GIS-based Software Applications for Environmental Risk Management

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Abstract

Over the past few decades, there has been an increasing concern that human actions and natural catastrophes have been adversely impacting the environment, and posing serious ecological and health hazards. This concern has led to an increased emphasis on environmental risk assessment studies all over the world.

Environmental risk assessment aims at studying the nature of environmental hazards, (emission of a pollutant/contaminant, natural hazard events, use of a hazardous technology, or any possible combination of these), and estimating the associated probability of occurrence of such events. The study also aims at characterizing the adverse effects of environmental hazards resulting from human and ecological exposures.

Environmental risk management seeks to minimize the impact of natural catastrophes, based on a detailed analysis of the risk assessment results. This helps in effective planning of the remedial steps, prioritizing of the action items, and early decision-making. This also helps in the quick enforcement of suitable policy or regulatory mechanisms. Today, environmental risk management is practiced by a wide range of industry segments, such as general and life insurance, real estate and construction, government and development funding organizations, agriculture, and utilities sectors.

In the past, GIS based software applications have been used widely for environmental risk assessment and analysis studies. The usage of GIS in environmental risk management ranges from development of databases/inventory systems, and simple to advanced GIS layers overlay, to complex spatial decision-making systems for study of the impact of air, water and soil pollution, ecological imbalance, and natural disasters on the environmental and human receptors.

Environmental risk management also uses inputs and expertise from many other disciplines. Chemistry, physics, biology, ecology, geology, hydrology, engineering and statistics being some of them. Typically, a large number of complex variables are involved in the risk assessment and analysis process.

The environmental risk management process involves usage of information derived and presented in various ways. For example, comparative (or relative) risk analysis, cost-benefit analysis, scenario analysis, probabilistic analysis, decision matrix, sensitivity analysis etc. Due to the need for displaying and analyzing a huge volume of the spatial as well as non-spatial environmental hazards, and exposure data, in a fast and accurate manner, GIS based software applications serve as powerful tools for effective environmental risk assessment and management.

This paper discusses an approach for the use of GIS-based software application framework for environmental risk management. The paper shall also present three case studies on the use of this approach for resolving some specific environmental risk management problems.

Introduction

Environmental risk assessment aims at identifying all possible types of environmental hazards to which a particular geographic region or specific communities are exposed, and assessing the risk in terms of historical as well as probable ecological, human, property and other losses associated with these hazards. Using the results of the risk assessment as an input, environmental risk management involves examining, implementing & evaluating the options available for effectively management of these risks.

Options available include prevention, reduction or mitigation of these risks, and planning for preparedness, response and recovery for the probable or real-time environmental disasters. The main objective of environmental risk management is to minimize the possible damage to various environmental components, and to ensure a long-term sustainability of the overall environment.

A reasonably accurate assessment of the magnitude and extent of the possible risks is an important step in the overall environmental risk management cycle. It includes: 1) quantification of the spatial as well as non-spatial characteristics of the environmental hazards affecting a particular region (for example- emission of a pollutant/contaminant, a natural hazard event, use of a hazardous technology, or any possible combination of these); and 2) estimating the associated probability of occurrence of such events, followed by characterization of expected adverse effects resulting from human and ecological exposures to these environmental hazards. This analysis helps in effective planning of the action items, in prioritizing and decision-making, and in enforcing suitable policy or regulatory mechanisms.

Environmental risk management, in its various forms, is practiced by a wide range of industry segments – including general and life insurance industry, real state and construction industry, government and development funding organizations, agriculture and the utilities sectors.

