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GIS in emergency management

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This chapter examines the role of GIS in emergency management through the lens of comprehensive emergency management (CEM) and its four phases: mitigation, preparedness, response, and recovery. The primary concern before a potential disaster is mitigating the impact of a hazard. Here GIS is gaining favour in risk assessment and the development of long-term mitigation strategies. In the preparedness and response phases, GIS may serve either as the integrating centrepiece for a comprehensive disaster preparedness and response system or as a portable, on-site source of spatial information. In the wake of a disaster, GIS is becoming integral in supporting damage assessment, rebuilding, and public education. The chapter concludes with an example application of GIS in emergency planning: evacuation vulnerability mapping.

1 INTRODUCTION

Hoetmer defines emergency management as the discipline and profession of applying science, technology, planning, and management to deal with extreme events that can injure or kill large numbers of people, do extensive damage to property, and disrupt community life (Drabek and Hoetmer 1991). Recently, there has been increased interest in mitigating the effects of these extreme events, and this is exemplified by the United Nations' declaration of the *International Decade for Natural Disaster Reduction* (IDNDR) in 1990 and the Federal Emergency Management Agency's (FEMA) *National Mitigation Strategy: Partnerships for Building Safer Communities* in the USA.

In dealing with these extreme events, many of the critical problems that arise are inherently spatial. Whether an analyst is assessing the potential impact of a hazard, or an emergency manager is identifying the best evacuation routes during a disaster, or a civil engineer is planning a rebuilding effort following a disaster, all of these individuals face tasks with a strong spatial component. For this reason, geographical space is a valuable framework for reasoning about many problems that arise in the context of emergency management.

GIS were designed to support geographical inquiry and, ultimately, spatial decision making. The value of GIS in emergency management arises directly from the benefits of integrating a technology designed to support spatial decision making into a field with a strong need to address numerous critical spatial decisions. For this reason, new applications of GIS in emergency management have flourished in recent years along with an interest in furthering this trend. In addition to this growing interest, the adoption of GIS into the emergency management arena has been bolstered in some countries by favourable legislation regarding the use of spatial information in emergency (see, for example, Mondschein 1994).

There is a variety of interesting perspectives on GIS in emergency management, and this is evidenced by recent speculations on this topic (Bruzewicz 1994; Johnson 1992; Mondschein 1994; Newsom and Mitani 1993) and closely related topics like GIS in natural hazards (Coppock 1995; Dangermond 1991; Wadge et al 1993), risk (Rejeski 1993), and environmental hazards (Emani 1996; Gatrell and Vincent 1991; Vaughn 1996). Although this attention indicates that the use of GIS in emergency planning is increasing, it is still a relatively young academic research area with few refereed journal articles. For this reason conference proceedings, trade journals, and technical reports are essential in getting a complete picture of what is taking place in this area. However, like many other GIS applications, emergency management is not isolated, and there are numerous related theoretical, management, application, and technical innovations that affect this application arena, as detailed elsewhere in this book and as summarised in Figure 1.

The focus of this chapter is on the role of GIS in managing sudden impact disasters like floods and fires, rather than on slow onset hazards like radon, water pollution, land erosion, or other natural or technological hazards that occur gradually over time. The chapter purpose is twofold: first to review a number of example applications of GIS in emergencies; and, second, to demonstrate an example application of GIS in regional evacuation analysis, namely evacuation vulnerability mapping. In this way, the chapter can be viewed as a synoptic discussion of GIS in emergency management followed by a demonstration of one particular application.

2 CONCEPTUAL BACKGROUND

2.1 Comprehensive emergency management

An important step in examining the role of GIS in emergency management is selecting a conceptual framework to help organise existing research and development activities. One such framework that appears widely in the emergency management literature is *comprehensive emergency management (CEM)* (Drabek and Hoetmer 1991). This relies on the temporal dimension of disasters to organise the emergency management process into a cycle of four, often overlapping, phases: mitigation, preparedness, response, and recovery, as shown in Figure 2. Mitigation involves actions that are taken to eliminate or reduce the degree of long-term risk to human life and property from hazards. Preparedness is concerned with actions that are taken in advance of an emergency to develop operational capabilities and facilitate an effective response to an emergency. The response phase involves actions that are taken

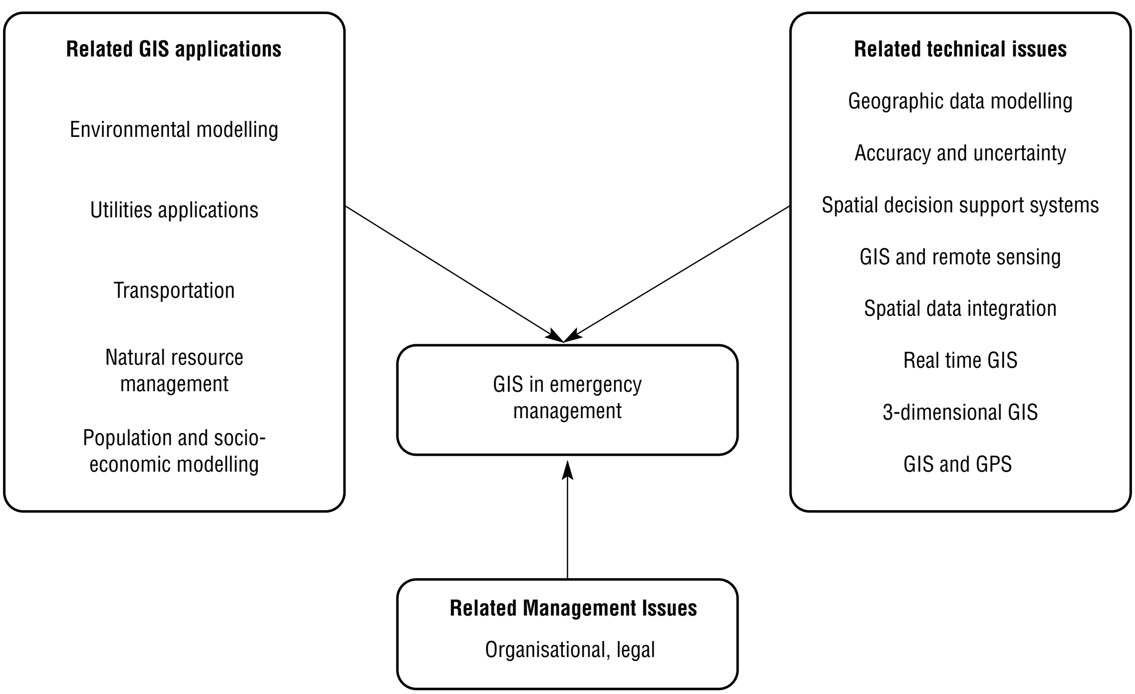

Fig 1. GIS in emergency management and related areas.

immediately before, during, or directly after an emergency occurs, to save lives, minimise damage to property, and enhance the effectiveness of recovery. The recovery phase is characterised by activity to return life to normal or improved levels.

In examining the GIS literature, perhaps it is more appropriate to reduce the four phases of comprehensive emergency management into three phases: mitigation, preparedness and response, and recovery. This is simply because many GIS developed in the preparedness phase are utilised in the response phase. In other words, systems designed to help emergency managers respond to an actual disaster are frequently utilised to train emergency personnel and develop preparedness plans. From a GIS perspective, this serves to blur the preparedness and response phases into a single phase. However, GIS applications in the phases of mitigation (e.g. risk mapping) and recovery (e.g. damage assessment) are clearly distinct from the proposed merged preparedness and response phases.

