Available online at www.sciencedirect.com

ScienceDirect

Journal of Hazardous Materials 147 (2007) 78–90

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Development of a terrestrial chemical spill management system

Derek L. Bryant*, Mark D. Abkowitz

Vanderbilt Center for Environmental Management Studies, Vanderbilt University, VU Station B 351831,
2301 Vanderbilt Place, Nashville, TN 37235, USA

Received 6 October 2006; received in revised form 15 December 2006; accepted 18 December 2006
Available online 28 December 2006

Abstract

Adequately preparing for and responding to terrestrial (land-based) chemical spills are critical to the protection of human health and the environment. To facilitate analysis and support decision-making for such events, the authors have developed an environmental risk management system that characterizes the ability of a spilled chemical to immediately impact human health, groundwater, surface water, and soil resources, and incorporates these four risk areas into an overall measure of terrestrial chemical risk. This system incorporates a risk index model, leverages geographic information systems (GIS) technology, and contains a comprehensive chemical and environmental database to assess and delineate the immediate threat posed by a terrestrial chemical spill. It is designed to serve a variety of stakeholders, including managers and policy-makers, who would benefit from generating screening-level environmental risk assessments without requiring a technical background or collection of detailed environmental and chemical data. Areas of potential application include transportation routing, industrial zoning, environmental regulatory compliance and enforcement, spill response, and security planning.

Keywords: Risk management; Chemical spills; Human health; Environmental protection; Information systems

1. Introduction

Each year, thousands of chemical spills occur in the United States [1]. 850,000 industrial sites in the US contain potentially hazardous chemicals [2] and the transportation system of the nation handles 800,000 shipments of these materials per day [3]. This situation presents a constant threat of spills with the potential to significantly impact human health and the environment. Managing these events before and during their occurrence is imperative to the protection of people and natural resources such as groundwater, surface water, and soils. This paper presents a new decision support tool that aids in planning and responding to a terrestrial (land-based) chemical spill. This system provides decision makers with a screening-level risk assessment for specific chemicals and locations and provides detailed data for further in-depth inquiries.

The system developed herein leverages geographic information systems (GIS) technology to assess and delineate the immediate threat to human and environmental receptors from a terrestrial chemical spill. The system characterizes the ability of a spilled chemical to immediately impact human health, groundwater, surface water, and soil resources, and incorporates these four receptors into an overall measure of terrestrial chemical risk. The methodology driving this characterization is a risk model, supported by a comprehensive database containing information on chemical properties and environmental resources, designed to speed calculations and minimize user burden. This tool differs from previous environmental risk indices in that: (1) it accounts for attributes of the local environment and chemical in question, (2) requires almost no data input or scientific knowledge from the user, (3) creates an easy to understand visual output that supports the decision process, and (4) has the potential for transferability to sites throughout the United States.

The purpose of this paper is to describe and demonstrate the terrestrial chemical spill management system and its associated risk model. A discussion of the model and the data used by the system are presented. This discussion is followed by a case study, in which the system is applied to a county in northeastern Ohio, to demonstrate its “proof of concept” and illustrate system results.

---

* Corresponding author. Tel.: +1 615 322 2739; fax: +1 615 322 3365.
E-mail addresses: derek.l.bryant@vanderbilt.edu (D.L. Bryant), mark.abkowitz@vanderbilt.edu (M.D. Abkowitz).

0304-3894/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2006.12.048

2. Model description

2.1. Model structure

The spill management system employs an index model that calculates a value corresponding to the relative magnitude of risk posed to each of the aforementioned four receptors and the corresponding measure describing overall risk. Index models involve characterizing physical attributes by using ratings or numerical scores to assign them to risk categories. The index method is commonly used in characterizing environmental risk, particularly with respect to groundwater, because it is typically relatively inexpensive, uncomplicated, and produces results that are easily interpreted by managers and policy makers [4]. One of the most widely used environmental index models is the DRASTIC model for determining groundwater vulnerability [4]. Other examples include those reported by Silka and Swearingen [5], LeGrand [6], and Civita and De Maio [7] for use in determining risks to groundwater, Sampaolo and Binetti [8] and Scott [9] for determining general environmental risk, and Cutter et al. [10] for determining human vulnerability from disasters.

A common form of the index methodology involves scoring a set of factors, which are then aggregated to produce a risk index number by the following equation:

$$\sum_{i=1}^{n} W_i R_i = \text{index value} \tag{1}$$

where R_i is the rating, or severity, assigned to the ith factor and W_i is its corresponding weight, or importance. In the terrestrial chemical spill management system, this formulation is used to calculate index values for each of the four risk components: health, groundwater, surface water, and soil resources. (In this system, air is not viewed as a separate environmental receptor, but is considered as an exposure pathway in determining the risk to human health.) These four components appear most often in the literature as the focus of response and remediation by factoring heavily into determining the impact of a spill and the resources required for its mitigation.

In the system described herein, weighting and ranking values specifically reflect the importance and severity, respectively, of given factors in assessing the potential magnitude of harm to receptors. These values reflect the judgment of the system user, or, in the case of default system values, that of a panel of experts (see Section 2.2). The values assigned to factor weights and rankings range from one to five, with higher index values implying a greater risk. Index values are normalized into percentages, according to the method of Civita and De Maio [7], for use in mapping and in producing an overall risk index. The overall index is calculated and mapped in the same fashion, using the normalized component scores as factor rating values.

A color-coding scheme was developed for map output such that areas of equal levels of relative risk appear in the same color. The color scheme was defined by running the model with a randomly selected subset of the chemical database and then partitioning the results into categories according to their deviation from the sample mean. For example, a region whose groundwater risk index is more than two standard deviations above the average value for chemicals in the database is colored red to indicate the highest risk category. The color moves from red to green as index values decrease for each risk component and the overall index.

In addition to map results, the user has access to all of the values used in the calculation of the risk indices. These values can be used to support spill planning and response decision-making as well as to provide initial data for more rigorous analyses.

2.2. Model factors

A certain amount of subjectivity is inherent to all index models [4]. In an attempt to minimize the degree of subjectivity attributable to individual users of the system, model factors and default weighting values used in calculating risk indices were determined through expert judgment by means of a Delphi survey [11].

The final list of model factors for each risk component, with corresponding default weighting values, is presented in Table 1. Default factor rating schemes are presented in Table 2.

Table 1
Risk model factors and weights

Risk model components	Factors	Factor weight
Human health	Chemical toxicity	4.63
	Spill proximity to dense populations	4.56
	Chemical volatility	4.13
	Chemical flammability	4.06
	Chemical reactivity	3.81
	Proximity to vulnerable populations	2.71
	Chemical solubility	2.71
	Chemical-specific gravity	2.36
Groundwater	Depth to groundwater	4.31
	Chemical solubility	4.07
	Chemical-specific conductivity of vadose zone	4.00
	Chemical adsorption to sediments	3.86
	Bedrock/aquifer material	3.69
	Chemical-specific conductivity of soil	3.63
	Chemical volatility	3.31
	Soil surface chemical-specific conductivity	2.93
	Slope of soil surface	2.88
Surface water	Spill proximity to surface water	4.81
	Slope of soil surface	4.25
	Chemical solubility	3.86
	Chemical viscosity	3.38
Soil resources	Chemical toxicity	4.50
	Chemical adsorption to soil	3.86
	Chemical persistence	3.71
	Chemical volatility	3.50
	Pre-spill quality of soil resources	3.00
	Slope of soil surface	2.94
	Chemical-specific conductivity of soil	2.81
Overall	Human health	4.69
	Surface water	4.06
	Groundwater	3.31
	Soil resources	2.94

