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Asthma and air pollution in the Bronx: Methodological and data considerations in using GIS for environmental justice and health research

Juliana Maantay*

Department of Environmental, Geographic, and Geological Sciences, Lehman College, City University of New York, 250 Bedford Park Blvd. West, Bronx, NY 10468, USA

Abstract

This paper examines methods of environmental justice assessment with Geographic Information Systems, using research on the spatial correspondence between asthma and air pollution in the Bronx, New York City as a case study. Issues of spatial extent and resolution, the selection of environmental burdens to analyze, data and methodological limitations, and different approaches to delineating exposure are discussed in the context of the asthma study, which, through proximity analysis, found that people living near (within specified distance buffers) noxious land uses were up to 66 percent more likely to be hospitalized for asthma, and were 30 percent more likely to be poor and 13 percent more likely to be a minority than those outside the buffers.

Keywords: Asthma; Air pollution; Geographic Information Systems (GIS); Environmental justice; Environmental health; Proximity analysis

Geographic Information Systems (GIS) for environmental health and justice research

GIS and associated spatial analytical techniques have been used extensively to study public health issues in recent years. Uses of GIS include disease mapping, epidemiological inquiries, health services analyses and planning, environmental health and justice analyses, exposure modeling, risk assessments, disease diffusion and clustering studies, health disparities research, and investigations of many other public health issues. Examples of health research using GIS cover a wide range of topics (Becker et al., 1998; Bowman, 2000; Bullen et al., 1996; Chakraborty and Armstrong, 1995; Chen et al., 1998; Cromley, 2001; Devasundaram et al., 1998; Glass et al., 1992; Guthe et al., 1992; Ihrig et al., 1998; Kingham et al., 1995; Kohli et al., 1997; Kulldorff et al., 1997; Love and Lindquist, 1995; Maantay, 2001b; Parker and Campbell, 1998; Pine and Diaz, 2000).

For more than a decade, Geographic Information Systems have also been used to examine the spatial realities of environmental injustice (Boer et al., 1997; Bowen et al., 1995; Burke, 1993; Chakraborty and Armstrong, 1997; Chakraborty et al., 1999; Maantay, 2002a; Morello-Frosch et al., 2001;

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*Tel.: +1 718 960 8574; fax: +1 718 960 8584.
E-mail address: juliana.maantay@lehman.cuny.edu.

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Neumann et al., 1998; Perlin et al., 1995; Pollock and Vittas, 1995; Sheppard et al., 1999). Environmental injustice can be defined as the disproportionate exposure of communities of color and the poor (or other vulnerable groups) to pollution, and its concomitant effects on health and environment, as well as the unequal environmental protection and environmental quality provided through laws, regulations, governmental programs, enforcement, and policies (Bryant, 1995; Bullard, 1994; Johnston, 1994).

GIS methods have been used in environmental justice research primarily to analyze the spatial relationships between sources of pollution burdens and the characteristics of potentially affected populations. A GIS is "a powerful computer mapping and analysis technology that allows large quantities of information to be viewed and analyzed within a geographic context," (Vine et al., 1997, p. 598). GIS is more than just computer hardware and software: it is an integrated system of components, consisting of information about the real world that has been abstracted and simplified into a digital database of spatial and non-spatial features, which, in conjunction with specialized software and computer hardware, and coupled with the expert judgment of the GIS user or analyst, produces solutions to spatial problems or questions.

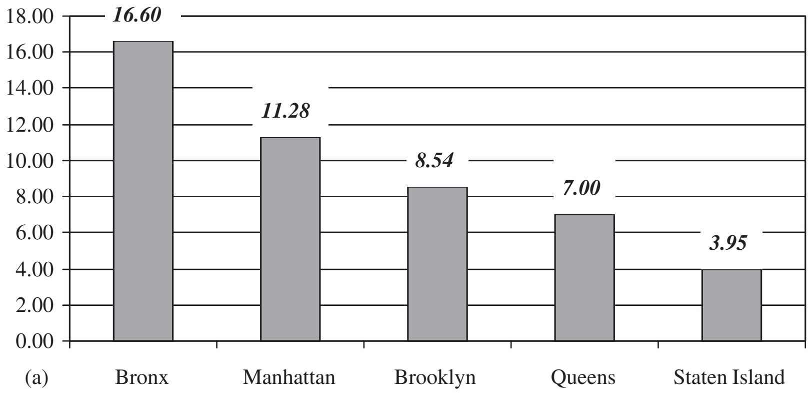
There are a number of limitations in using GIS for environmental justice and health research, such as spatial and attribute data deficiencies, and methodological problems, especially those related to geographical considerations (Maantay, 2002a; McMaster et al., 1997; Sheppard et al., 1999). Geographical considerations include the delineation of the optimal study area extent, determining the level of resolution and the unit of spatial data aggregation, and estimating the areal extent of exposure, as well as the various problems encountered in trying to statistically analyze and summarize spatial data. Due to the principle of spatial autocorrelation, which states that data from locations near one another in space are more likely to be similar than data from locations remote from one another, spatial data is by its very nature not randomly distributed, as traditional statistical approaches require (Tobler, 1979). Spatial autocorrelation, which is given in geography, becomes an impediment to the application of conventional statistical tests.

GIS approaches have proved to be quite controversial, and some researchers have questioned altogether the capabilities of GIS to adequately perform certain types of health research (Jacquez, 2000). Doubts also remain about the efficacy of GIS to pinpoint environmental injustices and the health impacts of pollution, and many researchers who use GIS have commented upon the challenges and limitations inherent in this method of spatial analysis (Clarke et al., 1996; Dunn et al., 2001; FitzGerald et al., 2004; Kulldorff, 1999; Moore and Carpenter, 1999; Richards et al., 1999; Rushton et al., 2000; Vine et al., 1997; Wall and Devine, 2000; Yasnoff and Sondik, 1999). This paper addresses some of the common concerns in using GIS for analyzing environmental justice and health, and places the on-going study of asthma and air pollution in the context of refining some of these methodologies and improving data sources for environmental justice and health research.

The purpose of this study is to determine if there is a spatial correspondence between the locations of land uses that contribute to poor air quality and the locations of people who have been hospitalized for asthma in the Bronx, New York City, and to examine the possible environmental justice implications of this association. I will discuss decisions about the geographic extent of the study area and the optimal spatial resolution; data sets required and their limitations; the approaches used in determining exposure potential; and the GIS methodology used in this analysis, in relation to the overall framework of environmental justice research questions and problems.

The problem of air pollution and asthma in the Bronx

Asthma is extremely prevalent in the Bronx, affecting people of all ages and diminishing their quality of life. In some cases, asthma can cause death, and the asthma death rate in the Bronx (6 per 100,000) is double that of New York City (see Fig. 1). The precise causes of asthma are not known, and there may be a multiplicity of causes. Some of these are thought to be outdoor air pollution, indoor air pollution, pollen, allergies, family history, and behavioral causes such as smoking or exposure to second-hand smoke (Guo et al., 1999). Many researchers have investigated the link between outdoor air pollution and asthma in other cities (English et al., 1997; Friedman et al., 2001; Neutra, 1999; Romieu et al., 1995; Schwartz et al., 1993; Studnicka et al., 1997; Sunyer and Spix, 1997), and have demonstrated that exposure to major air



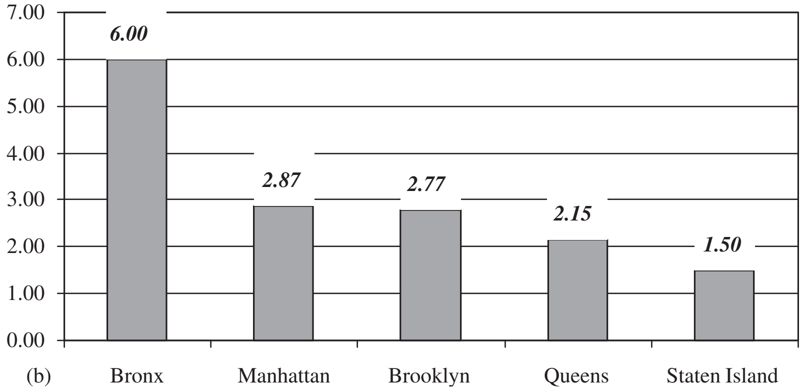


Fig. 1. (a) Asthma hospitalization rates for children aged 0–14, per 1000, by Borough (1997); (b) Asthma death rates for all ages, per 100,000, by Borough (1997). Data Source: NYC DOH (1999).

pollutants, including ozone, sulfur dioxide, nitrogen dioxide, and suspended particulate matter, is related to asthma prevalence or hospitalizations.

Children in the Bronx are especially affected by asthma—the asthma hospitalization rate for children is 70 percent higher in the Bronx than in New York City as a whole, and 700 percent higher in the Bronx than for the rest of New York State (excluding New York City), according to the New York City Department of Health's report, *Asthma Facts*, based on 1997 data collected by the state (New York City Department of Health (NYC DOH), 1999). The asthma hospitalization rate for children in the Mott Haven/Hunts Point sections of the South Bronx is 23.2 per 1000 children, nearly 140 percent higher than New York City's rate of 9.9 per 1000 children.

On average, approximately 9000 Bronx residents, nearly half of them children, were hospitalized for asthma, for each of the 5 years 1995–1999 (New York State Department of Health and Statewide Planning and Research Cooperative System (SPARCS), 2003) (see Fig. 2). Asthma hospitalization rates for children in the Bronx have doubled between 1988 and 1997. "Overall, in recent years, the Bronx is the New York City borough with the highest rates of both asthma hospitalizations and deaths," (NYC DOH, 2003, p. 2).

