

## Technical Note

# Adding Human Health Risk Analysis Tools to Geographic Information Systems

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### Abstract

The development of a module for performing human health risk analysis is presented. This risk module differs from other tools in that it is integrated into a geographic information system (GIS) in a plug-in fashion. The main challenge in the development of the risk module was handling the many different spatial data structures in an open GIS environment. Selection of programming language and other development issues are discussed. The application of the risk module to two mining activities in Bolivia is described.

## 1 Introduction

Industrial activities can result in concentrations of chemicals in environmental media that can pose a risk to human health. There are many tools available to aid in the evaluation of the potential risk associated with proposed or existing industrial activities. Due to the spatial distribution of chemicals of concern in environmental media, these tools typically use geographic information system (GIS) technology to manage and display data and perform spatial (e.g. overlay) calculations.

Most of the existing tools are 'stand alone' systems that contain the functionality and parameters required to perform a risk analysis. This includes calculating fate and transport of chemicals as well as displaying the results of the analysis. Some of these tools have undergone extensive review and testing and have been successfully applied in

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practice, such as the Multimedia Environmental Pollutant Assessment System (MEPAS) discussed in the next section. However, the standalone nature of these existing tools typically results in communication with other programs by importing and exporting data files. In addition, the level of usability and flexibility for many of these tools is typically below that of 'general-use' commercial GIS software packages due to the relatively small user base. While general-use GIS software programs provide the ability to manage and display spatial data, they do not contain the specific functionality required to perform human health risk analysis calculations. One solution is to develop an application that integrates the risk analysis tools with the general-use GIS program in a 'plug-in' fashion.

This paper presents a case study of implementing and applying human health risk analysis tools in a GIS environment in a plug-in fashion. The risk analysis tools were integrated into an existing GIS developed for the Bolivian government, which has the overall purpose of managing mining activities on a countrywide scale (Hellweger et al. 2000a). The GIS contains information related to mining activities. This includes sources of metals (e.g. smelter stacks), information related to their fate and transport (e.g. meteorological data) and information related to receptors (e.g. population centers). The GIS application also contains a number of simple, steady-state, screening-level fate and transport models used to estimate exposure concentrations of metals in air, surface water and ground water (Hellweger et al. 1999, 2000b). The purpose of the risk module presented in this paper is to estimate human health risk based on measured or modeled concentrations of metals.

First, a brief review of some of the existing risk analysis tools is presented. Then the methodology and implementation is discussed. Finally, the application to two mining activities is presented. The discussion focuses on the integration of the risk analysis in the GIS environment, which constitutes the novelty of the work presented.

## 2 Existing Tools

Numerous tools for performing human health risk analysis are documented in the literature and on the Internet. Moskowitz et al. (1996) and Fedra (1998) present overviews and comparisons of selected tools. The Multimedia Environmental Pollutant Assessment System (MEPAS) (Whelan et al. 1992, Strenge and Chamberlain 1995) integrates chemical fate and transport and exposure pathway calculations. The system contains many chemical fate and transport modules, including for example a module for calculating chemical transport in the vadose zone of the groundwater. The system is equipped with a user-friendly Windows graphical user interface (GUI). Several applications of MEPAS are presented in the literature (Castleton 1997).

Another system, called XENVIS (Fedra 1998), is a national level information system developed in the Netherlands by multiple institutions over a period of about ten years. It contains time-variable surface water and atmospheric transport models and is applicable to accidental and continuous chemical releases from industrial installations. The system also performs overlay analysis to identify the number of households within a given risk level. A system that includes modeling of groundwater flow and transport and calculation of risk to receptors is described by Chen et al. (1998). This system connects the models to a GIS. The use of the system is illustrated for a petroleum release site.

Using one of the existing systems was considered in this project. However, the primary objective for the development of the risk module was to provide a user-friendly program that could provide an estimate of risk based on limited data and be used by non-risk assessment professionals. It was feared that a system like MEPAS would be too complex and end up 'collecting dust.' For that reason it was felt that a more conservative, screening level approach, tightly integrated into the existing GIS environment would be more useful than a more complex standalone system.