2.2 Hazard, vulnerability, and risk

Another relevant area to address is *environmental hazards*. A few fundamental concepts that appear in this area are: natural hazard, technological hazard, vulnerability, risk, and disaster. As these terms often escape precise definition, there is a host of definitions and conceptual models that relate these terms (Alexander 1993; Burton et al 1993; Cutter 1996; Godschalk 1991; Palm 1990; Smith 1992).

Godschalk (1991: 132) provides a succinct set of working definitions for these concepts where a *hazard* is some threat, natural, technological, or civil to people, property, and the environment. *Risk* is viewed as the probability that a hazard will occur during a particular time period. *Vulnerability* is

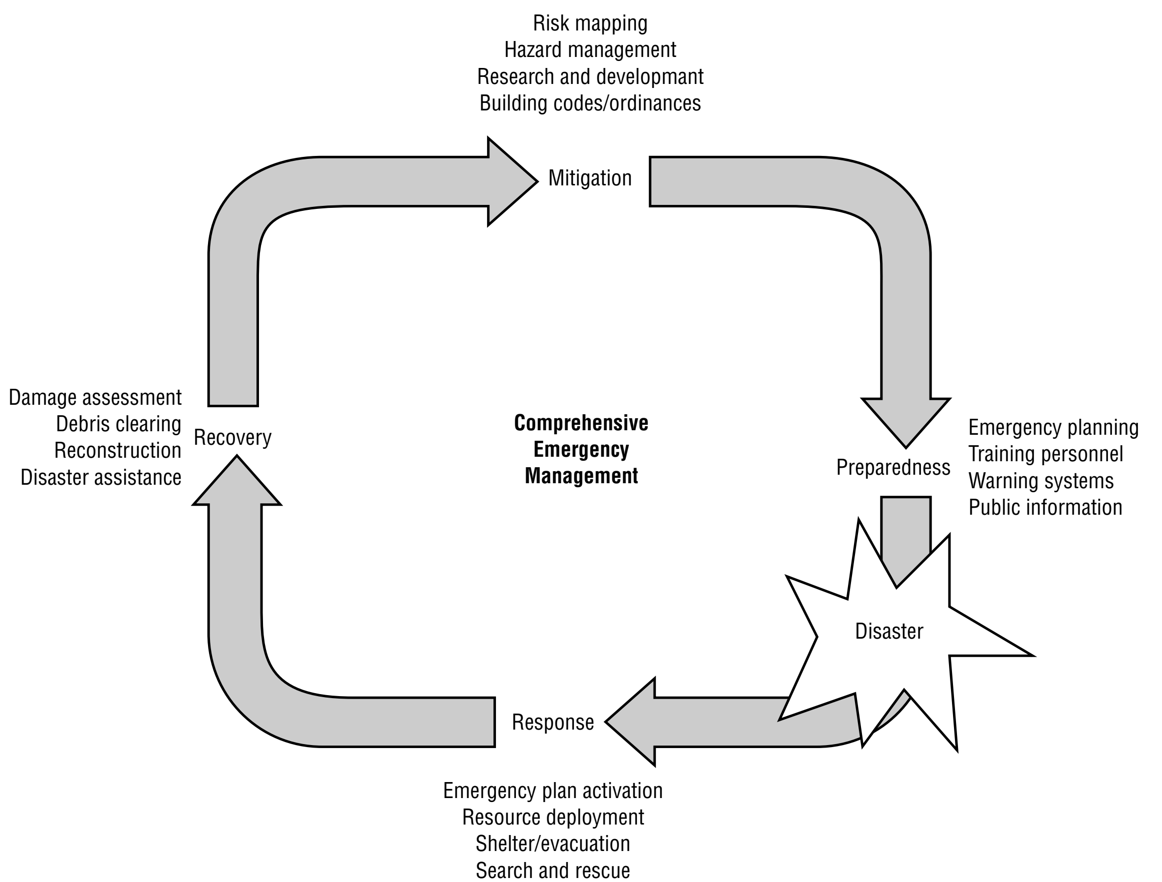

Fig 2. Comprehensive emergency management and a few examples during each phase where GIS plays a role (adapted from Godschalk 1991).

susceptibility to injury or damage from hazards. A *disaster* is a hazard occurrence resulting in significant injury or damage. As an example, a flood is a natural hazard; flood risk is defined in terms of the hundred-year flood; the people and buildings located within the hundred-year flood zone are vulnerable, and a flood disaster is a flood that injures a number of people, or causes significant damage.

Alexander (1993) has taken a relatively formal approach to this process by using conceptual equations, a system that lends itself well to the perspective of a GIS research community who often strive to formalise (see Johnston, Chapter 3). In Alexander's framework, a hazard is a pre-disaster situation where some risk of disaster exists, principally because the human population has made itself vulnerable in some way. In this framework, risk is viewed as a combination of hazard and vulnerability. Alexander highlights a formal definition relating risk to hazard and vulnerability originally provided by the Office of the United Nations Disaster Relief Co-ordinator (UNDRO) where:

$$Risk = elements\ at\ risk \cdot (hazard \cdot vulnerability)$$

Thus, risk is viewed as a function of the elements at risk, the hazard, and the vulnerability to that particular hazard. This is appealing from a GIS perspective as the elements at risk can be viewed as spatial information layers (e.g. population, properties, and infrastructure) and these layers can be combined through spatial modelling procedures to arrive at an effective estimate of hazard, vulnerability, and risk. This topic is taken up further in the subsequent section on risk mapping.

3 GIS ROLES IN EMERGENCY MANAGEMENT

3.1 Mitigation

In the emergency management phase well before a disaster, or more appropriately 'between disasters', the overarching goal is mitigation. Perhaps the most active role of GIS in this area relates to analytical modelling. This is a phase characterised by the opportunity to conduct long-term assessment, planning, forecasting, and management. Table 1 shows some of the spatial questions that have been posed in this phase along with the resulting application area and representative examples from the GIS literature.

One of the key avenues of inquiry in this phase is revealing the inherent spatial variation in hazard, vulnerability, and ultimately risk. Figure 3 shows one way in which the concepts of risk, hazard, and vulnerability are frequently related in a GIS context. The hazard and vulnerability elements exist as spatial layers and the concepts of hazard, vulnerability, and risk are couched in a spatial modelling process. This framework is a variation of the UNDRO equation described above where:

$$Risk = R(H(E_h), V(E_v))$$

As such, hazard is a function H of the hazard elements E_h, vulnerability is a function V of the vulnerability elements E_v, and risk is a function R of the results of the hazard and vulnerability functions. The task of developing spatial models for a wide array of hazards and their associated vulnerability is a significant GIS research focus in this phase. The risk mapping section of Table 1 is divided into natural hazard mapping, vulnerability mapping, and risk mapping. The division between vulnerability and natural hazards follows the familiar human/physical divide in environmental studies, where risk can be viewed as a primitive unification of the two worlds.

In natural hazard mapping, the primary focus is on the physical environment and its associated processes, although humans may intervene through resource management strategies like fire suppression, levy construction, or land use. In general, the human vulnerability component in this class of study is implicit. Wadge et al (1993) note that for natural hazards, the hazard model is generally either an inductive combination of the hazard layers (spatial coincidence) or a deterministic model of a physical process.