Role of GIS software applications for ERM

Environmental risk management needs a multi-disciplinary approach, with input and expertise required from many fields - civil and chemical engineering, physics, life sciences, ecology, geology, hydrology and statistics being some of them. A wide range of simple to complex, spatial as well as non-spatial, and quantitative as well as qualitative, input data sets are used in environmental risk assessment and analysis process. The environmental risk management process involves preparation and use of the processed information derived and presented in various ways – for example, comparative (or relative) risk analysis, cost-benefit analysis, scenario analysis,

probabilistic analysis, decision matrix, sensitivity analysis etc. Due the need for using and analyzing a huge volume of the spatial as well as non-spatial environmental hazards and exposure data in a fast and reasonably accurate way, GIS based software applications using a variety of modeling techniques serve as powerful tools for effective environmental risk assessment and management.

Such applications can be used for a diverse environmental risk assessment and analysis purposes. These applications can ranges from development of databases/inventory systems for simple to complex GIS layers overlays, to complex spatial decision-making systems for study of the impact of air, water and soil pollution, ecological imbalance, and natural disasters on the natural and man-made environment, including living beings, properties, infrastructure, vegetation and ecology. These systems could also be interlinked with other related systems, providing online and real-time input data feeds or communication systems, to allow continuous monitoring and tracking of environmental risks in an integrated way. Normally, it is good to start with a prototype application first, which could be expanded further based on the budgetary allocation, user needs and the user feedback obtained from the prototype's implementation.

A general GIS-based software application framework used for environmental risk management

Figure 1 illustrates suggested web-based n-tier architecture for a components-based environmental risk management application. It is good to use a components-based architecture approach, because it allows a parallel development of the components. The components can then be reused for similar other applications as well. The main elements of the architecture are: a) user interface (or the browser); b) the web server, which interfaces between the browser and the application/data servers, and c) application servers (and the associated data servers, as needed), which handle the spatial and non-spatial data query transactions and analysis algorithms.

The transitioning from an environmental risk assessment application to an ERM application is possible through adding an ERM guidelines/rules engine, which provides recommendations for action items/policy formulation based on a comparison of the results from the risk assessment engine with the system defined threshold values. The associated rules and recommendations, for the cases when the computed values go beyond the defined threshold values, are built into the system. Such a system would fall into the category of a "knowledge based system", which can provide spatial and non-spatial data display, analysis, and results interpretation functionality.