### 3 Methodology And Implementation

Human health risk calculations can be performed at several levels of detail and complexity ranging from simple, steady-state dose-response calculations to sophisticated, time-variable, multi-compartment biokinetic uptake models. In this project the calculations had to be implemented in a user-friendly program that could be used by non-risk assessment professionals using limited data. This constrained the methodology to relatively conservative, screening-level calculations. The risk analysis methodology used is for estimating human health risk from long-term exposures to chemicals in environmental media. The chemicals of concern identified for this project are metals resulting from mining activities. However, the methodology can be readily transferred to many other chemicals and environmental exposure scenarios.

#### 3.1 Risk Calculation Methodology

The approach used is based on the dose-response and exposure relationships developed by the US Environmental Protection Agency (USEPA) and the US National Academy of Sciences (NAS) (NAS 1983; USEPA 1989a, b, c). This approach estimates the risk of an individual excess cancer over a lifetime and/or the potential for non-cancer effects from exposures to chemicals of concern in environmental media. The reader is referred to the above referenced documents for details of the calculations. The remainder of this section provides an example calculation for the cancer risk from inhalation of air containing a chemical of concern. The individual lifetime excess cancer risk is calculated using:

$$R = \frac{C \times SFi \times IR_{air} \times ET_{outdoor} \times EF \times ED}{BW \times AT_c \times 365 \times 10^3} \quad (1)$$

where  $R$  is the individual lifetime excess cancer probability,  $C$  ( $\text{ug}/\text{m}^3$ ) is the exposure concentration,  $SFi$  ( $\text{kg day}/\text{mg}$ ) is the cancer slope factor for inhalation,  $IR_{air}$  ( $\text{m}^3/\text{hr}$ ) is the outdoor inhalation rate,  $ET_{outdoor}$  ( $\text{hr}/\text{day}$ ) is the exposure time (time spent outdoors),  $EF$  ( $\text{day}/\text{year}$ ) is the exposure frequency,  $ED$  (year) is the exposure duration,  $BW$  (kg) is the body weight,  $AT_c$  (year) is the averaging time for carcinogen, and 365 ( $\text{day}/\text{year}$ ) and  $10^3$  ( $\text{ug}/\text{mg}$ ) are unit conversion factors. Note that Equation 1 constitutes a linear risk model, where risk is directly proportional to the exposure concentration. This greatly simplifies the implementation of the methodology. Equations for other pathways (e.g. ingestion of lead) are not linear, but nevertheless constitute a simple algebraic conversion of exposure concentration to risk.

Risk is a function of the exposure concentration, the toxicity of the chemical of concern and the receptor characteristics. For carcinogenic effects from inhalation the

chemical toxicity is represented by the cancer slope factor for inhalation ( $SFi$ ). For non-carcinogenic effects a reference dose is used to quantify the toxicity of the chemical. The receptor characteristics quantify the exposure-dose relationship. For the air inhalation pathway the relevant receptor properties are the inhalation rate ( $IR_{air}$ ), exposure time ( $ET_{outdoor}$ ), exposure frequency ( $EF$ ), exposure duration ( $ED$ ) and body weight ( $BW$ ). Other pathways require a different set of exposure parameters. For wading in streams, for example, the surface area of the skin exposed to the water is required.

The risk to an adult resident receptor due to inhalation of air with an Arsenic concentration of  $0.10 \text{ ug/m}^3$  is calculated as:

$$R = \frac{0.10 \times 15 \times 1.4 \times 2.0 \times 350 \times 30}{70 \times 60 \times 365 \times 10^3} = 2.9 \times 10^{-5} \quad (2)$$

In the above calculation the cancer slope factor for inhalation ( $SFi$ ) for Arsenic is based on information provided in the USEPA Integrated Risk Information System (USEPA, 1999). The values for the exposure parameters are based on statistics on the US population (USEPA 1997a, c).

If there are multiple chemicals to which the receptor is exposed then the consequences of the multiple exposures needs to be quantified. For carcinogenic chemicals the cumulative risk of exposure to multiple chemicals can be calculated for each exposure pathway by summing the individual lifetime excess cancer risks for each chemical associated with the exposure pathway. For non-carcinogenic chemicals, the hazard quotients for each exposure pathway can be summed to develop a hazard index for that exposure pathway.