Table 2
Factor ranges and rankings

Factor		Range		Factor rating	Source[a]
Toxicity (NFPA rating)		0		1	[12]
		1		2	
		2		3	
		3		4	
		4		5	
Reactivity (NFPA rating)		0		1	[12]
		1		2	
		2		3	
		3		4	
		4		5	
Flammability (NFPA rating)		0		1	[12]
		1		2	
		2		3	
		3		4	
		4		5	
Persistence (half-life in days)		0–4		1	[13]
		4–20		2	
		20–50		3	
		50–100		4	
		>100		5	
Vapor pressure (Pa)	Human health		Soil and water		[14]
	0–100		>100,000	1	
	100–1000		100,000–10,000	2	
	100010,000		1000–10,000	3	
	10,000–100,000		100–1000	4	
	>100,000		0–100	5	
Solubility (ppm)		0–0.1		1	[15]
		0.1–100		2	
		100–1000		3	
		1000–10,000		4	
		>10,000		5	
Dynamic viscosity (Pa s)		>1		1	–
		0.1–1		2	
		0.01–0.1		3	
		0.001–0.01		4	
		0–0.001		5	
Specific gravity (dimensionless)		>1.5		1	[16]
		0.8–1.5		3	
		0–0.8		5	
Chemical-specific conductivity (μm/s)		0–0.1		1	[17]
		0.1–1		2	
		1–10		3	
		10–100		4	
		>100		5	
Adsorption (K_d)	Groundwater		Soil		[18]
	>5		0–2	1	
	4–5		2–3	2	
	3–4		3–4	3	
	2–3		4–5	4	
	0–2		>5	5	
Soil resource quality (SSURGO farmland ratings)	“Not prime farmland”			1	[19]
	“Prime farmland of local importance”			2	
	“Prime farmland if . . .”			2.5	
	“Prime farmland of statewide importance”			3	
	“All areas are prime farmland”			4	
	“Farmland of unique importance”			5	

Table 2 (*Continued*)

Factor	Range			Factor rating	Source[a]
Slope of soil surface (%)	Groundwater		Surface water and soil		[20]
	>18		0–2	1	
	12–18		2–6	1.5	
	6–12		6–12	2.5	
	2–6		12–18	4.5	
	0–2		>18	5	
Bedrock/aquifer material	Massive shale			1	[20]
	Metamorphic or igneous			1.5	
	Weathered metamorphic or igneous			2	
	Glacial till			2.5	
	Bedded SS, LS and SS sequences			3	
	Massive sandstone or limestone			3	
	Sand and gravel			4	
	Basalt			4.5	
	Karst limestone			5	
Depth to groundwater (m)		>23		1	[20]
		15–23		1.5	
		9–15		2.5	
		4.6–9		3.5	
		1.5–4.6		4.5	
		0–1.5		5	
Proximity to surface water (m)		750		1	[21]
		300–750		2	
		150–300		3	
		30–150		4	
		0–30		5	
Proximity to densely populated areas (ERG isolation and protection zones[b])		>LPM[c]		1	[22]
		SPM–LPM		2	
		LII–SPM		3	
		SII–LII		4	
		0–SII		5	
Proximity to vulnerable populations (ERG isolation and protection zones[b])		>LPM[c]		1	[22]
		SPM–LPM		2	
		LII–SPM		3	
		SII–LII		4	
		0–SII		5	

[a] Ratings were taken directly from or adapted from the sources listed.

[b] ERG = emergency response guidebook (US Department of Transportation 2004); for chemicals that do not have isolation and protection zones specified, the minimum values listed for chemicals with zone specifications were used.

[c] LPM = maximum large spill protection zone, SPM = maximum small spill protection zone, LII = large spill initial isolation zone, SII = small spill initial isolation zone.

Several of the survey factors were omitted from the risk model for various reasons. In order to decrease the burden of the user and increase the self-sufficiency of the system, factors dependent on real-time climatic data at the time of a spill incident were excluded. Historical data with the temporal precision necessary to describe climatic conditions at the time of a spill is not publicly accessible and can be relatively expensive. Similarly, factors that rely on data that must be collected in the field by the user or are beyond the scope of a screening-level tool were excluded, such as soil hydrophobicity and soil pH. Soil texture and sequencing was also removed from the list of factors based on the recommendations of Delphi panelists who argued that its effects were captured by other factors. Finally, chemical vapor density was excluded because all of the chemicals analyzed by the system have vapors that are heavier than air.

Eliminating these factors may, in some cases, reduce the level of detail associated with the risk model. However, system complexity must be balanced against the technical background of the target user and the level of analysis sophistication desired. In order to retain information while reducing system intricacy, the effects represented by some of the eliminated factors have been accounted for through indirect means. For example, when calculating health risks in the absence of real-time weather conditions, circular population protective distances are used instead of down-wind distances. Similarly, the effects of soil texture and sequencing are accounted for in the risk model by using the effective vertical conductivity of the soil system, calculated as the harmonic mean of the soil horizons. These modifications result in a more simple, self-contained, screening-level tool with a higher potential for use in broad range of geographical areas.

Two factors, "soil surface chemical-specific conductivity" and "proximity to vulnerable populations", were adapted slightly from their original form in the survey, based on the comments of panelists. "Soil surface chemical-specific conductivity" is based on the factor "surface permeability" from the Delphi survey. This minor change more directly addresses the ideas of panelists on representing infiltration potential in the risk model with regard to specific chemicals. "Proximity to vulnerable populations" is derived from the factor "age of exposed persons" in the Delphi survey. Panelists indicated that age is an important factor in determining human health risk since the elderly and children tend to be less mobile and more susceptible to health effects. Information in disaster planning literature is consistent with this concept (e.g., [10,23]) and further suggests that the location of concentrations of these vulnerable populations is more important than precise age data for individuals [24]. Hence, the proximity of assisted living facilities and schools to spill locations has been used in place of population age data in determining human health risk.

Analysis of model results indicates little correlation among model factors beyond those used in the calculation of more than one risk component (e.g., slope used in groundwater and soil resource calculations). These relationships do not directly affect component scores, but do have an effect on overall scores. For example, an increase in chemical solubility increases the scores of the human health, groundwater, and surface water components. As a result, solubility is the most influential factor in determining overall risk score, contributing 14.85% of its value (Table 3). This situation is consistent with the assertion of the Delphi panel about the importance of solubility in determining risk for more than one dimension of the model. Adsorption, on the other hand, is negatively correlated among soil resources and groundwater, resulting in a net contribution of only 0.58% to the overall risk score. Other than factors used in the calculation of multiple component scores, however, only soil surface conductivity and soil conductivity are strongly correlated (correlation coefficient = 0.78). These factors, which serve to represent the potential of a chemical to infiltrate the soil surface and to flow in the soil subsurface, respectively, were deemed to be individually important by the Delphi panel and were consequently retained in the model.

3. Data

The terrestrial chemical spill management system is designed for and based on widely available public data in order to increase the utility of the application and transferability. Chemical data is derived primarily from the Chemical Hazards Response Information System (CHRIS) database of the US Coast Guard [25]. A table was created containing physical data for 119 liquid organic chemicals selected from the CHRIS database based on completeness of entries. Necessary data that are not included in CHRIS, such as organic carbon partition coefficients, and data for any missing CHRIS values, were added to the table using information from the Hazardous Substance Data Bank of the National Library of Medicine [26]. Values for persistence were estimated using the EPI SUITE software of the EPA, version 3.12 [27] and appended for each table entry. Values for isolation and protective distances were added to each table entry from the emergency response guidebook [22].