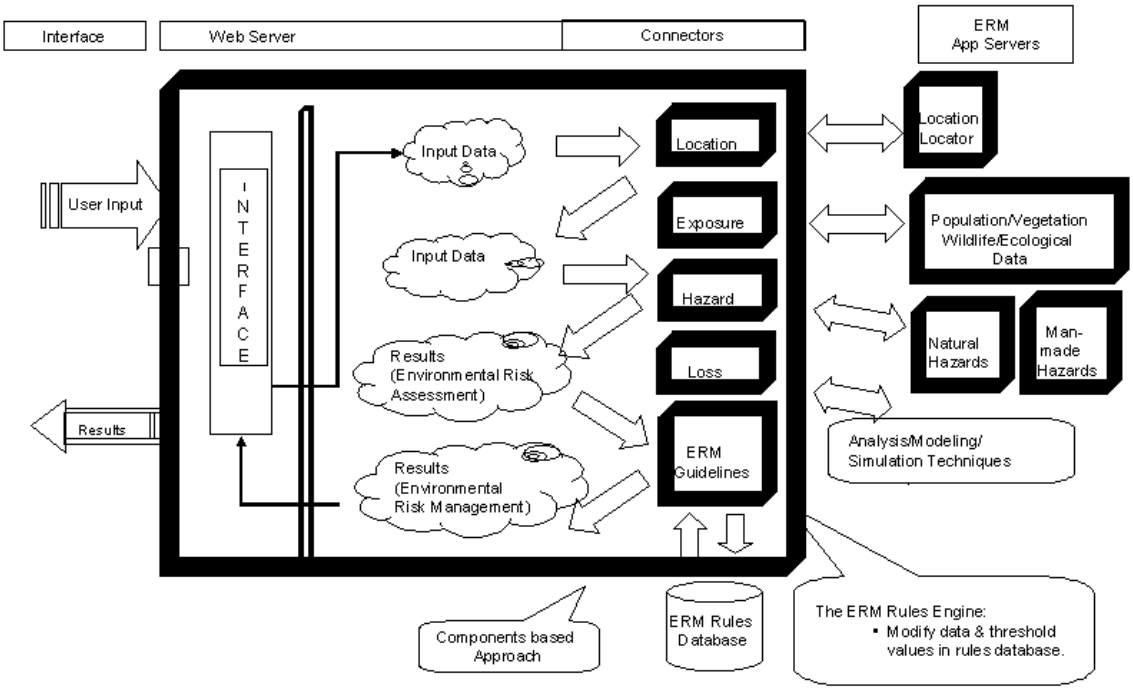


Figure 1: A typical architecture for a components-based environmental risk management application

Three examples of the GIS software ERM applications, which use this basic system framework, besides having other specific functionality for the intended purposes, would be discussed as a part of this paper. These include:

1. An environmental sustainability threat scenario modeling application for government policy formulation

2. A multiple-source industrial pollution/contamination modeling application for portfolio risk management by the real estate and insurance sector

3. A catastrophic modeling application for the emergency preparedness and response planning by a city administrator

An environmental sustainability threat scenario modeling application for government policy formulation

Building of a highway into a fragile hilly environment, excessive draining out of ground water, deforestation for housing infrastructure development – these are just some of the human actions aimed at meeting the short-terms needs. Caused by the changes in demographics and socio-economic profiles of a region, these *may* create long-term environmental degradation. Using a knowledge-based GIS software application, a set of scenarios can be simulated to visualize the long-term implications of planned human actions, based on which alternate actions can be planned – for example, a change in

alignment of a highway to shift it away from a fragile ecosystem or envisaging water harvesting option for a region.

Such a system would allow the users to develop possible scenarios using GIS and graphical icons (as indicated in figure 2). For example, a symbol of a polluting industry planned can be placed at a user defined locations on a given regional map, showing the terrain, rivers, soil, vegetation, population, employment, infrastructure, land-use and wild life attributes, and to evaluate the different aspects of the environmental risk, for a set of industry locations scenarios.

It can help in developing a prior understanding of the potential risks and for arriving at the best possible alternatives, within the given constraints. There actions could be a combination of human actions taking place in that region; for example, establishment of an industry zone, growing of cash crops, clearing of some forest area to build the industry & houses. These entire situation involves a complex set of multiple actions over a wide geographic region, so there would a need for the system to be able to analyze & manage the environmental risks posed by the combination of these actions.

Figure 2: Schematic diagram showing a sample catchments area under consideration and some of the "variables" to be used for scenario analysis, indicated through graphical icons

While the potential hazards are very clearly defined in this case, there is a need to develop the following "analysis engines" in the ERM system to work out a long-term environmental impact scenario (a simplified approach has been suggested for analysis of each factor):

1. **Hydrological impact:** Using the surface water, ground water, soil, and vegetation/crop input data, and the water life cycle approach, a series or a surface/ground water availability map for the for the region can be drawn, showing the spatial as well as temporal variation. For example, with establishment of an industrial zone, the water balance situation would change, depending upon the water needs of the industry and the increased population, and the extent of deforestation done for this purpose

2. **Demographic/economic shifts:** The industry could create new employment; some people may shift from the agriculture industry to jobs. This region could attract people from far away regions with less economic opportunities

3. **Growth in built-up/infrastructure environment**: There would be a need for new infrastructure to support the sudden changes; for example – new houses, roads, utilities

4. **Impact on wild life:** The wildlife in this region would get impacted, and there would be a need for defining protected areas. Impact on wildlife may impact the tourism potential of an area, which would further impact the economic factors in the region

5. **Air, water and soil pollution impact:** This is linked to the nature and magnitude of the pollutants dispersed by the industry (based on the nature of chemicals/gases released and their prior treatment, the source and the sink locations), growth of population in that region, extent of deforestation, and the shift to growing of cash crops which may affect the land fertility. Again, the overall impact of the pollution is linked to the tourism potential of the area, and to the health conditions of the local inhabitants. There would be an expected change in

all these aspects over time, and the long-term demographic, economic and ecological scenario could be quite different from the short-term ones.