The program includes a limited number of exposure pathways, chemicals of concern and receptors. The exposure pathways included in the risk assessment module represent many of the common exposure pathways that may be encountered for mining related releases of chemicals of concern; however, it is not an exhaustive list of potential exposure pathways. Table 1 presents the exposure pathways, chemicals and receptors included.

To obtain a spatial representation of the risk, the risk calculation is performed for every location within a defined area. The concentration of chemicals of concern in environmental media typically varies spatially, with higher concentrations at the source and declining with distance from the source, due to attenuation processes (e.g. dilution, biodegradation). Spatial variability could also apply to the activity patterns and exposure parameters for human receptors. However, the complexities of developing site-specific information on receptor properties were beyond the scope of this application and the receptor characteristics were assumed to be constant. In addition, the receptors were assumed to remain in the same location throughout the exposure duration, so the exposure concentration was held constant at the predicted value for each location. Detailed site-specific information would be necessary to include mobility patterns in the exposure concentration derivation. The exposure concentration is therefore the only spatial parameter considered.

### 3.2 *Programming Environment and Language*

Performing the human health risk calculation in a GIS environment is conceptually straightforward. Most GIS software programs contain the functionality to perform the

**Table 1** Exposure scenarios, chemicals and receptors (not all combinations are supported in the RISKMOD program)

Exposure Scenarios	Chemicals	Receptors
Ingestion of water as residential drinking water	Arsenic	Adult Resident
Inhalation of air	Cadmium	Child Resident
Incidental ingestion of and dermal contact with surface water during wading and washing	Chromium III	Combined Child/Adult Resident
Incidental ingestion of and dermal contact with surface water during swimming	Chromium IV	Adult Resident
Consumption of fish	Lead	Adult Worker
Consumption of crops	Mercury	
Direct contact with soil (includes dermal contact, incidental ingestion and inhalation of particulates)	Silver	
Incidental ingestion of lead in soils	Zinc	

relatively simple calculations using menu functions. However, for end-user applications it is more desirable to code the calculations into a user-friendly program. Most GIS software programs also contain programming or scripting capabilities.

The system had to be compatible with the existing GIS, which uses the Microsoft Windows NT (Microsoft 1999) operating system and ESRI ArcView GIS Version 3.2 (ESRI 1999) software. Several options for programming languages were considered. These included Avenue, which is ArcView's scripting language and C++ or Visual Basic (VB) in combination with MapObjects. MapObjects is a software product that adds GIS functionality (e.g. displaying maps) to 'standard' programming languages. In the latest release of ArcView, Avenue is replaced with VB. Unfortunately this release was not available at the time of the project.

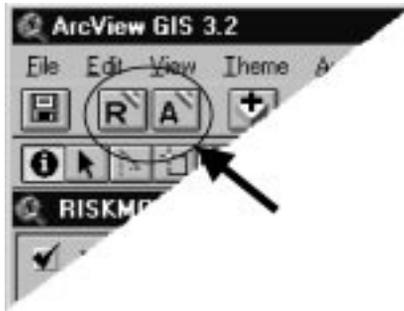
Avenue was selected, because it allows for seamless integration into ArcView's graphical user interface (GUI) and direct access to the GIS database. In addition, it supports the raster data structure with the Spatial Analyst Extension, and this was considered an important feature for this implementation. MapObjects does not support raster calculations. There are several disadvantages to the Avenue language. First, it is a relatively slow language. However, the program performs only simple, non-computationally intensive calculations. The program execution time is on the order of a few seconds and this limitation of Avenue was therefore not significant for this implementation. Second, Avenue does not provide as much functionality and flexibility for interacting with the user as the other languages. It is possible to create highly customized pop-up windows with the assistance of the Dialog Designer Extension. However, the process is tedious and time consuming. In this implementation, the user input mostly consists of selecting options from lists and entering parameter values. This

limitation was therefore not significant. Third, programs written in Avenue are interpreted by ArcView, which means that they cannot be executed without ArcView. This presents a significant limitation of Avenue for this implementation.

