Assessing the Impact of Airborne Toxic Releases on Populations with Special Needs*

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In this article, we 1) develop and demonstrate an approach for assessing the population at risk to airborne releases of extremely hazardous substances, 2) examine the relationship between potential sources of chemical hazards and the special needs population in a medium-sized metropolitan area (Cedar Rapids, Iowa), and 3) determine whether the distribution of environmental risks disproportionately impacts the special needs population. Our approach provides a comprehensive view of the risk burden imposed on the population by examining the effects of multiple sources of toxic releases. Disproportionate impacts are evaluated by comparing the existing distribution of the special needs population at risk to 1,000 randomly simulated distribution patterns. The results indicate that a significantly high proportion of the special needs population resides in areas susceptible to worst-case toxic releases. **Key Words: risk assessment, environmental justice, GIS, simulation modeling.**

Introduction

The analysis of technological and industrial hazards has received a considerable amount of attention during the past two decades, with researchers focusing on specific problems such as airborne toxic releases (Cutter 1987), the emergency management of chemical spills (Gould, Tatham, and Savitsky 1988), regional evacuation analysis (Cova and Church 1997), and the assessment of community vulnerability to hazardous contaminants (McMaster 1990; Chakraborty and Armstrong 1995; Lowry, Miller, and Hepner 1995). The federal government has also recognized the importance of hazards analysis in emergency management. The Superfund Amendments and Reauthorization Act (SARA) was passed in 1986 to improve planning and preparation for chemical emergencies; Title III of SARA contains the Emergency Planning and Community Right-to-Know Act, which is intended to encourage cooperation among government agencies, the public, and industry in preparing for possible chemical accidents. A more recent mandate of the U.S. Environmental Protection Agency's (USEPA) Risk Management Program (1996) requires all facilities that store or use substances regulated under section 112 (r) of the Clean Air Act to prepare, by 1999, analyses of the offsite consequences of accidental releases.

The perceived inequity in the distribution and impact of environmental hazards and risks has also led to the rise of the environmental justice movement, which contends that racial minorities and economically disadvantaged populations shoulder a disproportionate burden of the nation's environmental pollution problems. This movement has received considerable attention in recent years from the news media, policymakers, environmental activists, and academic scholars from various disciplines (e.g., United Church of Christ 1987; Bullard 1990; Mohai and Bryant 1992; Anderton et al. 1994; Pulido 1996). A growing research literature focuses on analyzing the disproportionate distribution of risk on people and places, using a variety of spatial analysis and statistical techniques (see reviews by Cutter 1995; McMaster, Leitner, and Sheppard 1997). The identification of sensitive population groups and institutions at risk has emerged as a critical element of this work. For example, the USEPA Risk Management Program stipulates that all facilities that store or handle extremely hazardous chemicals are required to identify populations with special needs and institutions (e.g., schools, hospitals, daycare centers) that would be exposed to accidental

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releases. Vulnerable population groups typically include people with mobility restrictions who are likely to face evacuation problems, the very young, and the elderly population (McMaster 1990). While geodemographic studies of environmental risk assessment and equity typically focus on socially disadvantaged groups such as minorities and low-income individuals, the impact of toxic hazards on individuals with special needs has not been analyzed. At the same time, geographers (e.g., Dear and Taylor 1972; Taylor, Dear, and Hall 1979; Golledge 1991; Marston, Golledge, and Costanzo 1997; Takahashi and Dear 1997) have examined several problems faced by population groups with special needs, but the locations of these individuals have not been investigated with respect to facilities that store or use hazardous substances. This group is particularly vulnerable to environmental risks and toxic releases, and their evacuation needs in an accident or emergency are significantly different than those of the general population.

The purpose of this article is to assess the potential exposure of people with special needs to accidental releases of extremely hazardous chemicals. Such individuals are subjected to increased levels of risk if they reside in areas containing multiple sources of toxic exposure that are located near low-income housing, and other urban areas with easy access to health care and related services. We develop and demonstrate an approach that can be used to estimate the population at risk to accidents involving airborne releases of extremely hazardous substances. This methodology is based on recent USEPA guidelines (USEPA 1998) for hazard assessment and modeling worst-case releases. We then examine the relationship between potential sources of chemical hazards and the geographic distribution of people with physical and mental disabilities, in a case study conducted in the metropolitan area of Cedar Rapids, Iowa. Finally, we analyze environmental equity in the distribution of the special needs population, to determine whether these individuals would be disproportionately affected by airborne releases of toxic chemicals.

Environmental Risk and Equity Assessment

Several different techniques have been used in prior research to define the geographic extent of the area potentially affected by a hazard. Most early studies used predefined political or administrative units (e.g., five-digit ZIP codes, census tracts, or block groups) to represent vulnerable zones. With the advent of geographic information systems (GIS) technology, several researchers (e.g., Glickman 1994; Zimmerman 1994) suggested that the shape and size of the affected area, and the range of hazards associated with a hazardous facility, could be represented more effectively by using GIS software to construct a circular buffer of a specified radius centered at each toxic release site. For example, Glickman (1994) used circles of radii 0.5, 1.0, and 2 miles around hazardous facilities to assess environmental equity in Allegheny County, Pennsylvania. However, a major shortcoming of this circular buffer approach is that the radius of the circle is often chosen arbitrarily (Chakraborty and Armstrong 1997), and does not reflect the quantity or toxicity of the chemicals stored at each site. An alternative approach, known as geographic plume analysis (Chakraborty and Armstrong 1995, 1997), overcomes some of these limitations by using a chemical dispersion model in conjunction with a GIS database to identify the area at risk. It is important to note, however, that a dispersion model requires an actual chemical release—i.e., worst-case—scenario, and is more data-intensive than the uniform circular buffer approach.