Air quality in the Bronx is adversely impacted by the concentration of Toxic Release Inventory (TRI) facilities, and other major stationary point sources of air pollution, such as power generating facilities, sludge processing plants, and waste disposal industries. In addition, the Bronx, being the only part of NYC on the mainland, has a dense network of highways and truck routes that connects it to the rest of the city, and connects the rest of the city to mainland USA. A substantial amount of the vehicular traffic in NYC and Long Island must first travel through the Bronx to access the several islands that comprise the rest of the city and suburban areas to the east. Consequently, highways

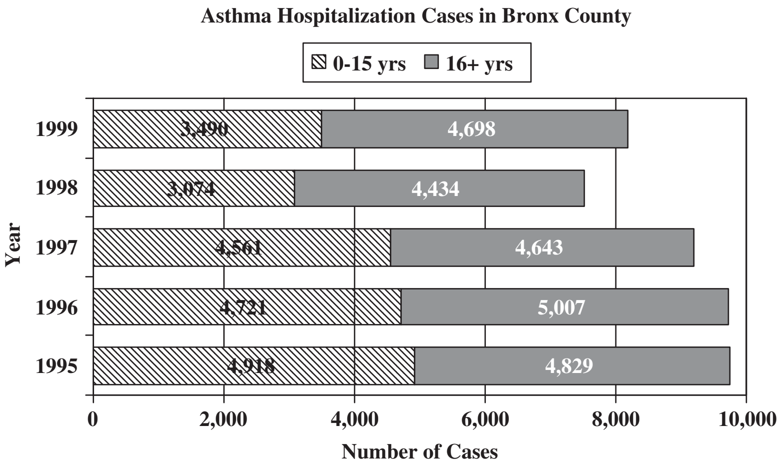


Fig. 2. Asthma hospitalization cases for the Bronx, 1995–1999. Data Source: NYS SPARCS (2003).

such as the Cross Bronx Expressway carry some of the highest volumes of traffic in the nation (Jackson, 1995). These mobile sources also have an adverse impact on air quality.

Environmental justice context of the Bronx

The Bronx is home to over 1.3 million people, according to the 2000 census, representing about 17 percent of the city's population (US Department of Commerce, Bureau of the Census, 2000a). Of the five boroughs of New York City, the Bronx is the least affluent, having the lowest mean household income, and the highest percentage of people below the federal poverty levels (30.7 percent, with some communities in the Bronx as high as 46 percent). The Bronx contains the highest percentage of minority population (85.5 percent) in the city, and is also the borough with the lowest average educational attainment levels (37.5 percent of adults have not graduated from high school, with some communities as high as 56 percent), and the highest percentage of female-headed households with children (19.2 percent). In a city known for its extremes of wealth and poverty, the Bronx stands out as being the most disadvantaged borough, overall (see Fig. 3).

Based on the locations of the industrial zones and the demographic and socio-economic characteristics of the proximate populations in New York City, it is almost a given that minority populations and poor people will be disproportionately impacted by noxious land uses, because most noxious uses are restricted to industrial zones. In New York City, as in many urban areas, minorities and poor people are more likely to be concentrated in or near industrial zones (see Figs. 4 and 5).

Many of the industries occupying these areas are waste-related or other polluting land uses. Industrial zones typically carry higher environmental burdens than residentially zoned areas. Since approximately 22 percent of New York City residents live within or adjacent to these major industrial zones, the environmental and health impacts of industrial zones are considerable in scope (Maantay, 2001b). Previous research has shown that in New York City over the past several decades, city planning changes to industrial zones had the effect of increasing the physical extent of industrial zones or the level of their allowable industrial (polluting) intensity in many predominantly poor and minority neighborhoods, while industrial zones near more affluent and less minority communities were decreased in extent or lightened in industrial intensity (Maantay, 2002b).

In the 1970s through the 1990s, while other areas of New York City were gentrifying and city planners were changing industrial zones into areas zoned for residential and commercial uses, the Bronx had large swaths of residential land re-zoned for industrial, and had existing industrial land re-zoned for heavier industrial uses (Maantay, 2002b). By decreasing the extent of industrial zones in the rest of the city and increasing those in the Bronx, the historical zoning change process has virtually assured that industrial areas in the Bronx are the proposed home of many new noxious facilities. Although there is not necessarily malicious or racist

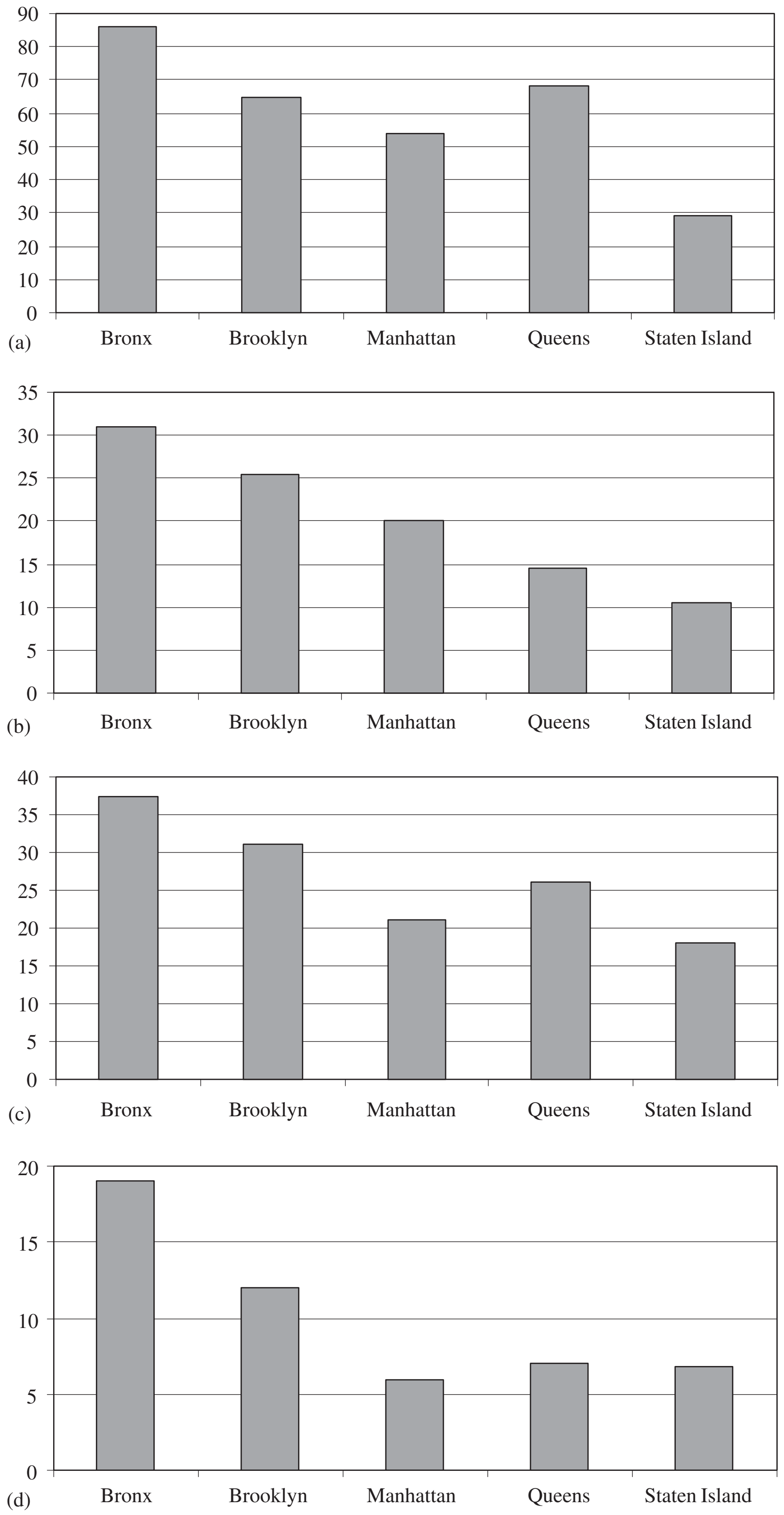


Fig. 3. Borough statistics (2000): (a) percent minority population; (b) percent persons below poverty; (c) percent adults without a high school diploma; and (d) percent female-headed households with children. Data Source: NYC DCP (2003); US Bureau of the Census (2000).