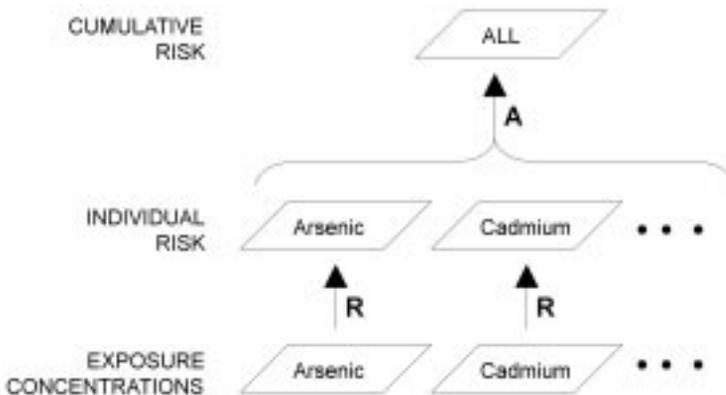
### 3.3 User Interface

The risk module was programmed as an ArcView Extension (plug-in). The user interface is embedded inside ArcView's graphical user interface (GUI), as shown in Figure 1. The program has two functions. The first function ('R' button) is a tool for calculating risk from a single chemical of concern (i.e. Equation 1). The second function ('A' button) is a tool for adding risk from multiple chemicals of concern. The functions represent two essential steps in the overall risk analysis process as illustrated in Figure 2.

The user interacts with the program through a set of pop-up input windows. There are a total of twelve different input windows and the specific ones presented to the user



**Figure 1** ArcView's graphical user interface (GUI) with buttons for the risk module



**Figure 2** Role of the 'R' and 'A' functions in the overall risk analysis process

The screenshot shows a dialog box titled "RISKMOD" with a close button in the top right corner. The main area is labeled "EXPOSURE PARAMETERS" and contains six input fields, each with a default value:
 

- daily outdoor inhalation rate [m3/hr]: 1.4
- time spent outdoors [hours/day]: 2
- exposure frequency [days/year]: 350
- exposure duration [years]: 30
- body weight [kg]: 70
- averaging time for carcinogen [also equals lifetime] [years]: 60

 To the right of these fields are two buttons: "OK" and "Cancel".

**Figure 3** Input window for specifying exposure parameters for the 'air inhalation' pathway (default values are for an adult resident receptor)

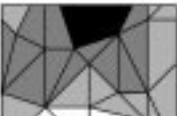
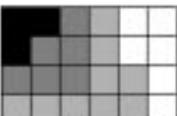
depend on the exposure scenario. Figure 3 presents an example of an input window, where the user is asked to specify exposure parameter values for the 'air inhalation' scenario. A default value for most parameters is provided based on USEPA and other sources (Dames and Moore 1997; USEPA 1997a, b, c).

### 3.4 Input/Output

The most challenging problems encountered in this project were related to data structures. Since the risk analysis tools had to be implemented in an existing GIS in a plug-in fashion, they had to accept exposure concentrations in a number of different data structures.

Figure 4 illustrates the data structures commonly used to store exposure concentration information. Points, for example, are commonly used to present measurements whereas lines are commonly used for model output. The input exposure concentrations are taken from the GIS database and the output risk values are stored in the GIS database. Figure 5 illustrates the concept. The risk module accepts input in several spatial data structures (points, lines, areas and raster) and file formats (ArcView shapefiles, ArcInfo coverages and grids). The program detects the data structure of the input and presents the output in the same data structure. For vector data the risk value is stored as a new attribute and for raster data it is represented by the cell value. The geographic shapes of the input are not modified. The program also accepts a single value, for a non-spatial calculation (e.g. point estimate). For this calculation the exposure concentration is entered in a pop-up input window and the result is presented in a pop-up output window.

As noted above, the program does not modify the geographic shapes of the input. This limits the presentation and interpretation of risk based on contoured exposure concentrations. Consider, for example, exposure concentrations from an air dispersion model presented as contours at intuitively spaced intervals (e.g. 0.05, 0.1, 0.5  $\mu\text{g}/\text{m}^3$ ). The program will produce a risk layer with the same lines. However, the values will be different. The values of the contour lines will now be numbered non-intuitively (e.g.

