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A comparison of GIS-based approaches to environmental equity analysis

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A COMPARISON OF GIS-BASED APPROACHES TO ENVIRONMENTAL EQUITY ANALYSIS

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ABSTRACT: GIS-based analyses of environmental equity have often relied on circular buffer zones around hazardous sites to represent the area affected by an environmental hazard. This approach is questionable because physical processes rarely operate in a perfectly symmetrical manner. A new integrated approach, known as geographic plume analysis, accounts for directional biases in the distribution of hazards by using a chemical dispersion model to identify the area that is likely to be exposed to toxic releases. In this paper we implement, evaluate, and compare circular and plume-based approaches to environmental equity assessment in the city of Des Moines, Iowa. The analyses are based on locations of hazardous facilities listed in EPA's 1994 Toxic Release Inventory (TRI) database. At each toxic site we generated: (i) circles of radii 0.5 and 1 mile, and (ii) a composite plume footprint based on the chemical released in the largest quantity at the facility, using a set of averaged weather conditions. Using the analytical capabilities of GIS software and 1990 Census data at the block group level of aggregation, we computed the racial and economic characteristics of the population residing within these two types of hazard zones. To determine the existence of inequity, we compared the results of each approach to the socio-demographic distribution for the entire city, and to populations residing outside each type of hazard zone in the city. Our results indicate that when a plume-based approach is used to determine the areas vulnerable to airborne toxic releases, a larger proportion of nonwhites and low-income households are found to reside within the high-risk regions.

1. INTRODUCTION

The environmental justice movement in the U.S. contends that the people most likely to be exposed to environmental hazards are racial minorities and the economically disadvantaged. The distribution of environmental risks with respect to income and race, also referred to as 'environmental equity', or 'environmental racism' has not only received considerable attention from the news media and environmental activists, but also has made a substantial impact on national public policy in recent years. For example, in 1994, the White House issued an executive order that requires all federal agencies to consider the impacts of their programs, policies, and activities on environmental justice, and the U. S. Environmental Protection Agency (EPA) has created a special office to facilitate these analyses. The issue has also attracted intense interdisciplinary research in recent years (United Church of Christ, 1987; Bullard, 1990; Mohai and Bryant, 1992; Been, 1994; Szasz, 1994; Rogers, 1995; Bowen *et al.,* 1995). Each of these policy actions and research efforts has been motivated by a concern that minority and low-income populations are shouldering a disproportionate share of the burden resulting from environmental pollution.

An important aspect of this rapidly emerging public debate has been based on the establishment of an association between the location of environmental hazards and the racial or socioeconomic status of the populations surrounding the hazards. A considerable amount of empirical research, conducted in the last two decades, has focused explicitly on the accumulation of empirical evidence that documents the occurrence of environmental inequity. Demographic studies on this subject, for example, have been conducted by the federal government, academic scholars, advocacy organizations, and industry. The traditional approach used by these researchers was to estimate and compare the characteristics of populations in pre-defined administrative units (e.g., census tracts or block groups) that contains environmental hazards with populations either in other similar units or in larger areas that do not contain such hazards. A good example is the widely cited nationwide study conducted by the United Church of Christ's Commission for Racial Justice (1987) that used 5-digit ZIP codes as the unit of analysis. With the advent of GIS, several researchers (e.g., Zimmerman, 1994; Glickman, 1994; Glickman and Hersh, 1995) have suggested that a more sensible way to represent the shape and size of the affected area and the range of hazards associated with a hazardous facility is to use GIS software to construct a circular buffer of a specified radius centered at each facility. One can then estimate the characteristics of the population inside the radial zone by extracting data from other polygons that contain attribute information (e.g., Census block groups containing socio-demographic data) within the circle, using the overlay analysis capabilities of the GIS software. This methodology was adopted by Glickman (1994), who used circles of radii of 0.5, 1 and 2 miles around each toxic facility in his analysis of environmental equity in Allegheny County, Pennsylvania based on block group level socioeconomic data. Likewise, the U.S. General Accounting Office (1995) analyzed the demographic characteristics of the population living within a mile of 500 metropolitan and 500 non-metropolitan randomly chosen landfills in their nationwide study.