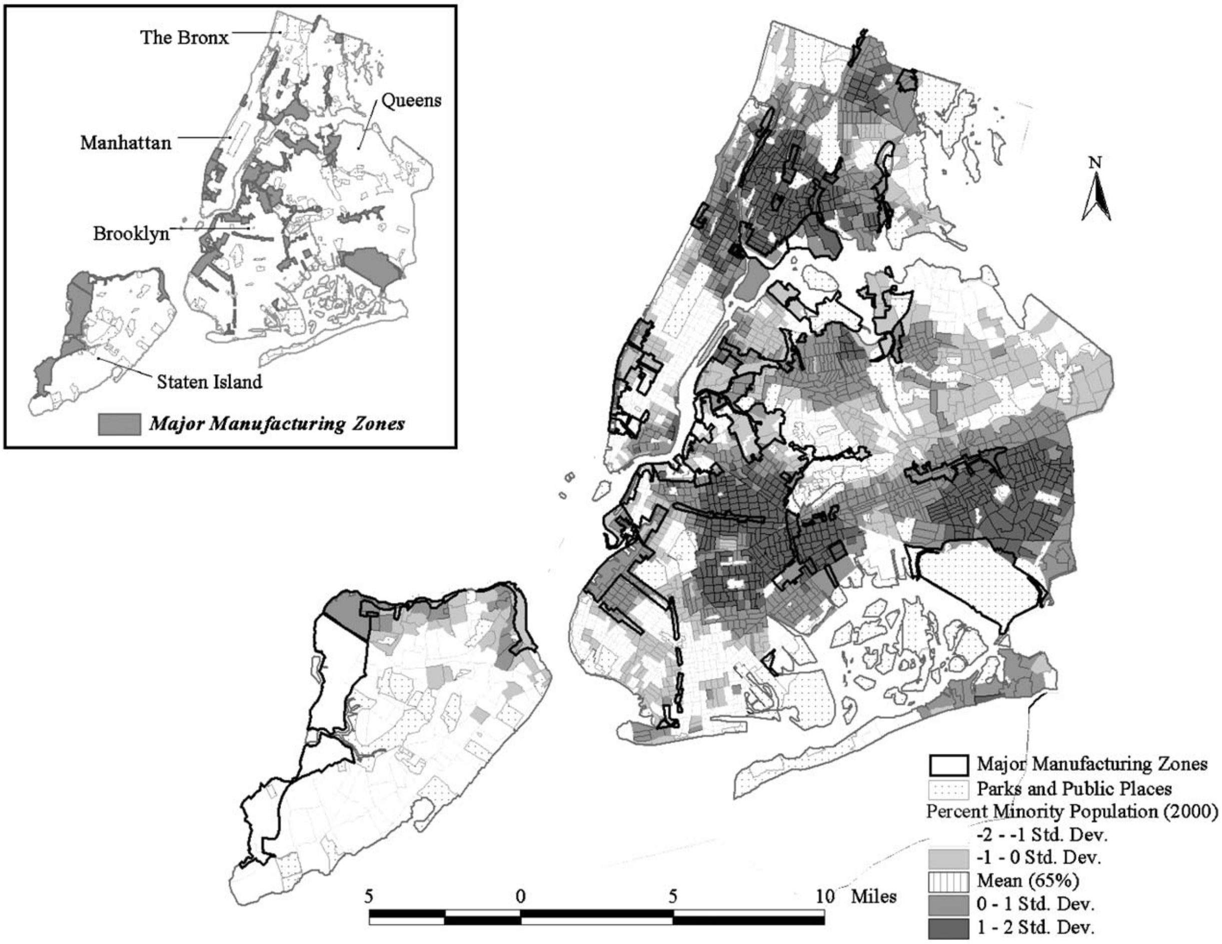


Fig. 4. Major industrial zones in the Bronx. Data Source: NYC DCP (1993); LotInfo (2002); US Bureau of the Census (2000).

intent ascribed to these re-zoning actions, the effect of disproportionate environmental burdens remains. This study seeks to ascertain whether or not the disproportionate environmental burdens correspond to an increased risk for asthma hospitalization.

What is the geographic extent of the study (scale), and the spatial resolution (unit of analysis)?

Among the first questions to be answered when using GIS for environmental justice research are "What is the appropriate study area (the scale or geographic extent of the study)?" and "What is the appropriate unit of analysis (the spatial resolution)?" In many cases, the answers to these questions are determined by the availability of data for all possible geographies; the known or probable geographical extent of the problem to be studied; the physical integration, transportation systems, cultural factors, and social dynamics of the particular region; existing political and jurisdictional boundaries; the geography of the existing health care infrastructure and service areas; the geographic interests of the project partners, collaborators, or funders; the funding sources and parameters; and many other considerations and constraints unique to each project.

Although these decisions about scale and resolution are often predetermined by such mundane and practical factors, their implications for analysis can be profound. A number of studies have demonstrated, for instance, that differences in the unit of analysis selected can have dramatic impacts on the results of the study (Anderton et al., 1994; Cutter et al., 1996; Glickman and Hersh, 1995; McMaster

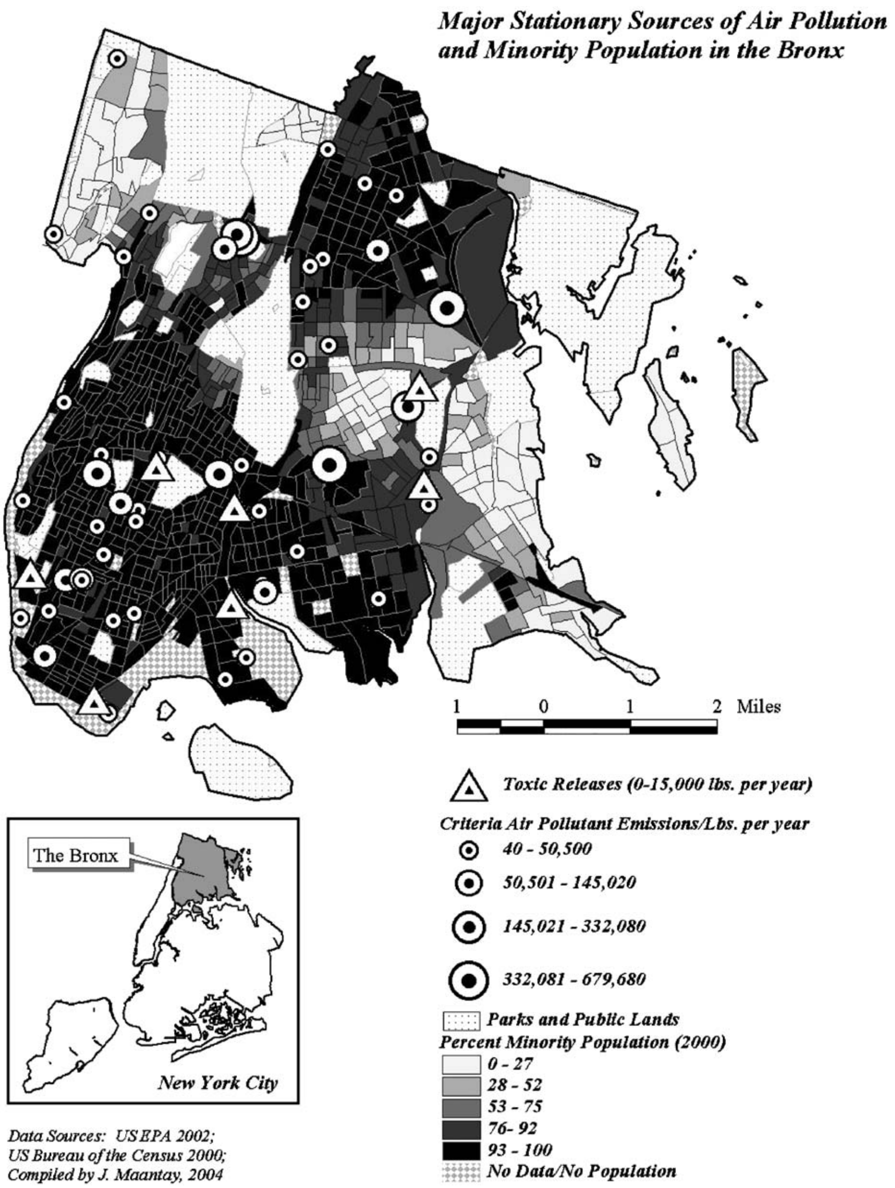


Fig. 5. Major stationary sources of air pollution and minority population in the Bronx. Data Source: US EPA (2002); US Bureau of the Census (2000).

et al., 1997). Different results reflecting different units of analysis are also influenced by the method of measuring or assessing exposure potential, as discussed below in the section "How is exposure potential determined?"

Data aggregation and administrative boundaries

One of the long-standing issues in many GIS studies is the selection of the type of administrative unit used to aggregate demographic and socio-economic data, and how well that unit represents the community. Most often, researchers use the geographic unit that makes sense in terms of available data, but these boundaries may have little to do with defining the actual or potential impacted community. The paper, "How We Manage is How We Measure," discusses this problem in detail (Zimmerman, 1994), explaining that the selection of political jurisdictional (e.g. municipal or county) boundaries versus administrative (e.g. census tract) boundaries as the unit of analysis will strongly affect the results of the study. On the one hand, the use of political jurisdictional boundaries such as the municipality may capture the sense of community inherent in the analysis, and may also lead to better policy solutions due to stronger involvement of political representation. On the other hand, municipal and larger political jurisdictional boundaries are generally much larger than the administrative units such as census tracts or block groups, and therefore do not depict the nuances of the potentially impacted populations and their characteristics as well as do census boundaries, nor can they delineate the extent of impact as well as the smaller units. Decisions about scale become crucial in nearly all environmental justice spatial studies, especially regarding advocacy and mitigation at the grass roots level. In "Applying the Political Geography of Scale: Grassroots Strategies and Environmental Justice," the scale selected for use in the analysis as being a more limited, narrow geography helped the constituents make their point and constructively affect policy (Towers, 2000).

Additionally, the issue of the modifiable areal unit problem (MAUP) has relevance to the selection of appropriate geographic units of analysis (Openshaw, 1984). Depending upon where the boundaries are drawn when aggregating data, the geographic pattern exhibited (by the distribution of health events, noxious facilities, minority populations, and so forth) can change substantially. "Even where similar units of analysis are chosen, e.g. census tracts, differences in how these units are combined have produced substantial differences in the portrayal of the prevalence of minority populations relative to the locations of waste sites" (Zimmerman, 1994, p. 645). Units used for data aggregation are often arbitrary with respect to the phenomena or events being investigated, yet will have a critical impact on the statistics that are generated based on the data aggregated in that way. Additionally, when dealing with point data, the exact location at which the boundary is drawn has implications for which geographic unit the point is "counted" in, and this in turn can have an enormous effect on data summaries and statistics.

It is generally acknowledged that using the smallest practicable unit of analysis yields the most accurate and realistic results in terms of environmental justice and health outcomes (Krieger et al., 2002, 2003). For demographic and socio-economic data, the smallest practicable unit of analysis means information aggregated at the smallest reliable enumeration unit that contains the variables of interest. For environmental data, this means information for each property lot or facility of interest. If continuous data is necessary, such as densities or variables best represented by a grid or raster, it means the smallest possible cell size. For health data, individual patient record level data for health outcomes is often the most useful to work with, but is not always readily available. The differences between using asthma hospitalization data aggregated at the census tract level and individual hospitalization record level data is discussed in the section "The Need to Build Better Databases" below.