		Sample Data	Delineation	Interpolation	Models		
					Surface Water	Ground Water	Air
(a)	 Points <sup>V</sup>	Yes					
(b)	 Lines <sup>V</sup> (Polylines)		Yes	Yes C	Yes C	Yes C	
(c)	 Areas <sup>V</sup> (Polygons)		Yes	Yes 2D			
(d)	 Triangles <sup>V</sup> (Triangulated Irregular Network, TIN)			Yes			
(e)	 Raster (Grid)			Yes	Yes 2D	Yes Yes	

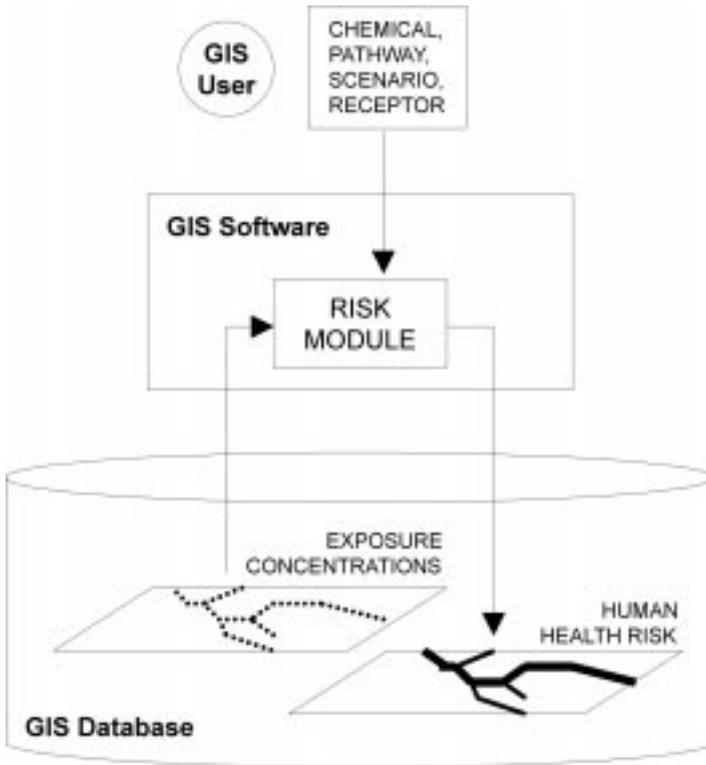
**Figure 4** Common spatial data structures for storage of exposure concentrations (V = vector data structure, 1D = 1-dimensional, 2D = 2-dimensional, C = contours)

$1.4 \times 10^{-5}$ ,  $2.9 \times 10^{-5}$ ,  $1.4 \times 10^{-4}$ ). This type of output can be difficult to interpret. This problem can be overcome by using a raster data structure.

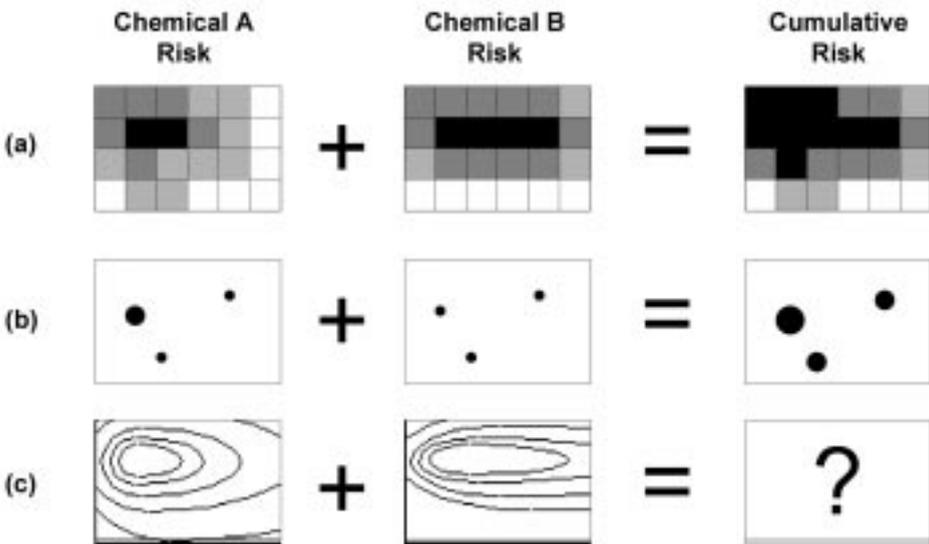
Performing the cumulative risk calculation requires adding two or more data layers. As illustrated in Figure 6, this is easy for raster data, but difficult for vector layers with different geographic shapes. In this program the additive risk calculation can only be performed on raster data or vector data with identical geographic shapes (e.g. cases a and b in Figure 6). This represents a shortcoming and an area of improvement of the program. More flexible additive risk calculations could be made by employing the data model concepts presented by Kemp (1997a, b).

