CREATION OF A SYSTEM FOR ASSESSING AND COMMUNICATING THE

RISKS ASSOCIATED WITH TERRESTRIAL CHEMICAL SPILLS

By

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For Layne
and our family

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CHAPTER I

INTRODUCTION

Thousands of chemical spills occur each year within the United States (NRC, 2005). With massive amounts of these materials stored at facilities and transported throughout the country daily, there is a constant threat of spills with a potentially significant impact to the environment. Managing these events before and during their occurrence is imperative to the protection of society and its natural resources. Recent advances in information technology and increased availability of environmental and chemical data have made the potential for effective management of chemical spills greater than ever before. With the continued development of geographic information systems (GIS), large amounts of data can now be stored, manipulated, and displayed spatially, facilitating assessment and communication of environmental risks, which are inherently spatial in nature (Lantzy, 1998).

Various government agencies charged with environmental management responsibilities, such as the Natural Resource Conservation Service, have recognized the value of GIS and are now publishing environmental data for use in these tools. Furthermore, web-based distribution of these resources has made them vastly more accessible than earlier paper-based versions of similar data. The availability of these types of resources make possible the formulation of a management system that can be used to assess and communicate the risk from terrestrial (land-based) chemical spills so that these events might be better planned for and mitigated should they occur.

A GIS-based application for analyzing and communicating the risks associated with terrestrial spills of specific chemicals at a local, state, regional, or national scale would be highly useful for many areas of industry, government, and the public interest. Such a system would facilitate decision making in areas such as hazardous material transportation routing, industrial zoning, spill response, and environmental and natural resource security planning. To be effective, this system must require very little of the user in terms of data and scientific or computing knowledge to ensure that managers and policy makers, who may not have access to these resources, can obtain useful results. Methods for achieving such accessibility include storing needed data within the system, concealing system components behind a single user interface, and using uncomplicated models for ease of interpretation and customization. Likewise, system output must be easy to understand and promote quick decision-making to be useful in spill response situations.

This document describes the design, development, and implications of a terrestrial chemical spill risk management system. The body of the manuscript is arranged into three separate manuscripts formatted as they would be for refereed journal publication consideration. The first paper (Chaper 2) describes previous GIS-based environmental risk management studies and describes the available resources and design specifications required for the spill management system, with a particular emphasis on groundwater vulnerability. The second paper (Chapter 3) builds on the ideals set forth in the preceding paper and presents the use of expert judgment in formulating a terrestrial chemical risk model for various environmental receptors. The third paper (Chapter 4) presents a case study application in which the functionality and applicability of the system is demonstrated so as to provide “proof of concept”. Finally, Chapter 5 contains an overall summary and conclusions of the dissertation research.

CHAPTER II

A CONCEPTUAL APPROACH TO ASSESSING THE RISKS OF TERRESTRIAL CHEMICAL SPILLS USING GIS

Introduction

Environmental risk management (ERM) is a process by which risks are systematically identified, assessed, and reduced to minimize their effects on human health, ecology, and societal well-being. This process requires tools that allow people to evaluate, prioritize, and communicate risks and risk reduction strategies. Furthermore, the inherent geographical component of all environmental risks calls for an instrument capable of relating the locations of hazards and receptors (human or environmental) to make managing these risks possible (Lantzy et al., 1998). To this end, geographic information systems (GIS) have been employed in a variety of roles in ERM. GIS facilitate the organization, manipulation, and display of large amounts of spatially-related data essential to the management of environmental problems. Examples of common uses of this technology in ERM include simple mapping of risk or impact areas, the spatial analysis of environmental and hazard data, and the coordination of a GIS with various other software, such as groundwater models.

GIS-based terrestrial ERM research has focused primarily on smaller, regional-scale land areas and can be grouped into two broad categories: soil contamination and groundwater pollution. Soil contamination studies have focused largely on risks associated with the presence of heavy metals in soils and various hazards associated with agricultural production, including pollutants in soils and nitrate leaching. The majority of groundwater GIS research has centered on non-point source pollution threats and the vulnerability of groundwater to potential pollutants. Because soil and groundwater are intimately connected, contaminants affecting one will often affect the other. As such, research in these two areas has at times overlapped. To date, however, little GIS-based research has been conducted on the risks associated with isolated point-source events introducing chemicals into soils and the effect these incidents could have on the underlying groundwater.

Terrestrial chemical spills present a unique problem in that the spilled pollutants have the potential to contaminate not only the soils in which they are introduced, but also to affect underlying groundwater. The behavior of these pollutants in the subsurface depends upon the various properties of the pollutant itself and the land on which it is spilled. The vast amount of data needed to characterize common hazardous chemicals and the spatially distributed nature of the hydraulic and chemical properties of soils and the subsurface make the use of GIS essential in this kind of ERM.

An example of the application of this technology would be the linking of a GIS with chemical transportation or risk models to support analyses of a spill at a given location. This would require modeling the spatial interaction of differing chemical and soil attributes for the site in question. Having this capability would allow for more informed ERM decisions in a variety of areas including the planning of hazardous chemical transportation routes and systems, the location of storage or use areas for these chemicals, and emergency response and contingency planning for spills, whether they be caused by natural, accidental, or intentional means.

The objective of this discussion is to outline the issues associated with creating a GIS-based risk assessment system for terrestrial chemical spills with a particular emphasis on groundwater vulnerability. It begins with a brief overview of previous research areas and methods regarding GIS-based ERM systems. The components needed to formulate such a tool for isolated terrestrial chemical spills are then presented. This is followed by a review of databases and models of particular interest in creating a location-specific spill risk management system for broad geographical areas, including recommendations on their use.

Literature Review

The majority of research in GIS-based terrestrial risk studies deals with pollutants such as metals and PCBs that tend to be in low concentrations, spread over a wide area, and accumulate over a longer period of time than chemicals from an isolated spill event. For example, Korre et al. (2002) used GIS in quantifying the risk to humans associated with elevated amounts of lead in soils over a 120 km^2 area. Other GIS-based research in this area includes studies of heavy metals by Facchinelli et al. (2001), ecological risk due to pollution of floodplain sediments by Kooistra et al. (2001), human risk from lead in soils by Tristan et al. (2000) and Korre (1999a,b), and human exposure to PCBs in soil by Hwang et al. (1999).

In contrast to the aforementioned work, Hudak et al. (1999) focused primarily on point source pollution. The authors used GIS to assess the hazard posed to soil and groundwater by leaking subsurface storage tanks to aid in underground tank planning. Tank locations were compared with spatial variability in soil shrink-swell capacity and corrosiveness to identify tanks vulnerable to leakage. Soil permeability was then used as the sole factor for determining the hazard posed to soil and groundwater by leaking tanks. This study is limited by not considering factors beyond permeability in estimating mobility risks and by not accounting for properties of the hazardous material in question. Unfortunately, beyond this paper, there is very little literature dealing with GIS and spill-type incidents in soils.

Groundwater Vulnerability Studies

While there is a lack of GIS-based research on terrestrial spills, for well over a decade GIS has been used in studies assessing groundwater vulnerability. This research has begun to culminate into a significant body of literature. Studies in this area tend to focus on the threat to groundwater from agricultural and non-point source pollutants, such as pesticide and nitrate contamination, and often combine GIS with pre-existing models such as the DRASTIC model for groundwater vulnerability assessment. A brief review of selected literature from such studies is presented below.

In 1990, Baker and Panciera (1990) describe the use of the Rhode Island GIS (RIGIS) by the Rhode Island Department of Environmental Management (RIDEM) to create maps of groundwater resources and threats. This effort was an attempt to provide groundwater information to local governments to help them implement effective protection strategies. REGIS was used to organize, overlay, and present data that had previously been disparate and at different scales. These data included geology, aquifers, recharge zones, water table contours, transmissivity, saturated thickness, supply wells, and both known and potential sources of groundwater contamination. REGIS output was then transferred to maps and Mylar overlays for distribution to local officials at regional workshops, as there were no means for file sharing or distributing electronic copies to the public. Since these maps and overlays are snapshots of the studied area at a particular moment in time, unlike the virtual maps in GIS from which they were generated, this created the potential for circulating out of date information. Furthermore, this system does not consider variations in risk associated with individual hazardous substances, accounting only for geologic and geographic variables.

A 1996 study by Tim et al. (1996) calls attention to the necessity of using GIS in groundwater vulnerability studies, stating that, without such a tool, computer simulation models are severely limited. These models are poorly suited to managing the huge amount of data needed for an accurate representation of real life processes and to account for spatial differences within these data. The authors coupled a GIS with three separate groundwater pollution potential models to create an interactive model for the assessment of groundwater vulnerability to pesticides. The user-friendly interface and map outputs described in this paper allow users to quickly evaluate pesticide pollution potential and facilitate ERM decisions. However, this system requires the user to find and manipulate all of the landscape data needed to perform the analysis. Also, the system is tailored for analysis of a known substance, namely pesticides, at a known location. This limitation means that it is not well suited to risk analysis for a range of chemicals or for possible spills over a wide geographical area. Furthermore, the system only accounts for a very limited set of chemical variables, neglecting potentially important characteristics such as volatility. Moreover, soil factors such as hydraulic conductivity must be derived from other difficult to determine variables, such as the mass of the chemical exiting the vadose zone.

Like Tim et al. (1996), Viex et al. (1998) developed an interface for a coupled GIS and groundwater model for aiding management decisions. The system allows users to make informed management decisions about wellhead protection areas by identifying possible contamination sources and delineates areas for future wellhead development. This study took into account land use (e.g., agricultural sites, etc.) when identifying potential pollution sources, as well as the locations of roads and railroads, and known illegal dumps and spills. One drawback to this model, however, is that it requires the user to know many input parameters, such as soil porosity and transmissivity, rather than relying on a database of values for the given area. Also, characteristics of possible pollutants are not factored into the risk analysis in this system.

Civita and De Maio (2004) developed a groundwater vulnerability assessment model and coupled it with a GIS to produce vulnerability maps for a county-sized area of northern Italy. The model produced by the authors, entitled SINTACS, categorizes land areas according to relative levels for groundwater vulnerability based on a subjective index methodology. This model was designed specifically for use in Italian environments and with data that is readily accessible in Italy (Civita and De Maio, 2000). The authors allude to the importance of the interaction between chemicals and the subsurface in determining contaminant mobility, but use subsurface characteristics independently as a proxy for these parameters (e.g., fraction organic content for distribution coefficient (K_d)). Thus, SINTACS, like many of the aforementioned studies, does not account for specific chemical characteristics in determining a pollutant's ability to migrate to groundwater.

DRASTIC Model Studies

A large portion of the existing literature regarding the assessment of groundwater pollution potential has involved the use of the DRASTIC model. This model was developed by the National Water Well Association under agreement with the US Environmental Protection Agency (USEPA), and is a tool for evaluating groundwater vulnerability for hydrogeologic settings within the United States. DRASTIC, like SINTACS, uses a subjective index methodology to rate aquifer susceptibility to pollutants (Focazio et al., 2000) and is based on earlier resource vulnerability models, such as those reported by LeGrand (1983) and Dee et al. (1973), among others. The acronym that serves as the name for this model is derived from the seven factors it employs to assess groundwater pollution potential: depth to groundwater (D), net recharge (R), aquifer media (A), soil media (S), topography (slope) (T), impact of the vadose zone (I), and hydraulic conductivity of the aquifer (C). A ranking for each of these factors is found for locations within the given hydrogeologic setting. The factor can then be weighted according to the importance of that factor within the given setting. A relative pollution potential index number is then computed using the following equation:

$$\text{Pollution potential} = D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w \qquad (1)$$

where r is the rating of the factor and w is the weight (Evans and Myers, 1990).

Numerous authors have used GIS in combination with DRASTIC to produce groundwater vulnerability maps for specific locations. One of the earliest examples of this type of research was conducted by Evans and Myers in 1990. This study followed the step-by-step approach to using the DRASTIC model as outlined by Aller et al. (1987) for a 100-square mile area in southeastern Delaware. In this study, Evans and Myers account for hazards posed by point source pollutants by modifying the DRASTIC methodology to account for human activity throughout the county. However, this study did not take into consideration the possibility of spills at locations other than industrial sites, such as points along transportation systems (e.g., railroads, highways, pipelines, waterways, etc.). Attributes of individual pollutants were also not taken into account when assessing the ground water pollution potential of the area.