Scale and resolution of the study's spatial data sets

The geographic extent of this study is the Bronx, a New York State county and one of the five boroughs of New York City, comprising approximately 42 square miles of land mass. The Bronx was selected as the study area primarily because of its high rates of asthma hospitalizations and high quantities of noxious land uses, and the likelihood of obtaining relatively complete and accurate asthma hospitalization data sets for this area. The Bronx serves as a pilot study for the methods developed for this work, and in the future the entire New York City could be analyzed in a similar way.

The unit of analysis for demographic and socio-economic data is the census block group, the smallest census enumeration unit for which demographic and socio-economic data is consistently available. The Bronx has 957 block groups, each containing an average of about 1400 people, with a minimum of 0 (no population) and a maximum of 24,400.

The unit of analysis for the asthma hospitalization cases is the individual patient record for each admission, and this level of resolution was crucial in developing accurate rates of asthma hospitalization inside and outside of buffered areas around polluting land uses, as described below. The asthma hospitalization cases have also been aggregated and summarized to the block group level, and used in conjunction with block group population totals to calculate rates of asthma hospitalization.

The units of analysis for the environmental data are the individual polluting land uses, and distance buffers constructed around each (see section below for proximity analysis methodology).

What is considered an environmental hazard?

In environmental justice research, it is necessary to decide which hazards will be considered as environmental burdens in order to assess if populations are disproportionately affected. Researchers have most often used databases that are publicly available and that track pollution information at the national or state level. The Toxic Release Inventory, maintained by the US Environmental Protection Agency (EPA), is used for this purpose because it is a fairly consistent database and covers the entire US Facilities within certain Standard Industrial Classification (SIC) codes (e.g., chemical, printing, electronic, plastics, refining, metal, paper industries) must report their emissions and waste to the TRI if they meet certain conditions, such as manufacturing more than 25,000 pounds per year or using more than 10,000 pounds per year of one or more of the 650 listed toxic chemicals (US EPA, 2001). Because of the high thresholds in the reporting regulations, TRI includes only the largest users and emitters of toxic substances.

In many communities, TRI facilities and other listed major stationary point sources represent just one component of the total environmental burden, and many other facilities (which individually are below the reporting thresholds for quantities of emissions, use, or production of toxic chemicals, and thus are not required to report to TRI) may contribute as much or more on a cumulative basis to the overall air emissions. Unfortunately, it is difficult to obtain reliable data about these facilities, since they are not listed in a publicly accessible format and often do not receive any governmental oversight. Many smaller facilities, such as auto body painting shops, electro-plating firms, waste transfer stations, and factories also emit contaminants to the air, but these emissions remain undocumented, for the most part, and thus are difficult to incorporate into the analysis.

Another major contributor to air pollution, especially fine particulate matter, is the high level of truck traffic in the Bronx, which is especially prevalent in the industrial zones. It is not uncommon for 1000 trucks per day to access one solid waste transfer station, and there are several dozen such transfer stations in the Bronx (Maantay, 2001a).

Although other vehicular traffic is a significant source of air pollution in the Bronx, it is more difficult than the truck routes to isolate and quantify. Limited access highways, which carry in excess of 50,000 vehicles per day (average annual daily count), were selected to represent the most significant pollution sources from vehicular traffic in addition to trucks.

A strength of this study is that it analyzes the relationship between asthma-related hospitalizations and the proximity to heavily traffic roadways (e.g. major truck routes and highways), as well as to point sources of air pollution (e.g. TRI facilities and other major stationary sources).

What pollutants should be investigated?

Previous research has demonstrated that exposure to major air pollutants, including ozone, sulfur dioxide, nitrogen dioxide, and suspended particulate matter, may be associated with asthma prevalence or hospitalization, and many of these studies focused on exposure based on proximity to roadways (Edwards et al., 1994; English et al., 1997; Friedman et al., 2001; Green et al., 2004; Guo et al., 1999; Neutra, 1999; Schwartz et al., 1993; Studnicka et al., 1997; Sunyer and Spix, 1997).

There are national air quality standards for these criteria pollutants, and their concentrations can be measured in the ambient air. However, there are only three air monitoring locations in the Bronx that record levels of criteria air pollutants in the ambient air, two of which have monitors that measure the levels of hazardous air pollutants (HAPs) (US EPA, 2002a). The existing air monitors are also not necessarily located in the areas of high polluting activities, nor are they distributed evenly throughout the borough. The low number of monitoring locations and their irregular coverage make it meaningless to perform spatial interpolation using the air monitor sites as sample points, especially when used in conjunction with the high resolution of the asthma hospitalization data in the study. Therefore, the monitored ambient air quality measurements were not used to determine areas of chronic poor air quality.

Instead, the locations of known sources of air pollution were used to derive approximations of the areas with poor air quality in the Bronx. In ascertaining which land uses are most likely to be associated with the suspected pollutants of concern for asthma, it was decided to focus on major stationary point sources of air pollutants, as well as mobile sources from major highways and truck routes as proxies for areas of poor air quality.

According to the relevant research, the majority of researchers now consider air pollutants a risk factor for asthma, although the roles that specific air pollutants play in various respiratory illnesses remain unclear (Brunekreef et al., 1995; Delfino et al., 2003). However, if the general effects of air pollution, rather than the effects of specific pollutants, are examined, there is a large body of literature demonstrating their relationship to adverse respiratory events. In light of this fact, air pollutants are best treated as a whole. Therefore, air pollution in this article refers to the substances that constitute the pollutant mixture from traffic and industrial related sources that has been associated with respiratory effects, typically including particulate matter (e.g. PM_{10}, $PM_{2.5}$), volatile organic compounds (VOCs, e.g. benzene, acetaldehyde, tetrachloroethlene, toluene), NO_2 (nitrogen dioxide), SO_2 (sulfur dioxide), and O_3 (ozone). The locations of the noxious land uses associated with these pollutants were mapped and examined in light of their spatial correspondence to areas of high asthma hospitalization rates.

Data quality and data uncertainty issues

A number of data problems and data limitations are encountered with the integration of health data in GIS. A basic data quality issue is data accuracy, which takes two forms: positional accuracy and attribute accuracy. Both have substantial ramifications for the asthma and air pollution study, as discussed further below:

> Positional accuracy refers to the nearness of the values describing the position of a real-world object to the object's 'true' position. Positional error may be introduced at the initial measurement of location. A second source of error is the chain of processing between the initial measurement or observation and its final 'resting place' in a GIS database. Because GIS analysis involved manipulations of databases like projection change and overlay, errors propagate…Attribute accuracy is an aspect of data quality that considers the nearness of the values describing real-world entity in the database to the entity's 'true' attributes… The amount of information available about uncertainty or error in these attribute data will vary depending on whether the agency collecting the data has carried out and described procedures for determining the level of error in the data…In public health GIS applications, consistent definitions of what constitutes a health event or health service are needed to ensure attribute accuracy…it is not always easy to define what is meant by a 'case'; moreover, case definitions may change over time. Attributes of cases, like race, ethnicity, or ICDM diagnosis, also need to be coded consistently to meet standards for attribute accuracy (Cromley and McLafferty, 2002, pp. 57–58).

The issue of representing a measure of data reliability or data uncertainty is discussed in "Visualizing geo-referenced data: representing reliability of health statistics," (MacEachren et al., 1998). Issues of data uncertainty are also treated further in the section below on "Geo-Referencing."

Asthma hospitalization cases—the use of record-level data

The basic data sets needed to conduct this analysis were asthma hospitalization records; the location of and emissions information about the polluting facilities or land uses; land use and zoning data; and demographic and socio-economic information. Due to issues of patient confidentiality, the patient-related data is typically the most difficult to obtain, especially at a fine level of spatial resolution.

Many of the previous studies relied on survey questionnaires and self- or parent-reported asthma symptoms, rather than use data on respiratory illness from medical facilities or physicians (Ciccone et al., 1998; Oosterlee et al., 1996; Van Vliet et al., 1997; Venn et al., 2001; Wyst et al., 1993). Studies based solely on questionnaires introduce a high amount of subject-based reporting bias, and therefore results may be less reliable. The cases used in this asthma and air pollution study all exhibit doctor-diagnosed asthma that, by virtue of the fact that hospitalization was necessary, is quite severe.

The database of asthma hospitalization cases was obtained from the New York State Department of Health's State Planning and Research Cooperative System (SPARCS). The data included 5 years (1995–1999) of asthma hospitalization records for all Bronx residents admitted to Bronx hospitals under the diagnostic codes associated with asthma attacks, the International Classification of Disease, Ninth Revision, Clinical Modification (ICD-9-CM) diagnostic code 493, with 12 sub-categories. Age and gender were given for each patient. Race and ethnicity were also fields in the database, but the information was voluntary and often unrecorded, and therefore was too inconsistent to be used in the demographic analysis.

The "Asthma Facts" report issued by the New York City Department of Health utilized the same SPARCS data, and the report comments upon this same issue of race/ethnicity data inconsistency:

> SPARCS data on the race and ethnicity of individual patients are imprecise. Primarily, these data are not collected in a standardized manner across hospitals. Data regarding Hispanic origin are missing for approximately 25% of the asthma cases. Finally, large numbers of records had race listed as 'other.' Consequently, race/ethnicity specified rates for asthma hospitalization could not be calculated (NYC DOH, 2003, p. 32).

However, although we could not characterize the race and ethnicity of individual asthma hospitalization admissions cases, information in "Asthma Facts" about asthma prevalence in adults (self-reported) in New York City shows that Hispanic and non-Hispanic Black rates for asthma, at 6.4% and 4.5%, respectively, are considerably higher than rates for Non-Hispanic White rates, at 3.5% (NYC DOH, 2003, p. 29).