#### 4 Applications

The GIS application with the risk module was applied to estimate the human health risk from several mining activities. Two examples are presented here. In the first



**Figure 5** Integration of the risk module into the geographic information system (GIS)



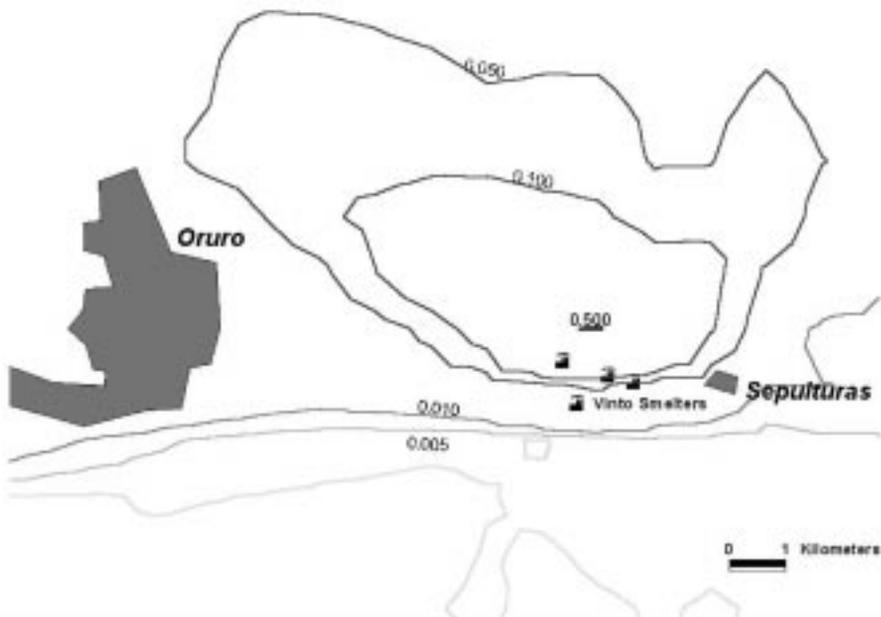
**Figure 6** Additive risk calculations using (a) a raster data structure, (b) a vector data structure with identical geographic shapes and (c) a vector data structure with different geographic shapes

example the module is used to estimate cancer risk due to inhalation of air containing metals from the emissions of a metal smelter facility. In the second application the risk from drinking surface water containing metals discharged from several mining operations is estimated.

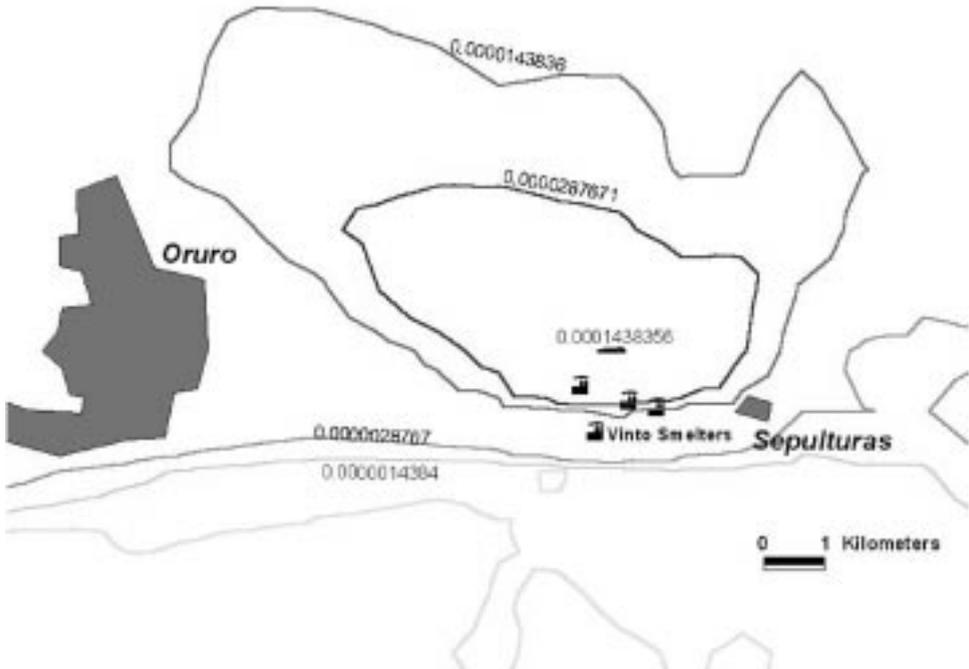
#### 4.1 Arsenic Air Emissions from the Vinto Smelter Facility

