Understanding the Role of Geospatial Information Technologies in Environmental and Public Health: Applications and Research Directions

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Abstract

For more than two centuries, epidemiologists, health care professionals, and medical researchers have sought to develop more refined methods of characterizing populations exposed to hazardous substances in the environment. This effort, for the most part, has involved using aspatial analysis techniques to explore the relationships between environmental quality and certain types of diseases, identify areas for the focus of public health education and community outreach programs, and delineate target and control populations for health studies. Although aspatial techniques have been quite useful in many applications, methods now exist that use rapidly emerging geospatial technologies to effectively manipulate, analyze, and display geocoded environmental and public health data on an unprecedented scale. Geographic information system (GIS) technology can be used to improve the level of understanding of environmental health problems and for exploratory data analysis to test or support hypotheses regarding disease causation. This paper examines the roles and limitations of GIS in environmental and public health research and illustrates, through an example application, the use of GIS functionality in the management and analysis of environmental and public health data. Future trends and issues in the use of GIS in environmental epidemiologic research are discussed. Given the recent advancements in GIS functionality and the widespread availability of digital public health data, it is timely to examine potential implications of geospatial technologies in this research area.

Keywords: environment, public health, epidemiology

Introduction

The need to examine and manage the health needs of a growing population has dramatically increased the demand for information systems that capture, manage, analyze, and display data. Geographic information systems (GIS) represent a powerful, new technology for integrating and manipulating large amounts of data obtained from different sources (1). Since its development in the 1960s, GIS technology has proven to be an extremely useful tool for acquiring, storing, manipulating, analyzing, and presenting georeferenced spatial data. Today, government agencies, utility companies, businesses, and researchers have invested billions of dollars in acquiring data as well as GIS hardware and software for application in such varied fields and disciplines as agriculture and natural resource management, health care, business, education, and

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military sciences. Numerous case studies in the literature suggest that the use of GIS is definitely making significant contributions to the integration, analysis, and presentation of spatial and non-spatial data in these application areas.

Inspired by the present and future potential of GIS, epidemiologists, medical geographers, and environmental scientists are beginning to adopt the technology for integrated analysis of environmental health data. The usefulness of GIS for environmental epidemiologic research is obvious, because all relevant data can be combined, stored, queried, analyzed, and displayed within a GIS to reveal the associations between environmental exposures and the spatial distribution of disease. Somewhat reminiscent of John Snow's classic case study of the association between a cholera outbreak and the Broad Street station water pump in London in the 1840s, GIS can be used to identify the space-time distribution of disease in relation to possible environmental factors (2). Asking many of the same types of questions as before but using techniques of spatial analysis, epidemiologists, medical geographers, and biostatisticians can evaluate the spatial distribution of disease or specify locations and system interaction points that may facilitate disease control or eradication. Disease ecology is inherently integrative and spatial, and GIS provides the environment in which the biophysical, social, behavioral, and cultural worlds can be combined for a systemic understanding of health and disease.

The 1986 Chernobyl accident and the subsequent deposition of radioactivity over large areas of northern Europe focused the attention of the environmental health science community on the inadequacies of aspatial techniques for establishing relationships of disease to environmental factors (3). GIS provides the data analysis and spatial modeling functions that could be used to integrate information on radiation fallout doses with perinatal mortality rates at different geographic scales. By explicitly linking health outcome to demographic and environmental factors, GIS can facilitate a reorientation toward population-based explanations for health differentials. Other potential applications include the following:

- GIS can be used to manipulate data collected from case-control studies to estimate exposure of individuals or segments of the population to different forms of pollution and disease.
- GIS databases on the location of environmental hazards, as well as disease and demography, can be used to develop or test etiologic hypothesis.
- Using GIS for exploratory spatial analysis of health data can establish disease causation. (Because of this, epidemiologists have been evaluating the capabilities of this technology.)

In spite of this potential, though, there are substantial problems and difficulties that must be addressed before the full benefits of GIS in environmental and public health research can be derived.