Subsequent authors have continued to make revisions to the framework of the DRASTIC model for use with a GIS. Research performed by Secunda et al. (1998) incorporates land use categories in defining ground water vulnerability. The authors suggest that extensive, long-term land use can alter soil properties. In this study, the authors specifically considered the spilling of a possible pollutant (oil) as a serious potential hazard, but characteristics of individual pollutants were not considered. Rupert (1999) suggests improving DRASTIC by coupling the model with a calibration scheme using measured pollutant concentrations from local aquifers. While this method shows increased accuracy in vulnerability prediction for the study area, it requires a considerable investment of time and resources beyond the standard screening-level DRASTIC scoring. Merchant (1994) argues that the DRASTIC methodology may be improved by reducing the number of variables (i.e., GIS layers) used. He suggests that the potential for error increases with an increasing number of data layers, each of which will contain their own inaccuracies.

Thirumalaivasan et al. (2003) developed a software package that uses the Analytic Hierarchy Process (AHP) to derive weights and ratings for DRASTIC model parameters. This tool is designed to take some of the uncertainty out of the DRASTIC model. A user-friendly interface allows the user to enter the criteria he or she wishes to use along with their relative importance. The software then calculates ranges and weights for the parameters and stores them as a database file. These output data are then joined to user-provided geographic data within a GIS to produce ground water vulnerability index maps.

The Thirumalaivasan et al. (2003) study, and DRASTIC-based research in general, determine groundwater vulnerability to a generalized pollutant without regard to specific contaminants. However, accounting for variations in specific chemicals' characteristics, such as viscosity, half-life, toxicity, etc., would greatly increase the value of such a tool by portraying a more accurate representation of the risk associated with a given spill. For example, the DRASTIC methodology assumes the mobility of a given contaminant to be equal to that of water (Aller et al., 1987), which would overestimate the risk of a less dense and more viscous pollutant. Another example is the spilling of an extremely volatile chemical. This situation would likely pose less of a threat to groundwater than predicted by a DRASTIC map because the pollutant may volatilize before contacting groundwater.

Despite the range of work that has been conducted on groundwater vulnerability using GIS, there still exists a need for a system that would facilitate ERM decisions dealing with specific chemicals at any given location over a broad geographical area. Most of the work done to date has focused on producing vulnerability maps of relatively small geographical areas. However, in making management decisions in areas such as the transportation of chemicals, location of chemical storage areas, or planning for specific national or environmental security threats, an interactive system with the ability to analyze multi-county, state, or nation-sized regions would be of greater use. This system would give a comprehensive view of the risks associated with one or more specific pollutants at a particular location or at a range of locations. It would be beneficial to a wide range of users including: local, state, and national government agencies, manufacturing and distribution businesses, and public interest groups.

Components of a New Application

A new GIS-based application for assessing the risks associated with terrestrial chemical spills should be user-friendly and require minimal user input in order to facilitate decision making by professionals without advanced training in chemistry, earth sciences, or GIS. These requirements make a “modeling-within” GIS system the preferable design for this particular application (see Figure 1). This type of system would allow users to access the functionality of the risk model and the GIS through a single user interface, as opposed to a “linked-model” approach, which requires the user to access the model and the GIS through separate interfaces (Poiani and Bedford, 1995). The interface in this instance would consist of an entry screen that would accept input from the user, such as the location of a spill and the chemical of concern. Stored, preexisting data on the characteristics of the environment of the location and the chemical would then be fed

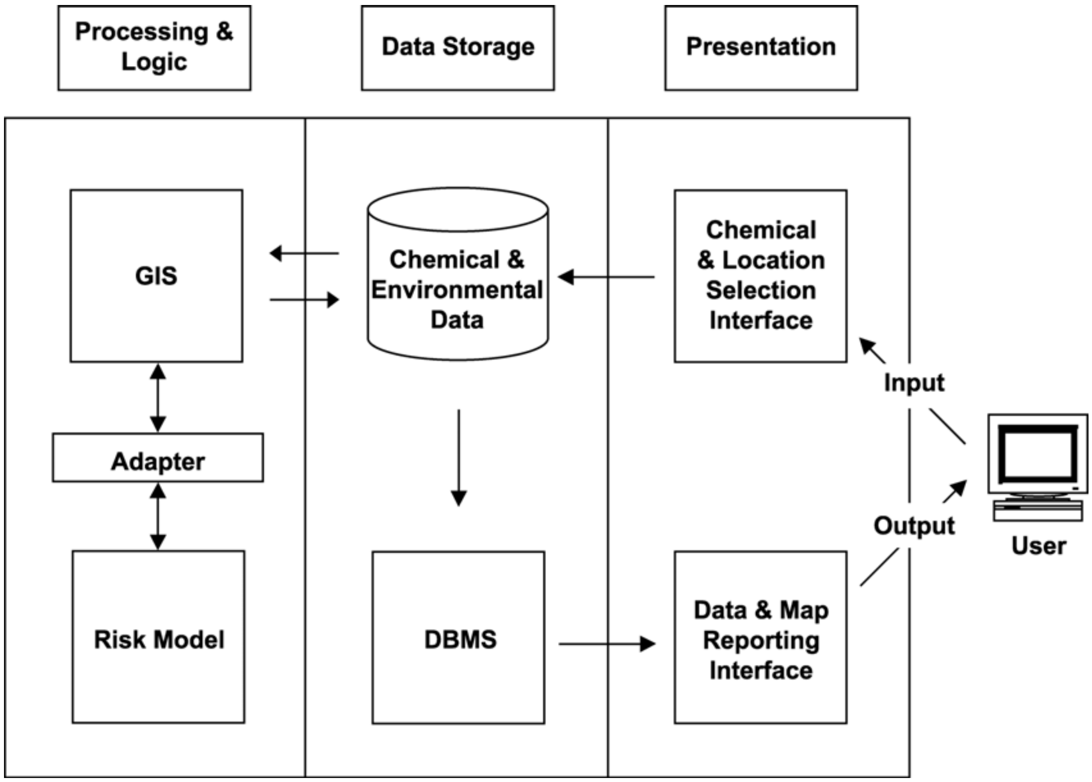

Figure 1 Conceptual design of a risk assessment system for terrestrial chemical spills.

into a processing system, consisting of a GIS and a risk model. This system would produce data on the relative risks associated with the spill of the chemical in the specified location and output results in graphical (e.g., a contoured or color coded map) and tabular form. The program would provide risk maps for quick and simple screening-level evaluation while also supplying relevant quantitative information needed for more in-depth analysis.

In creating this new ERM tool, one must decide what model(s) to use and associated data requirements. For example, pre-existing models like DRASTIC could be used or modified, or an entirely new model could be developed. Because subsurface mobility is inherently dependent upon the contaminant (Worrall and Kolpin, 2004), a major improvement over pre-existing models would be to include the attributes of specific chemicals in the risk analysis. Combining these factors with soil properties, geography, and other environmental attributes would better define the interaction of all of these elements. While it has been argued that in the case of GIS operations it may be detrimental to the accuracy of such an analysis to include too many factors (Merchant, 1994), a chemical's interactions with the environment can be very complicated and can require the consideration of a large number of criteria. Most previous models use a small selection of these factors and tend to focus primarily on those related to soil or the subsurface. A brief discussion of various chemical, soil, and environmental attributes that play a role in the interaction between a given chemical and location where it is spilled is presented below to provide a foundation on which to create a new model or modify a pre-existing one (see Figure 2).

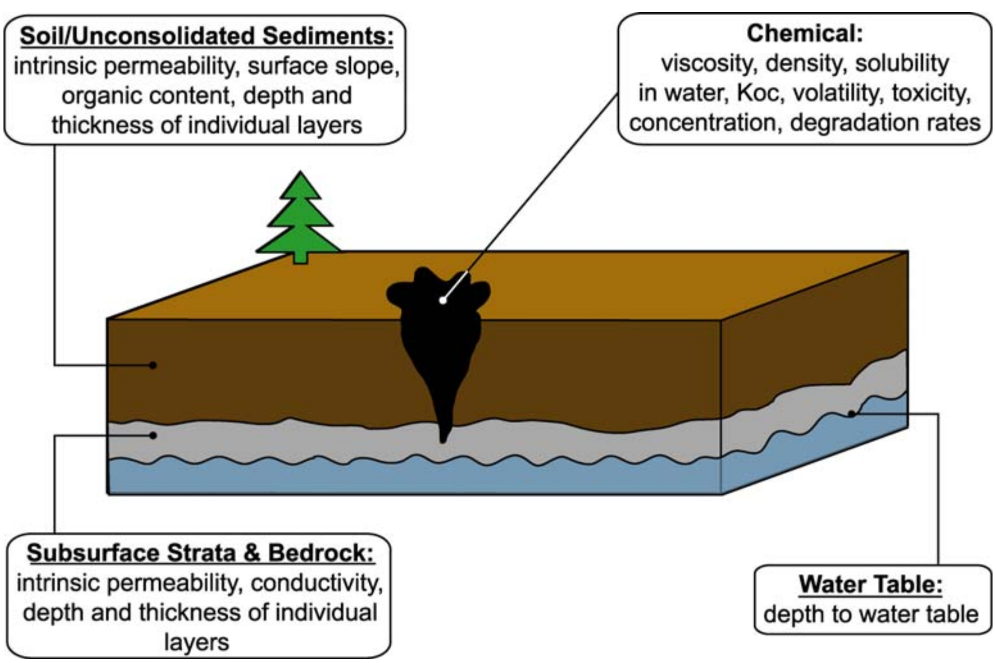

Figure 2 Schematic cross section of a spill site with sample criteria for utilization in a GIS-based risk assessment for terrestrial chemical spills.

Chemical Attributes

Individual chemical characteristics have tended to be overlooked in previous work. However, differences in chemicals' attributes have the potential to greatly change the way they interact with the environment. For example, a spill of acetone will present different risks than a spill of crude oil. Because of the potential differences among chemicals and the way they interact with the environment, a new application should take into account at least some of the major characteristics that cause chemicals to behave differently. These characteristics include viscosity, density, solubility in water, organic carbon partition coefficient (K_{oc}), volatility, toxicity, concentration, and degradation rates. Using these attributes in combination with the location-specific environmental characteristics will better define the associated risks.

Because the *viscosity* and *density* of a fluid are central to defining fluid properties of porous media, such as conductivity, it is important to consider them when modeling the movement of a given pollutant. The *volatility* of a chemical can help to estimate the amount of a spill that is available for transit into the soil; the spill of a highly volatile chemical may be more of threat to air quality than to groundwater. Furthermore, the volatility of a chemical could be used to determine the lateral extent of vapors of the substance in the subsurface. The *solubility* of a contaminant can describe how much of a threat the material is in terms of being mobilized by rainwater or dispersing in groundwater. In the DRASTIC model, the mobility of the contaminant is assumed to be equal to that of water (Aller, 1987), which may not be the case if its viscosity and density is not similar to water and it is not highly soluble. A pollutant's *organic carbon partition coefficient* (K_{oc}) also has the potential to affect its mobility. A chemical with a high K_{oc}

spilled into an organic-rich soil would likely not travel as far as a chemical with a low K_{oc} and would, therefore, present less of a risk to groundwater. The *toxicity* and *concentration* of a pollutant are major factors in describing the overall risk associated with a spill of a given substance. If a large amount of a non-toxic chemical or a low concentration of a toxic material is spilled, the risk associated with the spill would be minimal. *Degradation rates* are relevant since the amount of time a given material (e.g., pesticide) remains toxic can be highly variable, making it more or less of a hazard.

The aforementioned chemical attributes do not represent an exhaustive list of data elements that could be useful in a risk assessment of spilled contaminants. A subset of this data or the addition of other elements could be appropriate, depending on the application circumstances.