In contrast to natural hazard studies, GIS vulnerability studies generally focus on the human environment, where the hazard is either implicit or primitively modelled. In its most reduced form, vulnerability is simply population density, but there are much richer conceptualisations of vulnerability available. An interesting micro/macro division in vulnerability analysis is developing, whereby some studies focus on the vulnerability of individual structures (McLaren 1992), while others focus on the vulnerability of aggregate populations (Emani et al 1993). Conducting vulnerability studies using GIS is a relatively new research area, but the potential for GIS

Table 1 Example GIS inroads into the mitigation phase.

Spatial question	*Application arena*	*GIS examples*
What is the inherent spatial variation in the potential for a natural hazard?	Natural hazard assessment and mapping (emphasis on physical environment with implied vulnerability)	Avalanche and lava flow (Wadge 1988) Wildfire (Chou 1992) Landslide (Shu-Quiang and Unwin 1992) Hurricane (Watson 1992) Earthquake (Emmi and Horton 1995) Volcano (Kauahikaua et al 1995) Flood (Lanza and Siccardi 1995) Urban wildfire (Radke 1995)
What is the inherent spatial variation in human environmental vulnerability?	Vulnerability assessment and mapping (emphasis on human environment with implied hazard)	Toxic materials storage (McMaster 1988) Earthquake response (Hodgson and Palm 1992) Utilities lifelines (McLaren 1992) Environmental equity (Burke 1993) Extreme storms (Emani et al 1993) Contaminants (Lowry et al 1995) Plume analysis (Chakraborty and Armstrong 1966) Evacuation vulnerability (Cova and Church 1997) Contaminants (Lowry et al 1995) Plume analysis (Chakraborty and Armstrong 1966)
What is the inherent spatial variation in risk?	Risk assessment and mapping (emphasis on hazard and vulnerability)	HAZMAT management (Estes et al 1987) Seismic risk and bridges (Kim et al 1992) Toxic site inventory (Stockwell et al 1993) Arson (Vega-Garcia et al 1993) Toxic waste transport (Brainard et al 1996)
Which spatial strategy can be developed to reduce the effects of a particular hazard phenomenon?	Hazard mitigation	Fire (Kessel 1990) Flood (Bocco et al 1995)
Which spatial strategy can be developed to reduce human vulnerability to a particular hazard?	Vulnerability mitigation	Hurricane (Watson 1992) Earthquake (King et al 1995a) Flood (Bocco et al 1995)

to illuminate spatial issues in this area is becoming clear (Johnson 1994; Granger 1995).

The GIS risk mapping category of Table 1 highlights examples where the researchers strike a relative balance between modelling hazard and vulnerability. Figure 4 shows a few iconic examples of how hazard and vulnerability have been conceptualised and combined to arrive at an assessment of risk. Mejia-Navarro et al (1994) provide a nice example of this overall process for geological hazards in Glenwood Springs, Colorado, USA. Their interest was in assessing the risk of debris flows, so as to classify land parcels as either suitable for human settlement or better reserved for parks and forests. In their study, hazard is the potential for a debris flow and vulnerability is a land parcel's susceptibility to debris flow. Vulnerability is a function of *both* physical (e.g. slope and vegetation) and human (e.g. land use) elements. This study is indicative of the freedom available to researchers in defining hazard, vulnerability, and risk in addressing a particular problem.

Ultimately, risk assessment is intended to support the development of mitigation strategies, where these strategies relate to either reducing the physical force of a hazard or reducing vulnerability to that hazard. The degree to which mitigation strategies can be developed and adopted varies by hazard type.

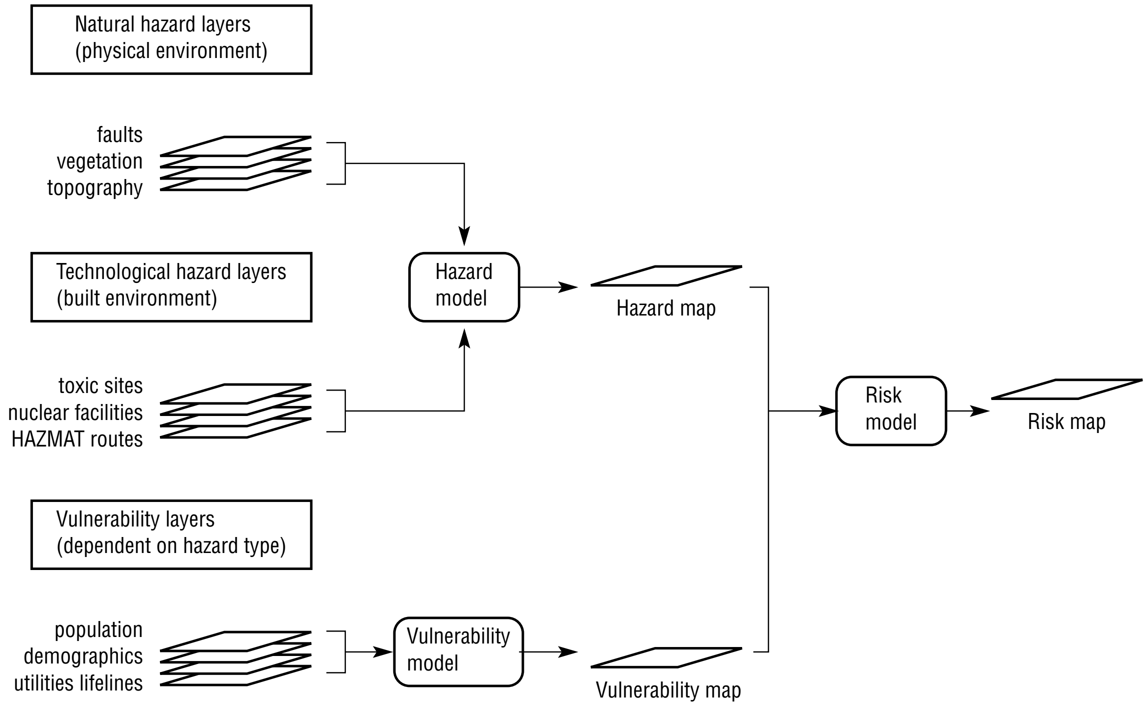

Fig 3. One approach to modelling the concepts of hazard, vulnerability, and risk in a GIS context.

Clearly, for some natural hazards like hurricanes there is little that can be done to mitigate the physical forces behind the hazard phenomenon. Thus, hurricane mitigation efforts focus on reducing human vulnerability through strategies like structure reinforcement, shelter assignment, or evacuation planning. However, some natural hazards like urban wildfire offer the opportunity to manage the hazard (e.g. vegetation management) as well as vulnerability (e.g. fire retardant building materials). This also holds for technological hazards, as the hazard and vulnerability are both created by humans.

3.2 Preparedness and response

In the preparedness and response phase, GIS is primarily utilised to help formulate and execute emergency response plans. Emergency managers take centre stage in this phase, which is frequently characterised by urgent, mission-critical decision-making. The tremendous demand for timely, accurate answers to geographical queries makes this GIS application area unique. The primary benefits of GIS in this phase lie in spatial information integration and dissemination. Emergency management personnel need to know where an event is occurring in order to minimise further loss and effectively deploy relief. GIS development activity in this phase currently focuses on designing comprehensive disaster management systems to serve the information needs of emergency management personnel under various disaster scenarios, such as those listed in Table 2.