However, there are limitations associated with the use of circular buffers in the analysis of environmental equity. Representing the hazards from a toxic facility in this fashion ignores directional biases in the distribution of environmental risks; it assumes that health hazards are equal and uniform in all directions. Any potential release of toxic chemicals into the air or water is assumed to expose the people within the buffer zone to similar risks. This is an unrealistic and inaccurate assumption. Two people living one mile from a toxic site but in different directions could have entirely different exposure effects, based on the direction and flow of air in the region. In addition, the radial zone approach fails to consider that living one mile from one hazardous facility may be significantly different than living one mile from another facility, given differences in the types and quantities of hazardous substance stored and handled, and the level of exposure to the hazard. The shape and size of the risk zones generated by all toxic chemicals are not the same, and this is not reflected in circular buffers of fixed sizes.

These limitations suggest that circular buffers of uniform width are not effective in accurately representing or identifying the areas susceptible to health risk, should a hazardous material release occur. A new approach, known as geographic plume analysis (Chakraborty and Armstrong, 1995) overcomes some of these limitations by integrating a chemical dispersion model with a GIS database to estimate the area and the composition of the population that is likely to be affected by airborne toxic releases from a hazardous site. The purpose of this paper is to implement and compare the results of the circular buffer and geographic plume-based approaches to environmental equity analysis through a case study in the city of Des Moines, Iowa. A brief description of geographic plume analysis is presented in the following section. The third section introduces the research methodology for implementing the two approaches, and the results of the analysis are summarized and discussed in section four. The final section contains our concluding comments and future research directions.

2. GEOGRAPHIC PLUME ANALYSIS

Geographic plume analysis consists of two major components: a chemical dispersion model and a GIS demographic database. Dispersion models serve as a major component of chemical hazard analysis for both transport planning and incident simulation, and have been continuously refined in recent years (Abkowitz and Lepofsky, 1993). This is evident in the number of commercially-available products that perform some type of dispersion modeling. These models typically combine attributes of the chemical released, with site-specific information and meteorological 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 Environmental Protection Agency (EPA), and is well-suited for estimating plume extent and concentration for short-duration chemical accidents (NOAA and EPA, 1992). 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. The diagram produced by the model illustrates the top view of the plume, and is referred to as the plume's "footprint". This diagram connects all points of the same concentration (e.g., the Immediately Dangerous to Life and Health [IDLH] concentration), and its shape represents the spread of the released gas cloud to the level of concern. The area inside the footprint is the region predicted to have ground level concentrations above the limit specified by the chemical's IDLH concentration.

After the chemical dispersion model (ALOHA) has been used to identify the shape and size of the area at risk, census data that describes demographic and socioeconomic characteristics of the population, street networks, and block group boundaries contained in a GIS database are used to estimate the number of people and the composition of the population located within the area at risk. This is achieved by overlaying the dispersal footprint, which is essentially a polygon originating from a point source (location of toxic release), on the street network and block group boundaries Because the shape of the footprint polygon normally does not coincide with block group boundaries, a method of simple areal interpolation is used to extract data from block groups. Areal interpolation is a term given to the process of transferring attribute information from one set of boundaries to another (Goodchild and Lam, 1980; Fisher and Langford, 1996). The method we use is based on the assumption that the population is distributed uniformly within each block group. This implies that for block groups that are partially contained within the footprint polygon, a fraction of the total counts is used, based on the proportion of the block group area that is contained within the footprint. Chakraborty and Armstrong (1994) used such footprints to estimate the areas and characteristics of the population likely to be affected by accidents involving the transportation of a hazardous chemical (chlorine) in Des Moines.