Geo-referencing—mapping the locations of asthma hospitalization cases

Geo-coding, a type of geo-referencing, is a common function in most GIS applications, and is used to plot on a map the locations of phenomena or events listed in a table. Usually, street addresses listed in a table are matched by the GIS program to a spatial file of street segments, each segment having an address range. The geo-coding program generally places the point at a location mathematically computed and interpolated from the street segment file, and not necessarily at the exact location of the address. Therefore, there is typically some imprecision in the absolute location of a given point, since the location is estimated along the correct segment and address range. Additionally, most addresses are geo-coded to the centerline of the street rather than to the location of the actual structure. In most cases in urban areas, spatial accuracy is quite high. However, there are almost always unmatched addresses, those addresses that the geocoding software cannot locate spatially for one reason or another. The addresses in the records database may be incorrect, due to mis-spellings or typos, the street segment spatial file may have errors, including missing street segments or address ranges, and there may be inconsistencies between the two, such as different names for the same street.

Because the geo-coding process is highly automated within GIS, the opportunities for errors abound. Although ground-truthing and field verification of addresses is possible for databases with limited numbers of locations, it is impractical when an address database contains thousands of records, as many health databases do. There is also a question of whether the geo-coding programs can duplicate their address-matching results during multiple attempts to geo-code the same address database. The "repeatability" of geo-coding results is an important consideration, along with absolute positional accuracy, when assessing the believability of a spatial database derived from geo-coded addresses (Whitsel et al., 2004):

> Even if an address is successfully matched, it may not be assigned to the correct location. A field check of over 500 geo-coded residential addresses to assess spatial accuracy uncovered a variety of errors (Cromley et al., 1997). The relative locations of 7% of the cases were incorrect. A few cases (less than 1%) had been geocoded to locations more than 500 feet away from the correct location. This type of error would be of particular concern in any study measuring distances from the geocoded location to another location because the true distance would be over- or under-estimated (Cromley and McLafferty, 2002, p. 87).

Since the asthma and air pollution study relied on buffer distances ranging from 150 m to one half-mile, depending on the type of hazard, geocoding errors resulting in positional inaccuracy could diminish the validity of the results. Additionally, because the individual hospitalization cases were later aggregated to the census block group unit that they fell within, in order to develop rates per block group unit, positional errors of the point data could place the case in the wrong block group unit, affecting the reliability of the rates. Errors could also accrue if the point was on or very close to a block group boundary, as the point may be assigned to the incorrect unit, also affecting the rates.

In the database obtained from SPARCS, the latitude and longitude of the patient's home address was given in lieu of the actual street addresses, in order to protect patient confidentiality. The street addresses had already been geo-coded and subsequently transformed into latitude and longitude before we were given the data. The latitude and longitude coordinates allowed us to geo-reference and plot the residential locations, without knowing the patients' street addresses. There were nearly 50,000 records of asthma hospitalization for the 5-year period. Some patient records had missing or incomplete addresses and thus could not be transformed to latitude and longitude coordinates, but approximately 85 percent of the street addresses were successfully geo-coded and transformed to lat-long. All of these were then geo-referenced by lat-long, and plotted on the map.

The latitude and longitude coordinates of patient addresses were mapped for each of the 5 years. The patients were also divided into two age cohorts (0–15 years, and 16 years and older) and their spatial coordinates were plotted separately by cohort. Through a point-in-polygon overlay analysis, the numbers of asthma hospitalization cases (points) were calculated for each block group (polygon), for each year, and then averaged for the 5-year study period, for total cases and for each age cohort. Annual and 5-year average rates for the overall population and for the two age cohorts were obtained by using the appropriate census populations for each block group as the denominator. The rates were mapped as choropleth maps (see Fig. 6), and were also interpolated by Kriging from the rate data attached to the block group centroids (the geometric center of each block group).

Data limitations

A major drawback to the data used in this analysis is that asthma hospitalization records only provide instances of hospital admissions, and do not reflect the magnitude of the asthma problem. Actual cases of asthma or even emergency room visits due to severe asthma problems are not tracked consistently by doctors or hospitals, and there is no statewide reporting of asthma and therefore no centralized asthma database. People suffering from asthma may be seen by a private doctor, a clinic, a hospital emergency room or a school nurse, or may not be seen by any health care provider. Asthma hospitalization records represent only one set of asthma patients, generally corresponding to the most severe cases, but do not represent the prevalence of the disease, or the locations of people with asthma.

The locations of the TRI facilities were obtained from the national databases maintained by the EPA, and were geocoded based on the street addresses given (US EPA, 2002b). Since information contained in the TRI database is self-reported by facility managers or their consultants, levels of accuracy and consistency are unknown, which limits its usefulness with regard to actual quantities of emissions. Also, quantities given are estimated and not measured amounts (Jia and Di Guardo, 1996). The potential positional inaccuracy discussed in relation to patient locations also applies to geocoding and plotting the locations of TRI facilities and other facilities of interest.

Other major stationary point sources are listed in the National Emissions Inventory (NEI) database for criteria and HAPs (US EPA, 2002c), and were also address-matched to locations. NEI contains information about emissions from each major stationary point source, such as power plants, major housing complexes, medical centers, and industrial uses that emit criteria pollutants or one or more of 188 listed HAPs. NEI also contains information about non-point sources, which are defined as small stationary sources that are not identified individually, such as neighborhood drycleaners, as well as on-road emissions from highway vehicles. These area and mobile sources are aggregated only at the county level, and thus would not be useful for this analysis.

Major industrial zones were digitized from information from the New York City Department of City Planning (New York City Department of City Planning (NYC DCP), 1993). This layer depicts major zones only, and does not include any isolated smaller pockets of industrially zoned land or individual parcels which may potentially house polluting land uses.

Data about the limited access highways and the major truck routes were obtained from New York City Department of Transportation (New York City Department of Transportation (NYC DOT), 2002) and digitized using the US Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER) Files of street segments as a base (US Department of Commerce, Bureau of the Census, 2000b). Trucks of a certain size (two axles with six tires, or three axles) are

Fig. 6. Asthma hospitalization rates by block group, 5-year average, 1995–1999 Data Sources: SPARCS (1995–1999); US Bureau of the Census (2000).

restricted to traveling on these routes that are designated by the city, but in reality they often use other less congested streets for convenience. Although much anecdotal evidence exists for this practice, there was no way to reliably incorporate these unofficial truck routes into the analysis.

The demographic and socio-economic data used in this study came from the 2000 US census. The main limitation of the census data for this study is the possible undercounting of population in poor and immigrant communities. Patient addresses for asthma hospitalizations were occasionally recorded in block groups where there was no census-reported population. This could be due to census undercounting of population in these areas, or could also be due to geocoding errors, incorrect transformation of street address to lat–long coordinates, or patients inadvertently or purposefully providing wrong addresses. Fewer than 1 percent of the block groups in the Bronx had no population recorded yet had patient address records for asthma hospitalization. Because rates could not be developed for these block groups (since the denominator equals 0) they were not included in the analysis.

How is exposure potential determined?

Two commonly used methods of determining exposure potential in environmental justice research are the spatial coincidence method and proximity analysis. The spatial coincidence method entails examining and characterizing the populations within a certain geographic unit (such as a census tract, ZIP Code, or county) and noting whether or not a polluting facility exists in that unit. Populations within a unit containing a polluting facility are considered to be impacted by it, and thus potentially exposed to environmental burdens. Populations within a unit not containing such a facility are considered not impacted. Although relatively easy to analyze, it is a simplistic determination of exposure potential and an inaccurate way of characterizing impacted populations. For instance, one could live within the same ZIP code as a polluting facility, but be quite far away from it, yet still be considered impacted by it with this method, whereas one could live right across the street from a polluting facility, but because it is in a different ZIP code you would be considered not impacted by it.