This paper examines the role of GIS in environmental epidemiology. Specifically, it addresses the three most important issues related to the use of GIS in environmental health research: the benefits of GIS in environmental epidemiology, the factors that impede the use of this technology, and the emerging trends in GIS technology as they relate to environmental health research. The potential benefits of GIS are examined from two primary perspectives—GIS and environmental health research. From the GIS perspective, demand is increasing for tools and information systems that not only add value to spatial data, but also support policy decision-making. From the environmental health research perspective, tools are needed to efficiently collect, store, manage, analyze, and display large volumes of health data that examine known or suspected associations between human health and environmental quality, establish the spatial patterns of disease etiology, or generate etiologic hypotheses.

This paper cannot do justice to the full range of issues related to the use of GIS in environmental epidemiology; it may even raise more questions than it answers. But current and emerging applications of GIS in environmental epidemiologic research make this an appropriate time to examine the role of the technology and speculate on what the future holds. The remainder of the paper is organized as follows: First, the role of GIS in environmental epidemiology is briefly examined. Next, the factors that limit the use of the technology are discussed. Finally, the future in GIS trends and challenges are discussed with emphasis on how these trends impact environmental health research.

Role of GIS in Environmental Epidemiology

Nearly all health problems related to environmental pollution have spatial dimensions that make them candidates for GIS analysis. The GIS technology provides a dynamic environment for evaluating and predicting both the short-term and long-term public health risks of environmental hazards. It provides a framework within which to analyze adverse impacts of environmental pollution and facilitates effective presentation of public health information in an easily understood manner. Douven and Scholten (4) identified several applications of GIS in environmental epidemiologic research. These include:

- Collection, storage, and organization of spatial and non-spatial data.
- Mapping of environmental health data to uncover the spatial pattern of disease.
- Spatial modeling to disclose the spatial and temporal nature of disease ecology.
- Statistical analysis to explore the association between diseases and other covariate factors (e.g., socioeconomic, demographic).
- Searching for spatially related aspects of disease etiology.

In these application areas, the benefits of GIS include:

- Rapid access to environmental, demographic, public health, and other relevant data for use in decision-making tasks.
- Easier update of surveillance data and associated geocoded databases.
- Transformation and analysis of disparate data to investigate a wide range of space-time relationships.
- Identification of geographic regions that, because of their unique physical attributes, may act as a source or sink for contaminants that are major health concerns.
- Dissemination of environmental health information in a variety of forms.

During the past several years, the number of professional and research papers and case studies documenting the relevance of GIS in environmental epidemiology has rapidly increased (2,5). Specific examples include a study of the role of environmental variables in the spread of vector-borne diseases by Glass et al. (6), a determination of community vulnerability to hazardous materials by McMaster (7), and an evaluation of public health effects of toxic chemicals by Stockwell et al. (8). In addition to these, Geschwind et al. (9) investigated the proximity of residences of persons with congenital malformations to hazardous waste sites. Dunn and Kingham (10) combined air quality estimates with health outcome data to explore spatial variation in respiratory ill health, specifically to determine whether emissions from an industrial pollution source might be influencing health status. Kingham et al. (11) integrated statistical analysis techniques with GIS to study the environmental correlates of children's respiratory health. Collins et al. (12) combined atmospheric dispersion modeling, statistical analysis, and knowledge-based techniques with GIS to examine the relationship between exposure to nitrogen dioxide and respiratory health in children. Guthe et al. (13) combined data from various sources to map the spatial patterns of lead exposure and sensitive populations in New Jersey. Wartenberg et al. (14) used GIS to assess health risks of populations living near high-voltage power transmission lines. Stallones et al. (15) proposed a data retrieval approach based on the concepts of GIS for the surveillance of the health status of populations living near hazardous waste sites. Andes and Davis (16) manipulated the 1990 US Census TIGER/Line file data within a GIS to evaluate the geographic distribution of infant mortality in Alaska. Glass et al. (17) used GIS map overlay techniques to investigate residential environmental risks for Lyme disease in Baltimore. These studies all recognized the unique role and utility of GIS in explaining how the environment, demography, and other factors interact to determine health status and disease causation. Indeed, many of the functions and operations available in most GIS facilitate integrated analysis of environmental health data.

