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Geographic information systems in public health: a review of spatial technologies and epidemiological applications

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ABSTRACT

Geographic information systems (GIS) have become important technologies for understanding the spatial distribution of diseases, environmental exposures, population characteristics, and healthcare resources. By integrating geographic data with epidemiological information, GIS enables researchers and public health professionals to identify disease patterns, investigate potential risk factors, monitor disease transmission, and support evidence-based health interventions. This review examines the fundamental technologies, spatial analytical methods, and epidemiological applications of GIS in public health, emphasizing developments documented up to 2013. The discussion covers spatial data acquisition, geocoding, remote sensing, disease mapping, spatial statistics, environmental health assessment, infectious disease surveillance, and healthcare accessibility analysis. The review also highlights methodological limitations related to data quality, spatial uncertainty, ecological bias, privacy, and analytical scale. Overall, GIS provides a valuable analytical framework for transforming geographically referenced health data into actionable information for epidemiological investigation and public health planning.

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1. INTRODUCTION

Geographic location is an important determinant of population health because disease occurrence and health outcomes are influenced by environmental, socioeconomic, demographic, and behavioral conditions. Differences in geographical environments can create variations in exposure to infectious agents, air pollution, contaminated water, healthcare facilities, and other health-related factors. Therefore, understanding the geographical distribution of diseases is essential for identifying population-level health inequalities and developing effective public health interventions.

Geographic information systems (GIS) provide an integrated technological framework for collecting, managing, analyzing, and visualizing geographically referenced information. GIS enables the combination of epidemiological records with geographic features, including administrative boundaries, population distributions, transportation networks, environmental conditions, and healthcare facilities. Clarke *et al.* [1] identified GIS as a valuable technology for epidemiological investigation because it allows researchers to examine disease distributions and explore geographical relationships that may otherwise remain difficult to recognize.

The application of GIS in public health has expanded beyond conventional disease mapping toward more advanced spatial analytical techniques. These applications include identifying disease clusters, examining environmental risk factors, estimating disease distributions, evaluating healthcare accessibility, and supporting epidemiological surveillance. Previous reviews by Rushton [2], Cromley [3], McLafferty [4] and Elliott and Wartenberg [5] demonstrated the growing importance of spatial technologies in understanding disease patterns and supporting public health decision-making.

This review aims to examine the fundamental GIS technologies, spatial analytical methods, and major epidemiological applications relevant to public health. Particular attention is given to the relationship between geographic information, disease distribution, environmental determinants, and population health.

The review also discusses methodological challenges and future research directions based exclusively on literature published no later than 2013.

2. GIS TECHNOLOGIES AND SPATIAL DATA INFRASTRUCTURE

GIS is fundamentally designed to integrate spatial and non-spatial information within a common analytical environment. Spatial information describes the geographical location and characteristics of objects, while non-spatial information provides additional attributes, such as disease incidence, patient characteristics, population density, and environmental measurements. Combining these information types allows epidemiological researchers to examine relationships between health outcomes and geographical conditions.

2.1. Spatial data acquisition and georeferencing

Spatial data acquisition is a fundamental component of GIS-based public health research. Geographic information can be obtained from satellite imagery, aerial photographs, field surveys, administrative databases, census records, global positioning system (GPS) measurements, and health information systems. These sources provide complementary information for identifying population distributions, environmental characteristics, disease locations, and healthcare infrastructure.

Geocoding is particularly important because it transforms descriptive location information, such as residential addresses or healthcare facility locations, into geographic coordinates. This process enables epidemiological records to be connected with spatial datasets and analyzed according to geographical proximity, administrative boundaries, and environmental characteristics. However, inaccurate addresses, incomplete records, and differences in geographic reference systems can introduce positional errors that affect subsequent spatial analyses.

2.2. Remote sensing and environmental information

Remote sensing complements GIS by providing geographically distributed environmental information derived from satellite and airborne sensors. Satellite imagery can be used to characterize land cover, vegetation, surface temperature, water bodies, urban development, and other environmental conditions associated with population health. These variables are particularly relevant for investigating vector-borne diseases, environmental exposure, and the geographical distribution of infectious diseases.

The integration of remote sensing and GIS allows researchers to examine environmental conditions across large geographical areas. For example, vegetation indices, surface temperature, rainfall estimates, and land-use characteristics can be combined with disease records to investigate environmental factors associated with malaria and dengue transmission. This integration provides an opportunity to identify potentially vulnerable geographical areas and support environmental risk assessment.

2.3. Spatial databases and GIS architecture

A spatial database provides the infrastructure for storing and managing geographical information alongside epidemiological and demographic records. Typical GIS architectures integrate data acquisition, spatial database management, analytical processing, visualization, and information dissemination. Such integration enables public health organizations to maintain geographically referenced datasets and perform consistent spatial analyses.