The characteristics of the population at risk are typically estimated by overlaying the boundary of each vulnerable zone with the boundaries of other polygons (e.g., census enumeration units) that contain attribute information. The analytical capabilities of GIS software are used to extract data from these units. Since the census provides neither individual nor household level information, most demographic studies of environmental risk assessment and equity estimate the composition of the population at risk on the basis of predefined geographic units (e.g., census tracts, block groups) for which such data are available.

However, there are two major problems associated with the use of aggregated census data for assessing risk exposure. First, the shape and size of a vulnerable zone (e.g., a circle) normally does not coincide with underlying census enumeration units (e.g., tracts or block groups). Consequently, areal interpolation (Goodchild and Lam 1980;

Goodchild, Anselin, and Deichmann 1993) techniques must be applied to transfer information from census units (source zone) to the area at risk (target zone). However, the method of areal interpolation supported by most GIS software packages assumes that the population within each census unit is distributed uniformly and homogeneously. This assumption is often unrealistic and may lead to inaccurate estimates of the population at risk, particularly when the size of the unit is too large (e.g., a census tract). Second, temporal inaccuracies result when analysts compare the current distribution of environmental risks or toxic releases with outdated demographic data from, for example, the 1990 census. Certain variables (e.g., median house value) may not have changed significantly, but data on demographic characteristics (e.g., race, age) have probably now reached their usable limit. We avoid these common limitations by using more recent and disaggregated information on the special needs population in our study area.

Methodology and Data Sources

The Cedar Rapids metropolitan area in Linn County, Iowa was used to investigate the impact of airborne chemical releases on the special needs population. This area, which includes the cities of Cedar Rapids, Hiawatha, and Marion, has a total population of approximately 145,000. This region has the greatest risk potential among the metropolitan areas in Iowa because manufacturing activities located there require that large quantities of hazardous chemicals be stored and transported. The timing of this research project also coincided with the Linn County Emergency Management Agency's effort to revise and update its emergency preparedness and response plans for chemical spills.

Information on each facility that reported extremely hazardous substances (EHS facilities) in 1996 was obtained from the *Linn County-Wide Multi-Hazard Emergency Operations Plan*, compiled by the Linn County Emergency Management Agency. This document provided the street address of each facility and the types, quantities, and properties of each hazardous chemical stored there on-site.[1]

The special needs population in our study consisted of self-identified individuals in the Cedar Rapids metropolitan area who had indicated to the Linn County Emergency Management Agency that they required special assistance in case of a public emergency. This group included wheelchair users, people with walking difficulties, vision, speech, and hearing impairments, the mentally disabled, and those suffering from heart problems, chronic illness, and terminal diseases. The Linn County Emergency Management Agency provided us with the street address and the nature of disability associated with each individual belonging to the special needs category in 1996. The digital representation of the street network for the study area was imported from the 1994 Census TIGER/Line files. The locations of members of the special needs population and of EHS facilities were geocoded to this street network (Fig. 1). We were able to successfully match 97% of the individuals residing in this region. A geographic masking procedure (see Armstrong, Rushton, and Zimmerman 1999) was used to perturb their actual locations and thus preserve confidentiality in maps that display their residences. By using information on the special needs population and toxic facilities for the same year (1996), we avoided the temporal inconsistencies that are often associated with studies of environmental risk and equity assessment.

Our research methodology consisted of the following steps:

1. prepare worst-case release scenarios and estimate the maximum release distance for each hazardous substance in the study area, using a chemical dispersion model;
2. create circular vulnerable zones around locations of all EHS facilities on the basis of each reported toxic chemical, using the buffer analysis capabilities of GIS; and
3. compute the special needs population residing within each vulnerable zone, using the point-in-polygon capabilities of GIS.

Developing Worst-Case Release Scenarios

Our first step was to prepare worst-case chemical accident scenarios for each toxic chemical stored at each EHS facility in the study area.