Undoubtedly, one of the most ambitious of these projects is FEMA's All-hazard Situation Assessment Programme (ASAP), designed to support the short-term assessment of hurricanes, storm surges, floods, chemical spills, earthquakes, urban and wildland fires, and chemical releases (Linz and Bryant 1994). GIS help integrate information from different sources, scales, accuracies, and formats into a single source that can be utilised for modelling, mapping, and spatial decision support. These systems may be used for training (preparedness) or in responding to actual emergencies. Innovations in real-time GIS (Raper, Chapter 5; Peuquet, Chapter 8; Elliot 1994), remote sensing (Barnsley, Chapter 32; Rosenfeld et al 1996), interoperable GIS (Sondheim et al, Chapter 24), and

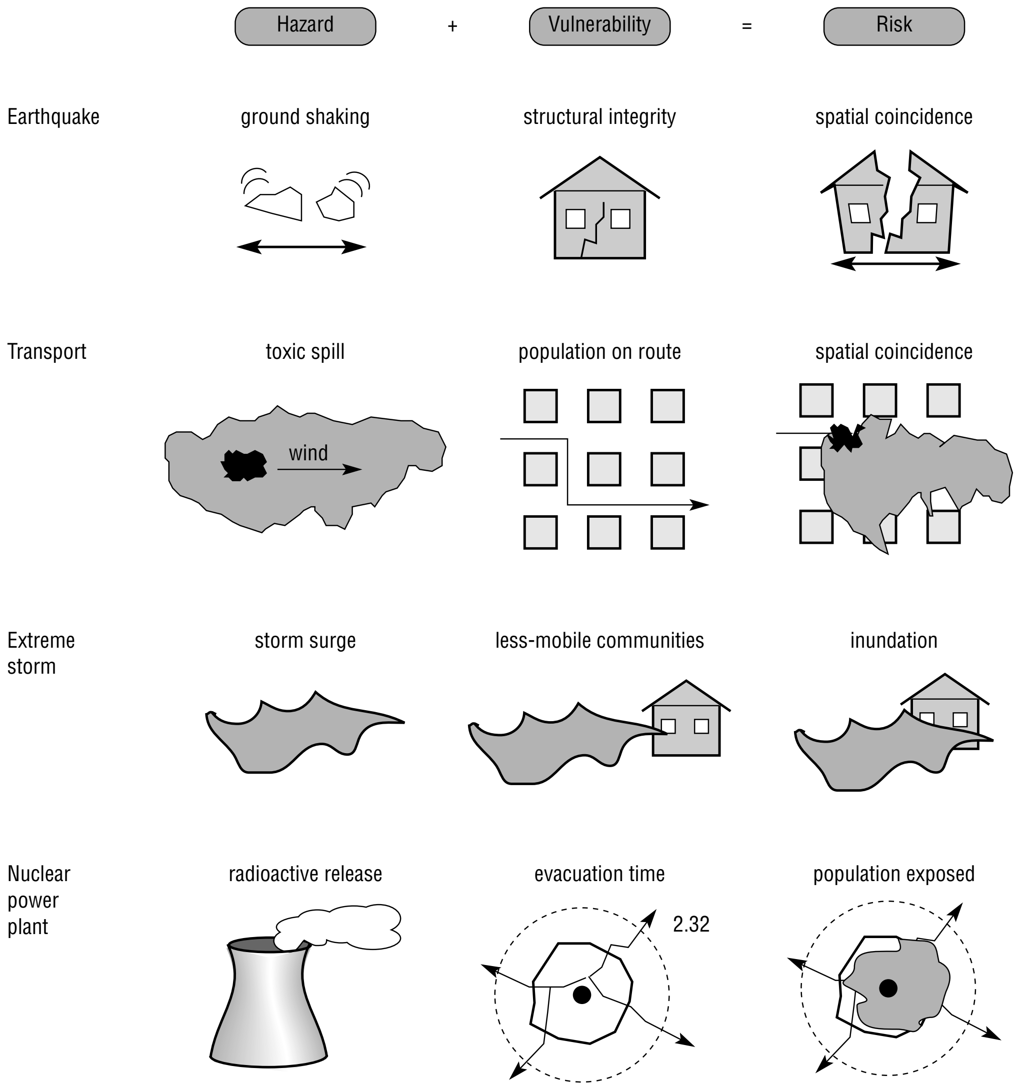

Fig 4. Examples of how hazard, vulnerability, and risk have been conceptualised in a GIS context.

the Internet (Coleman, Chapter 22) are having a significant and beneficial impact on research and development in this phase. Effective communication is paramount in this phase and for some hazard types, like hurricanes and floods, GIS is being utilised in a real-time monitoring and warning context.

One of the hallmark applications in the preparedness and response phase is automated mapping. Dymon (1990) has noted the value of maps during this phase which include:

- coordinating the efforts of emergency groups;
- providing the public with guidance;
- aiding the flow of resources during and after a disaster;
- revealing the elements at work in a geographical area;
- visualising the physical constraints of the incident site;
- producing public relations information.

Corbley (1995) conveyed many of these points in an article on the value of GIS during the immediate aftermath of Hurricane Andrew which struck the USA in 1992. The GIS in this case was developed by the South Florida Water Management District

Table 2 Example GIS inroads into the preparedness and response phase.

Spatial question	*Application arena*	*GIS examples*
What is the spatial extent of the impacted area, and what are the expected losses?	Disaster preparedness and response systems	Earthquake (Routh 1990) Oil spill at sea (Friel et al 1993) Dam failure (Kragt et al 1993) Forest fire (Goulstone-Grunland et al 1994) All hazards (Linz and Bryant 1994) Chemical spill (Lu and Xiang 1995) Flood (Fulcher et al 1995) Radiological accident (Guber et al 1995) Hurricane (Corbley 1995)
Which are the best routes available for emergency vehicle deployment?	Emergency vehicle routing	Automatic vehicle location (Zografos and Dougligeris 1991) Fleet management (Karimi 1993)
How can we identify good evacuation routes and develop evacuation plans?	Evacuation planning	Path analysis (Dunn 1992) Simulation modelling (Silva et al 1993) Evacuation vulnerability (Cova and Church 1997)
Which populations need to be evacuated?	Evacuation zoning	Chemical spill (Cartwright 1990) Hurricane (Corbley 1995)
How can we immediately locate an emergency caller on a map?	Enhanced 911 (E-911 emergency calls)	All emergencies (Fitzgibbon 1993)

(SFWMD) for routine and emergency management of water resources. Some of the problems that South Florida faced immediately following the hurricane included tracking debris pickup to keep the canals flowing, clearing downed trees and power lines, directing disaster relief efforts, and monitoring burn sites in an attempt to prevent the ensuing rains from washing hazardous waste into canals. Automated mapping played an essential role in addressing many of these tasks, as maps provided crews with the necessary information to deal with many of these problems. One challenge was simply navigation, as landmarks had been erased by the hurricane. The transportation network layer quickly became the most valuable information source. Corbley notes that the GIS must survive the disaster to assist in this phase, thus distributing a spatial database across sites or via the Internet is an important security measure. Increasing dependence on GIS during future disasters may lead to the notion of a *spatial information lifeline*. As circular as it may sound, a GIS lifeline analysis regarding the risk incurred due to the loss of a critical GIS during a disaster may be a likely study in the future.