Soil and Subsurface Attributes

Taking into account every soil or subsurface characteristic that could potentially impact the transport of a chemical would be nearly impossible. Some of the key factors to consider are: intrinsic permeability or conductivity, depth to water table, slope of the land surface, and organic content. *Intrinsic permeability* can be used in concert with individual chemical viscosity and density data to determine the conductivity of the medium for the specific contaminant in question. The *conductivity* and *depth to the water table* would give an estimate of the amount of time it would take for the pollutant to move through the vadose zone and come in contact with ground water. This time estimate is essential to ground water risk estimation because many contaminants may degrade significantly in the subsurface over time (Kalinsky et al., 1994) and it can be assumed that the deeper the water table, the less likely a pollutant is to reach it (Merchant, 1994). The *slope of the land surface*, which can be derived from topography, can be used as an indicator of the likelihood that a liquid will run off of the surface rather than infiltrating it (Aller, 1987). O*rganic content*, when used in conjunction with a chemical's K_{oc}, will provide information about a chemical's potential mobility, as discussed above. Other soil characteristics, such as pH and ion exchange capacity, also have an effect on a chemical's mobility, though it is commonly assumed that adsorption (immobility) is primarily attributable to the organic component of sediments, particularly with regard to organic contaminants (Krupa et al., 1999).

Potential Resources

Chemical Data

There are numerous sources for pertinent chemical data, including a number of commercial and government databases. One such database is the Chemical Hazards Information Response System (CHRIS) compiled by the US Coast Guard. This resource contains a variety of information on the physical attributes of specific chemicals, including viscosity, solubility in water, and saturated vapor pressure (US Coast Guard, 2002). Other databases with similar chemical information include the Chemical Database Service and the Chemical Abstracts Service (CAS) Registry. Recently, Dobbins and Abkowitz (2003) created a chemical reference database as an aid for hazard response agencies. This database compiles information from a number of sources such as the CHRIS database, the NOAA CAMEO database, and the National Institute for Occupational Safety and Health (NIOSH) "Pocket Guide to Chemical Hazards". By collecting information from a variety of sources, a more comprehensive description of specific chemicals is assembled. In addition, material safety data sheets (MSDS) can be used as a complement to any of these databases and are widely available.

Soil and Subsurface Data

Historically, detailed data on soil and subsurface properties have been difficult to obtain. This shortage of information has been encountered by many researchers (i.e., Tim et al. (1996), Stark et al. (1999), Thanpinta and Hudak (2003), etc.) and has often placed constraints on research methodologies. Currently, the most promising sources for soil and subsurface data for use in a GIS-based application are the spatial databases compiled by the Natural Resource Conservation Service. These databases include information on soil attributes such as particle size distribution, organic matter content, soil reaction, available water capacity, salinity, and bulk density, as well as data on the water table, bedrock, and potential land uses (Reybold and TeSelle, 1989). All of these data are linked to digital maps of varying scales for use in a GIS.

The National Soil Geographic Data Base (NATSGO) is available on a national scale (1:7,500,000). This database was constructed using information from the 1982 Natural Resources Inventory (NRI), which was comprised of over 800,000 sampling sites on non-federal land (federal land was not sampled and was assumed to be similar to non-federal land within the same map unit) (Bachelet et al., 1998). Map unit boundaries were formed using major land resource areas (MLRA) and land resource region boundaries developed by the US Department of Agriculture (USDA) (1995). The NATSGO database is intended for “national and regional resource appraisal, planning, and monitoring” (USDA, 1994).

The State Soil Geographic Data Base (STATSGO) provides valuable information on a state scale (1:250,000). The STATSGO maps were created by generalizing the more detailed Soil Survey Geographic Database (SSURGO) maps, where available, and using various geologic, climatic, topologic, and biologic information to make inferences on data in the remaining areas. Map unit boundaries for STATSGO were determined by statistically expanding data from more detailed maps to form map units. The STATSGO database was designed for “regional, multistate, river basin, state, and multicounty resource planning, management, and monitoring” and are “not detailed enough to make interpretations at a county level” (USDA, 1994).

The SSURGO database is a county level resource mapped on a 1:12,000 to 1:63,360 scale, but typically 1:15,840, 1:20,000, or 1:24,000 is used. As such, the SSURGO database provides more detailed and accurate information than STATSGO (Manis et al., 2000). SSURGO maps were constructed using standard field methods and following National Cooperative Soil Survey (NCSS) mapping standards. This database is intended for “farm and ranch, landowner/user, township, county, or parish natural resource planning and management” (USDA, 1995).

All three databases link environmental attributes to spatial information via digital maps, making them potentially valuable resources for creating a GIS-based terrestrial chemical spill risk management system. In the development of such an application, it would be beneficial to have the most comprehensive information possible to more accurately model real world processes. This requirement would suggest a preference for using SSURGO data over the less detailed STATSGO and NATSGO data. Historically there have been two problems with this approach: the limited geographical extent of the SSURGO database and constraints imposed by the computing power needed to process SSURGO data for large areas (i.e., state or nation-sized regions). The former problem is quickly becoming irrelevant, however, with the approach of the 2008 scheduled conclusion of SSURGO digitization for approximately 97% of the counties within the Unites States (USDA, 2006a). Computational requirements, while becoming less of an obstacle with advances in computer technology, can still pose an issue when dealing with large land areas as single file sizes sometimes exceed 100 megabytes. In such cases, it may be possible to substitute the less detailed STATSGO database. Hudak et al. (1999), for example, employed the STATSGO database in a study involving relatively small-scale soils analysis. However, the Soil Conservation Service does not recommend using STATSGO in instances where such fine spatial resolution is required (USDA, 1994). A study by Lathrop et al. (1994) comparing soil characteristics for counties using both the SSURGO and STATSGO databases found that the STATSGO data had a large variability within individual units and was not well suited to landscape or county-scale studies. The authors also pointed out that soil maps, as a rule, will have a high degree of heterogeneity within map units because soils rarely, if ever, occur as completely homogenous units with well defined boundaries as represented on maps.

A small number of widely accessible soils resources exist beyond those described above including the National Soil Characterization Database (NSCD), the international unsaturated soil database (UNSODA), and the Official Soil Series Descriptions (OSD). The NSCD has standard soil data on over 20,000 specific soil pedons for counties within the US (USDA, 2006b). UNSODA contains potentially useful information about unsaturated soil hydraulic properties, but contains only 790 samples world wide represented in the database (Nemes et al., 2001). Finally, the OSD is a file containing text descriptions of every soil series officially recognized in the US (USDA, 2006c).

There are also a number of soil parameter estimation programs with limited potential value for supplementing the above mentioned resources. For example, the programs Pedon-E, SWLIMITS, Rosetta, and SOILPROP can all be used to estimate hydraulic properties of soils. One program of particular interest is SOILPAR 2.00, because it estimates both soil parameters and can be used to create map layers for GIS in ESRI format (Acutis and Donatelli, 2003). This capability could be used as a means for filling in map locations where resources like SSURGO do not have coverage.

Information on subsurface characteristics beyond the soil layer, such as depth to groundwater and vadose zone properties, are less accessible than soil resources listed above. While the NRCS databases contain fields for such data, they are intended primarily as a source for soils information and do not include subsurface data below two meters depth. At present, no similar databases exist for subsurface data throughout the US. A growing number of individual states have begun to make electronic subsurface databases available over the internet, however. These states include Nebraska, Wyoming, Montana, and most recently, Michigan. Geological surveys, such as the US Geological Survey (USGS) and state surveys, are alternate sources for subsurface information, but most of this data is in paper-based formats, and lending itself less readily to use in a GIS.

Topographical information, in the form of soil slope estimates, can be found within the NRCS soil databases described above. Additional topographical data is available from a variety of sources such as the USGS, state surveys, and numerous on-line GIS data sources.

System Design Recommendations

The SSURGO database is the most favorable foundation upon which to build a GIS-based risk management decision-support tool for terrestrial chemical spills. Use of the SSURGO database would support spatial computations and map display while providing much of the needed data on soils and the physical environment. Multiple SSURGO survey areas can be used in concert to analyze larger geographical areas, though computational memory may often become a limiting factor for very large regions. SSURGO also requires supplemental subsoil data for areas where the water table lies below two meters. Despite these potential restrictions, it remains preferable to all other existing resources, as it is the only database with the spatial precision required for analysis on a spill-sized scale.

The CHRIS database is an appropriate resource for deriving chemical data for a spill risk application. It is easily accessible, in a format that can be readily incorporated into calculations using GIS, and provides extensive data for many commonly used chemicals. Most missing values or data for chemical characteristics not listed in the CHRIS database can be easily acquired using supplemental references, such as an MSDS for a given chemical.

As mentioned above, the operation of a new application would be less cumbersome for the user if it were designed as a “modeling-within” system. This scheme would lend itself more readily to use by decision making personnel not trained in hydrogeology or chemistry, or highly skilled with computers and GIS. Such a system would also facilitate quick analysis of risks for use by emergency responders, response coordinators, water utilities, and other stakeholders that might be required to react to spill events. Finally, a “modeling-within” scheme would lend itself more readily to the possibility of use via the internet, enabling decision makers to use the system without requiring access to GIS software. A web-based approach, however, may present environmental security concerns and would require measures for protecting system information from potentially dangerous parties.

Conclusions

Existing GIS-based ERM systems for terrestrial chemical hazards tend to deal with non-point source pollutants, cover relatively small areas, and rarely take into account the physical properties of the chemical itself. Small-scale point source pollutants (i.e., spills) are often overlooked despite the significant environmental hazards they present, particularly to groundwater (Baker and Panciera, 1990). The ability to analyze the risks posed by these chemicals on a county, state, or national level is crucial to making well-informed management decisions in areas such as transportation, industrial planning, and planning for environmental or resource security threats. The analysis of these risks must not only take into account the properties of the soil where the chemical is spilled. It must also consider the characteristics of individual chemicals to more thoroughly estimate the behavior of those chemicals in a given environment.

An interactive GIS-based system for assessing the risks associated with terrestrial chemical spills would allow for the visual display of risks to facilitate ERM decisions for a wide range of government entities, businesses, and the public. The system could best serve such a diverse group of users by having the data, model, and GIS functionality all housed within the system and operating behind a single user interface. Numerous resources exist for the construction of this type of application, including the National Resource Conservation Service databases (SSURGO, STATSGO, etc.) and CHRIS databases for environmental and chemical information, respectively. Further system functionality could be provided by linking the system to contaminant transport models or various biological and environmental screening models to provide a more holistic view of risks for spill planning and response.

CHAPTER III

ESTIMATION OF TERRESTRIAL CHEMICAL SPILL RISK FACTORS USING A MODIFIED DELPHI APPROACH

Introduction

During the past fifteen years, there have been, on average, over thirty thousand oil or chemical spill events reported annually in the United States (NRC, 2006). The management of these events is critical to protecting human health and environmental resources, including groundwater, surface water, and soils.

In order to assist decision-makers in spill planning and mitigation, a screening tool is being developed, utilizing geographic information systems (GIS) technology, to assess the immediate threat to human and environmental receptors from terrestrial (land-based) chemical spills. This tool will characterize and map risks according to a spilled chemical's ability to immediately impact human health, groundwater, surface water, and soils, thereby providing critical data and visual information needed to plan for and respond to spill events. As part of this development effort, a modified Delphi survey was employed to determine the most important factors influencing acute human and environmental risk from chemical spills. This process included the estimation of weights to be applied to each of the factors, indicating their relative importance in contributing to overall terrestrial chemical risk. The focus of this paper is to describe the method and results of this survey.

The spill risk screening tool currently under development is meant to facilitate planning and mitigation decisions for users who may not be highly trained in the scientific background needed to evaluate chemical accidents, including knowledge of hydrology, geology, and chemistry. The system is designed to calculate risks to human and environmental receptors, as well as an overall risk measure, from terrestrial chemical spills, leveraging GIS technology in conducting the analysis and profiling the results. Locations are displayed as color-coded areas according to the magnitude of risk presented by the spilled chemical and the environment characteristics of the spill site, allowing for quick and easy comparison by the user. The tool is based upon an index model used to calculate relative level of human and environmental risk. The model considers attributes of the specific spilled chemical, as well as the surrounding environment, and is supported by a comprehensive database containing information on chemical properties and environmental resources.