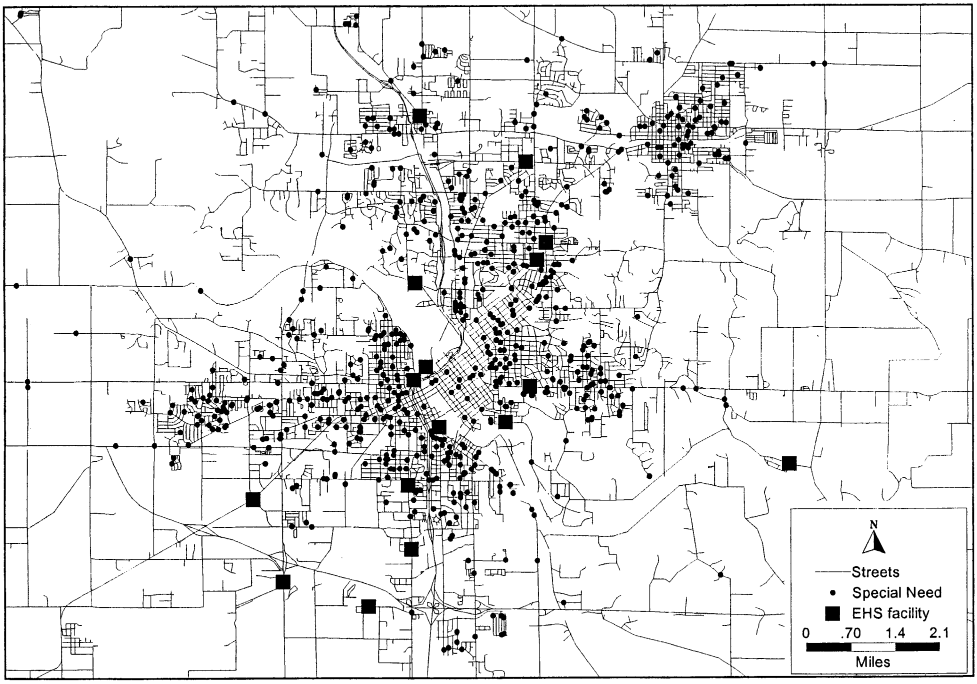

Figure 1 *Locations of EHS facilities and individuals with special needs in the Cedar Rapids metropolitan area, 1996.*

The methodology for developing and modeling worst-case releases was based on guidelines provided by the USEPA's Offsite Consequence Analysis Guidance (USEPA 1998), a manual designed to help facilities conduct analyses of offsite consequences of accidental releases in accordance with the requirements of the USEPA's Risk Management Program (1996) mandate. A worst-case release is defined by the USEPA (1998) as the release of the largest possible quantity of a regulated substance from a vessel or process line failure that travels the greatest distance in any direction to a specified endpoint before dissipating sufficiently to become harmless. According to the USEPA guidelines (USEPA 1998, 2), all worst-case releases occur at ground level (0 feet) under a set of specific weather conditions: a stable (Class F) atmosphere, a wind speed of 1.5 meters per second, outdoor temperature of 77°F (25°C), and 50% humidity. For all toxic gases, and those handled as a liquid under pressure, the total quantity stored on-site was assumed to be released as a gas in one hour (continuous release). For example, if a facility reported 6,000 pounds of chlorine, we assumed that entire quantity was released in 60 minutes at a rate of 100 pounds per minute. The USEPA guidance document provides two choices for surface roughness or topography: *rural*, an area with no buildings in the immediate area and unobstructed terrain, and *urban*, an area with many obstructions. We selected the "urban" option for our analyses.

This set of assumptions was used to develop release scenarios for toxic chemicals stored at each EHS facility in the study area. A chemical dispersion model was then used to compute the maximum release distance associated with each worst-case scenario, and this distance was used as a radius to create vulnerable zones around EHS facilities.

Dispersion Modeling to Estimate Maximum Release Distances

Dispersion models typically combine data on the quantity and properties of a released chemical with site-specific information and atmospheric conditions to determine the area that would be affected by a spreading plume. The Areal Locations of Hazardous Atmospheres (ALOHA) model, used in this research, was developed by the National Oceanic and Atmospheric Administration and the USEPA, and is well suited for estimating plume extent and concentration for short-duration chemical releases (NOAA and EPA 1996). It provides estimates of pollutant concentrations downwind from the source of a spill, taking into consideration four kinds of information: the toxicological and physical characteristics of the spilled chemical, the physical characteristics of the spill site, atmospheric conditions, and the circumstances of the release. ALOHA contains two separate dispersion modules: Gaussian and heavy gas. The Gaussian dispersion model is used to describe the movement and spread of a gas that is neutrally buoyant (approximately the same density as air). The heavy gas model is used when the density of the released gas is substantially higher than the density of air. ALOHA uses the molecular weight of the chemical to select the appropriate dispersion model. The diagram produced by the model illustrates the top view of the plume and is referred to as the plume's "footprint" (Fig. 2). The area inside the footprint is the region predicted to have ground-level concentrations above a user-specified limit or threshold concentration. Plume footprints were generated at each EHS facility in the study area on the basis of the worst-case release scenarios; the distance between the source and the endpoint of a plume represents the maximum release distance for each chemical stored.

Our threshold values for each hazardous chemical were based on its Immediately Dangerous to Life and Health (IDLH) level, a limit originally established for selecting respirators for use in workplaces by the National Institute for Occupational Safety and Health (NIOSH). A chemical's IDLH is an estimate of the maximum concentration in the air to which a health worker could be exposed for 30 minutes without suffering permanent or escape-impairing health effects (NIOSH 1994). The IDLH values, originally established in 1974, were updated and revised in 1994. We used these revised values as threshold concentrations in the ALOHA model for our analysis.