Another GIS role in the preparedness and response phases relates to hazard modelling, which differs slightly from the hazard modelling in risk assessment. In this context the disaster *is* occurring, and it is possible to gather many of the environmental parameters to aid in short-term prediction. One example of this class of hazard models is the US National Oceanic and Atmospheric Administration's (NOAA) sea, lake, and overland surge from hurricane (SLOSH) model (Griffith 1986). SLOSH is a simulation model that uses current wind speed, direction, precipitation predictions, and topography to predict land areas most likely to be submerged during a storm, to aid in evacuation planning. The model output can be integrated into a GIS as another spatial layer to support further inquiry. CAMEO (Cartwright 1990) is another well known hazard model in use by HAZMAT teams in the USA that supports response efforts during chemical spills. CAMEO has three modules that allow a user to identify hazardous chemicals and their risks, display spatial information about an area, and model atmospheric plume dispersal respectively. It is designed to be carried on emergency vehicles, an anticipated trend in GIS development for this phase.

Another preparedness and response strategy that has received attention in GIS and emergency management is evacuation planning. Dunn (1992) has examined the potential role of GIS in generating alternative evacuation routes, Silva et al (1993) have developed and integrated an evacuation simulation model into a GIS to support the development of evacuation contingency plans around nuclear facilities, and Cova and Church (1997) describe a GIS-based method for revealing potential evacuation difficulties in advance of a disaster.

3.3 Recovery

In the recovery phase after the initial relief has been provided and the goal is returning life to normal or improved circumstances, a GIS can serve as a spatial inventory system for coordinating recovery activities. Table 3 shows some of the spatial questions that arise in this phase with the resulting application arena and a few representative examples. Government agencies, policy makers, and civil engineers figure prominently in this phase. Some of the challenges during recovery include assessing the damage, assuaging and educating the public, rebuilding, and preventing reoccurrence. The goal of preventing reoccurrence ties the comprehensive emergency management cycle back to the mitigation phase.

Difani and Dolton (1992) note that during the recovery phase an initial priority is performing a cursory damage assessment to minimise the time necessary to apply for government relief. Following the Oakland, California fire and Florida's Hurricane Andrew in 1992, this process was complicated by the fact that nearly everything in the disaster zone had been obliterated. Officials had difficulty navigating without landmarks to assess structures that were no longer there. Also, GIS can help in managing the tremendous spatial detail associated with a structure by structure damage assessment. In the Oakland fire each of the 2500-plus structures was assessed with a 12 page, 203 question survey (Difani and Dolton 1992). The Global Positioning System (GPS: see Lange and Gilbert, Chapter 33) was also invaluable in this phase for gathering locational information. During the Oakland fire, GPS and GIS were used to map the fire perimeter and georeference the location and number of each damaged or destroyed structure. This information was then overlaid with census data and existing parcel maps to assess individual losses to help support the process of applying for rebuilding loans and grants. Environmental information layers were also utilised (e.g. scarred soils, riparian damage) to prevent mud slides and erosion. The overall application of GIS in the Oakland fire inspired a fire risk assessment study of other similar areas in California. An increase in adoption of GIS technology following disasters is a general trend.

Table 3 Example GIS inroads into the recovery phase.

Spatial question	*Application arena*	*GIS examples*
What can be done to assist in managing the spatial detail associated with assessing the losses from a disaster?	Damage assessment	Urban fire (Difani and Dolton 1992) Earthquake (King et al 1995b) Hurricane (Corbley 1995) Nuclear meltdown (Jones et al 1995)
How can we track the recovery and rebuilding efforts over time?	Recovery analysis	Hurricane (Harrison 1995)
What can be done to develop a historical spatial database of prior hazard events?	Disaster database design	Landslides (Harp 1995) All disasters (Dymon and Platt 1995)
What can be done to educate the public on the spatial consequences of a prior disaster?	Risk education	Nuclear meltdown (Battista 1994)

Another significant issue in the recovery phase is educating the public. Battista (1994) describes a project for educating the public within the contaminated zone surrounding the site of the Chernobyl radioactive release. A GIS was developed to help people who live in the contaminated areas lower the radiation in their diet. Farmers are shown how much and what type of radiation is absorbed from the soil by various crop planting strategies. They can then plant to maximise (cleanse) or minimise (harvest) the amount of radiation absorbed by a particular crop. The key value of GIS relates to the inherent spatial variation in radiation absorption levels across a landscape.

4 EXAMPLE APPLICATION: MAPPING REGIONAL EVACUATION VULNERABILITY

One of the most effective response strategies available to emergency managers during a disaster is evacuation. For this reason, there is great interest in developing sound evacuation plans for many communities subject to known hazards. Dunn (1992), Cova and Church (1997), and Silva et al (1993) have utilised GIS to address various problems in this context. This section examines one example application of GIS in regional evacuation analysis: evacuation vulnerability mapping.

A significant problem that arises in long-term regional evacuation planning involves establishing a credible emergency planning zone (EPZ) in advance of a disaster to serve as a zone to evacuate during an emergency. An EPZ is a valuable spatial construct as it tells an analyst who needs to be evacuated (population in the zone) and where they need to be routed to reach safety (outside of the zone). As Sorensen et al (1992) note, delimiting a credible EPZ can be a significant political and technical endeavour. For nuclear power plants, this zone is generally a 10-mile radius around the plant.

However, a credible EPZ is nearly impossible to establish in the context of hazards with a highly uncertain spatial impact. As Gatrell and Vincent (1991) note, the effects of hazards can occur in an untimely fashion in the most improbable of places. Urban firestorms and toxic highway spills are two examples where a credible EPZ simply cannot be established in advance of a disaster. These hazards often strike with little or no warning, require immediate clearance of a localised area, and can result in significant traffic congestion, an increase in the potential for accidents, and the frequent loss of evacuation routes due to the hazard.

Cova and Church (1997) have proposed one method for addressing this problem. Rather than focusing on any single zone to evacuate, it is possible to view regional evacuation as a generic spatial process (Perry 1985) and pursue the nature of the space that comprises all possible evacuations. Formalising this space and a measure for evacuation difficulty allows an analyst to perform a spatial search for the most difficult evacuations that might occur in a given region. Systematically mapping the results of this search in a GIS environment led to the concept of *evacuation vulnerability mapping*.

The process relies on a network data model of geographical space, where people are assigned to their nearest intersection (node) in the network using Thiessen polygons (see Boots, Chapter 36). A valid evacuation is any contiguous subset of nodes (Thiessen polygon centroids) in the network. The links connecting this set of nodes to the rest of the network are considered the *exit choice set* for that particular evacuation. Although the definition of evacuation difficulty is flexible within this method, one definition is simply the population involved in the evacuation over the number of lanes connecting the population to the rest of the network, or:

evacuation difficulty = population/number of exit lanes

With this definition, it becomes possible to inquire as to the worst case evacuation *starting scenario* that the residents assigned to a particular intersection might experience (maximum difficulty). For this question to be meaningful, however, evacuation size must be constrained, as the global worst case evacuation in any urban area is almost always the entire urban area. However, with a limit on the size of an evacuation, it is possible to reveal local variation in evacuation vulnerability from node to node. The maximum difficulty value for a given node and given evacuation size is referred to as a node's *spatial evacuation vulnerability*. Figure 5 shows three potential evacuations that all contain the node labelled A: each node has 100 people, and each link has one lane in each direction. The nodes involved in the evacuation are shown in black and the exits are shown as bold arrows. The population assigned to each node (Thiessen polygon) is shown with dashed lines. Population in the shaded zones needs to be evacuated in each case. In the left and centre cases, there are three exits, but in the right case there are only two. The right case is node A's worst case (maximum average population per lane) evacuation because there are 300 evacuees per exit lane, where there are only 200 per exit lane in the other two cases.