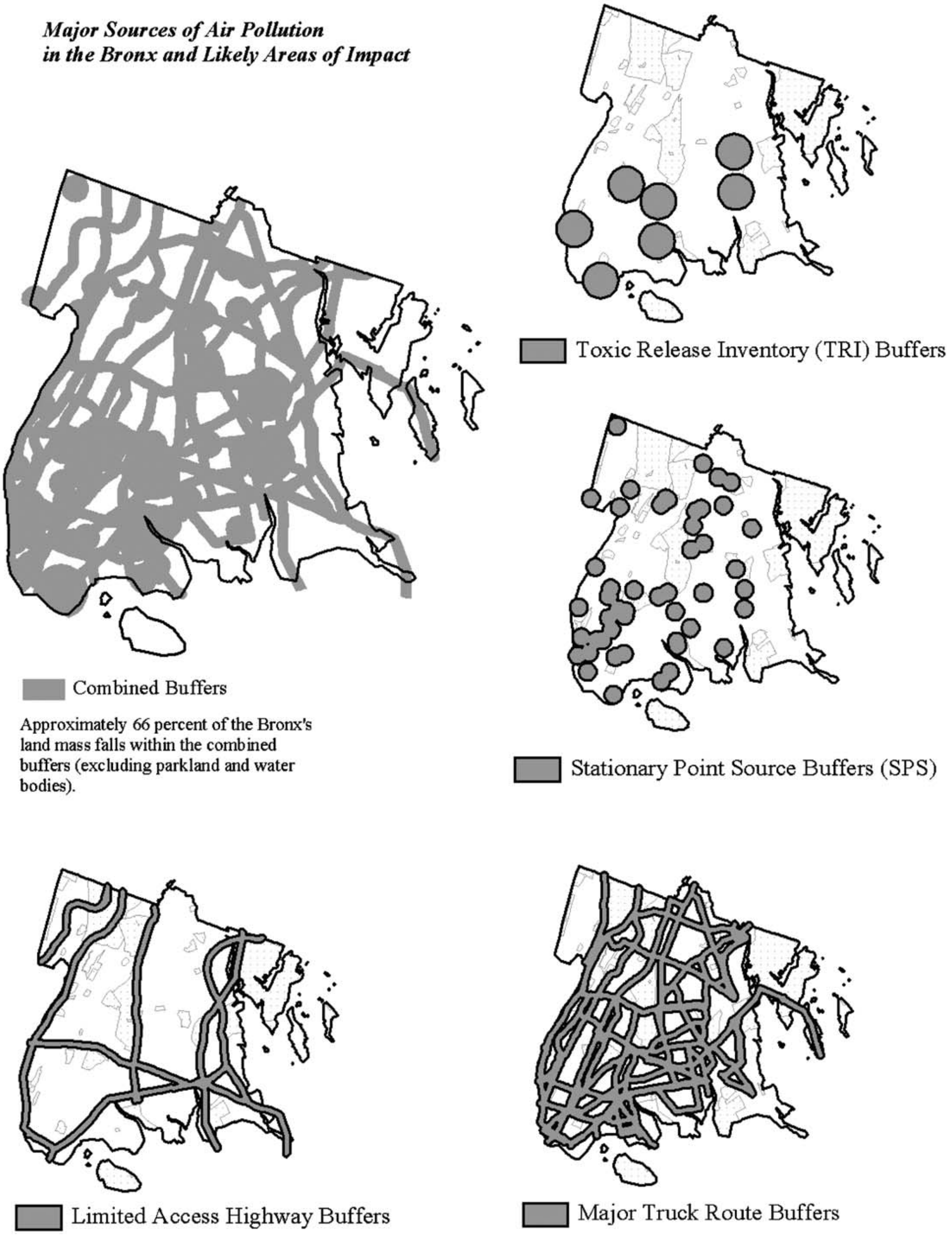
Proximity analysis examines the population within a certain specified distance of the polluting facility. The distance used in calculations is related to the type of facility involved and its likely emissions. Populations within the appropriate buffer distance are considered to be impacted, and those outside the buffer are considered not impacted. This method has been generally acknowledged to be superior to the spatial coincidence method because it more adequately captures the potential for exposure (Maantay, 2002a, McMaster et al., 1997).

However, proximity analysis also has its drawbacks. It assumes that everyone within the (usually circular) buffers is impacted equally, when we know that air pollution does not disperse equally in all directions from a source. The distances used for the buffer constructions are also best "guestimates," based on existing environmental quality standards, empirical evidence about pollutant fate and transport, and generalized model results. Polluting facilities emit differing quantities and qualities of pollution, and although in reality the magnitude and type of emissions would affect the areal extent and severity of exposure potential, constant buffer distances do not take these factors into account. It is also unknown how the distance from a source of pollution is related to health risks or exposures. Nevertheless, short of conducting a much more detailed and individualized environmental assessment of each pollution source, proximity analysis using standard buffers remains a valid means of evaluating environmental justice concerns.

GIS methods for proximity analysis

This study accounts for exposure to air pollution burdens of these noxious land uses by creating buffer zones around the TRI facilities and other listed major stationary point sources as a proxy for areas of impact. All TRI facilities and many of the listed major stationary point sources are located within industrial zones, and these zones are also usually the home of the smaller polluters. Through visual inspection of the buffers and land use and zoning data, it was determined that, in most cases, the buffers constructed around the listed facilities also capture the likely locations of the smaller polluters within the industrial zones, although there may be important exceptions if the unlisted industrial facilities are located illegally in a non-industrial zone (see Figs. 4 and 7).

Exposure to the pollution from truck traffic is accounted for by the creation of buffers surround-



Major Sources of Air Pollution in the Bronx and Likely Areas of Impact

Approximately 66 percent of the Bronx's land mass falls within the combined buffers (excluding parkland and water bodies).

Fig. 7. Proximity Buffers (TRI, SPS, MTR, LAH and combined buffers). Data Source: US EPA (2002); NYS DOT (2002); NYC DOT (2002).

ing the major truck routes, many of which traverse residential neighborhoods. Buffers were also constructed around limited access highways to represent areas of impact from other vehicular traffic in addition to trucks.

The buffers constructed for this study were based on distances established as standards by environmental agencies or used most often by other researchers as the area of greatest potential impact from sources. One half-mile radius buffers were constructed around TRI facilities (Neumann et al., 1998; Chakraborty and Armstrong, 1997); one-quarter mile radius buffers around other major stationary point sources of criteria pollutants (New York City Mayor's Office of Environmental Coordination, 2001); and a 150 m buffer from roadway centerline around both limited access highways and major truck routes (Hitchins et al., 2000; Zhu et al., 2002). 150 m from a main road "is the distance within which concentrations of primary vehicle traffic pollutants are raised above ambient background levels" (Venn et al., 2001, p. 2177). The majority of similar studies found significant associations between traffic-related emissions and respiratory symptoms within the 100–200 m range (Edwards et al., 1994; Livingstone et al., 1996; Nitta et al., 1993; Wilkinson et al., 1999).

Each of these buffer types constituted a separate layer that was then intersected with the asthma hospitalization layers. A layer of all the buffers combined was also created and intersected (see Fig. 7).

Using the locations of the asthma hospitalization cases, it was possible to determine which cases fell within each of the four different buffer types, as well as the combined buffer, by "clipping" the asthma layer by each of the five buffer layers. The clip function was performed for total asthma hospitalization cases, as well as for each of the age cohorts separately. Rates based on the 5-year average were calculated for the portions of the block groups within each type of buffer and the combined buffer. Because the locations of the asthma hospitalization cases are pinpointed with accuracy by latitude and longitude and are not aggregated by census tract or block group, it is possible to derive rates for the block groups that can be differentiated by whether the portion of the block groups is in or out of the buffer. This would not be possible using data aggregated by enumeration unit, and is only feasible because individual patient record level data was used.

In order to develop and compare rates for inside and outside the buffer areas, a process called areal interpolation was performed on the census block groups. The boundaries of census block groups are not coincident with the buffer areas, and therefore the population data for each tract or block group must be re-calculated based on the portion of the tract or block group that falls within the buffer. In order to obtain accurate estimates of population counts and other population data within the buffer areas, areal interpolation, or areal weighting, was required. This consists of an algorithm that is applied to the area information of each tract or block group. The (rectangular) census tracts or block groups that fall partially, but not totally, within a certain (circular) buffer are weighted by the proportion of the area that falls within (Flowerdew and Green, 1994; Goodchild and Lam, 1980). For instance, if a tract or block group is exactly half within the buffer, the ratio would be 0.5. These ratios are then applied to the population variables to get a reasonable estimate of the population within the buffers.

The set of demographic and socio-economic characteristics that we were interested in were quantified and mapped for the within-buffer population, and compared to the outside-of-buffer population. In comparisons of other methods, areal interpolation was found to be most accurate method for obtaining reliable estimates of intersected, non-coincident polygons (Goodchild and Lam, 1980). Since the proportion of each variable within the buffer is based on the proportion of area within the buffer, the underlying assumption in this method is that the data for an entire unit of analysis (in our case, the block group) is homogeneous throughout its extent, with its population spread evenly throughout, which obviously may not be the case. For instance, a large housing project in one corner of the tract would impact the accuracy of areal interpolation, as would a large part of the tract being parkland or water, where people are not likely to live. In general, the smaller the unit of data aggregation, the greater the likelihood of homogeneity and the more reliable the method of areal interpolation.

Asthma hospitalization rates were developed by using the actual number of cases in each portion of the block group within the buffers divided by the number of people estimated in that portion of the block group within the buffers. The population of the portion of the block group within the buffer was estimated by applying areal interpolation, using an areal weighting script. This GIS script, or mini-program, calculates the proportion of the total area of the block group that is within each of the buffers. This ratio is then applied to the block group population, under the assumption that the proportion of area that falls within the buffer reflects the proportion of the total population of the block group that falls within the buffer. As noted above, this is a simplification; however, considering the small areal extent of the typical Bronx block group, it appears to be reasonably accurate. Rates in and out of buffers were calculated for the total population and the age cohorts separately, for each of the 5 years, and then calculated based on the 5-year average.

Results of proximity analysis

The most noticeable visual aspect of the buffers that were created around major polluting land uses is the extent of the Bronx that is covered. Approximately 66 percent of the Bronx's land mass falls within the buffers (excluding major parkland and water bodies). Since, in this study, the buffers represent those areas most impacted by air pollution, a majority of the Bronx population may be exposed. According to calculations based on the areal weighting script, 88 percent of the people within the buffers are minorities, and 33 percent are below the federal poverty level. This contrasts with 79 percent minorities and 25 percent people below poverty in the areas outside the buffers (see Fig. 8a). Even though the buffers cover so much of the Bronx, there is still a marked disparity between the characteristics of the populations inside and outside of the buffers, indicating the likelihood of disproportionate environmental burdens. As mentioned earlier, the SPARCS database did not provide useable information at the individual record level regarding race/ethnicity or poverty status. Therefore, we could not link racial or economic data to the asthma hospitalizations cases, and can only examine the spatial correspondence between the individual level asthma hospitalization cases and rates in the buffers and minority and poverty rates