Cumulative Assessment of Environmental Risk

To analyze the impact of airborne toxic releases on the special needs population, we constructed plume-adjusted circular buffers centered on each EHS site, using the buffer gener-

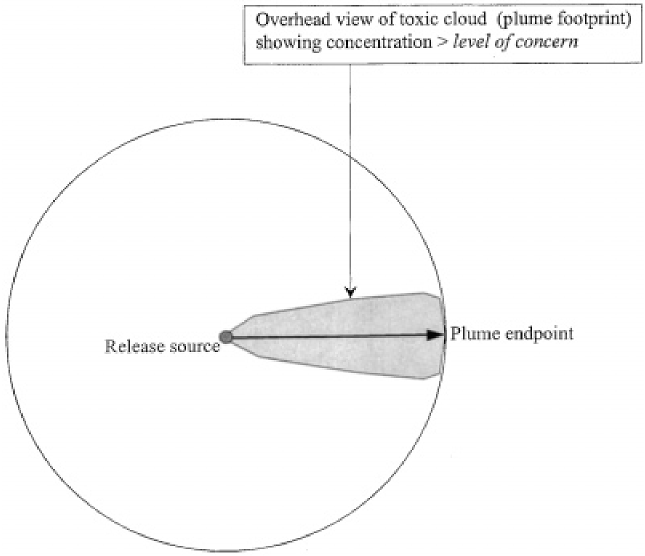

Figure 2 *Application of ALOHA footprint to estimate radius of plume-adjusted circle.*

ation capabilities of GIS software. The radius of each plume-adjusted circle was equal to the maximum (worst-case) release distance associated with each chemical stored at that location. This allowed us to create multiple circles or worst-case zones around each EHS facility, depending on the number of toxic chemicals stored on-site. Figure 3, which illustrates both these plume-adjusted circular buffers in the Cedar Rapids metropolitan area and the locations of the special needs population, indicates that some of these individuals reside within multiple circles, originating either from the same EHS facility or from different facilities. This implies that the entire special needs population is not exposed to equal risk; certain individuals are more likely to be impacted by hazardous chemical releases than others. The number of potential toxic releases to which a person is exposed is the sum of the number of plume-adjusted circles in which they reside. It should be noted, however, that different substances have considerably different toxic effects and are stored under conditions that result in different release probabilities. Additional research should incorporate these considerations and elucidate interaction effects among hazardous chemicals.

Table 1 shows the number of individuals located inside the overlapping buffer zones generated from toxic release sources. The special needs population in the study area totals 903; 554 members (61.35%) of this group are located within at least one plume-adjusted circle, or would be potentially exposed to one or more hazardous chemical releases under the scenarios we developed. 342 individuals (37.87%) reside within two or more plume-adjusted circles, or are potentially exposed to at least two worst-case releases of hazardous chemicals. Five individuals (0.55%) are potentially exposed to six releases of hazardous substances from EHS facilities in the study area.

This approach to exposure assessment enables us to cumulate the effects of multiple sources of hazardous chemical releases. However, the conventional method of constructing uniform circular buffers around all toxic facili-

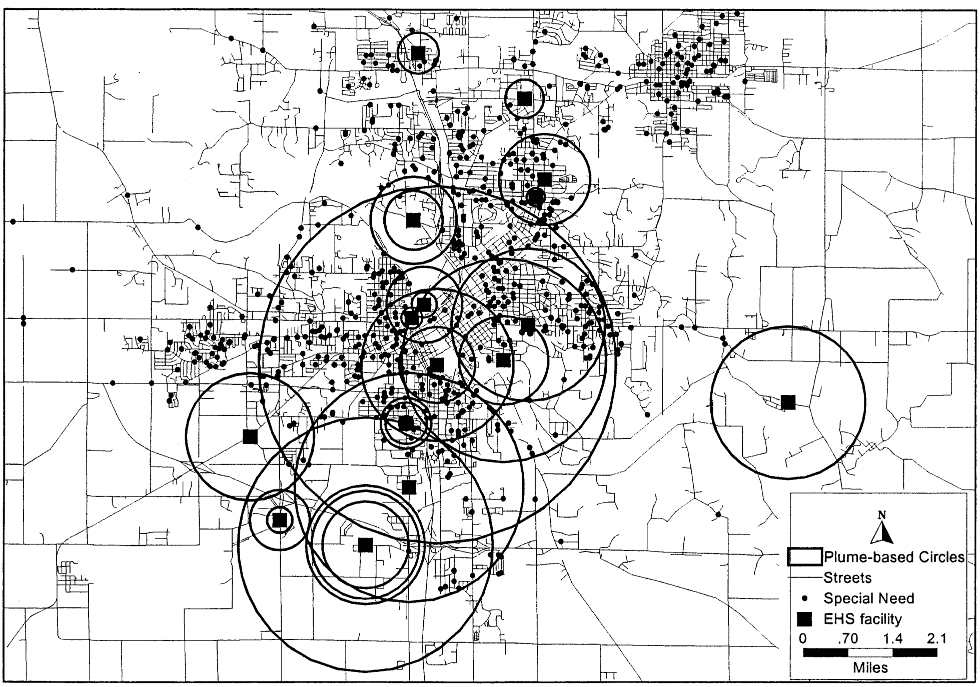

Figure 3 *Plume-based circular buffers around EHS facilities and locations of special needs individuals in the Cedar Rapids metropolitan area.*

Table 1 *Cumulative Assessment of Potential Exposure of Special Needs Population to Worst-Case Chemical Releases*

Number of Vulnerable Zones	Population Exposed	Proportion of Population Exposed
At least 1	554	61.35%
2 or more	342	37.87%
3 or more	256	28.35%
4 or more	141	15.50%
5 or more	67	7.42%
6	5	0.55%

ties provides an entirely different set of population estimates. Figure 4 illustrates buffer zones with the same radius of one mile at each EHS facility in the study area. Comparison of these zones with the plume-adjusted circles in Figure 3 clearly indicates that the uniform circular buffers in Figure 4 do not distinguish between the EHS facilities in terms of the number and toxicity of chemicals stored on-site. An individual residing within two circles as depicted in Figure 4 might actually be exposed to more than two potential releases of hazardous chemicals, or none at all, depending on the quantity and worst-case release distances associated with the substances stored at these facilities.