Development of the index model began with a review of relevant literature and compilation of a list of potentially important factors involved in determining the ability of a chemical to immediately impact human health and environmental receptors. Since the spill system is intended for screening level decision making, there was a need to balance the potentially infinite number of contributing factors with the availability of corresponding data . This initial list of factors contains chemical and environmental attributes that govern a spilled chemical's mobility and immediate ability to complete an exposure pathway between the spill and the receptor and, where applicable, the ability of the chemical to impact the receptor. The initial list appears below and is organized into four major components:

1) *Degradation of Human Health*:
   Risk factors: chemical toxicity, spill proximity to dense populations, chemical volatility, chemical flammability, chemical reactivity

2) *Migration to Groundwater*:
Risk factors: depth to groundwater, chemical-specific conductivity of unconsolidated sediments, nature of bedrock, chemical-specific conductivity of soil, chemical volatility, slope of soil surface

3) *Contact of Surface Water*:
Risk factors: spill proximity to surface water, slope of soil surface, chemical viscosity

4) *Degradation of Soil Resources*:
Risk factors: chemical toxicity, chemical volatility, pre-spill quality of soil resources, slope of soil surface, chemical-specific conductivity of soil

The modified Delphi survey presented in this paper was used to confirm the importance of the factors on this list, to supplement the list with any overlooked factors, and to quantify the relative importance of these factors. The survey was further used to gauge the relative importance of each of the four components above in determining the overall risk from a terrestrial chemical spill at a given location.

Methodology

Overview of the Delphi Method

The Delphi survey technique is a widely-used method for addressing problems requiring expert judgment (Okoli and Pawlowski, 2004). This method seeks to gather the opinions of a panel of experts while eliminating the counterproductive effects often encountered using a traditional committee (Martino, 1983). The approach consists of a series of questionnaires presented to a group of experts. With each new round of questionnaires, panelists are asked to reconsider their answers in light of statistical feedback from the moderator and anonymous comments from other panelists. The ideal outcome of this process is consensus among the group or clarification as to why a consensus can not be reached (Gordon, 1994).

The practice of applying the Delphi method to managing environmental issues is well established. For example, as early as 1973, Dee et al. used a Delphi survey to create a system for water resource planning. Since then, an abundance of environmental Delphi studies have been conducted, examples of which include research on environmental decision-making (Richey et al., 1985), groundwater vulnerability (Aller et al., 1987), and soil resource management (Zhang et al., 2004).

Panel Recruitment

At the outset of the survey, prospective panelists were invited to participate in the exercise. In order to increase the quality of the Delphi survey results and minimize potential field-related biases (Martino, 1983; Powell, 2003), a wide variety of experts were contacted. The 95 invited individuals represented the fields of environmental engineering, environmental sciences, chemistry, emergency response, and environmental regulation and policy. This group was composed of individuals from academia, industry, and local, state, regional, and national government agencies. Individual participants were selected using the three techniques described by Gordon (1994): a literature search and recommendations from other experts and institutions. Employing all of these methods helps to ensure that the list of potential participants represents a wide array of experts, including those who are published in the topic, individuals who are well-known in the field, and those less widely known. The invitation to prospective panelists explained the survey purpose and, to provide an incentive to participate, promised a donation to the American Red Cross in proportion to the number of completed questionnaires received.

Survey Design

The survey was conducted on-line via an internet link to surveying software. On-line surveys are considered as valid and reliable as paper-based surveys (Ladner et al., 2002), and save time and expenses associated with the traditional mailed-questionnaire Delphi technique (Snyder-Halpern et al., 2000). The opening web page explained the purpose and structure of the survey, assured panelists of anonymity, and required them to enter contact and professional information before beginning. The panelists then progressed through a series of four subsequent survey sections where they were asked to rate the importance of various factors governing the immediate ability of any volume of a spilled chemical to: 1) degrade human health, 2) migrate to groundwater, 3) contact surface water, and 4) degrade soil resources. The final section asked participants to rate each of these four areas of risk according to its contribution to the immediate overall risk from a terrestrial chemical spill. Each question required the panelists to rate the factors on a zero to five scale, with zero being not important and five being extremely important. In addition to the ratings, respondents were asked to supply comments explaining their answers, particularly if any of the answers were at the extreme ends of the numerical scale. Participants were also asked to suggest other potentially important factors for consideration beyond those already listed.

The survey consisted of a total of three rounds, in line with the typical Delphi format (Powell, 2003). Each round began with a notification and link to the survey sent via email to participants. Following the first round, only panelists who had participated in all previous rounds were invited to participate in subsequent rounds. Approximately two-and-one-half weeks were allotted for panelists to complete each round, with two reminder emails sent in the interim.

In the first round of the survey, panelists were asked to rate an initial list of risk factors compiled by the authors based on a review of existing literature and widely available data. Presenting participants with an initial list, as opposed to a completely unstructured first round, reduces panelists' confusion (Martino, 1983), response time, and burden (Snyder-Halpern et al., 2000). In addition to rating the listed factors and supplying comments, participants were asked to suggest other factors that were as important or more important than those already listed. This technique has been previously described by Gordon (1994) and Martino (1983), among others. Throughout the questionnaire, definitions or illustrations were provided to alleviate potential for confusion regarding terminology.

At the end of the submission period for the first questionnaire, several steps were taken to prepare the responses for use as feedback to the panel in the second round. First, a statistical analysis of the numerical results was performed. Second, participants' comments were consolidated; whenever possible, the panelists' language was not altered in order to avoid misrepresenting their remarks. Finally, the newly suggested risk factors were added to the list of factors to be evaluated by the panel in the succeeding round.

In the second round, panelists were provided the statistical feedback for each question from the first round, including the median response, high and low responses, and the range of values that represented the majority of the responses. These statistics were accompanied by anonymous panelist comments about each rated factor as well as a box plot of the values in order to help respondents visualize the spread of the data. The participants were first asked to reconsider the evaluations they gave in the first round in light of the feedback they had been provided. Participants were then asked to rate the new factors that had been suggested during the first round and to provide any comments they may have about any of the "old" or "new" factors.

After the second round, panelists' responses were gathered and analyzed in the same manner as with the first round. This data was then presented to the participants in the third round. In an attempt to shorten the questionnaire and control participant drop-out, however, the third round asked participants to only re-evaluate those factors which they had rated just once previously (i.e., those factors suggested by the panelists in first round). This arrangement ensured that all risk factors under consideration by the panel were rated exactly twice, whether they were part of the initial list or suggested during the first round. Two rounds of evaluation have been proven to be sufficient to determine a group consensus, specifically when dealing with environmental issues (Richey, 1985).

Results and Discussion

Respondents

Of the 95 prospective panelists initially invited to take part in the survey, 22 actually participated in the first round. Of these 22 participants, 16 completed the second questionnaire and 14 of those completed the third round. There is no universally agreed upon minimal number of respondents for a Delphi study. However, the resulting panel size for this survey appears to be adequate based on research by Dalkey (1972), who found that the correlation between Delphi group response and real-world data can approach 0.8 with as few as 11 participants.

Table 1 Participant organization types by round

	Round 1	Round 2	Round 3
National laboratory	5	5	5
University	4	3	3
Emergency management/ environmental protection	9	5	4
Resource management	4	3	2
Total participants	22	16	14

The 22-member panel was largely representative of the originally-invited group of 95 with respect to fields of work and employment agencies. A breakdown of the types of organizations represented by survey participants is presented in Table 1. Panel members included specialists in one or more of the following areas: geology, soil science, hydrology, chemical engineering, environmental engineering, emergency management, environmental protection, ecology, and human and societal health. Drop-outs from round to round did not appear to be systematic or correlated to fields of work, employment agency, or geographical location.

Notably absent from the panel were local first responders and private industry. While members of these groups were invited to sit on the panel, none chose to participate. The inclusion of these individuals may have helped to reduce the effect of any commonly held biases among government employees or academics. While their absence from the survey does not diminish the expertise of those that chose to participate, it does create the possibility of panel expertise being skewed more toward theoretical and large-scale thinking than toward small-scale field experience.

Statistics

Table 2 shows the statistical results for each round of the survey, with participant-suggested factors listed in italics. For each round, average values tended to lie between 3 and 5 and never fell below 2.36. Responses show a move toward convergence (consensus) from the first to the second evaluation of factors as evidenced by a decrease in the standard deviation for all but 4 of the 42 factors evaluated. Of the factors that exhibited an increase in standard deviation, only one increased by more than ~10% of the original value (chemical persistence). After the second evaluation, standard deviations of all of the factors were less than or approximately equal to 1 (see Table 3), with an average value of 0.66.

Potential to Degrade Human Health

When evaluating a spilled chemical's immediate risk to human health, the panel found the chemical's toxicity, reactivity, and flammability to be particularly important (i.e., rating > 4), along with weather conditions and spill proximity to densely populated areas. According to panelists' comments, the above mentioned chemical attributes were important because they have the potential not only to influence the effects on the health of the population, but also on the health of first responders. Furthermore, participants suggested that reactivity, flammability, and weather conditions play a role in the ability of responders to gain control of the spill situation. Proximity to densely populated areas

Table 2 Survey Response Statistics by Round[a]

	Factors	Round 1			Round 2			Round 3		
		Avg.	St. Dev.	Med.	Avg.	St. Dev.	Med.	Avg.	St. Dev.	Med.
Human Health	Chemical Toxicity	4.48	0.81	5	4.63	0.50	5	-	-	-
	Spill Proximity to Dense Populations	4.33	0.80	5	4.56	0.63	5	-	-	-
	Chemical Volatility	4.14	0.57	4	4.13	0.50	4	-	-	-
	Chemical Flammability	3.76	1.18	4	4.06	0.77	4	-	-	-
	Chemical Reactivity	3.90	0.89	4	3.81	0.75	4	-	-	-
	Weather	-	-	-	3.81	0.91	4	4.00	0.55	4
	Chemical Vapor Density	-	-	-	2.88	0.96	3	3.64	0.63	4
	Chemical Solubility	-	-	-	2.88	1.02	3	2.71	0.61	3
	Age of Exposed Persons	-	-	-	2.88	1.15	3	2.71	0.99	3
	Chemical Specific Gravity	-	-	-	2.38	1.09	2	2.36	1.08	2
Groundwater	Depth to Groundwater	4.14	1.06	4	4.31	0.87	4.5	-	-	-
	Chemical-Specific Conductivity of Unconsolidated Sediments	3.81	1.12	4	4.00	0.63	4	-	-	-
	Nature of Bedrock	3.29	1.27	3	3.69	0.95	4	-	-	-
	Chemical-Specific Conductivity of Soil	3.00	1.22	3	3.63	0.81	4	-	-	-
	Chemical Volatility	2.48	1.25	3	3.31	0.70	3	-	-	-
	Slope of Soil Surface	3.00	1.10	3	2.88	0.72	3	-	-	-
	Chemical Solubility	-	-	-	3.56	0.63	4	4.07	0.27	4
	Chemical Adsorption to Sediments	-	-	-	3.88	0.89	4	3.86	0.36	4
	Precipitation	-	-	-	3.56	0.89	3	3.57	0.51	4
	Soil Texture Sequencing	-	-	-	3.19	0.75	3	3.29	0.83	3
	Soil Moisture	-	-	-	3.06	1.06	3	3.21	0.43	3
	Soil Surface Porosity	-	-	-	3.13	1.26	3	2.93	0.83	3
	Soil Hydrophobicity	-	-	-	2.88	1.09	3	2.71	0.61	3

Table 2 (continued)

	Factors	Round 1 Avg.	Round 1 St. Dev.	Round 1 Med.	Round 2 Avg.	Round 2 St. Dev.	Round 2 Med.	Round 3 Avg.	Round 3 St. Dev.	Round 3 Med.
Surface Water	Spill Proximity to Surface Water	4.52	0.51	5	4.81	0.40	5	-	-	-
	Slope of Soil Surface	4.29	0.72	4	4.25	0.58	4	-	-	-
	Chemical Viscosity	3.76	0.83	4	3.38	0.50	3	-	-	-
	Precipitation	-	-	-	3.94	0.68	4	4.07	0.47	4
	Chemical Solubility	-	-	-	3.63	0.50	4	3.86	0.53	4
	Environmental Resistance to Flow	-	-	-	3.75	0.86	4	3.71	0.61	4
	Chemical Adsorption to Eroded Sediments	-	-	-	3.00	1.26	3	2.93	0.73	3
Soil Resources	Chemical Toxicity	4.29	0.78	4	4.50	0.52	4.5	-	-	-
	Chemical Volatility	3.33	0.91	3	3.50	0.73	3.5	-	-	-
	Pre-Spill Quality of Soil Resources	3.00	0.95	3	3.00	0.97	3	-	-	-
	Slope of Soil Surface	2.86	1.06	3	2.94	0.77	3	-	-	-
	Chemical-Specific Conductivity of Soil	3.57	1.40	4	2.81	0.91	3	-	-	-
	Chemical Adsorption to Soil	-	-	-	3.56	0.63	3.5	3.86	0.53	4.0
	Chemical Persistence	-	-	-	3.75	0.77	4.0	3.71	0.91	4.0
	Soil pH	-	-	-	2.75	0.77	3.0	2.79	0.58	3.0
Overall	Human Health	4.67	0.58	5	4.69	0.48	5	-	-	-
	Surface Water	3.95	0.86	4	4.06	0.57	4	-	-	-
	Groundwater	3.62	0.86	4	3.31	0.70	3	-	-	-
	Soil Resources	3.10	1.14	3	2.94	0.57	3	-	-	-

[a]Italicized factors were suggested by panelists in the first round.