Surface and soils data were taken from the Soil Survey Geographic (SSURGO) database of the National Resource Conservation Service (NRCS) [28]. This database contains detailed spatial, physical, and chemical features of soils for county-sized land areas. The spatial information contained within SSURGO

Table 3
Factor contributions to risk components (in %)

Factor	Human health	Groundwater	Surface water	Soil resources	Overall
Chemical solubility	9.31	12.54	23.78	0	14.85
Chemical toxicity	15.86	0	0	18.52	10.43
Proximity to surface water	0	0	29.27	0	9.76
Slope of soil surface	0	8.87	26.22	11.93	9.18
Chemical viscosity	0	0	20.73	0	6.91
Proximity to dense populations	15.86	0	0	0	6.06
Chemical-specific conductivity of soil	0	11.01	0	11.52	5.67
Chemical flammability	14.14	0	0	0	5.40
Chemical reactivity	13.10	0	0	0	5.01
Chemical persistence	0	0	0	15.23	3.59
Proximity to vulnerable populations	9.31	0	0	0	3.56
Depth to groundwater	0	13.15	0	0	3.53
Chemical-specific conductivity of vadose zone	0	12.23	0	0	3.28
Chemical-specific gravity	8.28	0	0	0	3.16
Bedrock/aquifer material	0	11.31	0	0	3.04
Pre-spill quality of soil resources	0	0	0	12.35	2.91
Soil surface chemical-specific conductivity	0	8.87	0	0	2.38
Chemical volatility	14.14	10.09	0	14.40	0.70
Chemical adsorption to sediments	0	11.93	0	16.05	0.58
Total	100.0	100.0	100.0	100.0	100.0

is used to create maps of soils, in which the smallest individual unit depicted is known as a “map unit”. While most of the soils data required by the spill management system is ready for use with the map component of SSURGO, data for conductivity and organic content are given only for individual soil horizons that make up components of map units. This data must, therefore, be aggregated to the map unit level in order to use it spatially. To this end, the effective vertical hydraulic conductivity of a map unit component was calculated as the harmonic mean of soil horizon values within that component. Similarly, organic carbon content was calculated as a thickness-weighted average of horizon values for each component. Conductivity and organic carbon content values were then assigned to map units based on the values for the dominant component of a unit, as outlined in NRCS guidance documents [29]. Values for index model variables, such as adsorption and chemical-specific conductivity, that depend on characteristics of the spilled chemical and the media through which it flows, are calculated through a series of queries at the time of execution of the system.

Other information contained in the spill management system includes spatial data for surface water and densely populated areas, both of which come from the Topologically Integrated Geographic Encoding and Referencing system (TIGER) of the US Census Bureau [30].

There are two areas of data required by the spill management system for which data is not widely available at the present: subsurface data below two meters and spatial data for vulnerable populations. While SSURGO contains data columns for environmental characteristics such as depth to bedrock and water table, it is primarily a soils database and does not contain any subsurface data below two meters. Unfortunately, no single resource with national coverage exists for any of the subsurface data that the spill management system requires, such as vadose zone conductivity, aquifer type, and depth to groundwater. There are, however, a growing number of states, such as Ohio and Nebraska, making these kinds of data available digitally. Publicly available data on locations of vulnerable populations, however, are less accessible in digital form. Some states, such as Alabama and Kentucky, have school addresses published online, which can be used for geocoding locations, though data for retirement facilities and assisted living quarters are more rare.

4. Case study application

4.1. Description

In order to test the functionality of the system, a case study was conducted in which theoretical spills of a range of chemicals were analyzed for Geauga County, in northeastern Ohio (Fig. 1). Geauga County was selected as the test county due to an abundance of available subsurface data and the variability of its soil types, water table depths, subsurface composition, and population density. Soil types in this county range from gravels to clays and include a small number of organic-rich mucks. Water table depth ranges from near-surface to greater than 23 m. The vadose zone of the county varies from gravels and sands to shales, silts, and clays, as does the composition of its aquifers. Population density varies from rural areas with less than 10 persons/km^2 to urban areas such as greater Cleveland.

Subsurface data for the case study area was collected from the online Geographic Information Management System [31] of the Ohio Department of Natural Resources. Locations of vulnerable populations were obtained from the Geauga County GIS Department through its website [32] and through communications with Department staff.

4.2. System operations

Upon selection of the chemical to be analyzed, the system uses a series of queries to calculate the two model parameters that are dependent on the interaction of the contaminant and the soil/subsurface environment: the distribution coefficient (K_{d}) and chemical-specific conductivity. In order to calculate K_{d}, the fraction of soil organic matter listed for each soil horizon in the SSURGO database is divided by 1.724 to yield fraction organic carbon (f_{oc}), as described by Hamaker and Thompson [33]. f_{oc} values for each horizon are aggregated using a thickness-weighted average to produce a single value for each SSURGO component. SSURGO values for hydraulic conductivity are converted to chemical-specific conductivity values for each soil horizon by substituting the density and viscosity of the contaminant for that of water in the following equation Fetter [34]:

$$K = K_i(\rho g/\mu) \tag{2}$$

where K is the conductivity, K_i is the intrinsic permeability of the soil, ρ is the density of the liquid, g is acceleration due to gravity, and μ is dynamic viscosity of the liquid. (The same procedure is used in calculating the chemical-specific conductivity of the vadose zone.) Horizon values are aggregated to the SSURGO component level by using the following equation from Tindall and Kunkel [35] for finding the effective vertical conductivity of layered media:

$$K_z = \frac{\sum_{j=1}^{m} d}{\sum_{j=1}^{m} \frac{d_j}{K_j}} \tag{3}$$

where K_z is the effective vertical conductivity, the summation of d in the numerator is the entire thickness of the soil, and the summation expression in the numerator represents the resistance to flow summed for each horizon, assuming perpendicular flow. Component values for chemical-specific conductivity and f_{oc} are then aggregated to the SSURGO map unit level using the dominant component technique previously discussed in section 3 above. Sorption coefficients are calculated for each map unit by multiplying the soil f_{oc} by the coefficient of contaminant soil sorption (K_{oc}), as described by Stephens [36]:

$$K_{\mathrm{d}} = K_{\mathrm{oc}} F_{\mathrm{oc}} \tag{4}$$

The calculated K_{d} and conductivity values are subsequently organized into a single table along with all other pertinent soils and chemical data. This table is then joined to the SSURGO GIS layer using unique map unit identifiers in the SSURGO database.