A major drawback in using such a footprint for demographic analysis is the underlying assumption that climatic conditions (air temperature, relative humidity, cloud cover, wind speed, and direction) remain constant, since it is based on the specific weather conditions at the time of the chemical release. A different month of the year, or even slight change in wind speed or direction would generate a footprint from the same source with a different shape, size, and orientation. Consequently, the characteristics of the population lying within this affected area could be substantially different from the composition of the population likely to be affected by another toxic release occurring at the exact same location. This implies that the population estimates obtained might have little long term reliability. This limitation has been addressed by developing a composite plume model (Chakraborty and Armstrong, 1995) that takes into account general trends in wind direction, as well as the overall climatic variability in the area. This would enable users to compute the expected number of people and the composition of population likely to be exposed to a toxic chemical from any given hazardous site.

The composite plume approach is implemented through the computation of a set of twelve (monthly) dispersion footprints that are generated at the same location. Historical weather data (on air temperature, relative humidity, cloud cover, wind speed, and direction) from the long term averages for each month are used as input data in the ALOHA model to obtain twelve monthly plume footprints (one for each month). These footprints are then composited, and the external boundaries of the polygon produced from the twelve plumes are used to define a single composite footprint. Figure 1 illustrates a typical composite footprint superimposed on the street network of Des Moines, which was generated on the basis of a set of averaged weather conditions using historical records for the city. The seasonal variations in prevailing wind direction in the region are reflected in the shape of this composite footprint, as the three predominant wind directions in Des Moines (NW, SE and S) produce this tri-directional footprint shape.

Figure 1: A Typical Composite Plume Footprint

3. RESEARCH METHODOLOGY

Our research objective was to generate circular buffers of fixed radii and appropriate composite plume footprints from locations releasing hazardous chemicals in the city of Des Moines. The primary data source for this study is the EPA's Toxic Release Inventory (TRI), which is considered to be the most comprehensive data source for facilities releasing toxic substances in the U.S. The TRI is an annual compilation of information on industrial toxic releases for approximately 320 toxic chemicals. For each toxic release site, this database provides detailed data on the coordinates of its location, the type of chemicals released at each site, and the total quantity released.

The data on toxic release sites in Des Moines were obtained from the RTK Net's (Right-to-Know Network)'s on-line copy of EPA's TRI area report for 1994. From the 30 industrial facilities that appeared in the TRI database, eight did not report airborne releases of any toxic chemical in 1994, and two others reported releases of insignificant amounts. The remaining 20 TRI sites were included in our analysis, and they were geocoded to the street network of Des Moines obtained from the 1994 TIGER/Line files (Figure 2). Demographic and socioeconomic information from the 1990 Census Summary Tape File Extract 3A (Census of Population and Housing, 1990) were merged with block group boundaries for the city, which were also translated from 1994 TIGER/Line files.