There are several areas of environmental epidemiologic research that could benefit from GIS analysis, including spatial epidemiology, analytical epidemiology, descriptive epidemiology, and exposure/risk assessment. Spatial epidemiology uses area-based or point-based approaches to examine differences in the frequencies of disease and health outcomes. Analytical epidemiology involves not only determining the relationship between environmental determinants and disease but also confirming hypotheses of disease causation. In descriptive epidemiology, the objective is to develop thematic, isopleth, or choropleth maps that demonstrate the spatial pattern of disease etiology. These maps can be aggregates of political units (such as census block groups) or geocoded points that express spatial clusters in the health data. Exposure/risk assessment deals primarily with the use of stochastic and deterministic modeling techniques to determine whether high levels of exposure to single or multiple environmental hazards present unreasonable risks in an area. In exposure/risk assessment, results from stochastic/deterministic models provide data on the spatio-temporal distribution of the contamination. Using GIS, for example, data from exposure/risk assessment, as well as biomarkers of human susceptibility to an environmental hazard, could be combined and analyzed to determine the spatial association between disease and environmental covariates, develop etiologic clues that facilitate public health decision-making, or provide new insight into the health risks associated with specific environmental hazards. The size and complexity of public health databases and the complexity of public health problems make the use of GIS all the more necessary. But the major limitations and hindrances of GIS must be recognized; some of those impacting most strongly are discussed below.

Limitations of GIS in Environmental Epidemiology

Until recently, most GIS users paid little attention to the issue of data quality, which is of particular significance in environmental epidemiologic research because the data are obtained from many sources. Generally, the attributes of data quality include correctness, reliability, currency, completeness, timeliness, accuracy, and accessibility. Many epidemiologists and environmental scientists take solace in the notion that public health data are reliable (i.e., the data yield the same result on repeated collection, processing, analysis, and display from the same database), current (i.e., the data are recorded at the time of the event or observation and are continually updated), and accessible (i.e., the data are available to authorized users when needed). These professionals also demand quality in the data collected, analyzed, interpreted, and reported. However, most data used in epidemiological research are incomplete, due in part to the high capital and human resources required to collect and assemble them. Using such data with GIS to explore associations between disease incidence rates and environmental, socioeconomic, and demographic factors can be problematic.

The creation of integrated databases depicting changes in disease distribution through space and time is central to many studies in environmental epidemiology. This creation requires not only the maintenance of consistent surveillance and monitoring procedures but also demands that the data be current and contemporaneous. Thus, currency and timeliness of environmental health data are another data quality issue that concerns users. A frequently cited problem is the use of incorrect point data—caused by migration across the boundaries of health reporting zones—for GIS analysis (18,19). According to Davis and Chilvers (20), currency problems resulting from migration in and out of a surveillance zone can produce a "dilution effect" in many studies that evaluate spatial variation in disease incidence rates. An issue related to currency and timeliness in health data is latency, caused by, for example, the considerable lag time between human exposure to an environmental hazard and the emergence of a disease. In many circumstances, significant problems can be introduced when attempting to discover current relationships between exposure and disease incidences. Recording a patient's history and physical examination months after patient discharge is another common form of latency.

Another data quality issue has to do with striking an appropriate balance between data accuracy and the desired scale for spatial analysis. While exploratory analysis of health data using individual case locations or census blocks can be very attractive compared to counts in aggregated regions (e.g., census block groups or census tracts), this attractiveness is lost if the data on individual locations are inaccurate or if covariate information is only available as spatial aggregates. King (21) categorized limitations of this type as "ecological fallacy," in which individual-level relationships are inferred from analysis of aggregate-level data.

