to lack of monitoring data (for model calibration), potential sampling errors, low soil permeability, and subsurface stratification. For example, simulated concen-

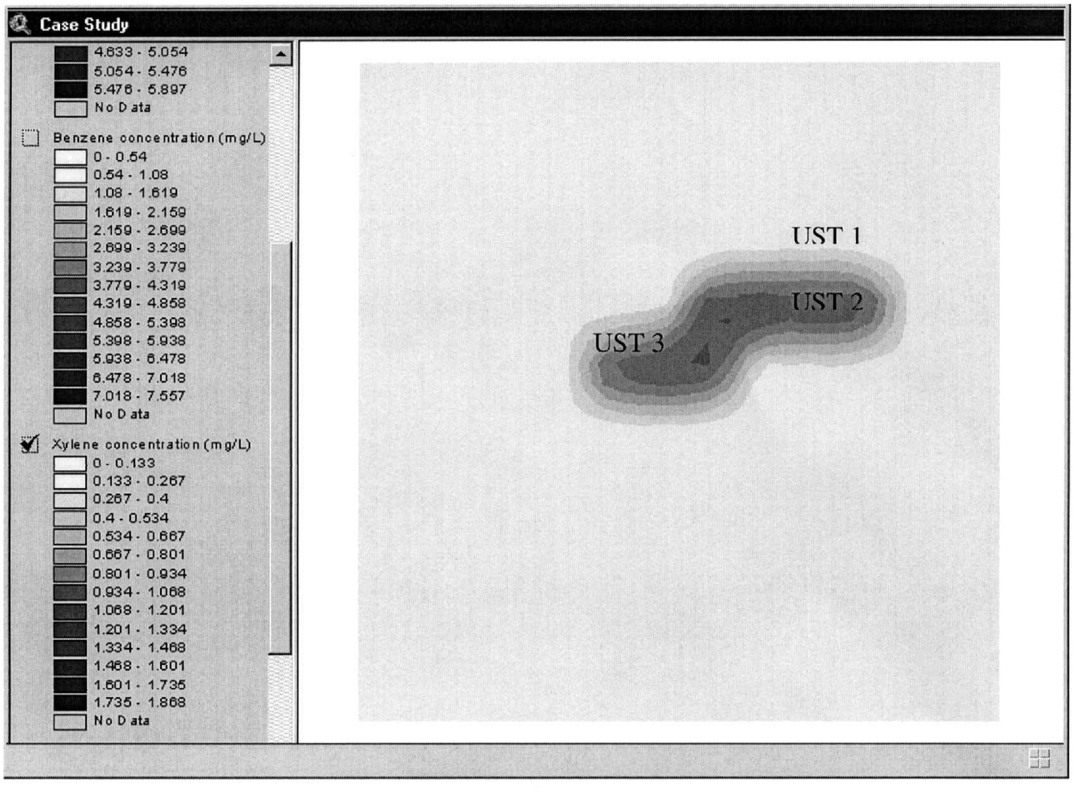


FIG. 10. Predicted xylene concentrations.

tration of toluene (4.37 mg/L) in a monitoring well close to UST-2 is remarkably different from observed data (2.48 mg/L). This observed value is associated with many uncertainties, which significantly increased the average error of simulating the fate and transport of toluene. If this observation is considered as an outlier, the mean relative error for toluene will be reduced to 57%. In general, the above verification results indicate that the developed model can simulate the fate of BTX in groundwater with reasonable errors.

RESULTS

After the model is well calibrated and verified, it can then be used for dynamically simulating the fate of contaminants under a number of remediation scenarios. Figures 8 to 10 show distributions of benzene, toluene, and xylenes concentrations 10 years later when no remediation action is undertaken. It is indicated that the peak benzene concentration will still be 7.40 mg/L 10 years later, which is higher than the regulated level of 1.90 mg/L in the local Non-Potable Groundwater Quality Guidelines. This peak occurs at about 30 m west of UST-2 and 30 m northeast of UST-3. The results also demonstrate that, due to the large contamination area and the specific stratigraphic and hydraulic characteristics of the site, BTX in the unsaturated zone will be continuously released to groundwater if no remediation action is undertaken. It is thus recommended that the on-site groundwater not be used for irrigation or drinking water, even 10 years later under this scenario.

The peak toluene concentration 10 years later will be 6.46 mg/L, which is still higher than the regulated level of 5.90 mg/L. In comparison, the peak xylenes concentration (2.41 mg/L) is lower than the regulated upper limit at 5.60 mg/L. If a remediation action with 60% efficiency is undertaken, all pollution problems at the site will be completely resolved 10 years later. The peak concentrations of benzene, toluene, and xylenes 10 years later would be reducecd to 1.49, 2.10, and 0.46 mg/L, respectively, which are lower than the regulated values.

Potential impacts on communities

The impact information is incorporated within the GISSIM system, through systematic links to the GIS database, the modeling outputs, and the related environmental guidelines. The farm residences to the north and northeast of the study site withdraw groundwater for domestic use. Fortunately, the on-site groundwater flow direction is generally to the south. No complaint has yet been received from the farmers regarding the quality of groundwater in the north. However, due to the high dispersivity and volatility of BTX, substantial impacts may arise in the future.

There is a large area of crop and grazing land in the south and west of the study area. The subsurface area under these lands is seriously contaminated, based on the *in situ* investigation and the model output. Therefore, interactions between the contaminated subsurface and the above-ground vegetation may lead to health impacts on humans and livestock.

CONCLUSIONS

A GIS-based simulation (GISSIM) system has been proposed for petroleum waste management. It contains an advanced 3D numerical model for simulating the fate of contaminants in soil and groundwater and a GIS for supporting the simulation process and presenting spatial-temporal information graphically. Through incorporation of GIS within the modeling framework, an object-oriented simulation environment with an open software architecture is provided. It can be used by environmental engineers for supporting decisions of site remediation and risk management. The GISSIM is available for use on a shareware or a contract basis.

The developed GISSIM system has been applied to a North American case study. Concentrations of benzene, toluene, and xylenes in groundwater under a petroleum-contaminated site are dynamically simulated. Conditions of the contamination in different time stages under a variety of remediation scenarios are prediced and graphically presented. Generally, it is indicated that benzene is the most important contaminant at the site. If no remediation action is undertaken, serious benzene contamination problem will still exist at the site even 10 years later.

Implications of the modeling outputs have been analyzed based on the local guidelines for nonpotable groundwater quality. They provide quantitative and scientific bases for further assessment of site-contamination impacts and risks, as well as decisions of practical remediation actions.

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