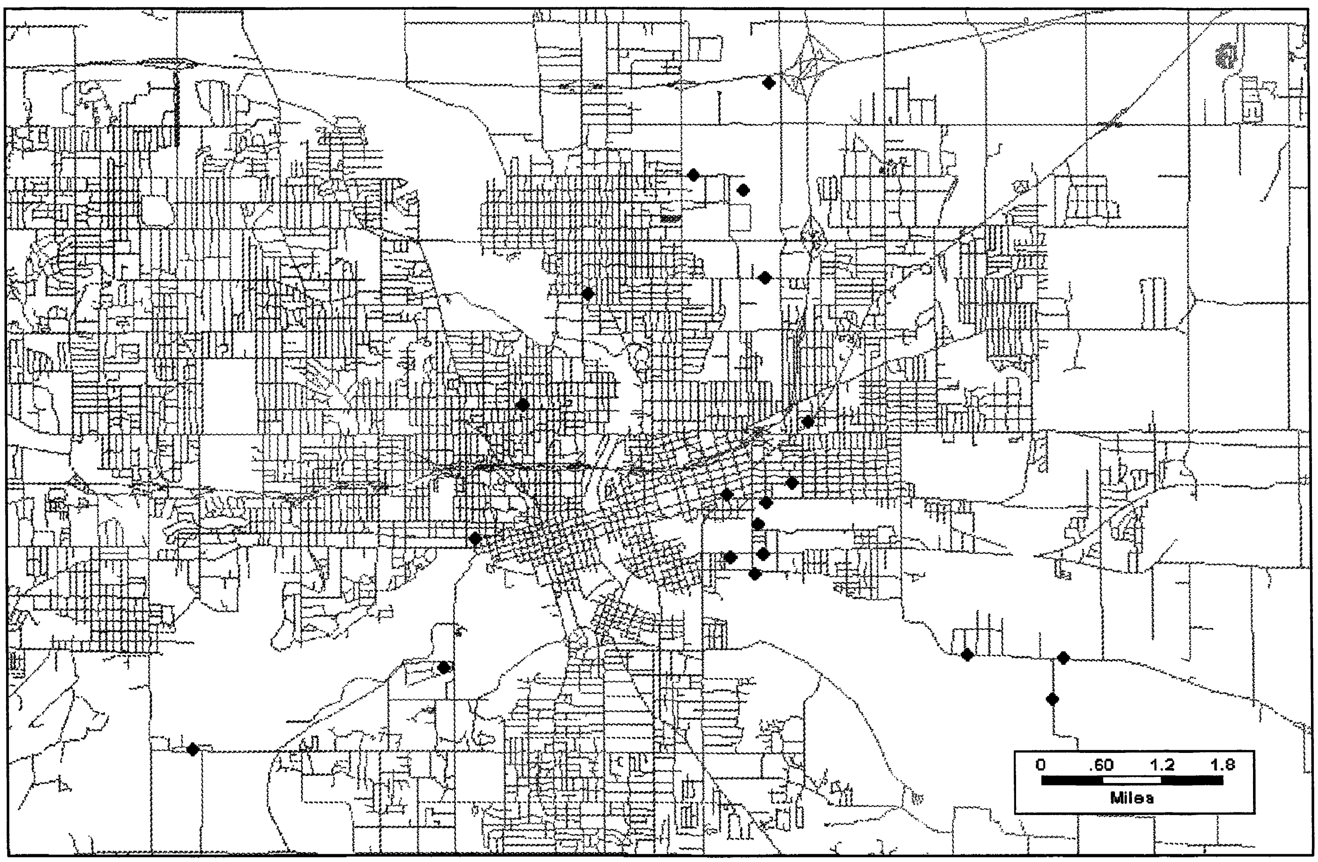

Figure 2: TRI sites in Des Moines Reporting Airborne Toxic Releases in 1994

3.1 Circular Buffers

A review of the existing literature on environmental equity analysis indicated that the radii of the circular buffer zones around hazardous sites range from 0.5 mile for metropolitan-level studies (e.g., Glickman and Hersh, 1995, in their study of Pittsburgh) to 1 mile or 1.5 miles for county-level studies (Glickman, 1994; Zimmerman, 1994). For our Des Moines study, circles with radii of one-half mile and one mile were constructed around each TRI facility shown in Figure 2, which was consistent with the size of radial zones used by previous researchers. Then, for each radius, the city of Des Moines was divided into two parts, one being the area formed by the outer edges of the circles and their overlapping portions, and other being the rest of the city (the area outside all the circles). The racial and household income characteristics of the populations in both these areas were then computed on the basis of block group level census data using the areal interpolation capabilities of the GIS software.