Estimation of Disproportionate Impacts on Special Needs Population

Our final research objective was to determine whether the special needs population is disproportionately distributed with respect to worst-case releases of hazardous chemicals. A randomization methodology was used to investigate the hypothesis that the number of special needs individuals potentially exposed to toxic releases in the study area is significantly high. Randomization tests have been used in numerous studies to analyze point patterns (e.g., Besag and Diggle 1977; Openshaw et al. 1987), environmental equity (Sheppard et al. 1999), and a variety of other geographic issues and problems (e.g., Openshaw and Taylor 1979; Hubert, Golledge, and Costanzo 1981; Fisher and Langford 1995). Our methodology compares the actual or observed number of special needs individuals potentially exposed to toxic releases to the frequency distribution of possible values, ob-

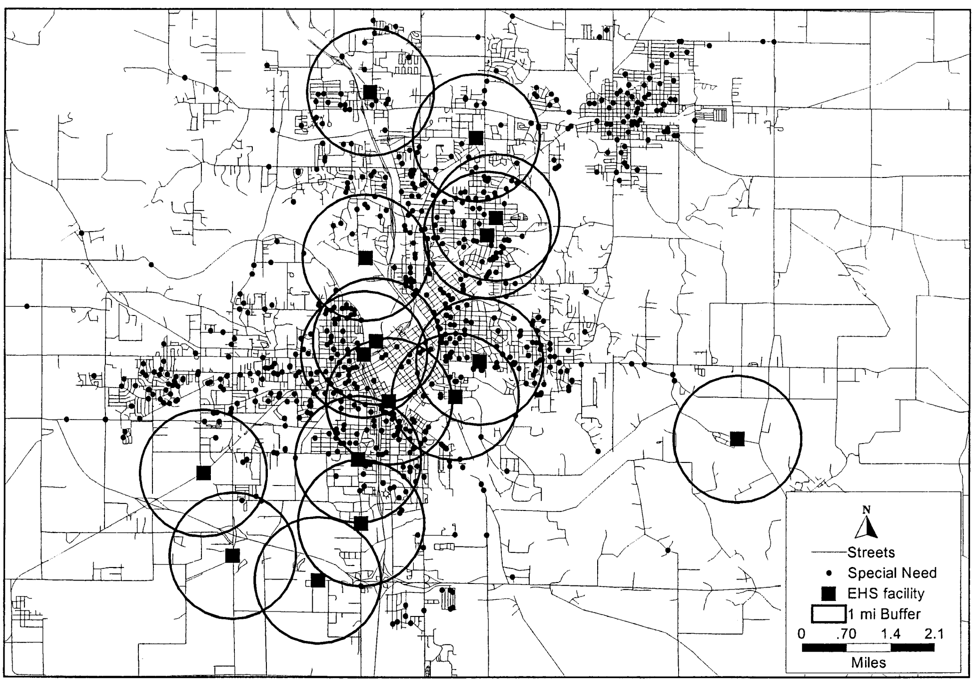

Figure 4 *Uniform circular buffers of radius 1 mile around EHS facilities.*

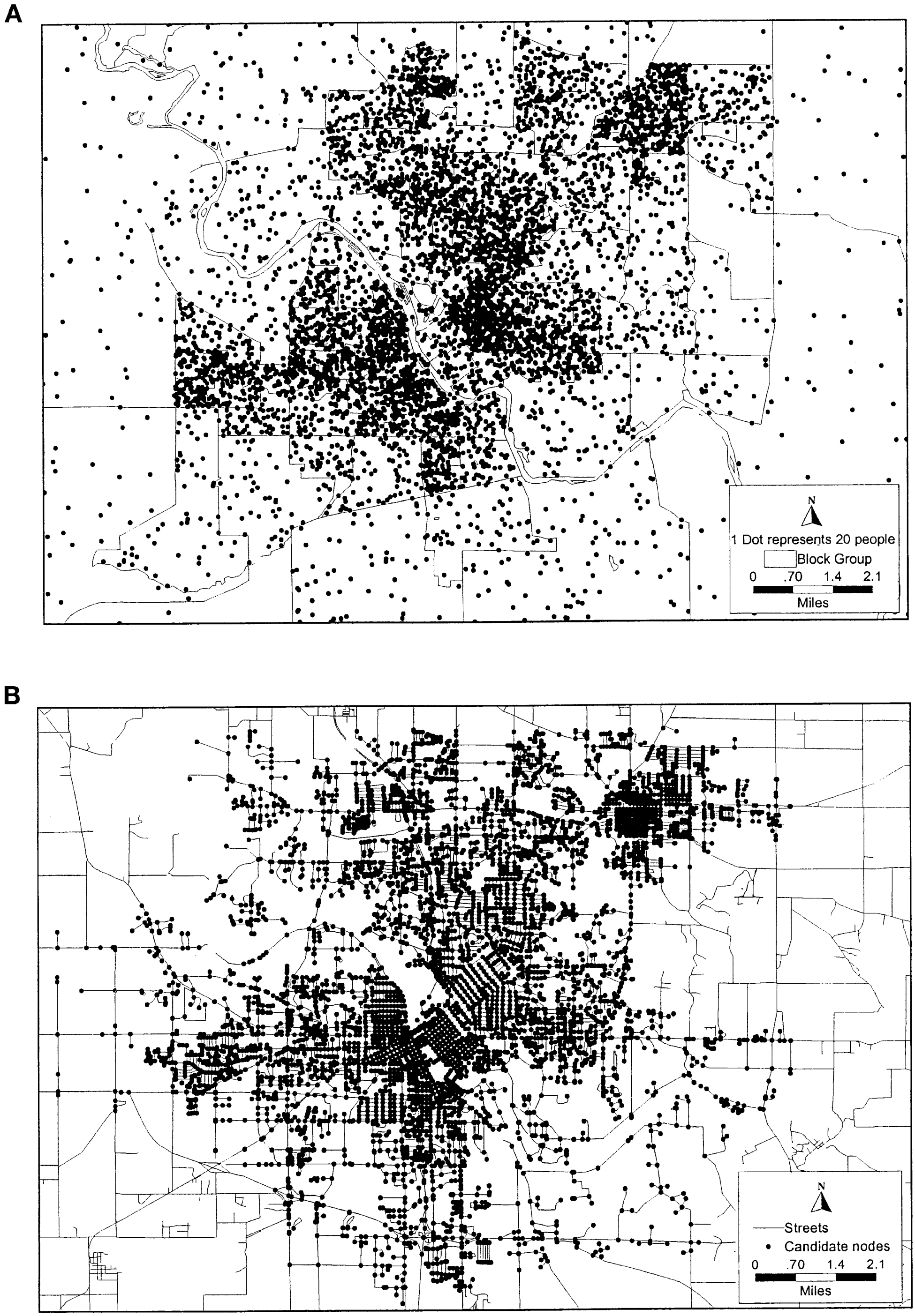

Figure 5 *(A) Distribution of 1990 population by census block group in the Cedar Rapids metropolitan area. (B) Locations of candidate nodes in the Cedar Rapids metropolitan area.*

tained from a set of randomly simulated location patterns. The first step, therefore, was to generate this set of simulated location patterns of the special needs population in the study area. To simplify the computations used to obtain these random patterns, a finite, but large set of candidate locations (n = 6,260) was used: Census TIGER/Line file nodes or street intersections. This allowed us to restrict the residences of this population group to the street network and avoid lakes, parks, and other nonresidential areas.

Our choice of candidate locations would provide a valid basis for comparing the existing location pattern only if the location pattern of nodes approximated the geographic distribution of the general population in the study area. We examined the relationship between the 1990 population density and the number of nodes per square mile in each census block group in the Cedar Rapids metropolitan area. Both variables were modified using a logarithmic (base 10) transformation, because of their apparent nonnormality. A strong positive correlation (r = 0.95) was observed. Figure 5 shows the geographic distribution of candidate nodes and the general population in the study area. The dot density map representing the 1990 block group population (Fig. 5A) indicates substantial spatial correspondence with the location pattern of TIGER/Line nodes (Fig. 5B).

The next step in our analysis was to delineate the area at risk to airborne chemical releases. This vulnerable zone included the area enclosed by at least one circle, and defined the area potentially exposed to one or more worst-case releases (Fig. 6). To allow comparison with the random distribution patterns, each person with special needs in the study area was assigned to the nearest TIGER/Line file node. In areas of high population density, this assignment resulted in the aggregation of multiple individuals at the same node. Since several individuals with special needs may reside in the same building or at the same location, such aggregation effects are unlikely to have a significant impact on the analysis. Although the node-assignment technique introduces a small