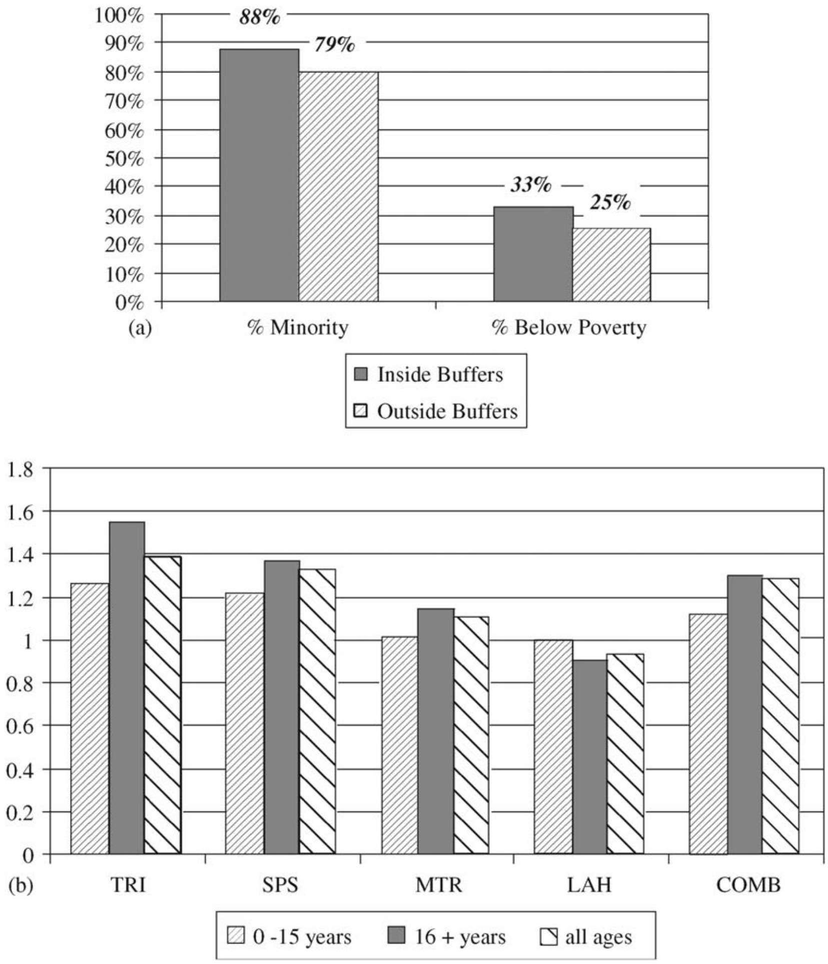


Fig. 8. (a) Percentages of minority population and percentages of persons below poverty, in and out of the buffers, 2000. (b) Odds ratios for asthma hospitalization rates, in and out of buffers, 1999.

aggregated by block group. Behavioral factors such as smoking and other factors such as educational attainment which may have a bearing on asthma hospitalization rates cannot be ascertained from the SPARCS data, and therefore could not be incorporated into the analysis.

In addition to the differences seen in poverty and minority status inside and outside of the buffers, there is a difference, too, in asthma hospitalization rates inside and outside the buffers. Applying odds ratios to the rates, it is seen that it is 30 percent more likely for people within the combined buffers to be hospitalized for asthma than people outside the buffered areas. Within some of the individual buffers, such as TRI and major stationary point sources, it is 60 and 66 percent more likely, respectively, to be hospitalized for asthma than if outside the buffers (see Fig. 8b and Table 1). The odds ratios, in general, are higher for adults 16 years and older than for children 0–15. This is true for every type of buffer, and for nearly every one of the five years analyzed.

Although the analysis found that people within the buffers were much more likely to be hospitalized for asthma than those living outside the buffers, the risks vary depending on the type of buffer. Living within TRI and major stationary point source buffers poses a higher risk than living within the limited access highway and major truck route buffers, according to the proximity and odds ratio analyses. People within the highway and truck route buffers do not appear to have an increased risk of asthma hospitalization, except for adults aged 16 and over, living near the truck routes, who have a 17 percent greater likelihood of asthma hospitalization. These neutral findings for the truck routes and highways may be an artifact of how the population numbers within the buffers were calculated. The areal weighting algorithm used to estimate population within the buffered areas assumed population is spread evenly throughout the census block group. However, these highway buffer areas may, in fact, be less densely populated than the remainder of the block group, for various reasons including building clearances at the time the highways were constructed. If the population near the highways is actually less than that estimated by the areal weighting script, then the denominator used to calculate rates would be too high, making the asthma hospitalization rates lower than they actually are within these buffers. One way to test this theory would be to obtain finer resolution population data to compare to the asthma hospitalization cases.

Table 1
Odds ratio ranges for the 5-year study period 1995–1999

Buffer type	Adults	Children	Total population
Combined	1.28–1.30*	1.11–1.17*	1.25–1.29*
TRI	1.29–1.60*	1.14–1.30*	1.33–1.49*
SPS	1.26–1.66*	1.16–1.3*	1.23–1.32*
MTR	1.07–1.17*	1.00–1.09	1.10–1.15*
LAH	0.90–0.93	0.83–0.99	0.86–0.93

*Indicates results are statistically significant at $p<0.01$.
TRI = Toxic Release Inventory; SPS = stationary point sources; MTR = major truck routes; LAH = limited access highways.

The analysis also looked at differences in asthma hospitalizations by gender, and did not find any significant difference in rates between males and females, either in or out of the buffers.

A sensitivity analysis was conducted using different buffer distances. The buffers around the limited access highways and major trucks routes were revised to be 100 and 200 m wide from the road centerline. Buffers around the TRI were revised to be 1/4 and 1 mile radii. Buffers around major stationary point sources were revised to be 1/2 mile radius, and the proximity analyses were re-calculated. There was no significant difference in the odds ratios using the revised buffer distances, and the original buffer distances were retained.

In looking at the number of observed cases versus the number of expected cases, based on the overall Bronx 5-year average asthma hospitalization rate. Table 2 shows that the observed cases within the combined buffer areas are higher than expected, and those in the areas outside the combined buffers are lower than expected. A standardized incidence ratio (SIR) was calculated by dividing the observed number of asthma hospitalizations by the expected number of asthma hospitalizations for each subpopulation as defined by buffer state (inside buffer, outside buffer) and further refined by age cohort (all ages, 0–15, and 16+). The overall Bronx hospitalization rates were calculated by dividing the total number of asthma hospitalizations by age cohort by the appropriate susceptible populations of the Bronx. The resultant rates were then multiplied by each of the sub-populations in order to arrive at the expected numbers of hospitalizations. 95% confidence intervals of the expected values confirmed that there was a statistically significant higher incidence of asthma hospitalizations within the

Table 2
Expected versus observed cases of asthma hospitalizations

Standardized incidence ratio (SIR) for combined buffers 5-year averages

Age group	Relationship to combined buffer	Observed hospitalizations	Expected hospitalizations	SIR	95% Confidence interval
All ages	Inside	6374.0	5953.54	1.071	1.097–1.044
	Outside	2498.4	2918.86	0.856	0.890–0.822
0–15	Inside	3000.4	2889.71	1.038	1.075–1.001
	Outside	1150.8	1261.49	0.912	0.965–0.860
16 +	Inside	3379.4	3124.93	1.081	1.118–1.045
	Outside	1341.8	1596.27	0.841	0.886–0.796

Based on 5-year average (1995–1999).

buffers than outside of them for each age cohort examined.

Integration of air dispersion modeling and GIS

Exposure potential can also be estimated using a plume buffer rather than a circular or linear buffer. A plume buffer is constructed based on results from a model that estimates the extent and direction of the pollutant dispersion, as well as pollutant concentration levels. While this obviously yields more realistic results than a simple circular or linear buffer, there are several problems in using air dispersion models. The first, most difficult to solve, is the lack of readily obtainable data needed as inputs for the model. The second is a software limitation which, due to rapid advancements being made in GIS and related modeling software, may be rectified before long.

Air dispersion models typically require a number of data inputs, including detailed meteorological information, such as a year's worth of average hourly wind speed and direction; the facility's stack height and diameter; gas exit velocity and exit temperature; accurate emissions data, such as specific substances emitted and average hourly quantities and rates. Although the TRI reporting process requires facility managers to provide much of this information, it is often lacking altogether, or is woefully inaccurate. The air dispersion models cannot be run if some of the inputs are missing. Unfortunately, at this time none of the TRI facilities in the Bronx had complete enough data to provide the necessary inputs to the model.

A trial study was conducted of one TRI facility in Westchester County, the county immediately to the north of the Bronx. This facility, the Consolidated Edison power plant, had sufficient data available to run the model for polycyclic aromatic hydrocarbon (PAH) emissions. The pilot study used the Industrial Source Complex Short Term (ISC-ST) American Meteorological Society/Environmental Protection Agency Regulatory Model—AERMOD—and put into a user-friendly PC format by Lakes Environmental Corp. (Lakes Environmental, 2004). The resultant contaminant concentration contour map was then compared to the simple one half-mile circular buffer that had been created around the same facility. The circular buffer contains parts of several tracts, most of which have very low percentages of minority population. There is just part of one tract with a high percentage of minority population in the northeast sector of the buffer. If the percent minority population per tract is averaged over the entire buffer, the percentage of minority people within the buffer is very small indeed. Therefore, with the circular buffer, the impacted population includes a low percentage of minorities. However, with the model showing actual contaminant concentration contours, it can be seen that the area of highest impact from the facility's pollutant emissions is that area occupied by the high percentage of minority people (see Fig. 9).