GIS platforms can also incorporate information from multiple institutional sources, including hospitals, laboratories, environmental agencies, census organizations, and local government institutions. Data interoperability is essential because public health investigations frequently require information collected using different formats, spatial resolutions, and administrative standards. Consequently, standardized geographic references and reliable data-management procedures are necessary for developing effective GIS-based public health systems.

3. SPATIAL ANALYTICAL METHODS IN PUBLIC HEALTH

Spatial analytical methods provide the foundation for investigating geographical variations in disease occurrence and identifying relationships between health outcomes and potential determinants. GIS supports several analytical approaches, ranging from basic spatial visualization to advanced statistical modeling. The selection of an appropriate method depends on the research objective, geographical scale, data characteristics, and epidemiological assumptions.

3.1. Disease mapping and spatial distribution

Disease mapping is one of the most established applications of GIS in epidemiology. It involves representing disease incidence, prevalence, mortality, or other health indicators across geographical units, such as districts, municipalities, or census areas. These maps provide an initial understanding of geographical variations in disease occurrence and can help identify areas requiring further investigation.

However, conventional disease maps may be affected by differences in population size and unstable rates in areas with relatively small populations. Spatial smoothing and statistical estimation can improve the interpretation of geographical patterns by reducing random variation in observed disease rates. According to Rushton [2], advances in disease mapping and spatial analytical methods have strengthened the role of GIS in public health research.

3.2. Spatial clustering and hotspot detection

Spatial clustering techniques are used to identify geographical concentrations of disease cases that may indicate unusual epidemiological patterns. Global spatial statistics evaluate whether observations exhibit overall spatial dependence, whereas local spatial statistics identify specific geographical locations characterized by unusually high or low values. These methods provide useful analytical support for identifying potential disease hotspots.

Local indicators of spatial association (LISA), introduced by Anselin (1995), provide a framework for identifying local spatial associations and distinguishing different spatial cluster configurations. In epidemiology, cluster detection can help identify areas where disease incidence is higher than expected and where additional investigations may be necessary. Nevertheless, detected clusters should be interpreted carefully because their statistical significance does not automatically establish a causal relationship or identify the underlying transmission mechanism.

3.3. Spatial interpolation and predictive mapping

Spatial interpolation estimates values at locations where direct observations are unavailable by using measurements collected at surrounding locations. Techniques such as inverse distance weighting and kriging can be applied to environmental variables, including air pollution, temperature, rainfall, and other geographically distributed exposures. These estimated surfaces can subsequently be integrated with population and disease datasets.

Predictive mapping extends this capability by combining spatial observations with statistical or epidemiological models. Such approaches can support the identification of geographical areas with potentially elevated disease risk and improve the allocation of public health resources. However, the reliability of predicted distributions depends on sampling density, model assumptions, spatial resolution, and the quality of the underlying datasets.

3.4 Spatial regression and epidemiological modeling

Spatial regression methods are designed to investigate relationships between health outcomes and explanatory variables while accounting for geographical dependence. Traditional regression models may produce misleading estimates when observations are spatially correlated or when important geographical characteristics are not adequately represented. Spatial statistical approaches can help address these limitations and provide more appropriate estimates of geographical relationships.

Spatial epidemiological modeling can incorporate demographic characteristics, environmental exposures, socioeconomic conditions, and geographical proximity to potential risk sources. Hierarchical Bayesian approaches and spatial smoothing methods are particularly useful when disease observations are aggregated across geographical areas and exhibit substantial statistical variation. Elliott and Wartenberg [5] emphasized that spatial epidemiology requires careful consideration of geographical dependence, exposure assessment, and the limitations of available spatial data.

4. EPIDEMIOLOGICAL APPLICATIONS OF GIS

GIS has been applied across several public health domains because geographical information provides an important context for understanding disease occurrence and healthcare delivery. Its applications range from infectious disease investigation to environmental epidemiology and healthcare resource planning. The following subsections summarize major application areas documented in the literature up to 2013.

4.1. Infectious disease surveillance and control

GIS supports infectious disease surveillance by integrating reported cases, population distributions, environmental conditions, and geographical information about potential transmission sources [6]. Mapping disease cases can reveal spatial patterns and identify geographical areas that require

epidemiological investigation. Combining these datasets with temporal information can further support the examination of disease spread and changing transmission patterns [7], [8].

Vector-borne diseases are particularly suitable for GIS-based investigations because their transmission is influenced by environmental and geographical conditions. Malaria and dengue studies have used spatial information to examine relationships among disease occurrence, climate, vegetation, land use, vector habitats, and human settlements. Oliveira *et al.* [9] reviewed geospatial methods applied to dengue epidemiological studies and demonstrated their contribution to understanding the geographical diffusion of dengue transmission.

GIS has also been used to investigate relationships between different infectious diseases and population health conditions. Aimone *et al.* [8] examined the application of GIS in studying geographical relationships between malaria and childhood anaemia. Their work illustrates how spatial technologies can support investigations involving multiple health outcomes and overlapping geographical risk factors.