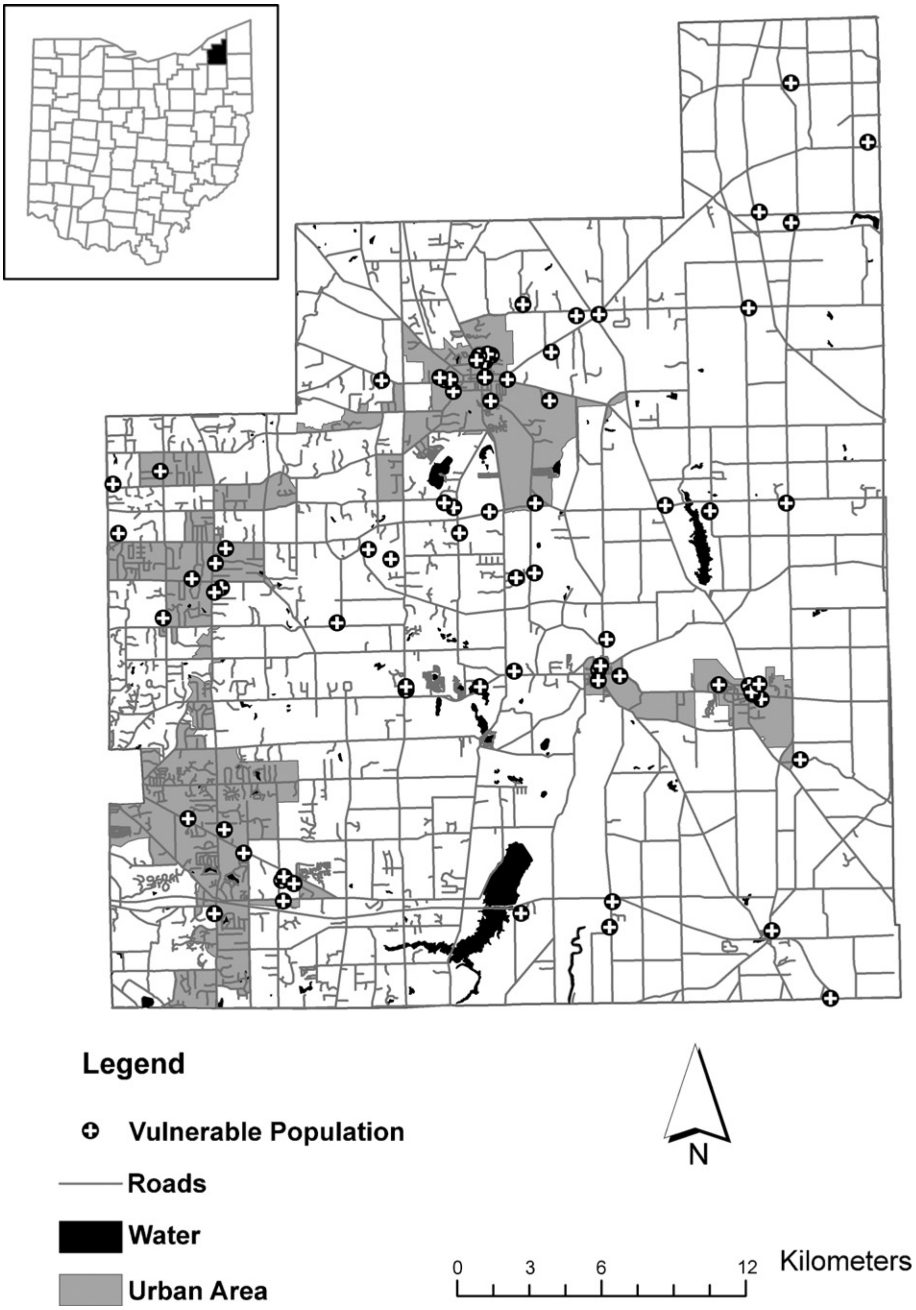

Fig. 1. Geauga County, Ohio.

The next step in the analysis involves using the GIS to create buffer areas using the surface water and population data layers. These buffers represent the ranges listed in Table 2 for the factors “proximity to surface water”, “proximity to vulnerable populations”, and “proximity to dense populations”. The buffer areas are then combined with soil and subsurface data into a single layer using spatial overlay (union) functions within the GIS. Next, ratings are assigned for each risk factor according to the scheme laid out in Table 2. An example of the risk factor values and their corresponding model ratings for a spill of malathion at a given location within the case study area is presented in Table 4. These rating values are then multiplied by the appropriate weight (Table 1) and summed to calculate index values for each risk component and the overall score according to Eq. (1) above.

4.3. System output

Analysis of the case study area indicates that the regions of highest relative risk in Geauga County tend to be associated with surface water and urban areas. This situation can be seen in the sample results presented in Fig. 2a and b, which display mapping output for ethylene dibromide and malathion, respectively, which will serve here as examples for the purpose of presenting sample system maps. Elevated risk in these regions

Table 4
Example values and ratings for risk index calculations of a malathion spill at a specific location in Geauga County, Ohio

Factor	Value	Ratings			
		Human health	Groundwater	Surface water	Soil resources
Toxicity (NFPA rating)	4	5	–	–	5
Reactivity (NFPA rating)	1	2	–	–	–
Flammability (NFPA rating)	0	1	–	–	–
Persistence (days)	30	–	–	–	3
Vapor pressure (Pa)	0.02346	1	5	–	5
Solubility (ppm)	140	3	3	3	–
Dynamic viscosity (Pa s)	0.04527	–	–	5	–
Specific gravity (unitless)	1.23	3	–	–	–
Soil surface chemical-specific conductivity (μm/s)	0.250848	–	2	–	–
Soil chemical-specific conductivity (μm/s)	0.025921	–	1	–	1
Vadose zone chemical-specific conductivity (μm/s)	4.103298	–	3	–	–
Adsorption (K_d)	0.13509	–	5	–	1
Soil resource quality (SSURGO farmland ratings)	"Farmland of local importance"	–	–	–	2
Slope of soil surface (%)	9	–	2.5	2.5	2.5
Bedrock/aquifer material	Massive sandstone	–	3	–	–
Depth to groundwater (m)	4.6–9	–	3.5	–	–
Proximity to surface water (km)	30–150	–	–	4	–
Proximity to densely populated areas (km)	0–0.03	5	–	–	–
Proximity to vulnerable populations (km)	>0.2	1	–	–	–

is a result of the weight placed on human health and surface water in calculating overall risk (see Table 1).

Human health risk component scoring is largely dependent upon the characteristics of the chemical being analyzed. Only two spatial factors, spill proximity to urban areas and proximity to vulnerable populations, contribute to the score. Thus, these two factors have a significant effect on the appearance of the health risk map, as can be seen in Fig. 3a and b. Malathion is more toxic and flammable than ethylene dibromide, resulting in higher health risk scores throughout the county. Ethylene dibromide, unlike malathion, is designated as a toxic inhalation hazard by the US Department of Transportation [22] and has been assigned isolation and protection zones for spill response. These zones are used to account for the air dispersion pathway between a spill and human receptors and appear as the regions of elevated health risk that outline the urban areas and assisted living facility locations of Geauga County as shown in Fig. 3a.

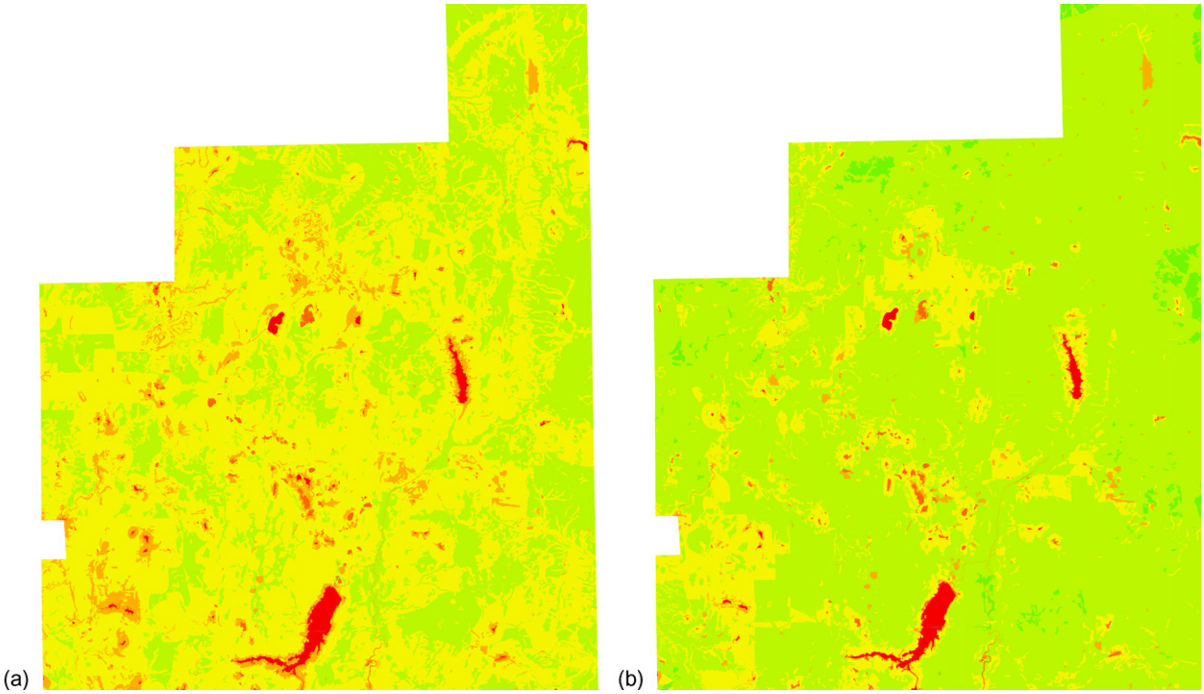

Fig. 2. Overall relative risk for Geauga County from the spill of ethylene dibromide (a) and malathion (b). (Color figures available online only.)