Currently, there is a need for research into various methods for constraining evacuation size and the resulting effect these methods have on the definition of spatial evacuation vulnerability. At this point, limiting the number of nodes (intersections) in an evacuation has revealed some intriguing neighbourhood configurations, but a simple distance measure may be more appropriate when node density varies substantially in a network.

The process of producing an evacuation vulnerability map is, then, one of moving from node to node in a network and satisfying the query regarding the worst case evacuation scenario.

This process can be accomplished by 'growing' a cluster beginning at each node in an attempt to find a node's worst-case evacuation. The underlying GIS query on which this algorithm is based is requesting a node's *forward star*. A forward star refers to the set of immediately adjacent arcs that can be reached from a given node. For cartographic purposes, each link is assigned the worst case spatial evacuation vulnerability values of its two end nodes.

The data requirements for an evacuation study of this nature are minimal. Census data provide the population information and a representation of the road network can normally be acquired. However, a significant zone to zone areal interpolation problem remains in mapping the census population areas to Thiessen polygons defined around the intersections in the network. Flowerdew and Green (1992) have researched various methods for accomplishing zone to zone transfers.

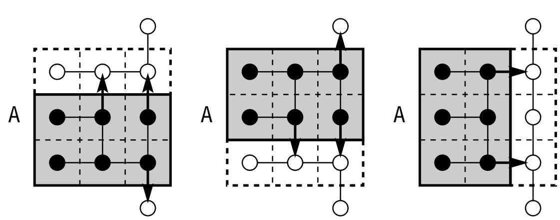

Fig 5. Three potential evacuations of six nodes that all contain the node labelled A.

Plates 51–54 show an evacuation vulnerability map for the Santa Barbara, California area. The evacuation size limit in all the plate maps was set to 25 nodes. This serves to focus the search on very small-scale evacuations. The thematic map scale of each plate map is the average number of evacuees per lane in a link's worst case evacuation. Plates 52 and 53 show local areas in Santa Barbara where it is easier to decipher the model output. The red neighbourhoods would have an average number of evacuees per lane greater than 500 in a worst case evacuation. For this reason, these neighbourhoods represent evacuation 'hot spots' and should be examined further. How many vehicles are there in these neighbourhoods? Does the neighbourhood have an evacuation plan? 'Worst case' in this context refers to the maximum average number of evacuees per exit lane, but in an actual evacuation, the number of evacuees utilising various exits would not be equal. This is because exits might be removed by a hazard (e.g. fire or flood), or human behaviour might result in an inordinate number of people utilising one exit. However, the maximum average number of people per lane still reveals interesting spatial variation regarding the initial starting conditions of various evacuations.

Plate 54 shows the effect of a road construction project (green link). Before the green link is added, there are two relatively close, but loosely connected, neighbourhoods with high spatial evacuation vulnerability values. After the road is built, the local evacuation 'pressure' has been released, and they each have a new exit. Each of these neighbourhoods has dropped one level in its spatial evacuation vulnerability values shown in the legend to Plate 51.

One of the limitations in conducting a study of this type is the lack of population data for various time periods within an urban area. Parrot and Stutz (1991) have noted the importance in emergency management of being able to assess where people are during the day, but daytime population fluctuations are difficult to model, and the approaches that exist tend to model these fluctuations at highly aggregated levels (see Martin, Chapter 6, for a general discussion of this problem). A means for arriving at a detailed representation of where people are in a city at a given time period remains one of the most significant 'unsolved' problems in GIS and emergency management.

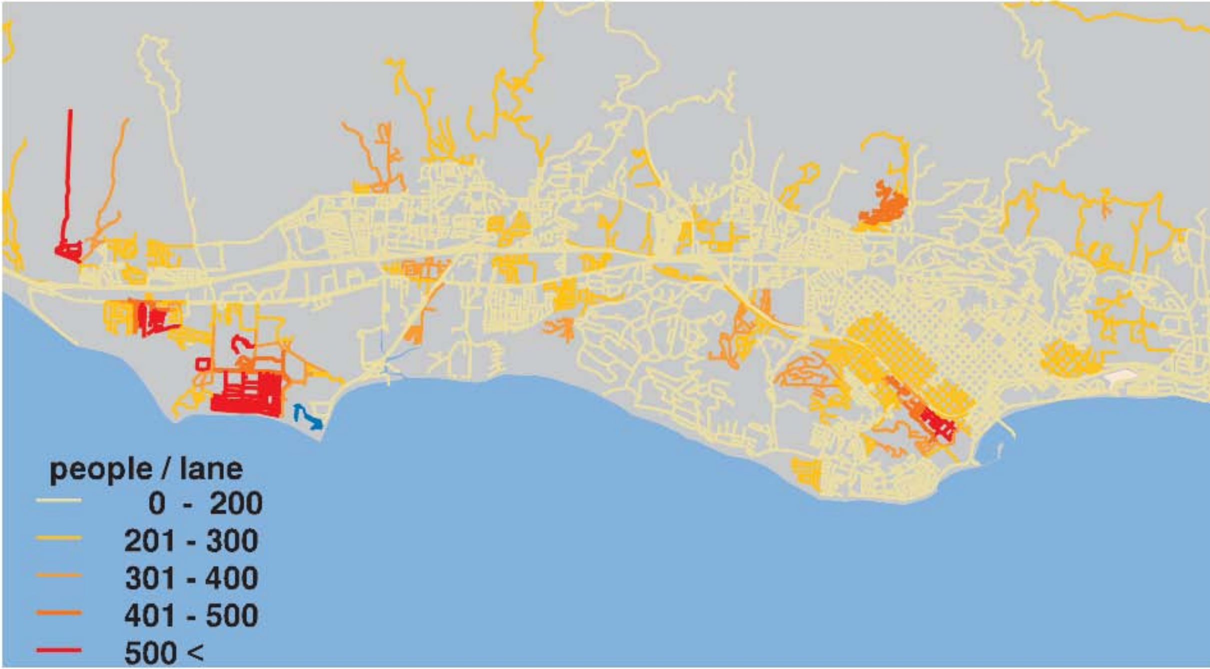

Plate 51 An evacuation vulnerability map for the Santa Barbara, California vicinity.

Plate 52
The Goleta, Santa Barbara, California area. Note the areas in red with a relatively high ratio (500+) of residents to exiting lanes in the worst case evacuation.

Plate 53
Downtown Santa Barbara, California. Note the neighbourhood in red which is sandwiched between a six-lane freeway and a steep hillslope (not shown) leaving only four available exits.

Plate 54
The green link in the lower panel is a currently proposed road project in Goleta, Santa Barbara, California. Note how it lowers the spatial evacuation vulnerability of the two neighbourhoods providing them each with a new exit.

5 THE FUTURE

The level of GIS activity in emergency management may be increasing, but in the eyes of the emergency management community, GIS has a long way to go to meet their needs. Numerous challenges still exist in the application of GIS in this area, as well as many of its related fields like hazard mitigation. Coppock (1995) lists five major limitations regarding the application of GIS in hazard mitigation:

- lack of data and the weakness of existing data (see Goodchild and Longley, Chapter 40);
- difficulty in developing, and understanding the error in, GIS models (see Fisher, Chapter 13);
- deficiencies of available software, particularly commercial GIS (see Openshaw and Alvanides, Chapter 18);
- failure to consider the needs of end-users adequately (see Shiffer, Chapter 52);
- lack of lead organisations and necessary infrastructure (see Rhind, Chapter 56).

