World Journal of Advanced Research and Reviews

eISSN: 2581-9615 CODEN (USA): WJARAI

Cross Ref DOI: 10.30574/wjarr

Journal homepage: https://wjarr.com/

(Review Article)

A review of GIS applications in public health surveillance

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World Journal of Advanced Research and Reviews, 2024, 21(01), 030–039

Publication history: Received on 22 November 2023; revised on 28 December 2023; accepted on 30 December 2023

Article DOI: https://doi.org/10.30574/wjarr.2024.21.1.2684

Abstract

This paper comprehensively reviews Geographic Information Systems (GIS) applications in public health surveillance. Tracing the historical evolution of GIS in public health, the literature review highlights key concepts, definitions, and frameworks. The role of GIS in disease surveillance is explored, encompassing tracking infectious diseases, monitoring environmental health, emergency response, and surveillance of non-communicable diseases. While GIS proves indispensable in providing a spatial lens for understanding health-related phenomena, challenges such as data quality, privacy concerns, and resource constraints must be addressed. Future directions and innovations, including integrating emerging technologies and improved spatial resolution, promise to propel GIS into a pivotal role in shaping the future of public health surveillance.

Keywords: Geographic Information Systems; Public Health Surveillance; Disease Tracking; Spatial Analysis; Emerging Technologies; Health Data Integration

1. Introduction

In the dynamic landscape of public health, integrating Geographic Information Systems (GIS) has emerged as a powerful tool, offering unprecedented insights into the spatial distribution and dynamics of health-related phenomena (Bluemke, Resch, Lechner, Westerholt, & Kolb, 2017; Boulos, 2004; Musa et al., 2013). As the world grapples with evolving health challenges, the fusion of GIS technology with public health surveillance has proven instrumental in monitoring and proactively addressing various health issues (Saran, Singh, Kumar, & Chauhan, 2020; Q. Wang, Su, Zhang, & Li, 2021). This paper embarks on a comprehensive review of GIS applications in public health surveillance, delving into this symbiotic relationship's historical evolution, current state, and prospects.

Historically, public health surveillance has played a pivotal role in safeguarding community well-being by tracking, analyzing, and responding to health events (Kamel Boulos et al., 2011; Saran et al., 2020). With the advent of GIS, this surveillance has transcended traditional boundaries, offering a spatial dimension to epidemiological data (Boulos, 2004; Greenough & Nelson, 2019). GIS allows the visualization of health-related information on maps, enabling health professionals and policymakers to discern patterns, identify hotspots, and make informed decisions (Chinnaswamy, Papa, Dezi, & Mattiacci, 2019; Delmelle, Delmelle, Casas, & Barto, 2011; Jarrahi, Zare, & Sadeghi, 2017). The spatial context provided by GIS enhances the understanding of disease spread, environmental factors, and socio-economic determinants, thereby augmenting the effectiveness of public health interventions.

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This review aims to synthesize the existing body of knowledge surrounding GIS applications in public health surveillance. By critically examining the literature, we aim to identify key trends, challenges, and innovations in the field. Moreover, the review seeks to elucidate the impact of GIS on disease monitoring, emergency response, and policy formulation. Through this comprehensive analysis, we aspire to contribute to the growing discourse on integrating spatial technologies in public health and provide a foundation for future research endeavours.

The significance of GIS in public health lies in its ability to transform raw data into actionable insights. Traditional public health surveillance often faces challenges interpreting complex datasets and discerning spatial patterns (Ogojiaku et al., 2020; Uelmen Jr et al., 2023). GIS addresses this gap by offering a visual and analytical platform that not only facilitates the interpretation of data but also aids in identifying relationships between health outcomes and various spatial determinants. The utilization of GIS, therefore, empowers public health professionals to make evidence-based decisions, allocate resources efficiently, and implement targeted interventions crucial for mitigating health risks and improving overall community well-being (Boulos, 2004; Nyemera).

As we navigate the intricate intersection of GIS and public health surveillance, this review aims to provide a comprehensive understanding of the field's current landscape, challenges, and promising avenues for future exploration. Through the lens of GIS, public health surveillance becomes a reactive measure and a proactive strategy in the ongoing pursuit of global health security and well-being.

2. Literature Review

2.1. Overview of the Existing Literature on GIS Applications in Public Health Surveillance

The convergence of GIS and public health has given rise to a burgeoning field with immense potential for revolutionizing disease surveillance. A thorough examination of the existing literature reveals a rich tapestry of studies, each contributing to understanding how GIS enhances public health surveillance. Researchers across the globe have explored the multifaceted applications of GIS, from tracking infectious diseases to addressing environmental health concerns.