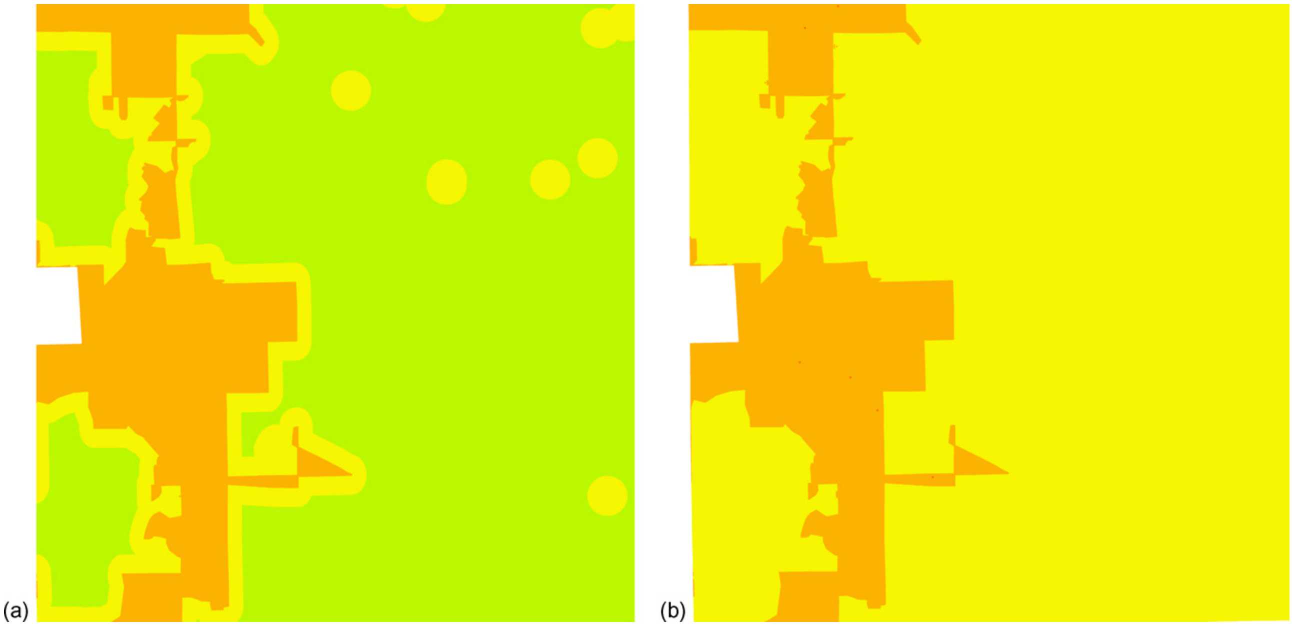

Fig. 3. Detail of the southwest corner of Geauga County indicating relative human health risk from the spill of (a) ethylene dibromide (b) and malathion. (Color figures available online only.)

Areas of highest relative risk depicted in the groundwater risk maps (Fig. 4a and b) are surface water locations and sites with less than 6% slope, a shallow water table (<1.5 m), and a vadose zone and aquifer both composed of sand and gravel. Malathion presents a smaller potential for migrating to groundwater because it is an order of magnitude less soluble than ethylene dibromide and has a much lower density to viscosity ratio, which significantly reduces its conductivity through the soil and subsurface.

Values for surface water risk (Fig. 5a and b) are highest in areas that are closest to water and have steep slopes. This condition reflects the high weighting values placed on these factors and the absence of additional spatially related factors to contribute to the surface water risk index. Ethylene dibromide is more capable of flowing to surface water than malathion, given its lower viscosity and higher solubility, which increases the levels of risk in Fig. 5a.

Of the two chemicals shown in the soil resources risk maps (Fig. 6a and b), malathion presents more of a threat, in general, to soil resources. This increased threat arises from the higher toxicity of malathion. Locations with the highest relative risk shown in the maps are areas where the slope is less than

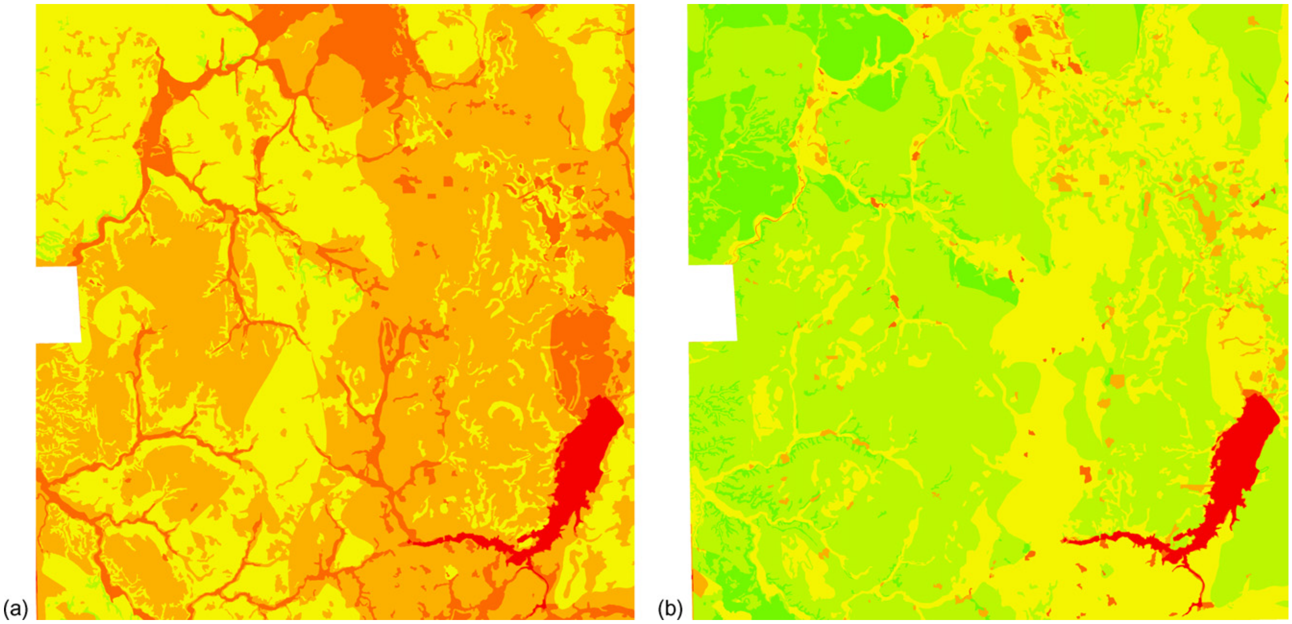

Fig. 4. Detail of the southwest corner of Geauga County indicating relative risk to groundwater from the spill of (a) ethylene dibromide and (b) malathion. (Color figures available online only.)