The Vinto smelter facility is located near the town of Oruro, Bolivia, a major population center of about 200,000 people. The facility discharges several chemicals of concern including Arsenic, Cadmium and Lead into the atmosphere via four stacks and one air vent. The mean annual exposure concentration in the area surrounding the site was estimated using an air dispersion model. The modeled mean annual ground-level exposure concentration of Arsenic is presented in Figure 7. The transport of the metal is mainly towards the north, due to the predominant southerly wind direction.

The risk module was used to estimate the human health risk due to inhalation of air containing Arsenic resulting from emissions from the facility. The air dispersion model is integrated into the GIS in the same manner as the risk module. The output of the dispersion model is presented as a layer in the GIS, which means it can be used directly as input to the risk module (i.e. without the need for data conversion). The resulting contours of estimated individual lifetime excess cancer risk for adult residents are presented in Figure 8. The risk to the adult residents of Oruro ranges from about



**Figure 7** Contours of modeled mean annual ground level exposure concentration of Arsenic ( $\mu\text{g}/\text{m}^3$ ) in the vicinity of the Vinto smelter facility



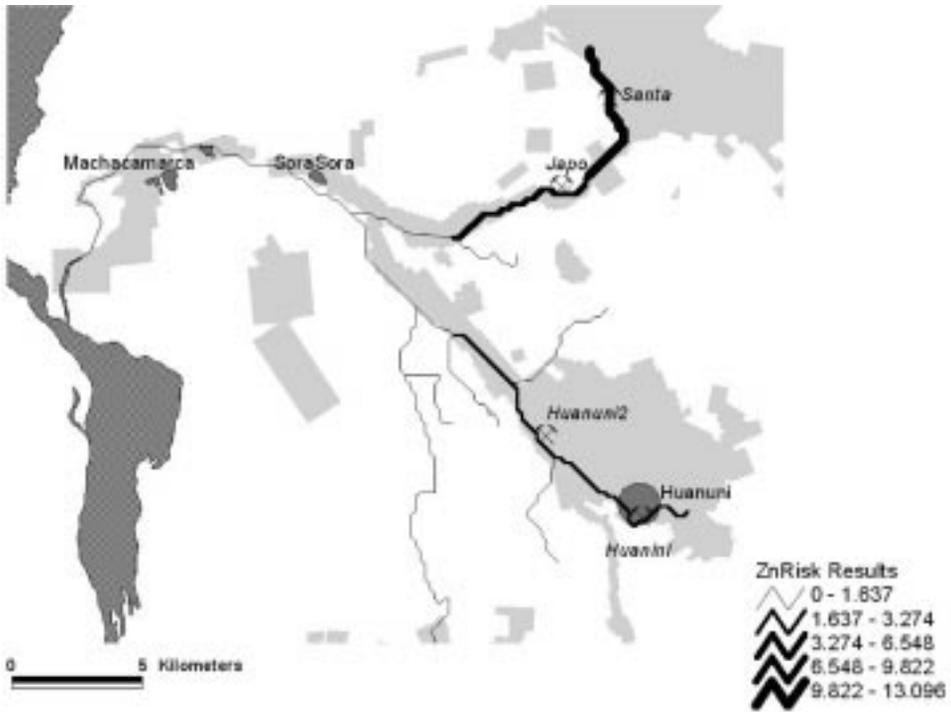
**Figure 8** Contours of individual lifetime excess cancer risk to adult residents due to inhalation of air containing Arsenic in the vicinity of the Vinto smelter facility

$2.9 \times 10^{-6}$  to  $1.4 \times 10^{-5}$ . In other words, the model predicts two of the 200,000 Oruro residents will get cancer from inhaling air containing Arsenic from the smelter ( $1 \times 10^{-5}$  risk times 200,000 population; assuming all adult residents).