Table 3 Final Survey Response Statistics[a]

	Factors	Average	St. Dev.	Median
Human Health	Chemical Toxicity	4.63	0.50	5
	Chemical Flammability	4.06	0.77	4
	Chemical Reactivity	3.81	0.75	4
	Chemical Volatility	4.13	0.50	4
	Spill Proximity to Dense Populations	4.56	0.63	5
	Chemical Solubility	*2.71*	*0.61*	*3*
	Chemical Specific Gravity	*2.36*	*1.08*	*2*
	Chemical Vapor Density	*3.64*	*0.63*	*4*
	Weather	*4.00*	*0.55*	*4*
	Age of Exposed Persons	*2.71*	*0.99*	*3*
Groundwater	Depth to Groundwater	4.31	0.87	4.5
	Slope of Soil Surface	2.88	0.72	3
	Chemical-Specific Conductivity of Soil	3.63	0.81	4
	Chemical Volatility	3.31	0.70	3
	Nature of Bedrock	3.69	0.95	4
	Chemical-Specific Conductivity of Unconsolidated Sediments	4.00	0.63	4
	Chemical Solubility	*4.07*	*0.27*	*4*
	Soil Texture Sequencing	*3.29*	*0.83*	*3*
	Precipitation	*3.57*	*0.51*	*4*
	Soil Moisture	*3.21*	*0.43*	*3*
	Soil Surface Porosity	*2.93*	*0.83*	*3*
	Soil Hydrophobicity	*2.71*	*0.61*	*3*
	Chemical Adsorption to Sediments	*3.86*	*0.36*	*4*
Surface Water	Spill Proximity to Surface Water	4.81	0.40	5
	Slope of Soil Surface	4.25	0.58	4
	Chemical Viscosity	3.38	0.50	3
	Precipitation	*4.07*	*0.47*	*4*
	Chemical Solubility	*3.86*	*0.53*	*4*
	Environmental Resistance to Flow	*3.71*	*0.61*	*4*
	Chemical Adsorption to Eroded Sediments	*2.93*	*0.73*	*3*
Soil Resources	Chemical-Specific Conductivity of Soil	2.81	0.91	3
	Pre-Spill Quality of Soil Resources	3.00	0.97	3
	Chemical Toxicity	4.50	0.52	4.5
	Slope of Soil Surface	2.94	0.77	3
	Chemical Volatility	3.50	0.73	3.5
	Chemical Adsorption to Soil	*3.86*	*0.53*	*4*
	Soil pH	*2.79*	*0.58*	*3*
	Chemical Persistence	*3.71*	*0.91*	*4*
Overall	Human Health	4.69	0.48	5
	Groundwater	3.31	0.70	3
	Surface Water	4.06	0.57	4
	Soil Resources	2.94	0.57	3

[a]Italicized factors were suggested by panelists in the first round.

was of particularly high concern because of the potential number of people exposed to the chemical and the difficulty in evacuating a large number of people from an urban area.

The panel found chemical solubility and specific gravity to be of lower importance (i.e., rating < 3) in determining immediate health risks. Survey participants suggested that chemical solubility is most important to human health with aqueous transport, which is less likely to be a major human exposure pathway in a terrestrial spill event. Panelists proposed that chemical specific gravity is of greater concern in spill remediation than in dealing with immediate health effects. Age of exposed persons was also rated as being one of the least important factors, though it was mentioned that particularly young or old populations might be more susceptible to chemical toxicity and less mobile in the event of an evacuation.

Potential to Migrate to Groundwater

In determining a spilled chemical's immediate ability to migrate to groundwater, the panel found the most important factors to be depth to groundwater, chemical-specific hydraulic conductivity of the sediments, and chemical solubility. Panelists indicated that depth to groundwater is a crucial factor because, with increasing depth, the travel time required for the chemical to reach groundwater increases. Longer travel times, they argued, translate into more time for natural attenuation processes to take place, as well as more time and more choices for human mitigation tactics. Respondents argued that conductivity is a major factor in determining migration to groundwater because of the wide range of conductivity values that are present in nature. A particularly high conductivity would allow a contaminant to easily migrate to groundwater in a relatively short period of time, while a very low conductivity may essentially prevent the chemical from ever contacting groundwater. Panelists stressed that a chemical's solubility is important since although some dense liquids may eventually reach groundwater without aqueous transport, many chemicals must be dissolved to migrate a significant distance. Factors found to be of low importance included the slope of the soil, porosity of the soil surface, and soil hydrophobicity (water repellency).

Potential to Contact Surface Water

Factors rated as particularly high for determining the immediate ability of a spilled chemical to contact surface water include the proximity of the spill to water, slope of the soil surface, and precipitation. Survey participants suggested that proximity to surface water is the most important factor because it is the only factor that can independently determine if the chemical will contact water when a spill occurs immediately adjacent to it. Panelists argued that soil slope is important because it controls the flow of the chemical over the ground. If the slope is not conducive to conducting the chemical to water by overland flow, the only means by which the chemical could contact surface water is through diffusion, which is an enormously slower process. Precipitation was given a particularly high rating because runoff could be a potentially significant transport mechanism for moving spilled chemicals toward water, both hydromechanically and as solutions. Chemical adsorption was rated as the least important of the factors although chemicals adsorbed to eroded particles are still capable of reaching surface water through transportation of the particles themselves.

Potential to Degrade Soil Resources

Panelists found the toxicity of a spilled chemical to be the most important contributing factor regarding the immediate potential for a spill to degrade soil resources (soil suitable for commercial agriculture or livestock production and grazing). Survey respondents commented that highly toxic chemicals could kill soil biota and render soil unsuitable for food or livestock production for long periods of time. Factors rated as being of lesser importance include the chemical-specific conductivity of soil, slope of soil surface, and soil pH. The pH of the soil, which was rated as the least important of the evaluated factors, was said to be of lower importance because its effect is highly variable and dependent on properties of individual contaminants. Respondents also suggested that many contaminants are more likely to be damaging in low pH soils, which are, in general, less suited to agricultural productivity.

Overall Risk

When evaluating the importance of each of the four risk areas (human health, groundwater, surface water, and soil resources) in contributing to overall immediate risk, the panel rated the potential to degrade human health and surface water as being particularly important and the potential to degrade soil resources as being least important. Survey participants suggested that the immediate potential to damage human health is the least dependent of the four risk areas upon site-specific conditions. The most common comment by panelists was that for human health, in contrast to the other risk areas under consideration, there is little or no opportunity for mitigation. When exposed to highly toxic chemicals, humans often immediately experience irreversible health damage or death. Environmental receptors, on the other hand, present more of an opportunity for remediation, as contaminated water and soil can be treated or removed over a period of time. Survey respondents also noted that in accident situations, as a general rule, human life is of greatest concern and is almost always the top priority of first responders.

Risk to surface water was rated as the most important of the environmental risks because it is most closely associated with human health. Respondents argued that of the three environmental receptors, groundwater, surface water, and soils, surface water is the most likely to present a completed exposure path to humans in a relatively short amount of time. Travel time to groundwater used as a drinking source is often long enough to allow for preventative measures to ensure that no one is exposed to contaminated water. Contact with contaminated soils can occur directly after a spill, however, soil is not likely to be a major exposure pathway for humans.

Discussion

The final list of factors from the survey (see Table 3) appear to be intuitive in determining immediate environmental and human health risks from a terrestrial spill. Most of the factors listed are commonly used in chemical or environmental risk assessments and many have data that are readily available through sources such as material safety data sheets, soil and geological surveys, censuses, etc. One particularly interesting factor that was suggested is the role of soil hydrophobicity in determining the immediate ability of a spill to migrate to groundwater. Soil hydrophobicity, while recognized as affecting liquid infiltration into soil for more than a century, has rarely appeared in groundwater vulnerability literature. Researchers have only recently begun to recognize it as a wide-spread phenomenon with potentially significant affects on groundwater quality (Dekker et al., 2005). As such, spatial data on hydrophobic soils is sparse as it is still not a component of major soil databases (e.g., SSURGO, etc.). Another interesting suggestion is the contribution of chemical persistence in determining the immediate potential for damage to soil resources. One of the participants suggested that this factor is a long-term, rather than an immediate, concern. Other comments, supported by the factor's final average rating, suggest that a chemical's persistence is a means of measuring the magnitude of the impact the contaminant would have on the soil. Since this impact occurs when the soil is contacted by the chemical, it is of immediate concern.

In general, the survey responses point toward a focus on human health. As mentioned earlier, the panel listed human health as the most important concern when evaluating overall risk and factored in potential human exposure when rating the remaining factors. The distance between the spill and receptors was also emphasized by the panel, highlighting the importance of the potential for exposure in the calculation of risk. In the case of human health, groundwater, and surface water distance, these factors were rated as the first or second most important elements. With soil resources, however, the importance of distance from the spill to the receptor appears to be implied by the panel. Panelists' comments suggested that spills would have to be either abnormally large or in a precise location to cause damage to soil resources of major consequences.

The average final ratings for each factor (see Table 3) range from 2.3 to 4.8. It is important to note that neither environmental nor chemical factors were consistently rated as being more important than the other. This indicates that human or environmental resource vulnerability assessments that neglect either category of risk factors are potentially incomplete.

It was somewhat surprising that no factor was rated as being less important than 2.3, on average. This may result, in part, from what Martino (1983) describes as a "temptation" for respondents to make his or her ratings correspond to the panel median. This situation occurs when questionnaires require a considerable time to complete and allows participants to answer the questions without having to justify an outlying response. This possibility was one reason for why only two iterations of evaluation were used.

The complexity of environmental systems makes the convergence of expert opinion in environmental Delphi surveys especially difficult (Virtanen et al., 1999). While the results of this survey did show a trend toward convergence, it is possible that further iterations of the evaluation process may have produced greater agreement among panelists. However, the number of iterations must be balanced against available time and participant fatigue (Powell, 2003). Truncating the survey to two evaluations of each factor presumably helped to combat participant drop-out and a declining number of respondent comments.

Following the final survey round, respondents were requested to provide feedback on the survey process. One panelist seemed frustrated by the lack of indirect communication among panelists and expressed concern that the comments she supplied might have been misunderstood by the rest of the panel. The Delphi survey technique is centered on indirect communication, however, to allow for anonymity and to combat pressure from individuals voicing their opinions loudly or more often than others. Future

Delphi moderators might consider employing real-time, controlled, on-line questionnaires, where answers and comments could be given instantaneously to the moderator. This feedback would be monitored for redundancy and redistributed to the panel. This approach would maintain anonymity of the panelists, reduce some of the pressures associated with a face-to-face committee, and with continuous feedback, ensure that each panelist's idea was accurately represented. Such an exercise might be carried out using instant messaging or internet-meeting software.