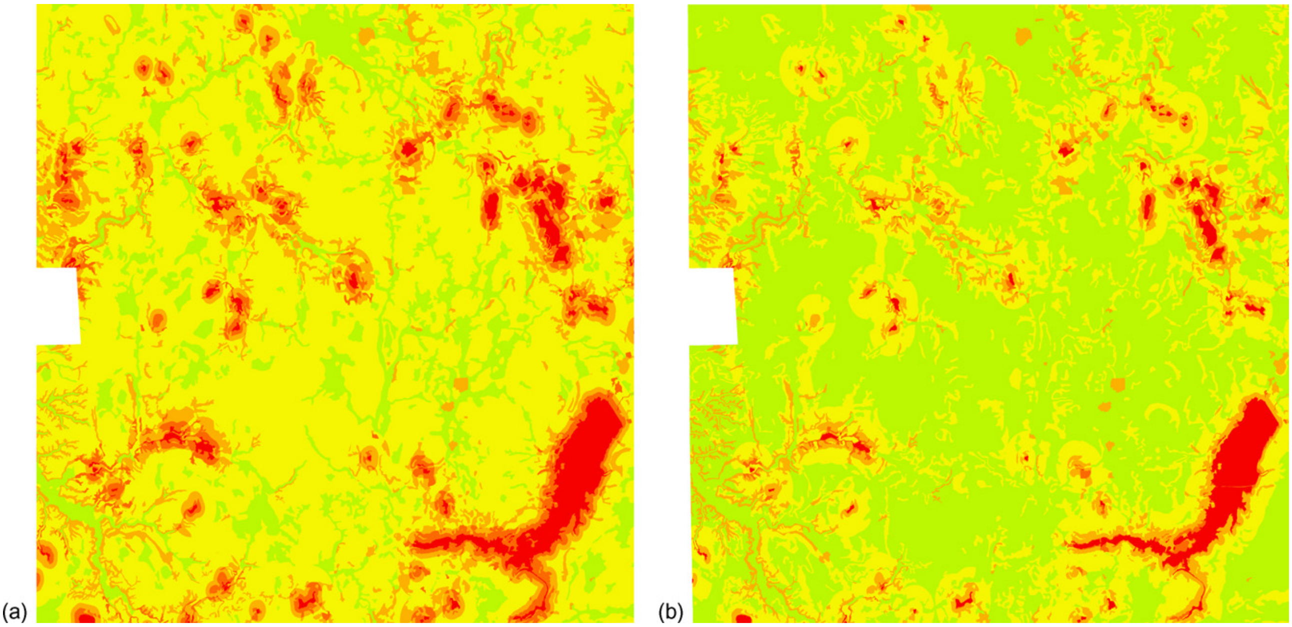

Fig. 5. Detail of the southwest corner of Geauga County indicating relative risk to surface water from the spill of (a) ethylene dibromide and (b) malathion. (Color figures available online only.)

6% and are important farmland or have high levels of organic material in the soil, increasing adsorption. Other areas that are depicted as being particularly high risk to soil resources may be those with missing soil texture data. In the case of such missing values, textures are conservatively assumed to present the highest risk for that factor. For this reason, areas of surface water in the soils maps often show high levels of relative risk.

System output for the case study area was used to test the sensitivity of model weighting values. To this end, overall risk indices were recalculated for the randomly selected subset of chemicals used to define the color-coding scheme (see Section 2.1). In these calculations, the weighting value placed on each component in the overall risk calculation (human health, groundwater, surface water, and soil resources) was varied individually by a decrease 10% from the default value, as determined by the Delphi survey. A second round of calculations was then carried out in the same manner with individual increases of 10% in each of the default weighting values of the components. The model output resulting from these calculations differed from the original output values by less than 1%, indicating a fairly robust model.

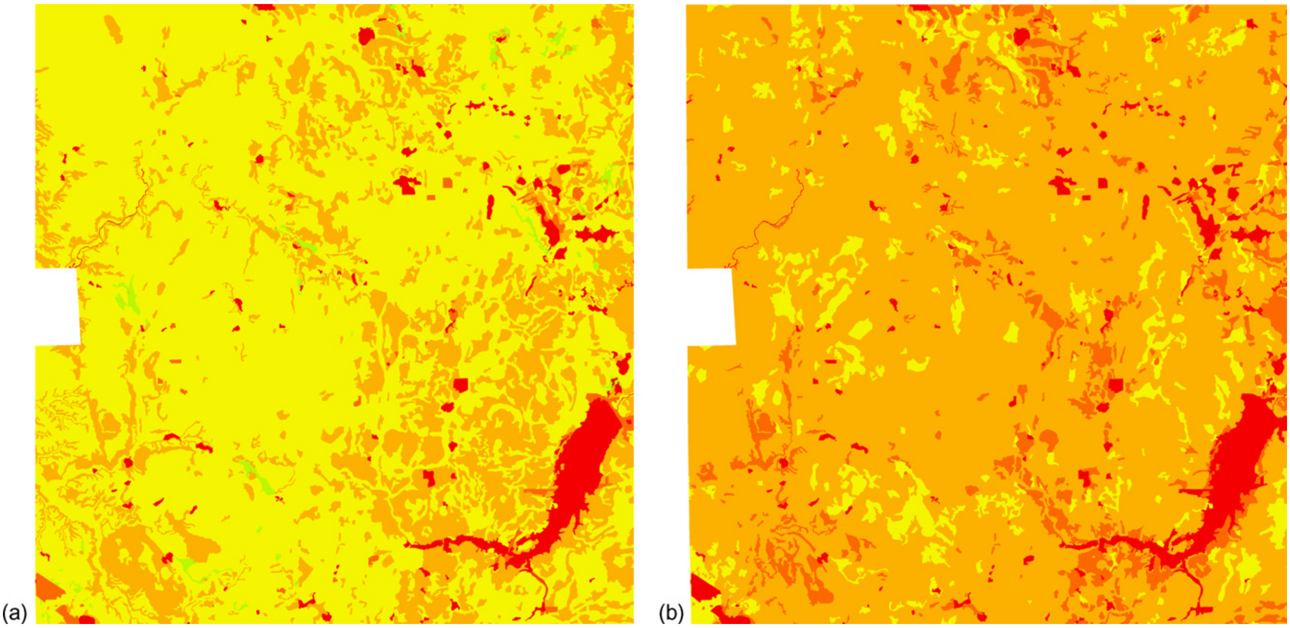

Fig. 6. Detail of the southwest corner of Geauga County indicating relative risk to soil resources from the spill of (a) ethylene dibromide and (b) malathion. (Color figures available online only.)

4.4. Implications for planning and response

The system output can serve as a valuable tool for planning for and responding to a chemical spill. When used for planning purposes, this tool can provide useful screening-level information, helping to focus more detailed inquiries requiring greater expenditure of resources. Some areas of applicability include industrial zoning, homeland security, hazardous material transportation routing, environmental regulatory compliance and enforcement, and response planning. For example, the maps presented above would be helpful in assisting local governments in Geauga County to site new chemical facilities. The lowest overall risk locations for such installations are shown to be primarily along the eastern border of the county for both chemicals, though the malathion map shows a greater area of low risk throughout the county. While these areas present low overall risk for both of the chemicals discussed, groundwater and soil risks from ethylene dibromide and health risks from malathion in the area are moderate to moderately high. Because these kinds of risk tradeoffs play a major role in most planning decisions, the system user has the ability to adjust the risk model weighting scheme from the default values to give greater priority to different risk components. For instance, community planners in a region whose economy is moving out of the agricultural sector might choose to decrease the weight placed on soil resources and increase that of human health in the overall risk calculation. Similarly, a community with a smaller number of response personnel available for rescue and evacuation procedures might increase the weight given to proximity to densely populated areas or vulnerable populations when calculating health risk scores.