Such a scenario simulation and analysis application could help in having a visual presentation of the possible situations, and planning suitable actions and alternatives, both in term of the specific locations (spatial) and the time factor (temporal) associated with such actions. This is possible through developing a GIS software application, with the data and analysis engine components, as indicated above, and the use of experts' opinion on developing a set of meaningful scenarios. The results obtained from this type of system can be used for preparing effective policy recommendations and guidelines for maintaining the long-term environmental sustainability of a specific region, while keeping the regional growth and development needs in mind.

A multiple-source industrial pollution/contamination modeling application for portfolio risk management by the real estate and insurance sector

Environmental risk insurance is increasing being used in real estate development projects. It allows the potential real estate sellers or buyers to eliminate or reduce the uncertainty associated with the possible contamination or damage to the property, covered under such custom-made insurance policies. The users of such insurance cover could be real estate developers, contractors, buyers or financial institutions providing real estate loans. These customized insurance packages could help in covering the expenses for the cleaning/reconstruction of the affected sites, and can help in mitigating the risks associated with the project management of the real estate development projects.

Having an effective, ERM insurance cover could significantly increases the chances of the success of a real estate deal, wherein there is some possibility of some environmental risks. Some examples of such real estate transactions would include the deals involving asbestos industries, steel mills, petrol pumps, or a real estate portfolio comprising of properties at least some of which are exposed to an environmental pollution or contamination risk from some hazardous source present in the neighborhood of such properties.

A GIS software application for environmental risk assessment of such properties/ portfolio could serve as a powerful risk management tool for the real estate as well as the insurance sector. The framework of such an application would comprise of three main parts:

1. **Exposure:** Spatial location of the buildings / area comprising the real estate portfolio to be insured, the building /area properties, and their insurance policies, including insured value, deductibles and limits

2. **Hazard:** Location of sources causing pollution/contamination risk, nature of pollutant/contaminant and probability of any leakage/accident, because of natural or man-made factors, "footprint" or the thematic concentration map for such scenarios. These can be prepared based on: a) the historic data of any past similar events; and b) modeling for the dispersion of the pollutant/contaminant originating from a source at a certain height, and spreading in the direction of expected wind direction, accounting for the uncertainties associated with the hazardous material release pattern, wind direction and magnitude (a sample plot has been shown in figure 3)

3. **Vulnerability of the building/area to such hazard:** This could be specified in terms of percentage damage or cleaning/reconstruction cost, for different pollution/contamination concentration ranges.

Using this data, the expected magnitude and extent of damage could be arrived at, which can help in estimating the optimum risk cover to be taken (by a real estate developer, or the insured), or for estimating the premium to be charged (by the insurance company).