As mentioned previously, the results of this survey will support a GIS-enabled system for planning for and responding to terrestrial chemical spills. The final list of factors from the survey will be used to create a set of elements to include in the system risk index model and the final ratings will be used as default weighting values for these elements. Some consideration must be given as to whether each survey factor should be included in the risk model, however. For example, there is the possibility of the interdependence or redundancy of some of the survey factors, which would result in "double-counting" of risk components. One such case may be the connection between chemical solubility and adsorption to sediments. Various studies have shown that there is a direct relationship between these two factors (Kenaga and Goring, 1980). Preliminary research indicates, however, that it is common, and even recommended (Thapinta and Hudak, 2003), for both of these factors to be considered in soil and groundwater vulnerability studies. Final decisions regarding the inclusion or exclusion of individual factors will require statistical analysis of model results. Such results, and details of the overall spill system, will be presented in a future paper.

Conclusions

This paper reports on the use of a modified Delphi survey approach to gain an understanding of the immediate threats to human health, groundwater, surface water, and soil resources from terrestrial chemical spills. The results of this survey provide an indication of the significant contributors to these threats, their relative importance, and how they contribute to overall risk. Important risk factors include both chemical and environmental elements, suggesting that both categories should be included in making informed decisions regarding spill planning and mitigation. The greatest concern during spill events is the risk to human health, which must be considered directly as well as factored into decisions concerning the protection of environmental receptors.

CHAPTER IV

DEVELOPMENT OF A TERRESTRIAL CHEMICAL SPILL MANAGEMENT SYSTEM

Introduction

Each year, thousands of chemical spills occur in the United States (NRC, 2006). 850,000 industrial sites in the US contain potentially hazardous chemicals (Smithson, 2000) and the nation's transportation system handles 800,000 shipments of these materials per day (CDC, 2005). 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 terrestrial (land-based) chemical spills. 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 terrestrial chemical spills. The system characterizes a spilled chemical's ability 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 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.

Model Description

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 (Focazio et al., 2002). One of the most widely used environmental index models is the DRASTIC model for determining groundwater vulnerability (Facazio et al., 2002). Other examples include those reported by Silka and Swearingen (1978), LeGrand (1983), and Civita and De Maio (2000) for use in determining risks to groundwater, Sampaolo and Binetti (1989) and Scott (1998) for determining general environmental risk, and Cutter et al. (2003) 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:

$$\sum_{i=1}^{n} W_i R_i = \text{Index Value} \qquad (2)$$

where R_i is the rating, or severity, assigned to the i^{th} 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 a spill's impact and the resources required for its mitigation. In the system described herein, factor weighting and ranking numbers were assigned a value range from one to five, with higher index values implying a greater risk. Index values were normalized into percentages, according to the method of Civita and De Maio (2000), for use in mapping and in producing an overall risk index. The overall index was 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 placed in the highest risk category and is colored red accordingly. 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.

Model Factors

A certain amount of subjectivity is inherent to all index models (Focazio, et al., 2002). In an attempt to minimize the degree of subjectivity associated with this model, factors and default weighting values used in calculating risk indices were determined through expert judgment by means of a Delphi survey (see Bryant and Abkowitz, *in review*).

The final list of model factors for each risk component, with corresponding default weighting values, is presented in Table 4. Default factor rating schemes are presented in Table 5.

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

Table 4 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

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

Table 5 Factor Ranges and Rankings

Factor	Range		Factor Rating	Source[1]
Toxicity (NFPA Rating)	0		1	NFPA, 2006
	1		2	
	2		3	
	3		4	
	4		5	
Reactivity (NFPA Rating)	0		1	NFPA, 2006
	1		2	
	2		3	
	3		4	
	4		5	
Flammability (NFPA Rating)	0		1	NFPA, 2006
	1		2	
	2		3	
	3		4	
	4		5	
Persistence (half-life in days)	0 - 4		1	Snyder et al., 2000
	4 - 20		2	
	20 - 50		3	
	50 - 100		4	
	> 100		5	
Vapor Pressure (mm Hg)	Human Health	Soil & Water		University of Arizona RM&S, 2006
	0 - 0.76	> 760	1	
	0.76 - 7.6	76 - 760	2	
	7.6 - 76	7.6 - 76	3	
	76 - 760	0.76 - 7.6	4	
	> 760	0 - 0.76	5	
Solubility (ppm)	0 - 0.1		1	USEPA, 2002
	0.1 - 100		2	
	100 - 1,000		3	
	1,000 - 10,000		4	
	> 10,000		5	
Dynamic Viscosity (g/cm*s)	> 10		1	-
	1 - 10		2	
	0.1 - 1		3	
	0.01 - 0.1		4	
	0 - 0.01		5	
Specific Gravity (dimensionless)	> 1.5		1	Sampaolo and Binetti, 1986
	0.8 - 1.5		3	
	0 - 0.8		5	

Table 5 (continued)

Factor	Range		Factor Rating	Source[1]
Chemical-Specific Conductivity (µm/s)	0 - 0.1		1	USDA, 2003
	0.1 - 1		2	
	1 - 10		3	
	10 - 100		4	
	> 100		5	
Adsorption (Kd)	Groundwater	Soil		Whitford et al., 2001
	> 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	USDA, 2005a
	"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	
Slope of Soil Surface (%)	Groundwater	Surface Water & Soil		Aller et al., 1987
	> 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	Aller et al., 1987
	Metamorphic or Igneous		1.5	
	Weathered Metamorphic or Igneous		2	
	Glacial Till		2.5	
	Bedded SS, LS & SS Sequences		3	
	Massive Sandstone or Limestone		3	
	Sand and Gravel		4	
	Basalt		4.5	
	Karst Limestone		5	
Depth to Ground Water (m)	> 23		1	Aller et al., 1987
	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	USEPA, 2006
	300 - 750		2	
	150 - 300		3	
	30 - 150		4	
	0 - 30		5	

Table 5 (continued)

Factor	Range	Factor Rating	Source[1]
Proximity to Densely Populated Areas (ERG Isolation and Protection Zones[2])	> LPM[3]	1	USDOT et al., 2004
	SPM - LPM	2	
	LII - SPM	3	
	SII - LII	4	
	0 - SII	5	
Proximity to Vulnerable Populations (ERG Isolation and Protection Zones[2])	> LPM[3]	1	USDOT et al., 2004
	SPM - LPM	2	
	LII - SPM	3	
	SII - LII	4	
	0 - SII	5	

[1]Ratings were taken directly from or adapted from the sources listed.
[2]ERG = Emergency Response Guidebook (USDOT et al, 2004); for chemicals that do not have isolation and protection zones specified, the minimum values listed for chemicals with zone specifications were used
[3]LPM = maximum large spill protection zone, SPM = maximum small spill protection zone, LII = large spill initial isolation zone, SII = small spill initial isolation zone

and soil pH. "Soil texture and sequencing" was also removed from the list of factors based on the recommendations of Delphi panelists who agued 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 target user's technical background 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 panelists’ comments. “Soil surface chemical-specific conductivity” is based on the factor “surface permeability” from the Delphi survey. This minor change more directly addresses the panelists’ ideas 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., Arnold, 2002; Cutter et al., 2003) and further suggests that the location of concentrations of these vulnerable populations is more important than precise age data for individuals (Morrow, 1999). 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 (see Table 6). This situation is

Table 6 Factor Contributions to Risk Components (in %)

Factor	Human Health	Ground-water	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

consistent with the Delphi panel's assertion of 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 a chemical's potential 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.

Data

The terrestrial chemical spill management system is designed for and based on widely available public data in order to increase the application's utility and transferability. Chemical data is derived primarily from the US Coast Guard's Chemical Hazards Response Information System (CHRIS) database (US Coast Guard, 2002). 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 National Library of Medicine's Hazardous Substance Data Bank (NLM, 2006). Values for persistence were estimated using EPA's EPI SUITE software, version 3.12 (USEPA, 2004) and appended for each table entry. Values for isolation and protective distances were added to each table entry from the Emergency Response Guidebook (USDOT et al., 2004).

Surface and soils data were taken from the National Resource Conservation Service's (NRCS) Soil Survey Geographic (SSURGO) Database (USDA, 1995). This database contains detailed spatial, physical, and chemical features of soils for county-sized land areas. The spatial information contained within SSURGO 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 a unit's dominant component, as outlined in NRCS guidance documents (USDA, 2006). 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 US Census Bureau's Topologically Integrated Geographic Encoding and Referencing system (TIGER) (US Census Bureau, 2000).

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 on-line, which can be used for geocoding locations, though data for retirement facilities and assisted living quarters are rarer.

Case Study Application

Description

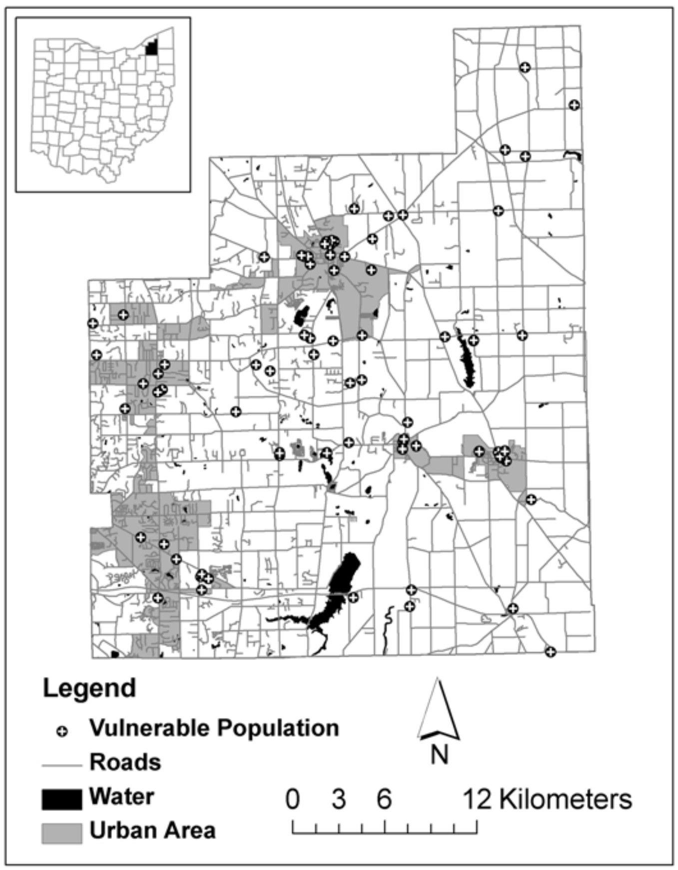

Figure 3 Geauga County, Ohio

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 (see Figure 3). 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 meters. The county's vadose zone 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 per square kilometer to urban areas such as greater Cleveland.

Subsurface data for the case study area was collected from the Ohio Department of Natural Resources' online Geographic Information Management System (Ohio DNR, 2006). Locations of vulnerable populations were obtained from the Geauga County GIS Department through its website (Geuaga County GIS Department, 2006) and through communications with Department staff.

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 (1972). f_{oc} values for each horizon are aggregated using a thickness-weighted average to produce a single value for each SSURGO component. Chemical specific conductivity is calculated for each soil horizon using the following equation from Fetter, 2001:

$$K = K_i\left(\frac{\rho g}{\mu}\right) \tag{3}$$

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 SSURGO values for hydraulic conductivity are converted to chemical-specific conductivity for each soil horizon by substituting the density and viscosity of the contaminant for that of water in Equation 3. (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 (1999) for finding the effective vertical conductivity of layered media:

$$K_z = \frac{\sum_{j=1}^{m} d}{\sum_{j=1}^{m} \frac{d_j}{K_j}} \tag{4}$$

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 the "Data" section. Sorption coefficients are calculated for each map unit by multiplying the soil f_{oc} by contaminant's soil sorption coefficient (K_{oc}), as described by Stephens (1995):

$$K_d = K_{oc}F_{oc} \tag{5}$$

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.

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 5 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. An example of factor values and ratings for the chemical malathion at a given location within the case study area is presented in Table 7. These rating values are then multiplied by the appropriate weight (see Table 4) and summed to calculate index values for each risk component and the overall score according to Equation 2 above.

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 Figures 4a and 4b, 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 is a result of the weight placed on human health and surface water in calculating overall risk (see Table 4).