Some of these limitations are frequently cited as limitations of GIS in general and they were recently reiterated in a session on the realities of GIS use in natural hazards mitigation at the 1996 Hazards Research and Applications Workshop in Colorado, USA. The lack of data for conducting GIS disaster studies and the difficulty in developing and understanding GIS models were cited limitations at this workshop.

In the mitigation phase, it is expected that there will be increasing application of GIS toward the actual development of large-scale, systematic mitigation plans. The last ten years have witnessed a significant increase in risk assessment and mapping using GIS for a wide variety of hazard contexts, but ultimately this work must feed into actual mitigation planning and policy. Risk mapping and modelling will continue to develop and there should be an increase in the use of GIS in developing and testing mitigation strategies for various hazard contexts.

In the preparedness and response phase, there is active research toward the real-time monitoring and management of hazards. This area is closely aligned with developments in remote sensing and GIS. Intelligent transportation systems (ITS) will also have an impact on this phase (see Waters, Chapter 59) and GIS will undoubtedly play a central role in the development of intelligent emergency preparedness and response systems. The Internet and other telecommunication technologies will additionally play a significant role in this phase. The synergy between GIS, ITS, remote sensing, and telecommunications technologies is sure to shape the face of emergency management well into the next century.

In the recovery phase, GIS has already carved out an essential role in damage assessment and rebuilding. It is anticipated that research in this area will focus on automating many of the tasks associated with this phase. Battista (1994), for example, indicates the potential for GIS to be used in educating and informing the public following a disaster. Examples of this type of research are expected to surface for other hazard types.

At this point, the future role of GIS in emergency management is expected to expand significantly as the GIS and emergency management communities continue to pursue innovative solutions to the numerous spatial problems in emergency management and its related fields.

References

Alexander D 1993 *Natural disasters*. New York, Chapman and Hall

Battista C 1994 Chernobyl: GIS model aids nuclear disaster relief. *GIS World* 7(3): 32–5

Bocco G, Sanchez R, Riemann H 1995 GIS affects flood planning efforts. *GIS World* 8(2): 58–60

Brainard J, Lovett A, Parfitt J 1996 Assessing hazardous waste transport risks using a GIS. *International Journal of Geographical Information Systems* 10: 831–49

Bruzewicz A J 1994 Remote sensing and GIS for emergency management. *Proceedings, First Federal Geographic Technology Conference.* Washington DC, GIS World Inc. Vol 1: 161–4

Burke L M 1993 Race and environmental equity: a geographical analysis of Los Angeles. *Geo Info Systems* 3(9): 44–50

Burton I, Kates R W, White G F 1993 *The environment as hazard*. New York, Guilford Press

Cartwright J 1990 CAMEO – present and future. *GIS World* December: 78–80

Chakraborty J, Armstrong M P 1996 Using geographic plume analysis to assess community vulnerability to hazardous accidents. *Computers, Environment and Urban Systems* 19: 341–56

Chou Y H 1992 Management of wildfires with a geographical information system. *International Journal of Geographical Information Systems* 6: 123–40

Coppock J T 1995 GIS and natural hazards: an overview from a GIS perspective. In Carrara A, Guzzetti F (eds) *Geographical information systems in assessing natural hazards.* Dordrecht, Kluwer: 21–34

Corbley K P 1995 South Florida fine-tunes GIS in hurricane's aftermath. *GIS World* 8(9): 40–3

Cova T J, Church R L 1997 Modeling community evacuation using GIS. *International Journal of Geographical Information Science* 11: 763–84

Cutter S L 1996 Vulnerability to environmental hazards. *Progress in Human Geography* 20: 429–39

Dangermond J 1991 Applications of GIS to the international decade for natural hazards reduction. *Proceedings, Fourth International Conference on Seismic Zonation.* Oakland, Stanford University, Earthquake Engineering Research Institute 3: 445–68

Difani C, Dolton L 1992 Battling the Oakland fire with GIS. *GIS World* 5(1): 43–5

Drabek T E, Hoetmer G J (eds) 1991 *Emergency management: principles and practice for local government*. Washington DC, International City Management Association

Dunn C E 1992 Optimal routes in GIS and emergency planning applications. *Area* 24: 259–67

Dymon U J 1990 The role of emergency mapping in disaster response. *Quick Response Research Report #42*. Colorado, Natural Hazards Research and Applications Information Center

Dymon U J, Platt R H 1995 Mapping the geographic distributions of disasters. *Proceedings GIS/LIS 95. ACSM/ASPRS* 1: 297–301

Elliot S 1994 Real-time GIS in today's world. *Proceedings, First Federal Geographic Technology Conference.* Washington DC, GIS World Inc. Vol. 1: 201–5

Emani S 1996 *Applications in hazard assessment and management*. Explorations in Geographic Information Systems Technology, Vol. 6. Worcester (USA), United Nations Institute for Training and Research (UNITAR)

Emani S, Ratick S J, Clark G E, Dow K 1993 Assessing vulnerability to extreme storm events and sea-level rise using geographical information systems (GIS). *Proceedings, GIS/LIS 93.* Bethesda, ACSM/ASPRS 1: 201–9

Emmi P C, Horton C A 1995 A Monte Carlo simulation of error propagation in a GIS-based assessment of seismic risk. *International Journal of Geographical Information Systems* 9: 447–61

Estes J E, McGwire K C, Fletcher G A, Foresman T W 1987 Coordinating hazardous waste management activities using geographical information systems. *International Journal of Geographical Information Systems* 1: 359–86

Fitzgibbon M 1993 A real-time display interface for emergency management using ARC/INFO. *Proceedings, Thirteenth Annual ESRI User Conference.* Redlands, ESRI 3: 185–92

Flowerdew R, Green M 1992 Developments in areal interpolation methods and GIS. *Annals of Regional Science* 26: 67–78

Friel C, Leary T, Norris H, Sargent B, Warford R 1993 GIS tackles oil spill in Tampa Bay. *GIS World* 6(11): 30–3

Fulcher C, Prato T, Vance S, Zhou Y, Barnett C 1995 Flood impact decision support system for St Charles, Missouri, USA. *Proceedings, Fifteenth Annual ESRI User Conference.* Redlands, ESRI

Gatrell A C, Vincent P 1991 Managing natural and technological hazards. In Masser I, Blakemore M (eds) *Handling geographical information: methodology and potential applications*. Harlow, Longman/New York, John Wiley & Sons, Inc: 148–80

Godschalk D R 1991 Disaster mitigation and hazard management. In Drabek T E, Hoetmer G J (eds) *Emergency management: principles and practice for local government*. Washington DC, International City Management Association: 131–60

Goulstone-Grunland A G, Wei-Ning X, Sox J 1994 GIS, expert system technologies improve forest fire management techniques. *GIS World* 7(2): 32–6

Granger K 1995 Dimensions of vulnerability: the human aspects of disaster. *URISA Proceedings* 1: 238–48

Griffith D A 1986 Hurricane emergency management applications of the SLOSH numerical storm surge prediction model. In Marston S A (ed.) *Terminal disasters: computer applications in emergency management*. Boulder, Boulder Institute of Behavioral Science

Guber A L, Best R G, Chatfield T A, Miller K A 1995 A geographic information system for radiologic emergency response. *Proceedings, Fifteenth Annual ESRI User Conference*. Redlands, ESRI