3.2 Composite Plume Footprints

For each hazardous facility, the TRI database provides information on the names of the chemicals released and the corresponding total (yearly) amounts. The toxic chemical released in the largest quantity at each TRI site was used to generate the dispersal footprints for airborne releases. However, the data on the quantity released is not broken down temporally, and there is no information on specific chemical accidents at each site. To prepare release scenarios we assumed that the yearly amount reported was released during a single accident at each TRI site. For instance, if the total quantity of a chemical (e.g., anhydrous ammonia) released at a facility was reported to be 250 lbs. we developed an accident scenario where 250 lbs. of ammonia were released on-site. This was used as input data in the dispersion model for generating plume footprints from each facility location. The scenarios prepared for the study were consistent with the worst-case chemical accident scenarios commonly used by the local HAZMAT officials for emergency response planning.

Historical weather data on air temperature, humidity, cloud cover, wind speed and direction in Des Moines from the long term averages for each month (National Oceanic and Atmospheric Information, 1993) are also used as input data in the ALOHA model to obtain twelve monthly footprints. These were then composited to form a single composite footprint at each TRI site that reported airborne toxic releases. As before, the city was divided into two parts, one being the area formed by the boundaries of the composite footprints, and other being the rest of Des Moines. The racial and household income profiles of the populations inside and outside the composite footprint areas were estimated on the basis of block group level socio-demographic data.

4. RESULTS

4.1 Circular Buffer Analysis

The two following tables summarize the results of the analysis using circular buffers. Table 1 indicates that while non-white residents comprise almost 23 percent of the population inside 0.5 mile buffer region, but only 9 percent of the population outside this region. Similarly, about 42 percent of the households within the hazard zone have an income of less than $15,000, as compared to 24 percent for the rest of Des Moines. Table 2 suggests that this effect on race and income is also evident in the analysis of the 1 mile circles around TRI sites. The percentage of nonwhites living inside this region is about 20 percent, while 6 percent of the population outside this region are nonwhite. As far as income is concerned, almost 37 percent of households inside the 1 mile circles earn less than $15,000, compared to 20 percent for the region outside.

Table 1. Comparison of Populations Inside and Outside 0.5 Mile Circular Buffers

	Inside 0.5 MI Circles	Outside 0.5 MI Circles
RACE:		
White	77.26%	90.72%
Black	16.69%	5.90%
American Indian/Esk./Aleut	0.32%	0.43%
Asian/Pacific Islander	4.71%	2.00%
Other Race	1.02%	0.95%
HOUSEHOLD INCOME:		
less than $5K	9.43%	5.58%
$5K-14999	32.24%	18.42%
$15K-24999	22.10%	20.12%
$25K-34999	17.16%	18.97%
$35K-49999	11.84%	19.05%
$50K-74999	5.47%	12.35%
$75K-124999	1.15%	3.92%
more than $125K	0.61%	1.59%

Table 2. Comparison of Populations Inside and Outside 1 Mile Circular Buffers

	Inside 1 MI Circles	Outside 1 MI Circles
RACE:		
White	79.67%	93.97%
Black	15.15%	3.10%
American Indian/Esk./Aleut	0.59%	0.33%
Asian/Pacific Islander	3.57%	1.67%
Other Race	1.02%	0.93%
HOUSEHOLD INCOME:		
less than $5K	9.19%	4.38%
$5K-14999	28.24%	15.71%
$15K-24999	21.44%	19.78%
$25K-34999	17.28%	19.53%
$35K-49999	13.79%	20.54%
$50K-74999	7.21%	13.82%
$75K-124999	1.88%	4.50%
more than $125K	0.98%	1.74%

4.2 Geographic Plume Analysis

The effect of airborne toxic releases on race and income, as indicated in Table 3, appears to be more pronounced when the geographic plume method is used to delineate risk zones. Almost 31 percent of the residents within the composite footprint areas are nonwhite, whereas only 10 percent of the population outside these areas are nonwhite. Similarly, 43 percent of households residing inside these risk zones earn less than $15,000, as compared to approximately 25 percent for those residing outside.