Table 7 Example values and ratings for risk index calculations of a malathion spill at a given 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 (mm Hg)	0.000176	1	5	-	5
Solubility (ppm)	140	3	3	3	-
Dynamic Viscosity (g/cm*s)	0.4527	-	-	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 (Kd)	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 Ground Water (m)	4.6-9m	-	3.5	-	-
Proximity to Surface Water (km)	30-150km	-	-	4	-
Proximity to Densely Populated Areas (km)	0-0.03km	5	-	-	-
Proximity to Vulnerable Populations (km)	>0.2	1	-	-	-

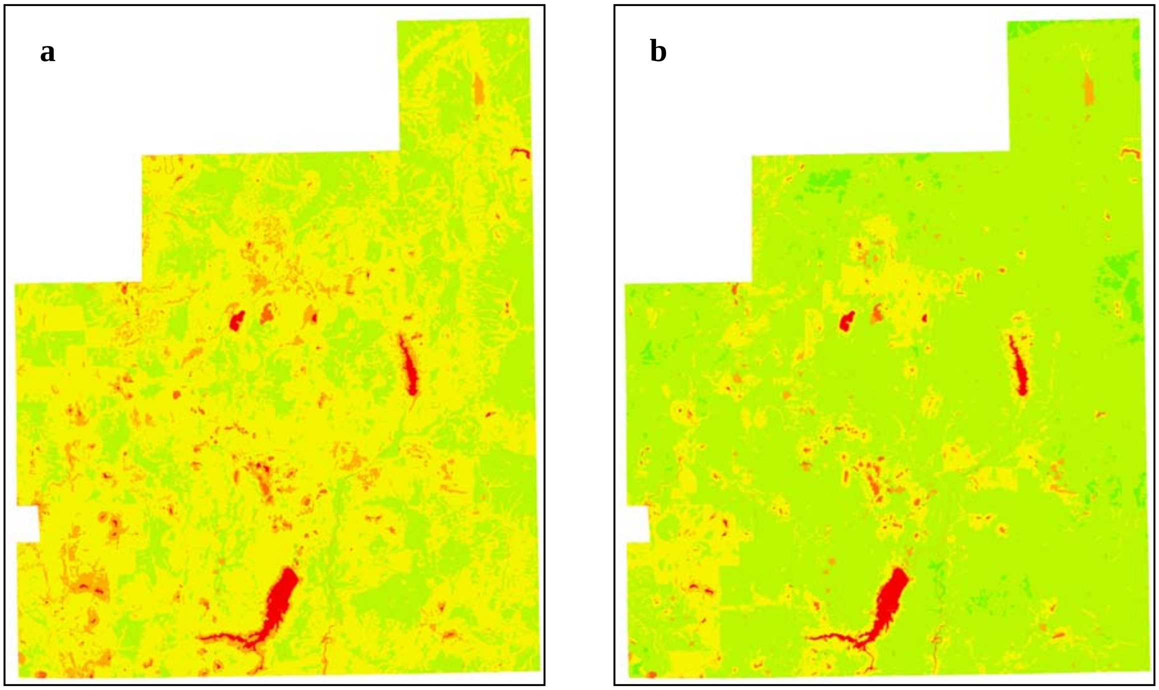

Figure 4 Overall relative risk for Geauga County from the spill of ethylene dibromide (a) and malathion (b)

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 Figures 5a and 5b. 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 USDOT and others (2004) and has been assigned isolation and protection zones for spill response. These zones are used to account for the air dispersion pathway between spills and human receptors and appear as the regions of elevated health risk that outline Geauga County's urban areas and assisted living facility locations shown in Figure 5a.

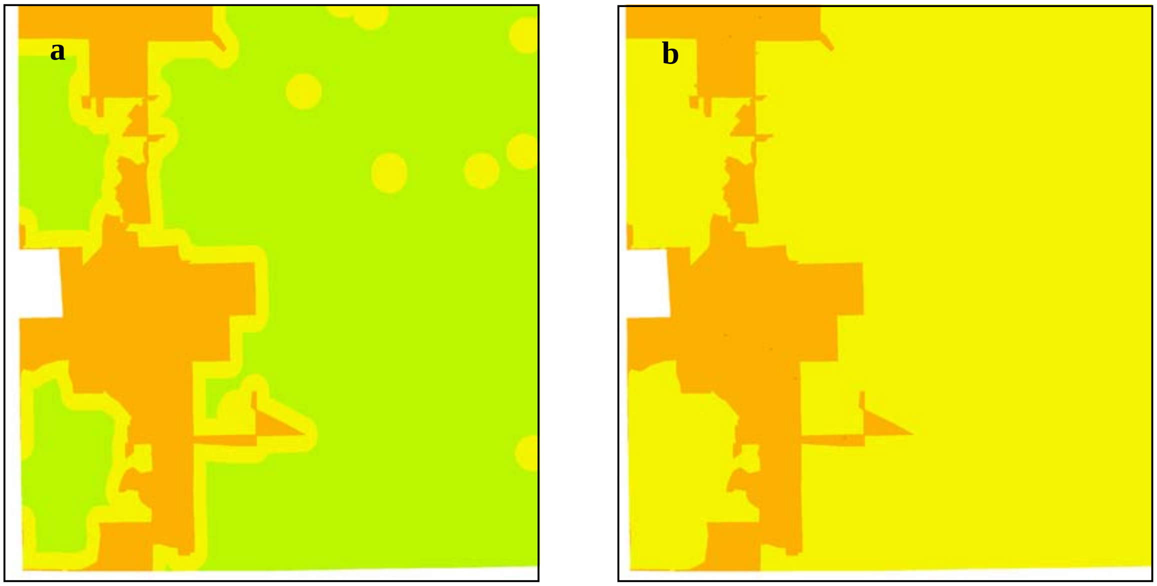

Figure 5 Detail of the southwest corner of Geauga County indicating relative human health risk from the spill of ethylene dibromide (a) and malathion (b)

Areas of highest relative risk depicted in the groundwater risk maps (see Figures 6a and 6b) are surface water locations and sites with less than 6% slope, a shallow water table (<1.5m), 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 (see Figures 7a and 7b) 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 Figure 7a.

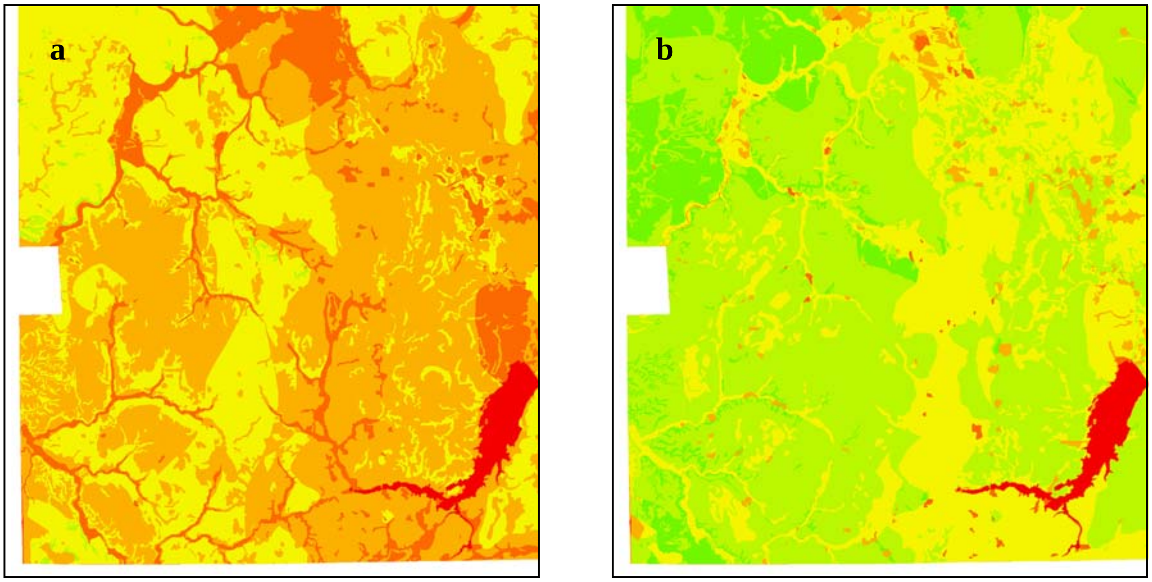

Figure 6 Detail of the southwest corner of Geauga County indicating relative risk to groundwater from the spill of ethylene dibromide (a) and malathion (b)

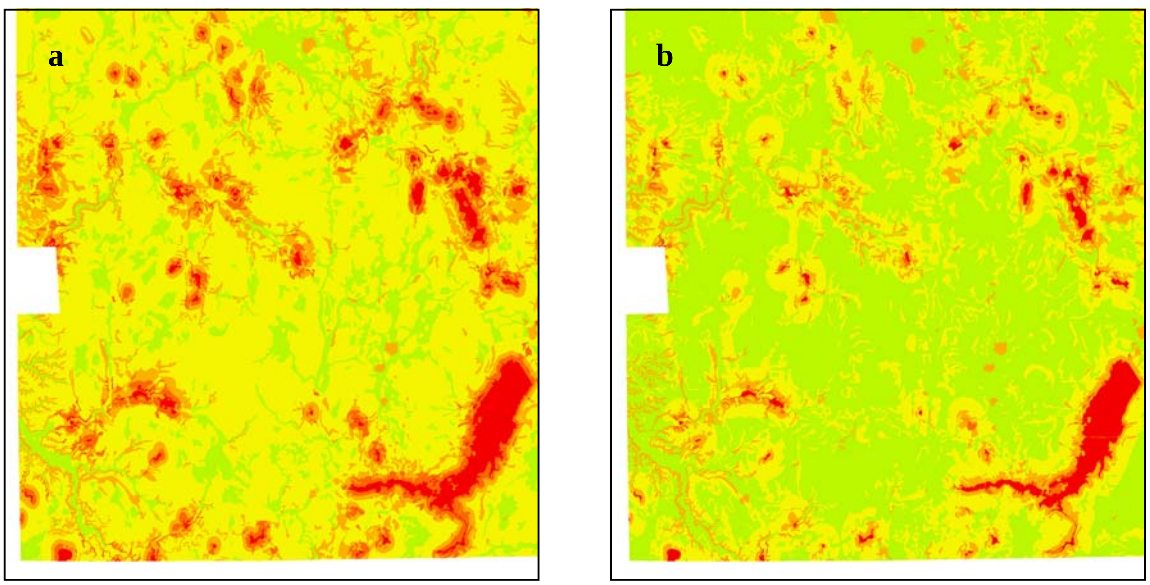

Figure 7 Detail of the southwest corner of Geauga County indicating relative risk to surface water from the spill of ethylene dibromide (a) and malathion (b)

Of the two chemicals shown in the soil resources risk maps (see Figures 8a and 8b), malathion presents more of a threat, in general, to soil resources. This increased threat arises from malathion's higher toxicity. Locations with the highest relative risk shown in the maps are areas where the slope is less than 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.

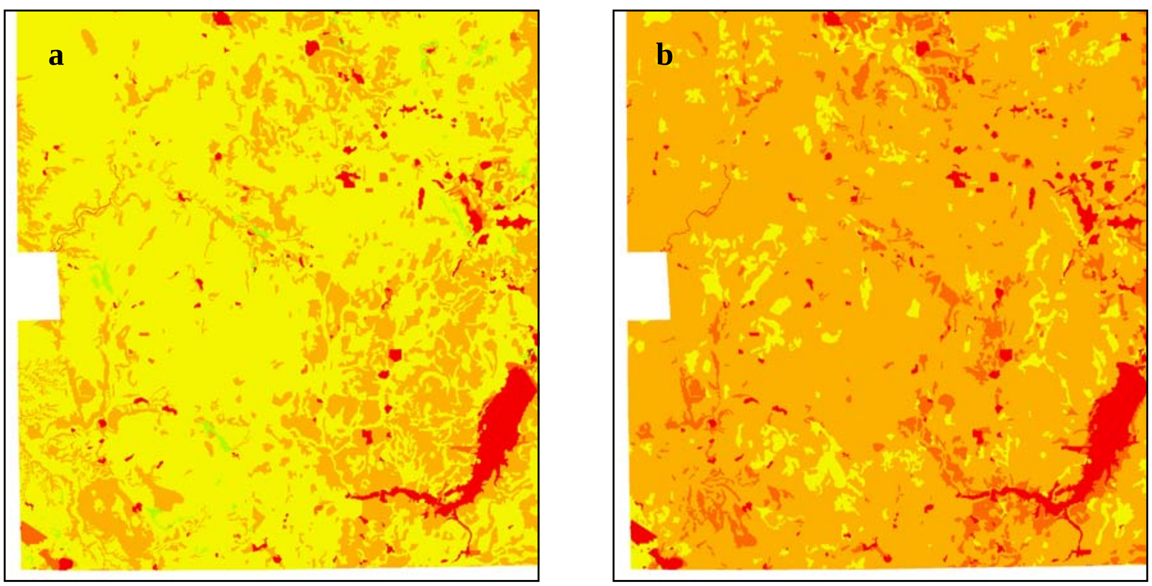

Figure 8 Detail of the southwest corner of Geauga County indicating relative risk to soil resources from the spill of ethylene dibromide (a) and malathion (b)

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 "Model

Structure" above). 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 components' default weighting values. The model output resulting from these calculations differed from the original output values by less than 1%, indicating a fairly robust model. An example of the results of this analysis is presented in Figure 9. This illustration shows the results of model calculations for malathion with a 10% decrease (see Figure 9a) and 10% increase (see Figure 9b) from the default weighting value placed on the human health component of the overall risk calculation. Subtle changes can be seen in these maps, including the appearance of very low risk areas in Figure 9a and higher risk areas more closely approximating the geometry of densely populated areas in Figure 9b.