In their seminal work, Cromley and McLafferty (2011) provided a foundational exploration of GIS in public health, emphasizing the spatial component as a critical factor in understanding health outcomes. They underscored the role of GIS in mapping disease clusters and facilitating targeted interventions (Ozdenerol, 2016). Subsequent studies expanded on this foundation, delving into specific diseases and regions, such as the work of Snow et al. (1854), which utilized early spatial analysis to identify the source of a cholera outbreak in London (Caplan, Kennedy, & Neudecker, 2020; Walford, 2020).

Recent literature has witnessed a proliferation of research focusing on the integration of GIS with emerging technologies. For instance, Hassan Zadeh, Zolbanin, Sharda, and Delen (2019) leveraged social media data through GIS to monitor the spread of infectious diseases in real-time, demonstrating the potential of dynamic, data-driven surveillance systems. These studies underscore the dynamic nature of GIS applications in public health surveillance and their adaptability to evolving technological landscapes.

2.2. Historical Development and Evolution of GIS in Public Health:

The historical trajectory of GIS in public health is marked by a gradual evolution from rudimentary mapping techniques to sophisticated spatial analysis tools. Early efforts were characterized by manual mapping of disease occurrences, as John Snow's iconic cholera map in the 19th century exemplified. This seminal work laid the groundwork for recognizing the spatial distribution of diseases and their correlation with environmental factors (Altschuler, 2017; Coleman, 2019; Pelling, 2022).

The 20th century witnessed the advent of computer-based GIS, marking a paradigm shift in public health surveillance capabilities. Notable contributions include the development of the Geographic Information System by Roger Tomlinson in the 1960s, which served as a precursor to contemporary GIS applications (Wright, Goodchild, & Proctor, 1997). The integration of satellite imagery and remote sensing technologies further expanded the scope of GIS, enabling monitoring of environmental factors that influence public health (Bishop, Grubesic, Bishop, & Grubesic, 2016; Obermeyer & Pinto, 2007; Wright & Barlett, 1999).

As GIS technology advanced, so did its applications in public health. The 1990s saw an increased emphasis on the spatial analysis of health data, allowing for more nuanced interpretations of disease patterns (Weeks, 2004). The integration of Global Positioning System (GPS) technology in the 21st century provided real-time data, enhancing the accuracy and timeliness of public health surveillance. The evolution of GIS in public health reflects a continual process of refinement, adaptation, and incorporation of cutting-edge technologies (Cummins, Curtis, Diez-Roux, & Macintyre, 2007; McLafferty, Widener, Chakrabarti, & Grady, 2016).

To navigate the intersection of GIS and public health, it is crucial to establish a foundation of key concepts, definitions, and frameworks. At its core, GIS involves collecting, analyzing, and interpreting spatial data, providing a visual representation of the geographic distribution of health-related phenomena. This spatial perspective allows for identifying patterns, correlations, and trends that may be elusive in traditional tabular data.

One fundamental concept in GIS and public health is spatial epidemiology, which examines the distribution and determinants of health-related events in a population (Nayak, Pai, Singla, Somayaji, & Kalra, 2021; F. Wang, 2020). The ecological fallacy and modifiable areal unit problem (MAUP) are critical considerations in spatial epidemiology, cautioning against drawing individual-level conclusions from aggregate data and emphasizing the sensitivity of results to changes in spatial units (Kok, 2021; Sui, 2004). Syndromic surveillance is another cornerstone, focusing on the real-time monitoring of symptoms or health-related indicators to detect outbreaks before traditional surveillance methods (Abrams Jr, 2019; Edo-Osagie, Smith, Lake, Edeghere, & De La Iglesia, 2019). GIS facilitates the integration of diverse data sources in syndromic surveillance, enabling a holistic understanding of health trends and potential threats.

In conclusion, the literature on GIS applications in public health surveillance is characterized by a rich history, reflecting the evolution of technology and a growing recognition of the spatial dimensions of health. The integration of GIS into public health has progressed from manual mapping to sophisticated spatial analysis, with each era contributing unique insights and methodologies. Key concepts and frameworks provide a theoretical foundation for understanding the interplay between spatial data and public health outcomes, guiding researchers and practitioners in harnessing the full potential of GIS for enhanced surveillance and improved community health.

3. The Role of GIS in Public Health Surveillance

Geographic Information Systems have become indispensable in public health surveillance, transforming how health professionals monitor, analyze, and respond to disease dynamics. The central role of GIS lies in its capacity to provide a spatial context to health data, allowing for a holistic understanding of the distribution and determinants of health-related events. This section explores the multifaceted role of GIS in public health surveillance, highlighting its contributions to disease tracking, spatial analysis, and the integration of diverse data sources.

3.1. Enhancing Disease Tracking

One of the primary functions of GIS in public health surveillance is the facilitation of comprehensive disease tracking. By mapping the geographic distribution of diseases, GIS enables health professionals to visualize patterns and trends that may be obscured in traditional tabular data. This spatial perspective is particularly crucial in tracking infectious diseases, where understanding the spread of pathogens is essential for effective containment and intervention.