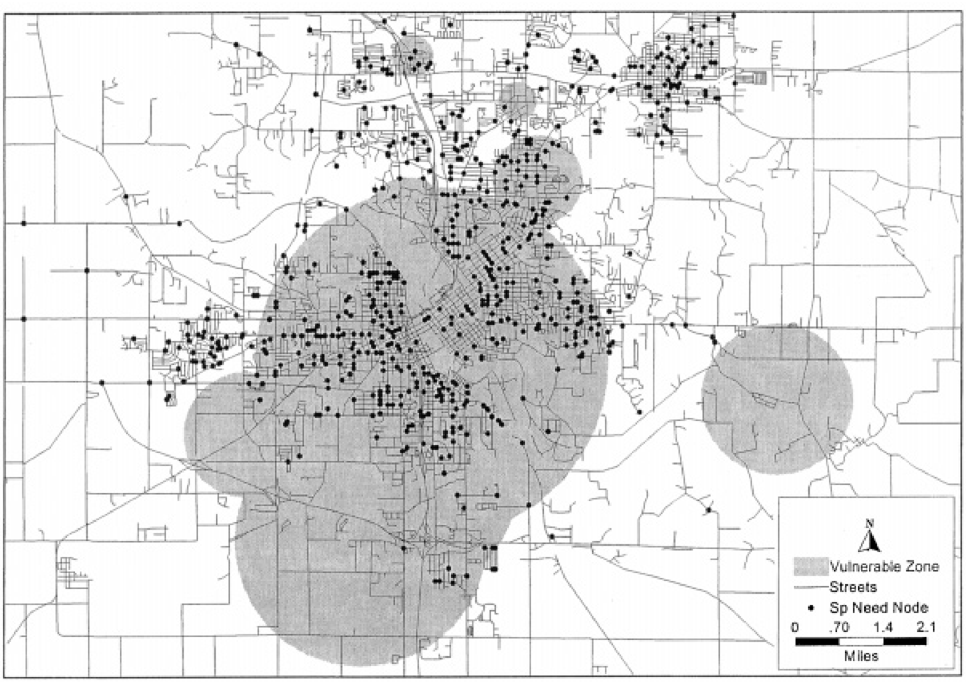

Figure 6 *Location pattern of the existing special needs population after node assignment and the region exposed to potential toxic releases.*

amount of positional error, the overall distribution pattern of the entire group remains unaffected; the average displacement of each person is only 0.02 mile. After the node assignment, 554 of the 903 individuals with special needs were found to reside inside the zone of vulnerability, and we considered them to be at risk.

Our next task was to distribute the entire special needs population (N = 903) randomly among all nodes in the study area and to compute the population inside the vulnerable zone in each simulated distribution pattern. For this purpose, we generated 1,000 independent sets of 903 nodes that were chosen at random from a uniform probability distribution, so that all nodes had an equal likelihood of being selected in each simulation. The number of nodes located inside the vulnerable zone in each random simulation represented the number of individuals at risk. Figure 7 provides an example of one of these simulated distribution patterns; the population inside the vulnerable zone associated with this map is 485.

Our analysis of 1,000 random distribution patterns indicates that the number at risk associated with the area exposed to a worst-case release ranges from a minimum of 436 to a maximum of 567, with a mean of 493. Figure 8 represents a frequency distribution of these values. The expected number of people within the vulnerable zone (493) is much lower than 554, the number obtained from the actual distribution pattern. We also found that the number at risk exceeds 554 in only four out of 1,000 simulated patterns. This implies that the probability of any random distribution pattern having a value lower than the observed value is significantly high (99.6%). In other words, the number of special needs individuals currently residing inside this vulnerable zone or the area potentially exposed to at least one worst-case toxic release is disproportionately high.

This methodology was also used to examine the significance of the number of individuals currently located in areas exposed to multiple worst-case releases of hazardous chemicals, delineated by two, three, and four or more plume-adjusted circles. As before, the observed

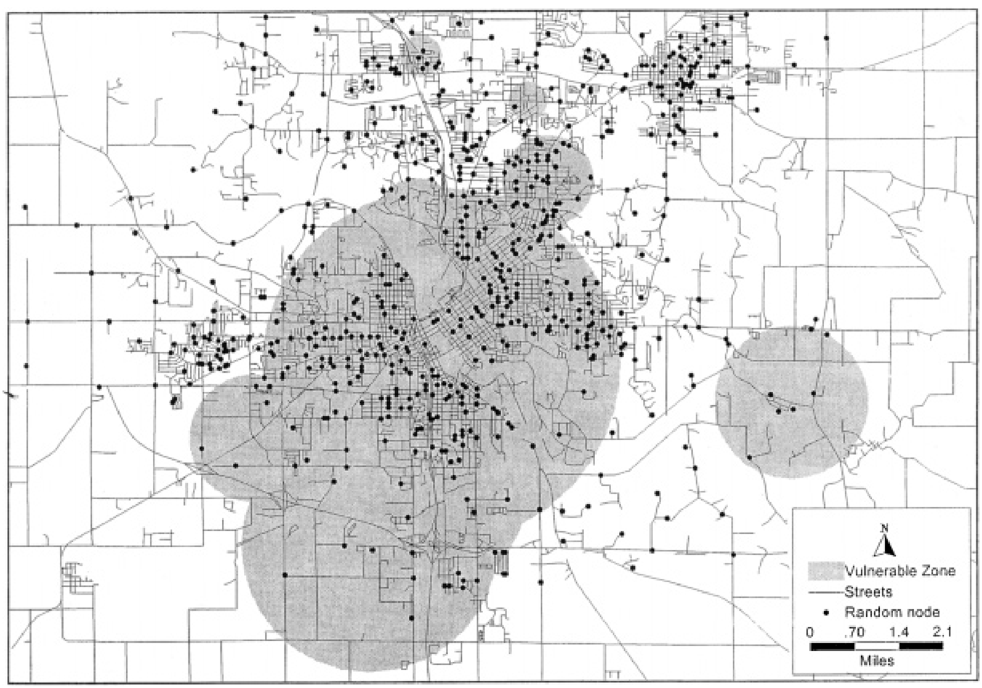

Figure 7 *A randomly simulated location pattern of the special needs population.*