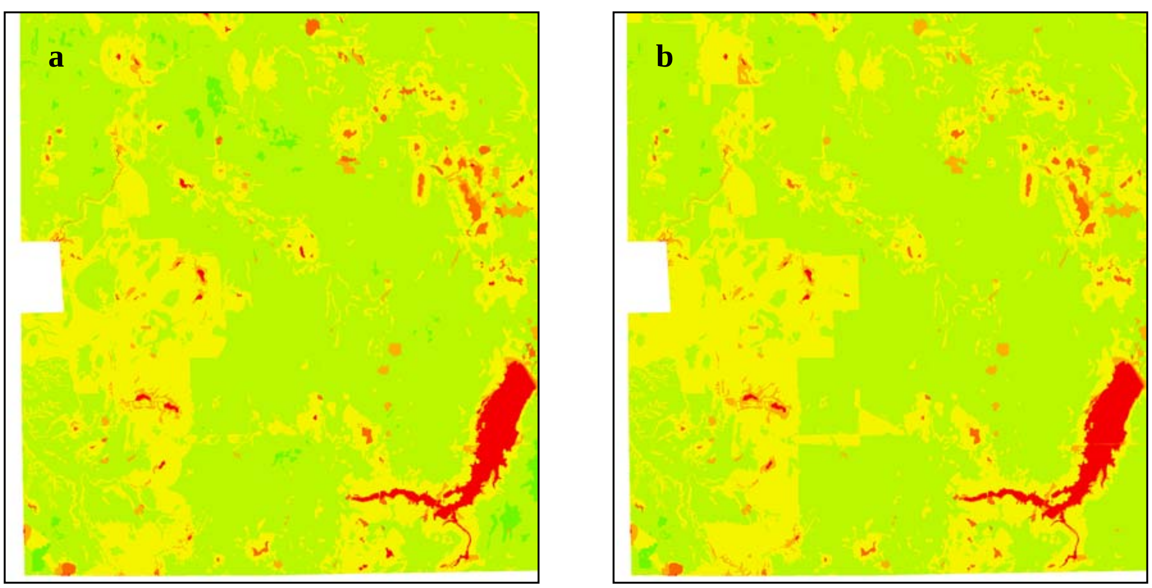

Figure 9 Detail of the southwest corner of Geauga County depicting change in the calculated overall risk from the spill of malathion due to a 10% decrease (a) and a 10% increase (b) from the default weighting value placed on the human health risk component

Implications for Planning and Response

The system output can serve as a valuable tool for planning for and responding to chemical spills. 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 the local government 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 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 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 be focused on areas where risks are high to the population or vital resources, such as the LaDue Reservoir in central southern Geauga County (see Figures 3-4, and 6-9). 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 (see Figure 4). 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 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 Figure 10 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 Figure 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.

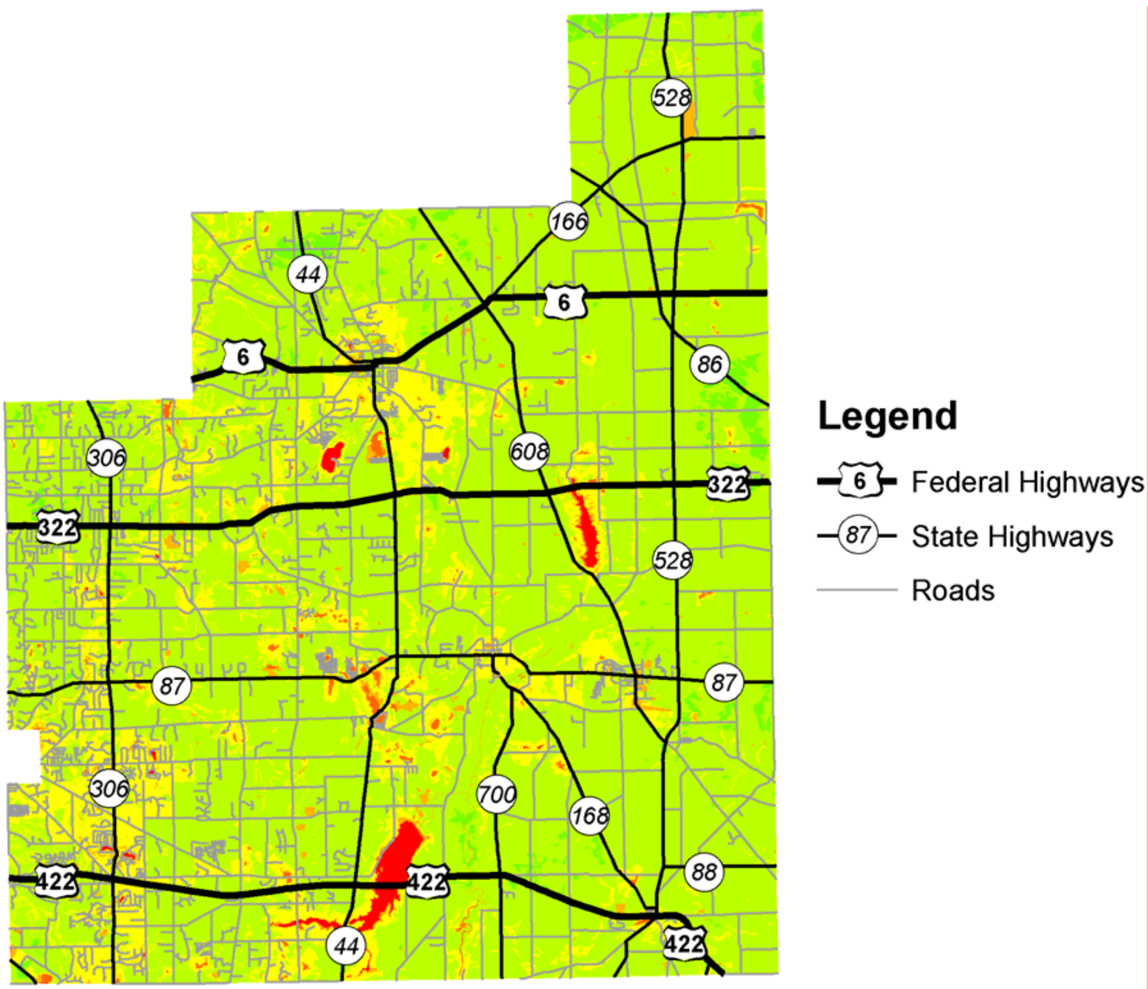

Figure 10 Example of transportation information paired with system overall relative risk map output for the spill of malathion

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 Figure 6. 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 (US Coast Guard, 2002), the Emergency Response Guidebook (USDOT et al., 2004), or the NIOSH Pocket Guide (NIOSH, 2005). 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.

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 chemical spills. 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 (Krupa et al., 1999), 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 (USEPA and NOAA, 2004) for air pollutants, or MODFLOW (Harbaugh et al., 2000) for subsurface and groundwater.

CHAPTER V

CONCLUDING REMARKS

Summary of Research Contributions

In this research, an environmental risk management (ERM) tool was developed to provide analysis and facilitate decision-making for terrestrial chemical spill planning and response. This system was created to serve a wide variety of stakeholders, including managers and policy-makers, who would benefit from screening level environmental risk assessments but may not have the training necessary to utilize technical environmental or chemical data. Areas of potential application include hazardous material transportation routing, industrial zoning, spill response, and environmental and natural resource security planning.

The system uses an index model to calculate component risks for human health, groundwater, surface water, and soil resources from chemical spills. This methodology results in readily understandable numerical output and allows users to easily adjust model parameters to fit their needs. The model was developed using the Delphi survey method for gathering expert judgment to incorporate real-world experience and overcome a lack of quantitative data in the literature. Model output is used to create a series of risk maps with color-coded areas corresponding to categories of relative risk. These maps help to convey risks to affected stakeholders and to facilitate timely and informed decision-making by depicting the magnitude of risks and their spatial relationship to receptors. Furthermore, output maps allow the user to gain an understanding of the risk to various environmental components, their contribution to overall score, and corresponding tradeoffs among them. System data and calculated model values are also made available to the user as a supplement the visual system output. This information serves as a resource for chemical and local environmental data during response situations and provides a foundation on which to base further in-depth inquiries.

The terrestrial chemical spill risk management system operates using data stored within the system to reduce the amount of time, resources, and technical knowledge required of the user. System data was compiled from resources that are widely available to the public, with the necessary exceptions of vulnerable population data and subsurface information. The system's chemical database contains extensive information for 119 common organic chemicals. Some examples of data included in this new resource include values for health, fire, and reactivity ratings, organic carbon partition coefficients, vapor pressure, solubility, viscosity, and recommended protective distances.

Because the system is built on widely available data sources, such as the SSURGO database and Census Bureau TIGER files, it is directly transferable for use in analyzing geographical areas beyond the case study region, including multi-county and regional-scale analyses. The lack of digital data for vulnerable population locations and subsurface information will require the user to supply values for these parameters and/or adjust the risk model accordingly. Complete transferability of the system will only be possible as these data become more widely available.

The chemical and environmental data stored within the system are used in concert with each other to provide indicators of subsurface mobility for soil and groundwater risk estimation. Using these two areas of information and combining them to produce parameters, such as sorption coefficients and chemical-specific conductivity, gives a more accurate representation of the potential for a chemical to migrate in the subsurface than the widely used approach of accounting only for environmental factors (Worrall, 2004).

In order to use system data with SSURGO GIS layers, an intricate series of database queries was created that aggregates soil horizon and component data to the level of map units. These queries calculate and convert chemical and environmental properties and allow the resulting data to be attached to SSURGO map units. The queries also have value beyond the terrestrial chemical spill risk management system. By importing them into the SSURGO template databases published by the USDA, data aggregation can be automated for other uses of SSURGO data layers.

Opportunities for Future Research

Opportunities for future research exist in expansion of the terrestrial chemical spill risk management system in terms of data and scope. One such opportunity is expansion of the chemical database to include a greater number of organic chemicals or other categories of chemicals and solutions. Increased detail in predicting chemical mobility could also be useful, such as including soil pH and ion exchange capacity in sorption calculations. Similarly, real-time climatic data could be incorporated and values in the chemical database updated to account for variation in environmental conditions, such as temperature. Finally, contaminant transport models could be coupled with the system to produce two or three-dimensional visual displays of a spilled contaminant's movement. While these increases in system complexity may provide more helpful information, they will also require more technical knowledge from users and must be weighed against the intended user's level of technical expertise and analysis sophistication desired.

Increases in spill response functionality also provide opportunities for further research. Incorporating a database containing contact information for authorities and responders that must be notified in the event of a spill is one such possibility. Furthermore, the system's chemical database could be updated to include the criteria (i.e., threshold limits) for contacting these parties in the event of a spill. The system could be further enhanced by linking it to response manuals, such as the Emergency Response Guidebook (USDOT et al, 2004) or NIOSH Pocket Guide (NIOSH, 2005), through Internet connectivity or documents stored within the system. This enhanced information would provide first responders with essential guidance on personal and community protection and spill mitigation.

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