Increasingly, health care professionals and epidemiologists face a dilemma: meeting the health care community's need for information while protecting patients from unauthorized, inappropriate, or unnecessary intrusion into their personal information in the database. The drive for increased use of digital health information linked together by modern networking technologies could expose sensitive health information to a variety of threats and misuse. The growing use of health data in environmental epidemiologic research demands that issues of privacy, confidentiality, and security be adequately addressed. A report by the federal Office of Technological Assessment emphasized that current laws generally do not provide consistent, comprehensive protection of health information (22). Currently, communication between patients and their health care providers is considered confidential and health care professionals are therefore bound by legal and ethical standards to maintain confidentiality and privacy. Nonetheless, the need for more uniform and acceptable guidelines for access, use, and presentation of health information is increasing. Also, GIS programs must be equipped with improved security facilities for conducting exploratory health data analysis without disclosing confidential information. With these initiatives, an increased role of GIS in future epidemiological research is inevitable.

In geographic analysis of health data, a recurrent theme is a strong, often localized, pattern and cluster in disease ecology. Spatial heterogeneity and localized variations can present problems for conventional statistical methods that assume global relationships with few or no spatial singularities. Increased recognition of spatial heterogeneity in health data has led to a resurgence of emphasis on understanding disease ecology in a spatially explicit context. Suggesting possible environmental and behavioral factors in disease causation, identifying strong spatial relationships between environmental factors and disease, and confirming etiologic hypotheses developed from manipulation of environmental health data fall within the domain of GIS. However, these activities require the use of sophisticated statistical techniques. Thus, another factor that limits the use of GIS in environmental epidemiology is the lack of statistical analysis functions in many GIS programs. Although a few GIS programs support basic statistical summarization of data, the functions and techniques needed for exploratory analysis of environmental health data are still lacking (23). Some attempts have been made during the last few years to couple statistical programs with GIS software packages. For example, Openshaw et al. (24) described a spatial statistical analysis environment that links statistical analysis programs with GIS to search for geographical correlates of leukemia. An increasing number of case studies involving the development of interfaces between GIS and statistical software programs has been reported (25).

Yet another factor that limits the use of GIS technology in environmental epidemiology relates to the methodological problems often encountered when exploring the spatial patterns of disease etiology using spatial analysis techniques. These problems arise from the fact that a GIS-based analysis of disease patterns involves complex manipulations and overlay of data themes; many epidemiologists and health care professionals are not fully familiar with the theoretical concepts that underlie most GIS programs. Rather, these individuals are experts in the use of aspatial techniques that incorporate socioeconomic, demographic, genetic, gender, and environmental factors to explain health outcomes. Standard GIS analysis, including map overlays, cartographic modeling, and other advanced operations on spatial data, have not entered the arsenal of epidemiological analysis. Familiarity with GIS concepts is necessary to determine if the results of GIS epidemiological analysis are accurate and appropriate. Newly formed collaborations between epidemiologists, health care professionals, and GIS builders should provide opportunities for improved spatial analysis, interpretation, and presentation of environmental health data.

Example Application

Given the utility of GIS technology in many disciplines, and realizing the need for GIS in environmental health, a study was initiated to develop an integrated system for organizing, managing, analyzing, and displaying environmental and public health data collected in Iowa. The system, called EMPHASIS (for **E**nviron**M**ental and **P**ublic **H**ealth dat**A** analy**SI**s **S**ystem), used ArcView GIS (ESRI, Redlands, CA) and an Oracle (Oracle Corporation, Redwood Shores, CA) relational database management system to integrate and manipulate public health outcome data with environmental, socioeconomic, and demographic data. Specifically, EMPHASIS was developed, through a Seed Grant from the Center for Health Effects of Environmental Contamination at the University of Iowa, to provide an interactive data management and display environment. EMPHASIS could be used to (1) assemble all pertinent information on the presence of contaminants in the environment and, through GIS analysis, correlate the information with various health outcomes; (2) generate or test hypotheses regarding the spatial associations between environmental contamination and disease incidence rates; and (3) identify study populations with potential exposure to environmental hazards.