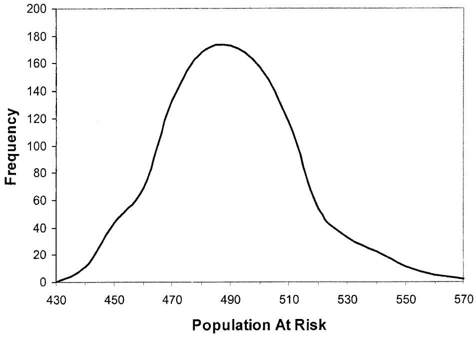

Figure 8 *Frequency distribution of population inside vulnerable zone in 1,000 simulated patterns.*

number of people in each of these vulnerable zones after the node assignment was compared to the numbers obtained from the 1,000 randomly simulated distribution patterns. The results of these analyses are summarized in Table 2. Our findings indicate that, in all cases, the observed number of special needs population at risk is substantially higher than the expected value. The level of significance, however, drops marginally as the degree of risk (number of chemicals) increases. For example, the probability of the number of individuals exposed to four or more releases being lower than the observed number is smaller (0.963) than the corresponding probability for the number of individuals exposed to three or more releases (0.971).

Concluding Summary

Increased awareness of and concern regarding the consequences of chemical accidents and related hazards has created a growing need to develop conceptual frameworks and methods that can be used to identify areas likely to be exposed to toxic releases, and the characteristics of the population that would be affected by such releases. At the same time, the perceived inequity in the spatial distribution of environmental risks has resulted in a variety of geodemographic studies that have attempted to examine whether environmental hazards, known or potential, are distributed differently across population groups. Most of these studies focus on minorities and low-income residents and rely on outdated and spatially aggregated census information. Our research used more recent and disaggregated data to analyze the potential impact of accidental releases of hazardous chemicals.

In our analysis, we developed a GIS-based methodology to compute the population potentially exposed to airborne releases of toxic chemicals. This methodology, which combines the circular buffer and plume analysis approaches from previous studies, is consistent with recommendations provided in the USEPA guidance document for conducting analyses of accidental releases of hazardous chemicals. We used it to examine the impact of worst-case airborne chemical releases on the special needs population in the metropolitan area of Cedar Rapids, Iowa. Our analysis provides a comprehensive view of the risk burden imposed on this population.

However, the actual public health impacts of potential toxic releases were not investigated in this research. Although a growing number of epidemiological studies (e.g., Elliott et al. 1992; Steenland and Savitz 1997) have analyzed the health effects of exposure to toxic substances, there is limited knowledge regarding the synergistic effects of different combinations of hazardous chemicals. Additional research is required to determine the health effects of multiple simultaneous releases of toxic substances.

Table 2 *Analysis of Disproportionate Impacts Based on 1,000 Randomly Simulated Location Patterns of the Special Needs Population.*

Number of Vulnerable Zones	Population at Risk* (P_{obs})	Population at Risk in Simulated Location Patterns (P_{exp})				
		Max	Min	Mean	Patterns with $P_{exp} < P_{obs}$	Significance Level
At least 1	554	567	436	493	996	99.6%
2 or more	341	368	259	311	982	98.2%
3 or more	257	284	182	228	971	97.1%
4 or more	140	161	89	120	963	96.3%

** Based on assignment to nearest TIGER/Line file node.*

We also examined the issue of environmental equity in the distribution of the special needs population to determine whether these individuals would be disproportionately affected by toxic chemical releases in the study area. Our methodology compared the existing location pattern of this population group to 1,000 randomly simulated location patterns. The validity of this comparison depends on the technique chosen to generate the random patterns. An accurate assessment in this case is possible only when the hypothetical location patterns of the special needs population reflect the geographic distribution of the general population. In order to simulate realistic "urban" patterns, we constrained our candidate locations to nodes or street intersections, instead of assuming that they were distributed uniformly and homogeneously in all parts of the study area. Our analysis of 1,000 randomly simulated distribution patterns indicated that the special needs population is distributed inequitably with respect to airborne chemical hazards. A significantly high proportion of this group currently resides in areas potentially exposed to worst-case releases of extremely hazardous substances. The results of the analysis, however, could be affected by the displacement of the special needs population when multiple individuals are assigned to the same candidate node. Although the impact of such aggregation effects on the results of this analysis are likely to be small, these effects should be investigated in future research.

Individuals with special needs require particular attention because they often have mobility restrictions that force them to depend on others in the event of a chemical accident or emergency that requires evacuation. If people with special needs reside in an area with a high probability of exposure to accidental toxic releases, this must be taken into consideration by engaging emergency personnel so that appropriate evacuation routes and contingencies can be identified and assessed. In this context, the methodology introduced in this article is capable of providing valuable assistance to decision-makers and emergency responders. ■

Notes

[1] Though the USEPA's Toxic Release Inventory (TRI) is a more popular and significant data source for industrial facilities reporting toxic releases, there are several limitations associated with this database (Cutter and Solecki 1996). The TRI contains only manufacturing facilities, in particular those that generate more than 25,000 pounds of toxics annually in manufacturing and processing uses. In addition, it does not include other facilities (e.g., the Cedar Rapids Water Department) that store or use toxic chemicals, as well as those that generate smaller amounts of pollution.

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