4.2. Environmental health and exposure assessment

Environmental epidemiology investigates how environmental conditions influence disease occurrence and population health. GIS enables researchers to combine health records with geographically referenced information about air quality, water resources, industrial activities, land use, and other environmental characteristics. This integration provides a basis for examining geographical variations in exposure and potential health risks.

Spatial proximity analysis can be used to investigate relationships between residential locations and potential environmental hazards. For example, researchers can examine population distributions around industrial facilities, waste disposal sites, contaminated water sources, or major transportation corridors. Nevertheless, geographical proximity alone is insufficient to establish actual exposure because individual mobility, environmental dispersion, and duration of contact must also be considered.

4.3. Population health and socioeconomic inequalities

GIS provides an effective means of investigating geographical inequalities in health outcomes. By combining disease records with census information, population density, income levels, education, and other socioeconomic indicators, researchers can identify areas experiencing disproportionate health burdens. Such analyses are valuable for understanding the geographical distribution of health disparities and supporting targeted public health policies.

Spatial analysis can also reveal relationships between urban development, population characteristics, and disease patterns. For instance, differences in housing conditions, sanitation infrastructure, and access to essential services may contribute to geographical variations in infectious and non-communicable diseases. GIS therefore provides a useful framework for examining how social and geographical environments interact with population health.

4.4. Healthcare accessibility and resource allocation

GIS has an important role in evaluating the geographical accessibility and distribution of healthcare facilities. Spatial network analysis can estimate distances and travel times between residential areas and hospitals, clinics, laboratories, and other healthcare services. These measurements help identify underserved populations and geographical areas where healthcare infrastructure may be insufficient.

Location-allocation analysis can further support decisions regarding the placement of new healthcare facilities and the distribution of limited public health resources. McLafferty [4] highlighted the contribution of GIS to analyzing healthcare needs, service utilization, accessibility, and facility location planning. These capabilities are particularly relevant for public health systems seeking to improve service coverage and reduce geographical inequalities.

5. CHALLENGES AND LIMITATIONS

Despite its considerable potential, GIS-based public health research faces several methodological and operational challenges. The reliability of spatial analysis depends on the quality, completeness, resolution, and consistency of geographical and epidemiological information. These limitations must be considered when interpreting analytical results and translating them into public health decisions.

One major challenge is the quality of spatial data, particularly inaccurate geocoding, incomplete disease reporting, and inconsistent geographical boundaries. Another important limitation is the modifiable areal unit problem (MAUP), in which statistical results may change depending on the geographical units used to aggregate observations. Ecological bias is also relevant because associations identified at the population or administrative-area level cannot necessarily be interpreted as relationships at the individual level.

Privacy and confidentiality represent additional concerns because geographical health information may reveal sensitive details about individuals or small communities. Appropriate spatial aggregation, data anonymization, controlled access, and institutional data governance are therefore essential when handling geographically referenced health records. Furthermore, the successful implementation of GIS requires trained personnel, adequate computing infrastructure, reliable interinstitutional collaboration, and sustainable data-management procedures.

6. FUTURE DIRECTIONS

The development of GIS in public health is closely associated with improvements in spatial data availability, computational capabilities, and information integration. Greater integration of GIS with remote sensing, GPS, electronic health records, and epidemiological databases can provide more comprehensive representations of geographical health conditions. These developments can strengthen disease surveillance and support more detailed investigations of environmental and population-level risk factors.

Another important direction is the development of dynamic and spatiotemporal analytical systems. Conventional disease maps generally represent geographical conditions at specific points or periods, whereas dynamic GIS applications can incorporate changing disease distributions, environmental conditions, and population movements. Such capabilities may improve early identification of emerging disease patterns and support more responsive public health interventions.

The integration of spatial statistics with predictive modeling also offers opportunities to improve epidemiological risk assessment. However, future applications should prioritize methodological transparency, model validation, spatial uncertainty assessment, and responsible use of health information. Greater attention to these aspects will help ensure that technological developments produce reliable evidence rather than merely more sophisticated geographical visualizations.

7. CONCLUSION

GIS have become valuable technologies for integrating geographical information with epidemiological and public health data. Their capabilities in spatial data management, disease mapping, cluster detection, spatial modeling, environmental exposure assessment, and healthcare accessibility analysis provide important support for understanding geographical variations in population health. Applications involving infectious diseases, environmental health, socioeconomic inequalities, and healthcare resource allocation demonstrate the broad relevance of GIS to public health practice. Nevertheless, the effectiveness of GIS depends on reliable data, appropriate analytical methods, adequate spatial resolution, and careful interpretation of geographical relationships. Issues involving spatial uncertainty, ecological bias, data confidentiality, and institutional capacity remain important considerations. Overall, GIS should be regarded not merely as a mapping technology but as an integrated analytical framework that can strengthen epidemiological investigation, public health planning, and evidence-based decision-making.

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