Note that the geographic shapes of the risk contour lines are identical to those of the exposure concentrations in Figure 7. The result is that the contour values do not correspond to intuitive risk values (e.g.  $10^{-7}$ ,  $10^{-6}$ ,  $10^{-5}$ ). This is a result of using a vector (line) data structure for the input, which limits the interpretation and presentations of the results as discussed previously. This risk due to Cadmium is added to the risk from Arsenic. The cumulative risk due to Arsenic and Cadmium to the adult residents of Oruro ranges from about  $1.2 \times 10^{-5}$  to  $1.0 \times 10^{-4}$ . Using the present program, the cumulative calculation could not have been performed with the contoured exposure concentrations, for reasons discussed above. However, the air dispersion model also produces raster layers of exposure concentrations. Raster layers are compatible with the risk modules' cumulative risk function (i.e. 'A' button in Figure 1).

#### 4.2 Zinc Discharges to the Huanani River from Several Mining Operations.

The Huanani River is located in the vicinity of Lake Uru Uru in Bolivia. Four mining operations discharge Zinc into the Huanani River or its tributaries. The steady-state exposure concentrations were estimated using a simple, dilution-type surface water fate and transport model (Hellweger et al. 2000b). As with the air dispersion model, the surface water model is integrated into the GIS, which means its computed exposure concentrations could be used without conversion as input to the risk module. The risk



**Figure 9** Risk to adult residents (expressed as hazard quotient, see text) due to drinking water from the Huanani River containing Zinc

module was used to estimate the risk to humans using the river as a drinking water supply. The risk is quantified using the non-carcinogenic hazard quotient, calculated as the ratio of the estimated dose to a reference dose. A hazard quotient of 1.0 and above indicates that adverse effects would be expected. The estimated risk to adult residents from drinking water from the Huanani River or its tributaries is presented in Figure 9. The spatial pattern of the risk is intuitively correct. The risk is highest directly downstream of the sources and lower further downstream, an effect of the dilution of the metal.

Presenting the results of the analysis as a data layer in the GIS has the advantage that risk can be visualized in relation to other geographic features, such as receptor locations. Consider, for example, the town of Huanani (population 10,000) located on the main stem of the Huanani River. The hazard quotient in the vicinity of the town is 3.1. This indicates that adverse effects would be expected if the river were to be used as a drinking water supply.

## 5 Conclusions

Relatively simple human health risk analysis calculations can be implemented inside 'general-use' GIS systems. The main challenge is handling the many different data structures used to present exposure concentrations. For vector data structures the

presentation of the results and the ability to perform cumulative risk calculations is limited. The raster data structure does not suffer these problems.

The methodology was implemented as a user-friendly program using ArcView's Avenue programming language. Avenue is powerful and flexible enough for applications of this level of complexity. A main advantage of Avenue is that the programs can be embedded seamlessly into ArcView's GUI. A significant disadvantage of the language is that programs written in Avenue require ArcView to be installed. In the latest release of ArcView, Avenue is replaced with Visual Basic (VB), which should facilitate the development of plug-in programs. Further, since VB is a popular programming language for standalone programs as well, the option now exists to have stand alone and plug-in versions of the same tool. The Adobe Acrobat Reader software is an example of this concept. It works as a standalone product, but also as a plug-in to Microsoft's Internet Explorer.

The risk module was applied to estimate the human health risk from several mining activities. A significant advantage of making the risk analysis calculations in a GIS is that the input data (in this case exposure concentrations from fate and transport models) can be accessed without requiring data conversion. The calculated risk also can be overlaid with population centers, and other geographic features, which facilitates the interpretation of the results.

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