Harp E, Jibson R 1995 *Inventory of the landslides triggered by the Northridge, California earthquake*. USGS Open File Report: 95–213

Harrison C M 1995 Housing characteristics and population: a GIS analysis of impact and recovery after Hurricane Andrew. *URISA Proceedings* 1: 273–82

Hodgson M E, Palm R 1992 Attitude toward disaster: a GIS design for analyzing human response to earthquake hazards. *Geo Info Systems* July–August: 41–51

Johnson G O 1992 GIS applications in emergency management. *URISA Journal* 4: 66–72

Johnson G O 1994 The value of computer methods for hazards vulnerability analysis. *URISA Proceedings* 1: 661–74

Jones A, Liedekerke M van, Cooper A 1995 Mapping the effects of Chernobyl: using GIS to show the European Perspective. *Proceedings, Fifteenth Annual ESRI User Conference.* Redlands, ESRI

Karimi H A 1993 Autonomous route management and guidance systems (ARMGS): a GIS for emergency fleet management. *Proceedings, First Sharjah Conference on Geographic Information Systems and Applications (GISA 93).* Sharjah: 121–8

Kauahikaua J, Margriter S, Moore R 1995 GIS-aided volcanic activity hazard analysis for the Hawaii geothermal project environmental impact statement. In Carrara A, Guzzetti F (eds) *Geographical information systems in assessing natural hazards.* Dordrecht, Kluwer: 235–57

Kessel S R 1990 An Australian geographical information and modelling system for natural area management. *International Journal of Geographical Information Systems* 4: 333–62

Kim S H, Gaus M P, Lee G, Chang K C 1992 A GIS-based regional risk approach for bridges subjected to earthquakes. *Proceedings, ASCE Specialty Conference on Computing in Civil Engineering, Dallas*: 460–7

King S A, Basoz N I, Kiremidjian, A S, Law K H 1995a Use of GIS for seismic hazard mitigation study. *Proceedings, Second ASCE Congress on Computing in Civil Engineering.* Atlanta

King S A, Kiremidjian A S, Law K H, Basoz N I 1995b Earthquake damage and loss estimation through geographic information systems. *Proceedings, Fifth International Conference on Seismic Zonation, Nice*

Kragt J E, Baker B E, Rourke T J 1993 A GIS decision support tool for modeling and managing flooding and dam failure for the readiness management system. *Proceedings, Thirteenth Annual ESRI User Conference.* Redlands, ESRI 3: 93–101

Lanza L, Siccardi F 1995 The role of GIS as a tool for the assessment of flood hazard at the regional scale. In Carrara A, Guzzetti F (eds) *Geographical information systems in assessing natural hazards*. Dordrecht, Kluwer: 199–217

Linz A, Bryant P 1994 The all-hazard situation assessment program. *Proceedings, First Federal Geographic Technology Conference.* Washington DC, GIS World Inc. Vol. 1: 165–9

Lowry J H, Miller H J, Hepner G F 1995 A GIS-based sensitivity analysis of community vulnerability contaminants on the Mexico/US border. *Photogrammetric Engineering and Remote Sensing* 61: 1347–59

Lu X, Xiang W N 1995 A GIS model for hazardous chemicals pathway analysis. *URISA Proceedings.* San Antonio 1: 293–9

McLaren M 1992 GIS prepares utilities for earthquakes. *GIS World* 5(4): 60–4

McMaster R B 1988 Modeling community vulnerability to hazardous materials using geographic information systems. *Proceedings, Third International Symposium on Spatial Data Handling.* Columbus, IGU: 143–56

Mejia-Navarro M, Wohl E E, Oaks S D 1994 Geologic hazards, vulnerability, and risk assessment using GIS: model for Glenwood Springs, Colorado. *Geomorphology* 10: 331–54

Mondschein L G 1994 The role of spatial information systems in environmental emergency management. *Journal of the American Society for Information Science* 45: 678–85

Newsom D E, Mitrani J E 1993 Geographic information system (GIS) applications in emergency management. *Proceedings, 1993 International Emergency Management and Engineering Conference.* San Diego, Society for Computer Simulation (SCS): 61

Palm R 1990 *Natural hazards: an integrative framework for research and planning.* Baltimore, Johns Hopkins University Press

Parrot R, Stutz F P 1991 Urban GIS applications. In Maguire D J, Goodchild M F, Rhind D W (eds) *Geographical information systems: principles and applications.* Harlow, Longman/New York, John Wiley & Sons Inc. Vol. 1: 247–60

Perry R 1985 *Comprehensive emergency management: evacuating threatened populations*. London, JAI Press Inc.

Radke J 1995 Modeling urban/wild-land interface fire hazards within a geographical information system. *Geographic Information Sciences* 1: 9–21

Rejeski D 1993 GIS and risk: a three culture problem. In Goodchild M F, Parks B O, Steyart L T (eds) *Environmental modeling with GIS*. New York, Oxford University Press: 319–31

Rosenfeld C L, Gaston G G, Pearson M L 1996 Integrated flood response in the Pacific Northwest: state and federal agencies, along with local governments, employ RADARSAT, aerial videography and GPS to aid in disaster response. *Earth Observing Magazine* 5: 20–3

Routh K 1990 Loma Prieta, California earthquake, 1989 spurs development of a GIS based emergency response system. *URISA Proceedings.* Edmonton (Canada) 1: 78–83

Shu-Quiang W, Unwin D J 1992 Modelling landslide distribution on loess soils in China: an investigation. *International Journal of Geographical Information Systems* 6: 391–405

Silva F N de, Pidd M, Eglese R 1993 Spatial decision support systems for emergency planning: an operational research/geographical information systems approach to evacuation planning. *1993 International Emergency Management and Engineering Conference*. San Diego, Society for Computer Simulation: 130–3

Smith K 1992 *Environmental hazards: assessing risk and reducing disaster*. London, Routledge

Sorensen J H, Carnes S A, Rogers G O 1992 An approach for deriving emergency planning zones for chemical munitions emergencies. *Journal of Hazardous Materials* 30: 223–42

Stockwell J R, Sorensen J W, Eckert J W, Carreras E M 1993 The United States EPA geographic information system for mapping environmental releases of toxic chemical release inventory (TRI) chemicals. *Risk Analysis* 13: 155–64

Vaughn B M 1996 'GIS applications for hazard preparedness, response, and mitigation'. Graduate project, MSc in Interdisciplinary Science Studies, Baltimore, Johns Hopkins University

Vega-Garcia C, Woodard P M, Lee B S 1993 Mapping risk of wildfires from human sources of ignition with a GIS. *Proceedings, Thirteenth Annual ESRI User Conference*. Redlands, ESRI 1: 419–26

Wadge G 1988 The potential of GIS modeling of gravity flows and slope instabilities. *International Journal of Geographical Information Systems* 2: 143–52

Wadge G, Wislocki A P, Pearson E J 1993 Spatial analysis in GIS for natural hazard assessment. In Goodchild M F, Parks B O, Steyaert L T (eds) *Environmental Modeling with GIS*. New York, Oxford University Press: 332–8

Watson C C Jr 1992 GIS aids hurricane planning. *GIS World* (special issue) July: 46–52

Zografos K G, Dougligeris C 1991 Integrating geographic information system (GIS) and automatic vehicle location (AVL) technologies for improving the emergency response capabilities of electric utilities. *Proceedings, VNIS 91 Vehicle Navigation and Information Systems Conference, Warrendale* 1: 91–5