System maps can also be used to support decisions regarding homeland security planning. Increased security measures can

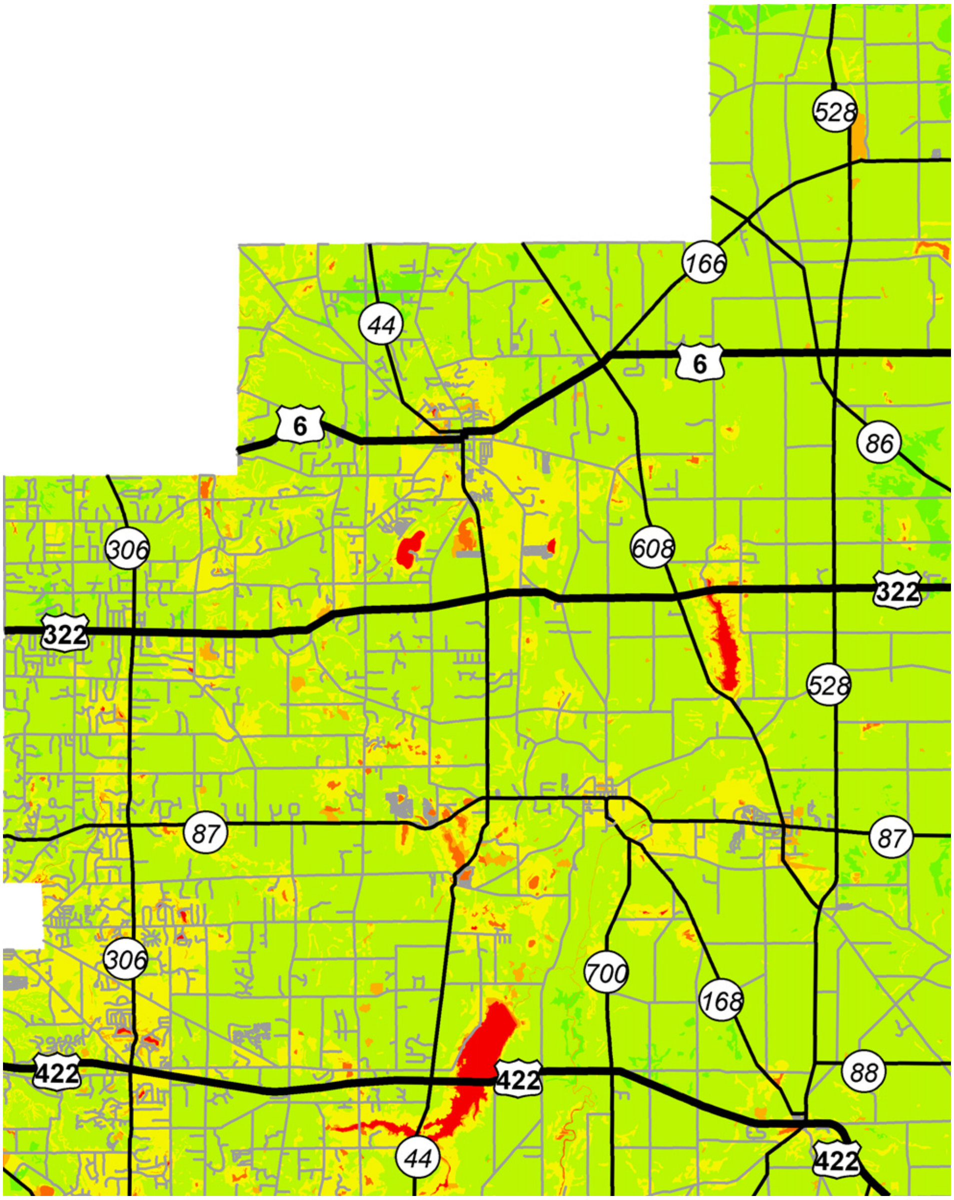

Fig. 7. Example of transportation information paired with system overall relative risk map output for the spill of malathion. (Color figures available online only.)

be focused on areas where risks are high to the population or vital resources, such as the LaDue Reservoir in central southern Geauga County (Figs. 1–2 and 4–6). Furthermore, the system can be used to determine which chemicals should be considered when planning for security threats at given locations. For example, an intentional release of malathion outside of urban areas and surface water locations in Geauga County would present a low overall risk (Fig. 2). In such areas, resources dedicated to detecting or mitigating accidental or intentional spills should be focused less on malathion and more on extremely hazardous chemicals such as acrolien that could present community-wide risks from remote locations.

Using system maps in conjunction with data layers depicting local infrastructure within a GIS can enhance the utility of the system. By overlaying transportation network information on the risk maps, government authorities would be able to make more informed decisions regarding the planning of new roadways or delineating routes for shipping hazardous materials. For example, in Fig. 7 it can be seen that shipments of malathion moving north or south through Geauga County could be routed along state highway 528 or a combination of 528 and 608 or 86 to minimize the risks from a spill. These routes would avoid high-risk areas associated with the LaDue Reservoir and urban areas along highways 44 and 306.

Similarly, using system maps with layers depicting the locations of industrial sites would assist local, state, and federal government agencies in focusing regulatory monitoring. Industrial sites in areas of higher risk could be monitored with greater frequency than those in low risk areas. Such focused monitoring would decrease the likelihood of an industrial spill of ethylene dibromide, for example, in the high risk urban areas, surface water locations, and areas with highly permeable geology depicted in Fig. 4a. Businesses could also employ this approach to facilitate the allocation of resources among individual locations so that plants situated in the highest risk areas are provided with more funding for risk management.

The system also provides useful information for response planners, first responders, and environmental response personnel. System maps can be used to prioritize response actions during major spill events so that areas facing higher risks are responded to first. When responding to spills of groundwater contaminants in Geauga County, for example, the highest priority for response would be placed on surface waters and the areas with low slope and shallow gravelly aquifers, such as those delineated in Fig. 4. The system also provides responders with a quick reference for chemical data, such as NFPA ratings and isolation distances, and can even be linked to chemical information response manuals and databases such as the CHRIS manual [25], the emergency response guidebook [22], or the NIOSH Pocket Guide [37]. By housing both chemical and local environmental data, the system also serves as a unique reference for information useful to environmental responders. This information includes not only data on the spilled chemical and local soils, but also information such as partition coefficients and chemical-specific conductivity for soil units that combines both types of data. Such information can be used to provide initial estimates of pollutant transport to prioritize response effort.

5. Conclusions

The terrestrial chemical spill risk management system presented here is a screening tool for supporting environmental decisions by predicting relative levels of risk from a chemical spill. This system analyzes risks to human health, groundwater, surface water, and soil resources to yield an overall risk score, unlike previous systems that have focused on individual components (e.g., DRASTIC). The system model accounts for characteristics of the spilled chemical and the local environment as well as parameters that are determined by interaction between the two. Previous environmental index systems have often required the user to collect data from the field or from sources that may be difficult to access, such as localized subsurface surveys. The data that supports this model is housed within the system, so that it requires only the name of the chemical to be analyzed from the user, which greatly decreases analysis time and resources. This data is drawn almost exclusively from easily accessible, publicly available data, such as the SSURGO database, to facilitate transferability of the model and analysis of multiple locations. Model output is displayed using easy to understand, color coded maps that enable informed decisions from managers and policy makers who may possess little technical background.

There are several opportunities for furthering system development and/or expanding the scope of the system beyond that of a screening-level tool. The current system, which includes data for 119 organic chemicals, could be improved by expanding the database to include a more comprehensive list of organic chemicals or by including other types of chemicals, such as solutions, mixtures, and metals. While it is commonly assumed that adsorption (immobility) of organic chemicals is primarily attributable to the organic component of sediments [38], increased detail in estimating chemical mobility could also be useful, such as including soil pH and ion exchange capacity in sorption calculations. As resources for environmental data become more complete and widely available, system subsurface data can be standardized for improved transferability and missing values in the system database can be updated. Finally, the system could be linked to outside information, such as real-time weather data, or models that would allow the user to visualize the movement of the contaminant, such as CAMEO [39] for air pollutants, or MODFLOW [40] for subsurface and groundwater.