Table 3. Comparison of Populations Inside and Outside Composite Footprint Boundaries

	Inside Toxic Footprint Boundaries	Outside Toxic Footprint Boundaries
RACE:		
White	69.45%	90.09%
Black	22.21%	6.43%
American Indian/Esk./Aleut	0.23%	0.42%
Asian/Pacific Islander	7.35%	2.08%
Other Race	0.77%	0.97%
HOUSEHOLD INCOME:		
less than $5K	10.10%	5.83%
$5K-14999	33.28%	19.37%
$15K-24999	22.77%	20.23%
$25K-34999	15.36%	18.91%
$35K-49999	11.21%	18.56%
$50K-74999	5.41%	11.86%
$75K-124999	1.31%	3.71%
more than $125K	0.56%	1.53%

The proportion of nonwhites and low-income households (earning less than $15,000) residing within each type of risk zone were also compared to the corresponding percentages for the entire city (Table 4). The figures in parentheses indicate the differences between the proportions inside and outside each set of buffer zones. It is evident that the proportion of nonwhites and low-income households are highest in the composite footprint areas, followed by the 0.5 mile circular buffers. The percentages drop slightly when a larger buffer (1 mile) is used. The same figures are also summarized graphically in Figures 3 and 4.

Table 4. Comparison of Results: Populations Inside Footprint Boundaries, 0.5 Mile Buffers, 1 Mile Buffers, and Overall Population Distribution for Des Moines

	Within Composite Footprints	Within 0.5 MI Circles	Within 1 MI Circles	City of Des Moines
RACE:				
Nonwhites	30.55% (+20.6)	22.74% (+13.4)	20.33% (+14.3)	10.75%
Whites	69.45%	77.26%	79.67%	89.25%
HOUSEHOLD INCOME:				
Less than $15,000	43.38% (+18.2)	41.67% (+17.7)	37.43% (+17.3)	25.93%
$15,000 or higher	56.62%	58.33%	62.57%	74.07%