Development of EMPHASIS was set within the context of using ArcView GIS to integrate, analyze, visualize, and display large quantities of data and identify those environmental factors that covary spatially with disease indices or are concerned in disease causation. Hence, effort was focused on designing the system to facilitate determination of the spatial relationships between morbidity/mortality data from cancer surveillance activities and other relevant demographic (e.g., population) and environmental (e.g., groundwater vulnerability, chemical use factors) information. Figure 1 shows the general architecture of EMPHASIS, which was implemented on a desktop personal computer and incorporates Oracle, ArcView GIS (version 3.0), and S-PLUS (MathSoft, Cambridge, MA). The choice of these programs should not be seen as restrictive, since similarly structured programs could easily be used in their stead. However, the unique combination of these software packages facilitates identification of geographic location, data integration, data management and query processing, spatial analysis and modeling, and display of a wide variety of environmental and public health data.

A primary goal in the design of EMPHASIS was to procure a turnkey GIS environment through which large volumes of information related to environmental and public health (mainly morbidity and mortality) data could be readily accessed, efficiently analyzed, and rapidly visualized. To achieve this goal, several options for data retrieval, query, and visualization were developed. In one option, users can directly retrieve and query the data in Oracle and generate tabular reports. Figure 2 shows how a standard and interactive database query produced a tabular summary of cancer morbidity data collected in Iowa between 1973 and 1992, keyed to the respective county federal information processing standard (FIPS) code. Figure 3 shows a typical query interface and the result of a map overlay performed by using some of the spatial and attribute information in the EMPHASIS database. In Figure 3, data on groundwater vulnerability by hydrogeologic region were integrated with the water quality database obtained from the 1988–1989 Iowa Statewide Rural Water Well Survey as well as morbidity and mortality data from the State Health Registry, maintained by the Center for Health Effects of Environmental Contamination at the University of Iowa, Iowa City.

Presently, EMPHASIS is structured so that new information can be added and

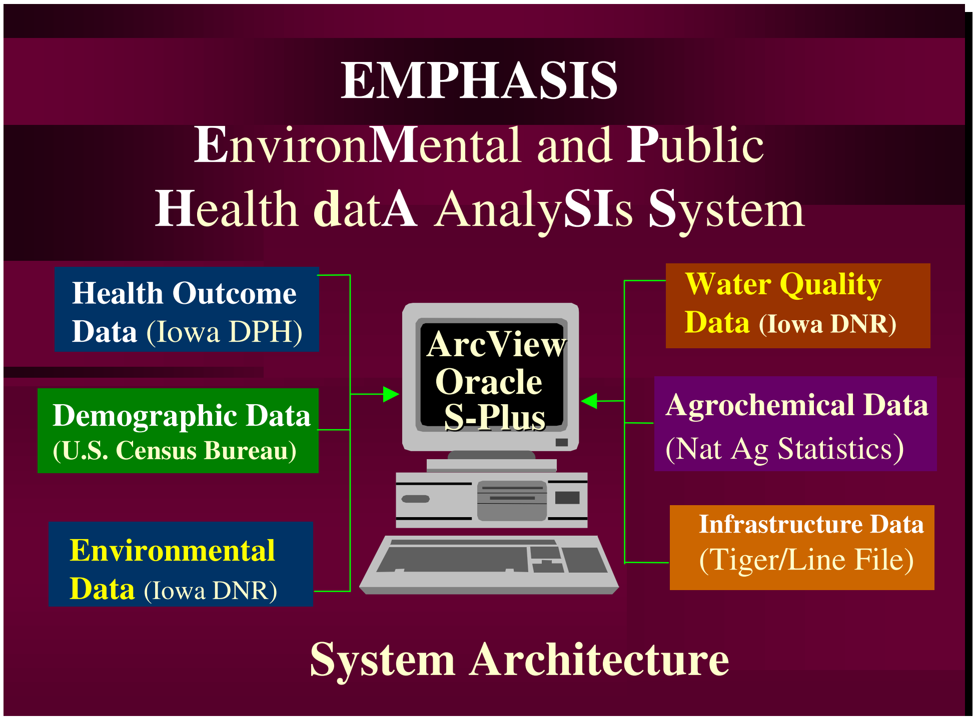

Figure 1 The conceptual structure of EMPHASIS.