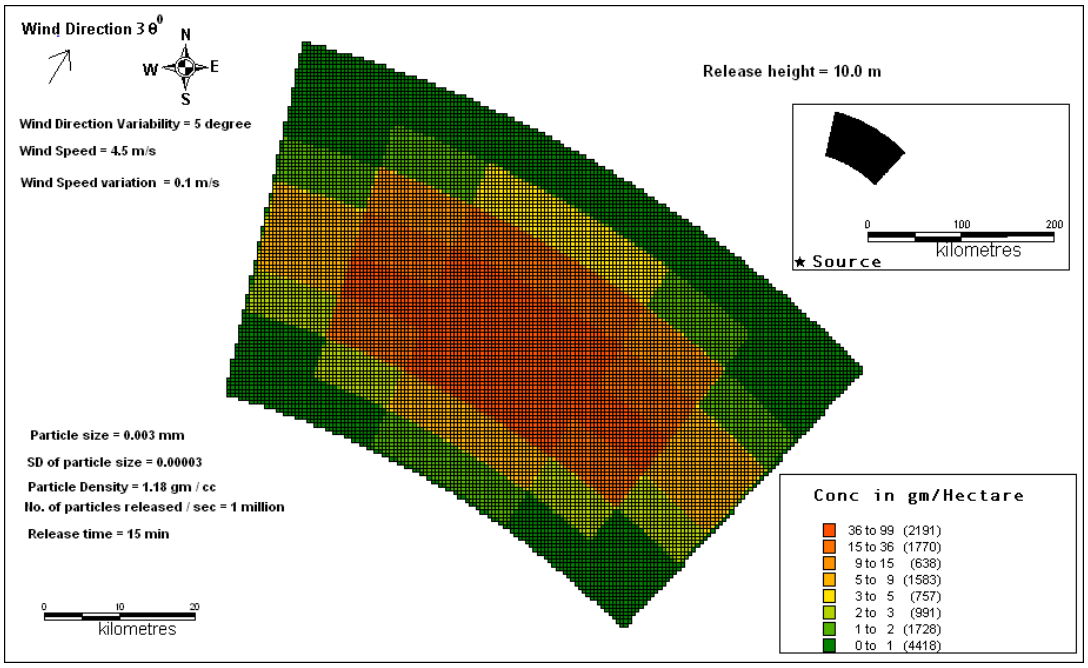


Figure 3: A sample hazard map showing the impact of a contamination scenario in a region due to the release of hazardous material from a certain height

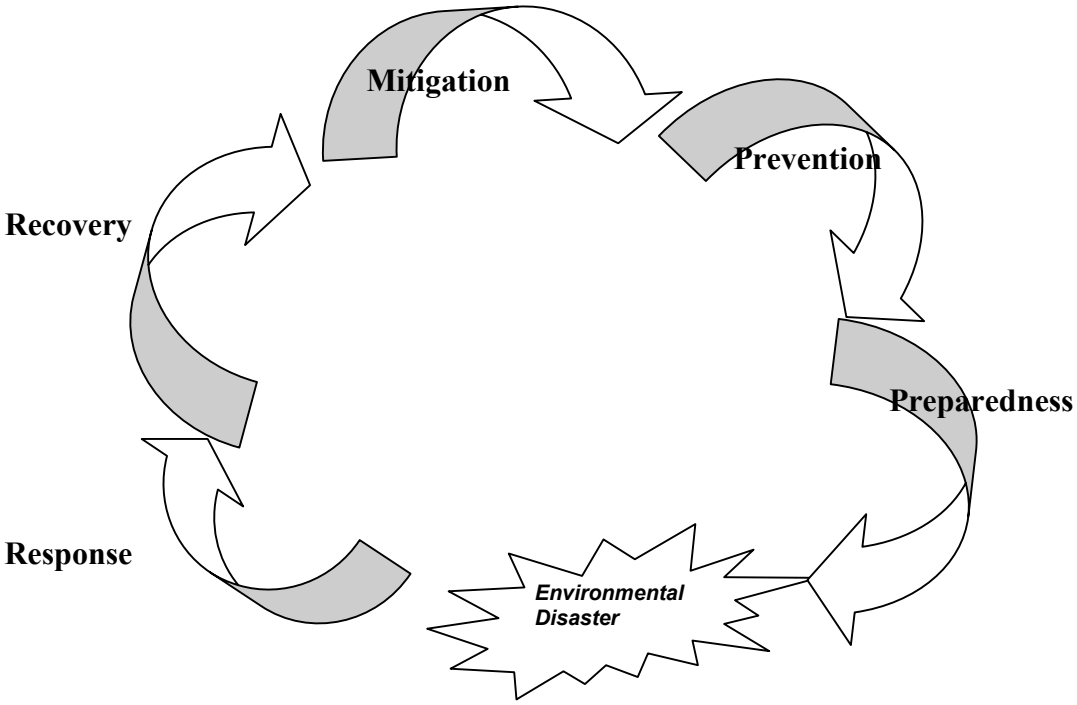
Use of GIS software application for this kind of application provides many benefits: 1) Visual display of the hazard, risk, and expected damage values; 2) Use of spatial modeling techniques to carry out the analysis using the GIS data layers as input; 3) Faster and efficient handling of huge and complex dataset.