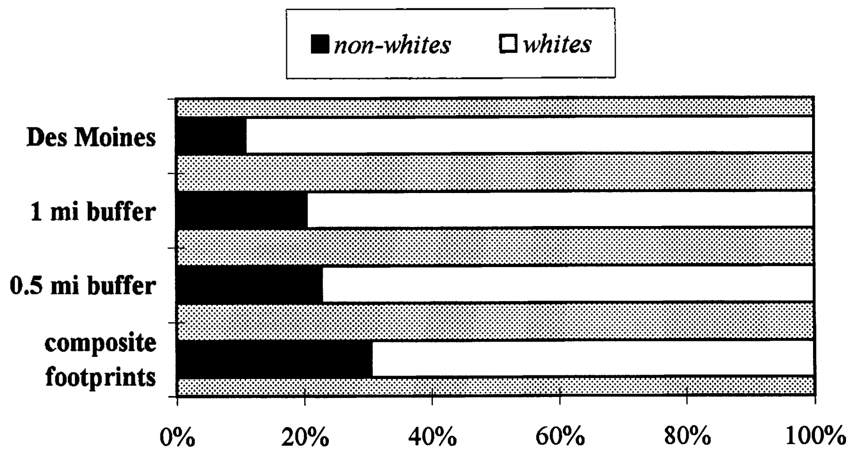

Figure 3. Comparison of Racial Characteristics

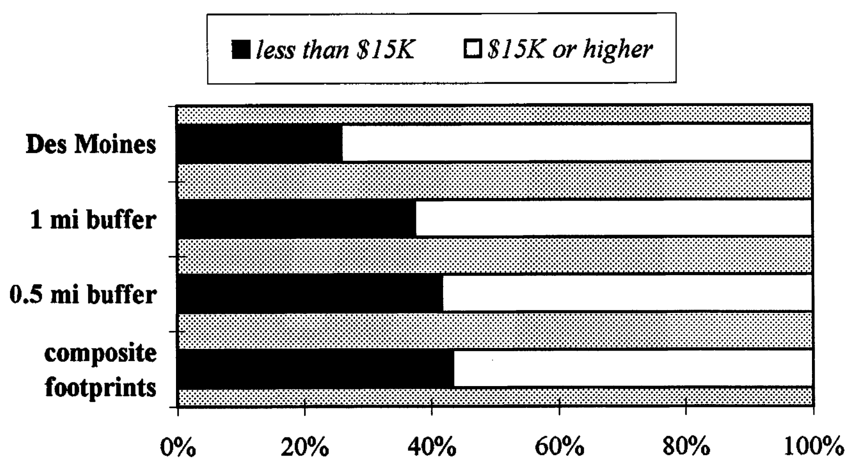

Figure 4. Comparison of Household Income Characteristics

The results of the analyses, as summarized in these tables and charts, clearly indicate that a large percentage of nonwhite residents and poor households live within the hazard zones generated through geographic plume analysis. The effect of race is more pronounced than income, since the proportion of nonwhites in these areas is almost 8 percent higher than the residents in the one-half mile buffers, and 10 percent higher than those in the one mile buffers. As far as economic conditions are concerned, the difference from the percentage of low-income households in the composite footprint areas and the one-half mile and one-mile buffer zones are only 2 percent and 6 percent, respectively.

5. CONCLUDING DISCUSSION

A general conclusion that can be drawn on the basis of these analyses is that the proportion of racial minorities and the economically disadvantaged in Des Moines is higher in populations residing nearer toxic release sites. When compared to the percentage of nonwhites and low-income households living inside the hazard zones (composite plume areas, one-half mile, and one-mile circular buffers) around the TRI sites, the corresponding percentages for the rest of the city were found to be much lower in all cases. These findings are consistent with other research that has shown TRI sites to be distributed inequitably with regard to income and race (e.g., Burke, 1993; Pollock and Vittas, 1995; Bowen *et al.,* 1995).

An effect of locality with respect to TRI sites is also evident in these analyses. In terms of size, the total area occupied by the hazard zone composed of footprint boundaries is the smallest (about 4 sq. miles), followed by the regions created by the one-half mile (12 sq. miles) and the one mile circles (33 sq. miles). The percentage of both nonwhite residents and economically disadvantaged households is highest in the areas generated through geographic plume analysis, followed by those in the one-half mile circular buffers. The corresponding proportions in the one-mile buffer areas are lower than those in the one-half mile buffers. Likewise, if we consider the entire city of Des Moines as our unit of analysis, the proportions are even smaller, as indicated in Table 4. Thus, larger zones of analysis tend to average out the effects, which means that the impact of toxic release sites in Des Moines on minorities and poorer residents is more focused in areas close to the site.

The results of the study, however, should be interpreted with several key assumptions and limitations in mind. First, the estimates of the racial and household income characteristics of the populations are based on census data at the block group level of aggregation. Given the size of block groups, we require disaggregated data for more precise estimates. Using block level census information is a solution, but there are a limited number of demographic variables at this level of aggregation and no data on income characteristics of the population. Second, the method of simple areal interpolation used to transfer information from the block group boundaries to the circles and plume footprints is based on the assumption of uniform distribution of population within a block group, which is not always realistic. Our future research plans include the use of alternative areal interpolation methods and examination of their effects on the results of environmental equity analysis. Third, the data on the quantity of a chemical released at each facility is not broken down temporally in the TRI database, which necessitates the use of hypothetical release scenarios for generating plume footprints. Future work would focus on collecting detailed information on actual chemical accidents at each site, instead of making assumptions about toxic releases. Finally, we used only the chemical that was released in the largest quantity at each TRI site to develop the dispersal footprints. We plan to incorporate the cumulative effects of all toxic chemicals released from a facility to provide a more comprehensive view of the burden of pollution source imposed on various demographic groups, including racial minorities and low-income residents. This would also include temporal refinement of the composite plume model, expanding the monthly (12) approach to weekly (52), or even daily (365) footprints, based on averaged weather conditions.

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