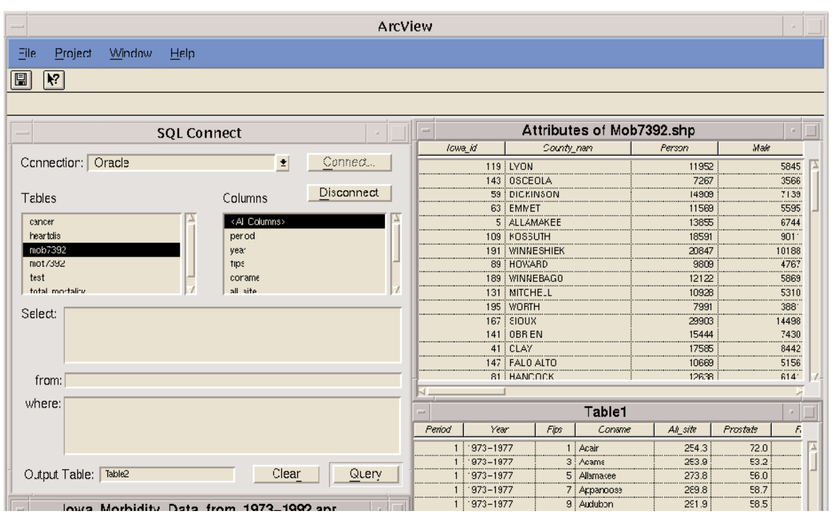

Figure 2 Typical screen display of an EMPHASIS query session.

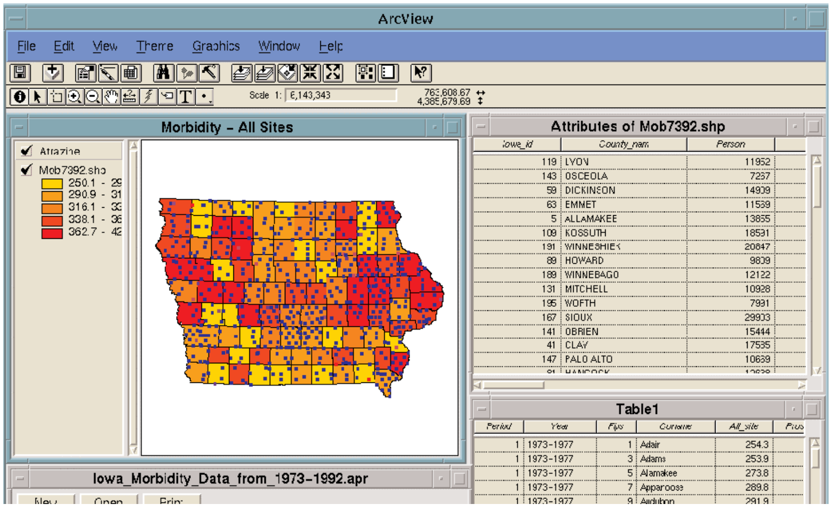

Figure 3 Screen display of environmental and public health data in EMPHASIS.

analyzed as it becomes available. It supports a user-friendly, icon-based menu with mouse interaction for selecting menu options and has two basic modules. One module supports interactive data management, analysis, and visualization, while the other supports online query and reporting. In both modules, the user has full control of selecting the attribute data for analysis and defining the geographic extent of data analysis and display by using the pan and zoom icons in ArcView GIS. Other unique features of EMPHASIS include: (1) it is designed to make optimum use of existing environmental quality data and public health information to minimize duplication of information among state agencies and institutions; (2) it can incorporate existing and future advances in information exchange (e.g., the Internet) to provide an interactive environment for efficient data access and data exchange; and (3) its data processing and display capabilities are powerful enough to facilitate integrated analysis of local or regional environmental health issues.