Depending upon the nature of environmental risk insurance policy, some other complexities many also be integrated in the system. For example, it may be important to assess the health risks, by measuring the chances that the people living in certain properties would experience health problems. Exposure to toxic air pollutants can cause serious health risks, and if this were covered in the insurance policy, the ERM system would need to include the data, analysis and output engines related to the health risk factors too.

A catastrophic modeling application for the emergency preparedness and response planning by a city administrator

The natural catastrophes, for example, earthquakes, cyclones, landslides, floods, forest fires, can potentially cause environmental changes in a significant and sudden manner.

Figure 4: A typical disaster management cycle



GIS software applications are extensively used for emergency preparedness and response planning by city administrators in such cases. In a typical disaster management cycle (as indicated in figure 4), disaster prevention, disaster mitigation, and disaster preparedness constitute the pre-disaster planning phase, and response, recovery and mitigation as the post-disaster planning phase. Pre-disaster steps are more useful since they help in preparing for the disasters in advance, however, proper post-disaster planning is equally important to cope up with the immediate impact of a disaster, as and when it occurs.

It involves responding to disasters by the city administrators and various organizations, providing many services that need to be mobilized at a moment's notice and functioning for an indeterminate period in a coordinated manner under stressful and difficult circumstances. These may be demobilized after the emergency is over. The ability of a city administrator to manage the emergencies in a proactive manner, rather than just react to the crises, is critically dependent on the availability and flow of real time and archived information from monitoring systems, thematic databases, and decision support systems that are linked to each other.

Use of GIS would be a necessity in these cases, in view of the spatial nature of the input as well as output data, and the software-based analysis engines would provide the abilities for fast and accurate analysis of the possible scenarios. Hence, a robust GIS software ERM application can be very effectively used for this purpose. It would comprise of a set of smaller sub-systems for 1) displaying the past hazard and loss data, 2) displaying the human, property and ecological exposure data, 3) storing the emergency management related departments' locations, contact details and capacity, 4) linkages with real time, online systems for tracking and communication of the hazard and
damage spread; and 5) models for risk analysis and resource mobilization based on the available data; etc. Having a "rules engine" would be an important part of this system, wherein a set of recommended thresholds and recommendations would be stored, enabling the automatic triggering of certain basic actions in the event of a catastrophe, while the advance actions or escalations would remain at the discretion of the city administrator.

Conclusion

A framework for developing GIS software applications for environmental risk management was described in this paper, along with three specific examples of its usage by different type of users. The advantages of using GIS software based ERM applications are immense, and these applications are increasingly being used by a wide variety of users. With the availability of a good range of GIS software technology options, for desktop, Intranet or Internet environments, it is becoming increasingly possible to develop such ERM systems in an efficient and timely manner.

Use of component based architecture allows modeling of a complex system with multiple and scalable components. However, besides the usage of appropriate architecture and spatial modeling technology, the use of expert opinion remains a very important factor in the success of such knowledge-based systems.

Within such a comprehensive GIS software based ERM system, the results obtained from spatial and analytical modeling tools for environmental risk assessment can be used in different ways – for example, for comparative (or relative) risk analysis, cost-benefit analysis, scenario analysis, probabilistic analysis, decision matrix, sensitivity analysis etc.

In conclusion, due to the need for displaying and analyzing a huge volume of the spatial as well as non-spatial environmental hazards and exposure data in a fast and accurate way, and also due to the progressive increase in the g-Readiness of the users, GIS based software applications would continue to serve as powerful tools for effective environmental risk assessment and management.