Acknowledgements

The authors gratefully acknowledge James Clarke, Mark Cohen, and Eugene LeBoeuf for comments and suggestions that helped to improve this research.

References

[1] National Response Center (NRC), Incident Type per Year, Online: http://www.nrc.uscg.mil/stats.html, 2006.

[2] A.E. Smithson, Observations and conclusions, in: A.E. Smithson, L.-A. Levy (Eds.), Ataxia: The Chemical and Biological Terrorist Threat and the US Response, The Henry L. Stimson Center, Washington, DC, 2000, pp. 281–304 (Chapter 7).

[3] Centers for Disease Control and Prevention, Public health consequences from hazardous substances acutely released during rail transit, South Carolina, 2005; selected states, 1999–2004, Morb. Mortal. Wkly. Rep. 54 (2005) 64–67.

[4] M.J. Focazio, T.E. Reilly, M.G. Rupert, D.R. Helsel, Assessing Groundwater Vulnerability to Contamination: Providing Scientifically Defensible Information for Decision Makers, US Geological Survey Circular 1224, US Geological Survey, Reston, Virginia, 2002.

[5] L.R. Silka, T.L. Swearingen, A Manual for Evaluating Contamination Potential of Surface Impoundments (EPA 570/9-78-003), U.S. Environmental Protection Agency, Office of Drinking Water, Washington, DC, 1978.

[6] H.E. LeGrand, A Standardized System For Evaluating Waste-Disposal Sites, National Well Water Association, Worthington, Ohio, 1983.

[7] M. Civita, M. De Maio, Valutazione e cartografia automatica della vulnerabilità degli acquiferi all'inquinamento con il sistema parametrico SINTACS R5, Pitagora Editrice, Bologna, Italy, 2000.

[8] A. Sampaolo, R. Binetti, Improvement of a practical method for priority selection and risk assessment among existing chemicals, Regul. Toxicol. Pharm. 10 (1989) 183–195.

[9] Å. Scott, Environment-accident index: validation of a model, J. Hazard. Mater. 61 (1998) 305–312.

[10] S.L. Cutter, B.J. Boruff, W.L. Shirley, Social vulnerability to environmental hazards, Soc. Sci. Q. 83 (2003) 242–261.

[11] D.L. Bryant, M.D. Abkowitz, Estimation of terrestrial chemical spill risk factors using a modified Delphi approach, J. Environ. Manage. (2006), doi:10.1016/j.jenvman.2006.08.006.

[12] National Fire Protection Association, Standard for the Identification of the Fire Hazards of Materials for Emergency Response, National Fire Protection Association, Quincy, Massachusetts, 2001.

[13] E.M. Snyder, S.A. Snyder, J.P. Giesy, S.A. Blonde, G.K. Hurlburt, C.L. Summer, R.R. Mitchell, D.M. Bush, SCRAM: a scoring and ranking system for persistent, bioaccumulative, and toxic substances for the North American Great Lakes, Environ. Sci. Pollut. R. 7 (2000) 1–11.

[14] University of Arizona Risk Management and Safety, Vapor Pressure, Online: http://fp.arizona.edu/riskmgmt/vapor_pressure.htm, 2006.

[15] USEPA, Pollution Prevention (P2) Framework, Online: http://www.epa.gov/oppt/p2framework/docs/pchem.htm, 2002.

[16] A. Sampaolo, R. Binetti, Elaboration of a practical method for priority selection and risk assessment among existing chemicals, Regul. Toxicol. Pharm. 6 (1986) 129–154.

[17] US Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Handbook, Online: http://soils.usda.gov/technical/handbook/, 2005.

[18] F. Whitford, J. Wolt, H. Nelson, M. Barrett, S. Brichford, R. Turco, Pesticides and water quality, Perdue Pesticide Publication No. 35, Purdue University Cooperative Extension Service, West Lafayette, Indiana, 2001.

[19] US Department of Agriculture, National Resource Conservation Service, Prime and other important farmlands, SSURGO Template Database, Version 32, 2005.

[20] L. Aller, T. Bennett, J.H. Lehr, R.J. Petty, G. Hackett, DRASTIC: A Standardized System for Evaluating Groundwater Pollution Potential Using Hydrogeologic Settings (EPA/600/2-87/035), R.S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, Oklahoma, 1987.

[21] USEPA, 40 CFR Part 300 Hazard Ranking System; Final Rule, Fed. Regist. 55 (1990) 51532–51667.

[22] US Department of Transportation, Transport Canada, Secretariat of Transport and Communications of Mexico, Emergency Response Guidebook, US Department of Transportation, Washington, DC, 2004.

[23] J.L. Arnold, Disaster medicine in the 21st century: future hazards, vulnerabilities, and risk, Prehospital Disaster Med. 7 (2002) 3–11.

[24] B.H. Morrow, Identifying and mapping community vulnerability, Disasters 23 (1999) 1–18.

[25] US Coast Guard, Chemical Hazard Response Information System Manual, Online: http://www.chrismanual.com, 2002.

[26] National Library of Medicine, TOXNET, Online: http://toxnet.nlm.nih.gov/.

[27] USEPA, EPI SUITE Version 3.12, Online: http://www.epa.gov/oppt/exposure/docs/episuitedl.htm, 2004.

[28] US Department of Agriculture, National Resource Conservation Service, Soil Survey Geographic (SSURGO) Data Base Data Use Information, Miscellaneous Publication Number 1527, US Department of Agriculture, Washington, DC, 1995.

[29] US Department of Agriculture, National Resource Conservation Service, SSURGO Data Packaging and Use, Online: http://soildatamart.nrcs.usda.gov/documents/SSURGODataPackagingandUse.pdf, 2005.

[30] US Census Bureau, Geography Division, TIGER, TIGER/Line and TIGER-Related Products, Online: http://www.census.gov/geo/www/tiger/index.html, 2002.

[31] Ohio Department of Natural Resources, GIMS Program Introduction and Index, Online: http://www.dnr.state.oh.us/gims/, 2000.

[32] Geauga County GIS Department, Geauga County GIS Data Downloads, Online: http://www.auditor.co.geauga.oh.us/gis/downloads/, 2003.

[33] J.W. Hamaker, J.M. Thompson, in: C.A.I. Goring, J.W. Hamaker (Eds.), Organic Chemicals in the Soil Environment, vol. 1, Marcel Dekker, New York, 1972, pp. 49–143 (Chapter 2).

[34] C.W. Fetter, Applied Hydrogeology, fourth ed., Prentice Hall, Upper Saddle River, New Jersey, 2001.

[35] J.A. Tindall, J.R. Kunkel, Unsaturated Zone Hydrology for Scientists and Engineers, Prentice Hall, Upper Saddle River, New Jersey, 1999.

[36] D.B. Stephens, Vadose Zone Hydrology, Lewis Publishers, New York, 1995.

[37] National Institute for Occupational Safety and Health, NIOSH Pocket Guide to Chemical Hazards, US Government Printing Office, Washington, DC, 2005.

[38] K.M. Krupa, D.I. Kaplan, G. Whelan, R.J. Serne, S.V. Mattigod, Understanding Variation in Partition, K_d, Values, vol. 1, USEPA, Washington, DC, 1999 (EPA402-R-99-004A).

[39] USEPA, NOAA, CAMEO User's Manual Online: http://www.epa.gov/ceppo/cameo/pubs/CAMEOManual.pdf, 2004.

[40] A.W. Harbaugh, MODFLOW-2005, The U.S. Geological Survey Modular Groundwater Model—the Groundwater Flow Process, US Geological Survey Techniques and Methods, Us Geological Survey, Reston Virginia 2005.