This experimental pilot study using the AERMOD model shows that air dispersion modeling can provide a more accurate locational assessment of environmental impacts than standard circular buffers. In the next phase of this project, the necessary data that is missing from the Bronx TRI database will be obtained through interviews with facility managers, surveys, or ground truthing on a case-by-case basis. Additionally, it is feasible to use

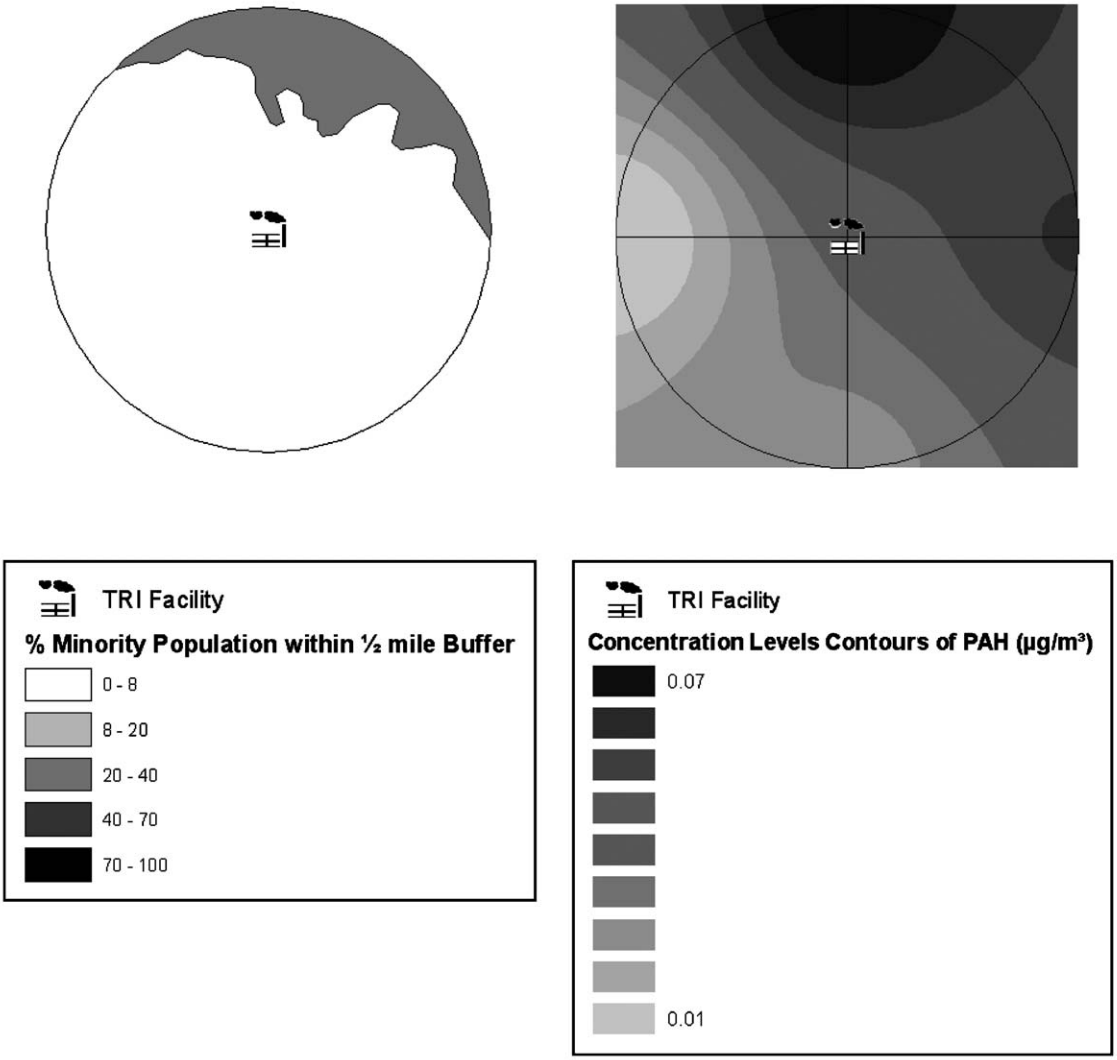


Fig. 9. Comparison of exposure methods: pollutant concentration contours versus circular buffer.

estimates as model inputs for any data values still missing after the inventory of facilities is taken. Mobile sources can also be modeled. It should be noted that due to the high overall high percentage of minorities in the Bronx, and the concentration of minority populations around the noxious land uses, the air dispersion modeling may not reveal any different patterns than those observed with the circular and linear buffers with respect to environmental justice implications. However, it could show more definitive results than the circular buffers regarding the relationship of the areas of higher air pollution to the asthma hospitalization cases.

Air dispersion modeling is problematic for another reason. Right now, the standard models are not integrated within the industry-standard GIS software applications, but instead utilize their own software. These stand-alone packages are cumbersome and rather difficult to work with, and the results are not always easily imported into standard GIS applications. If it is difficult to incorporate the plume buffers or concentration contours into the GIS and overlay with the demographic layers, spatial and geostatistical analysis cannot be done, only visualization of the data, and a visual comparison. One way to address this issue is to digitize the plume buffers or concentration contours manually as a layer within the GIS, using the outputs from the model, but this creates needless additional work and opportunities for error.

However, environmental models are much more closely coupled with GIS than they were even 5 years ago, and it is likely that these technical problems will be solved before the data problems are.

The need to build better databases and analytical methods

Specific data limitations were discussed above. In general, a major issue with environmental justice and health research is the difficulty in obtaining data at a resolution and accuracy level sufficient to reliably demonstrate the connections between environmental conditions and health outcomes. This is the case for both the health and the environmental data.

The lack of accessibility of health data is a significant drawback. Very few people have access to individual level health records, which are considered confidential. I was a consultant to the medical center sponsoring this research, and still had to wait nearly a year for my requests for the data to be approved at multiple levels. A person from outside the institution would likely fare even worse. At best, health data can often only be obtained at the ZIP code or census tract level of aggregation, but this resolution may not permit an analysis fine-grained enough to show linkages between environmental conditions and health risk or exposures. There is a considerable difference in the quality of conclusions based on aggregated health data versus data available at the patient record level. For example, the analysis of cases in and out of buffers would not have been possible except with patient level data.

Additionally, more health issues need to be tracked in centralized databases. Many diseases suspected of being environmentally linked do not have data compiled in a consistent manner. Data collected by one health care provider or medical center does not usually allow for valid spatial analyses.

Environmental data is also paltry. One of the most uniform sources of air emissions data is the TRI, but it falls far short of the mark and is dependent on self-reporting. Typically, there are huge holes in even the best of state- or federally compiled environmental data. Many sources of environmental burdens are not inventoried, and there is consequently no data available for these uses. This makes cumulative impacts or synergistic impacts difficult to assess.

For instance, the development of a comprehensive exposure index that would take into account actual quantities and toxicities of emissions is impeded by lack of data, especially regarding unreported emissions from small polluters, and fugitive emissions (those released through doors or windows as opposed to a stack). These are difficult to quantify accurately, yet may prove to be significant contributors to air pollution. Emissions from small polluters can be estimated by using parameters adjusted for size from TRI facilities having the same SIC code, but this is fraught with obstacles, and some small polluters have no equivalent among the listed facilities, and therefore nothing to base emissions type or magnitude estimates upon. Also, many pollutants have no health-based standards associated with them, or their toxicity is unknown. Measures of toxicity, then, could not be reliably incorporated into an exposure index. Cumulative exposure indices that have been developed are often at a resolution (county or tract level) that may be too low for optimal analysis with health outcomes (Rosenbaum et al., 2000).

In the asthma and air pollution study, these data deficiencies have likely led to an underestimation in the extent of pollution and exposure. By limiting our proximity analysis to include buffers around only the largest of the polluters, and by using standardized buffer distances, the extent of the areas potentially experiencing reduced air quality was minimized, and thus, the results are conservative. This study also did not take into account reported or measured emissions from these facilities, as this data is either self-reported and not necessarily reliable, or is not generally available in the case of monitored emissions. This study treated all the air quality impacts as equivalent, but in fact some facilities and land uses may be more egregious polluters than others, thus affecting different populations differently. If actual emissions and toxicity levels were taken in to account, the environmental justice implications may even be greater.

Neighborhood scale analysis may be the answer to obtaining much of the environmental data, since land uses can be inventoried lot-by-lot and detailed information can be used to characterize exposures in a more realistic way. However, this is a very labor-intensive task and may still not provide complete enough data. It may yield important information on the relationship between environmental conditions and health, but the neighborhood unit will likely be too small in geographic extent for use in drawing environmental justice comparisons.

Making the connection between environmental justice and environmental health

As discussed above, this analysis found that people within the buffers were not only much more likely to be hospitalized for asthma than those living outside the buffers, but also more likely to be minority and poor than those outside the buffers. Previous research has suggested that socio-economic status itself plays a role in diseases and deaths associated with air pollution (O'Neill et al., 2003; Schulz et al., 2002). It is possible that high asthma hospitalization rates reflect minority and poverty status as much or more than they do high exposures to environmental pollution, and most probably the factors are inextricably entwined (Krieger, 1999; Meliker et al., 2001).

Poor people, those lacking access or means to health services, support, or resources, may be more likely to be admitted to the hospital for asthma because they may not receive on-going preventative or maintenance care. Regular access to doctors and medicine might presumably tend to lessen emergency room visits and hospital admissions for asthma, and this might be tied to cultural background, educational attainment, or level of affluence.

Although further analyses will have important implications for whether or not high asthma hospitalization rates are correlated with high environmental burdens, the fact remains that the populations in the Bronx in closest proximity to noxious land uses are also those with higher risk of asthma hospitalization and higher likelihood of being poor and of minority status. Regardless of whether the high asthma hospitalization rates are due to environmental causes or result primarily from poverty and other socio-demographic factors, the findings of this research point to a health and environmental justice crisis. In order to identify more precisely the relationships between asthma, environmental burdens, and race and class, future phases of this project will include air dispersion modeling, examination of multiple-buffer exposures, multivariate regression analysis of asthma and socio-demographic data in and out of buffers, and extension of the analyses from the Bronx to all of New York City.

Clearly, these types of spatial analyses would be impractical without GIS technology and methods. With more complete and accessible health and environmental databases, more conclusive assessments will be possible, but nevertheless, GIS will continue to deepen our understanding of the connections between environmental conditions and health, and between environmental burdens and race and class.

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