Future Trends

Driven by technological innovations, the methods and tools used in environmental epidemiology are changing and will continue to do so. The technology for collecting, processing, storing, and retrieving environmental health data is evolving from a paper-driven, labor-intensive process to one that employs sophisticated computers and information systems. Just as the introduction of magnetic resonance imaging provided a new technology for collecting health data, recent spatial technologies, such as GIS, are revolutionizing the way health data are analyzed and presented. In the future, two major benefits are likely to emerge from the application of GIS in environmental epidemiology. The first benefit will be the ability of health care professionals and epidemiologists to use GIS as a tool to interactively manage and disseminate public health information; search for ecological associations among health data and environmental, socioeconomic, or demographic factors; and identify the spatial location and geographic distribution of disease outbreak to document changes in incidence and prevalence. The other benefit will be the ability to analyze disparate data interactively, emphasizing human health-environment relationships in the context of cultural and behavioral factors.

Challenges in environmental epidemiology during the past few years have ushered in a new era for integrated, spatially explicit data analyses that use GIS. While the application of GIS in this field is still in its infancy, certain observations about future trends and prospects can be made. Today, health, demographic, and socioeconomic data of various spatial scales are increasingly available on the Internet. Indeed, GIS application is entering an “information-rich” era in which large volumes of data are available through communication networks with interactive data filters and data access protocols. The ability to examine the spatial patterns of disease by integrating disparate health outcome data with other disparate information on the Internet and intranets is now within the reach of medical geographers, epidemiologists, and biostatisticians. However, maintaining the integrity of health data on the “information superhighway” will require the establishment of industry-wide standards for data access and data sharing. The ease of information transfer for multiple users without the need for human interaction will raise new concerns for health care professionals. The use of intranets and the Internet will also present new challenges.

As environmental epidemiology enters the 21st century, GIS application will become more widespread. Due to the factors discussed earlier, the full potential of GIS in environmental epidemiology has yet to be unlocked. In a number of existing applications, the need to combine environmental, social, cultural, economic, and demographic data to explore disease-environment-behavior relationships is at odds with the need to maintain security and confidentiality. Although security and confidentiality issues for demographic, socioeconomic, and health data have been established, these issues are only beginning to emerge in the integrated analysis and dissemination of environmental health data. While techniques such as encryption, security servers, user access/password authentication, and firewalls (26) have been widely implemented to control access to confidential information, the degree of concern over unauthorized, inadvertent disclosure, modification, and destruction of health data will increase in the future.

Summary

For over six decades, research activities in environmental epidemiology have focused on a series of fundamental questions: How do people and societies respond to environmental hazards and what factors influence their choice of adjustments? What relationships exist between incidence rates and socioeconomic variables? How can we model these relationships? What areas have extreme high and low disease incidence rates? Within the last decade, other questions have been added to this list, including: Are societies becoming more vulnerable to environmental contaminants? What spatial associations exist between disease incidence rates and other variables? Is there evidence of clustering in respect to specified sources or possible causes? Is there any evidence of trends, patterns, or other variation in environmental health data? To answer these questions, extensive use has been made of spatial information technologies such as GIS.

These technologies facilitate understanding of how humanity (e.g., culture, society, behavior), the physical world (e.g., topography, land use, climate), and biology (e.g., vector and pathogen ecology) interact to produce foci of disease. As discussed in this paper, GIS allows users to combine, query, transform, analyze, and present environmental health information in ways that were not previously possible.

GIS has indeed emerged as an efficient tool for understanding and characterizing the geographic, socioeconomic, demographic, and environmental variables that influence disease incidence rates. However, deriving the full benefits of GIS in environmental epidemiology will depend on how the environmental health research community approaches and resolves the issue of data quality. Also, integration of various multimedia tools to form a health care decision support system and the growing capability to link public and private databases require that issues of privacy, security, and confidentiality be fully addressed. Public perception about data privacy issues also needs to be changed. Citizens should be educated about the value of GIS and the many benefits that it offers in environmental epidemiology. Environmental scientists, medical geographers, and epidemiologists also need to understand the limitations of GIS, data, and GIS analysis.

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