GIS provides a static representation of disease maps and allows for dynamic tracking over time. Real-time surveillance, made possible by the integration of GIS with technologies such as the Global Positioning System (GPS), empowers health authorities to monitor the progression of outbreaks, identify emerging hotspots, and allocate resources strategically (Li, Batty, & Goodchild, 2020; Sorensen, 1997). This capability proved instrumental in managing outbreaks of infectious diseases like Ebola and Zika, where timely and accurate information was imperative for effective response efforts.

3.2. Spatial Analysis for Informed Decision-Making

GIS goes beyond mere mapping by offering sophisticated spatial analysis tools that deepen the understanding of health-related phenomena. Spatial analysis allows for identifying spatial clusters, correlations between health outcomes and environmental factors, and assessing accessibility to healthcare resources. For instance, GIS can help pinpoint areas with high incidence rates of a particular disease, guiding targeted interventions and resource allocation (Kost, 2019; Rushton, 2003).

Furthermore, GIS facilitates the integration of socio-economic and demographic data with health information, unveiling disparities and enabling a more nuanced understanding of health inequalities. This spatially informed approach is pivotal for developing tailored public health policies and interventions that address the specific needs of diverse populations (Fletcher-Lartey & Caprarelli, 2016; Pettygrove & Ghose, 2016).

3.3. Integration of Diverse Data Sources

In the big data era, GIS is a powerful tool for integrating diverse data sources, contributing to a more comprehensive and dynamic public health surveillance system. Beyond traditional health data, GIS can incorporate environmental, socio-economic, and behavioural data, creating a more holistic view of the determinants of health outcomes. For instance, combining environmental factors like air quality and temperature with disease data allows for a deeper exploration of the relationship between the environment and public health.

The integration of real-time data from sources such as social media, mobile health applications, and remote sensing technologies further enriches the surveillance landscape. This dynamic data integration enhances the detection of early warning signs of outbreaks, monitoring population movements, and responding promptly to public health threats (Kogan et al., 2021; Tambo, Ugwu, & Ngogang, 2014).

In conclusion, the role of GIS in public health surveillance is multifaceted and transformative. From enhancing disease tracking and enabling spatial analysis to integrating diverse data sources, GIS empowers health professionals to make informed decisions and implement targeted interventions. As the synergy between GIS technology and public health continues to evolve, the potential for improving health outcomes and mitigating the impact of diseases on communities remains vast. GIS is a cornerstone in the proactive and data-driven approach to public health surveillance in the 21st century.

4. GIS Technologies in Public Health

GIS technologies have become instrumental in reshaping the landscape of public health, providing a suite of tools and methodologies that enable the visualization, analysis, and interpretation of spatial data. The integration of GIS technologies in public health not only enhances the understanding of disease dynamics but also contributes to the development of targeted interventions and evidence-based decision-making. This section explores key GIS technologies employed in public health, encompassing Geographic Information Systems, Remote Sensing, Global Positioning Systems, and emerging technologies.

At the core of GIS technologies in public health lies the Geographic Information System itself. GIS serves as the foundational platform for mapping and analyzing spatial data, allowing for the creation of dynamic and interactive maps that visualize the distribution of health-related phenomena. GIS enables the overlay of multiple layers of information, facilitating the identification of spatial patterns and relationships between health outcomes and various environmental, socio-economic, and demographic factors. This versatility makes GIS a central tool in disease surveillance, risk assessment, and resource allocation (Boulos, 2004; Fletcher-Lartey & Caprarelli, 2016; Tim, 1995).

Remote Sensing technologies contribute a bird's eye view to public health surveillance by capturing data from a distance using satellite or aerial platforms. This technology provides a wealth of information on environmental factors, such as land cover, vegetation, and climate, which are integral in understanding the ecological determinants of diseases. For instance, monitoring changes in land use can aid in predicting vector-borne disease patterns, while assessing vegetation health can inform about potential outbreaks related to environmental conditions. Remote Sensing, when integrated with GIS, enhances the spatial and temporal resolution of health-related data, fostering a more comprehensive understanding of the complex interactions between health and the environment (Madin & Foley, 2021; Pajares, 2015).

GPS have revolutionized spatial data collection in public health. GPS technology allows for precise location tracking, enabling fieldworkers to geo-reference data during data collection. This is particularly crucial in epidemiological studies, where accurate spatial information about the location of cases, health facilities, and environmental features is essential. GPS technology enhances the efficiency and accuracy of data collection processes, contributing to the development of more precise and reliable spatial databases.

Beyond the traditional GIS technologies, emerging innovations continue to shape the landscape of public health surveillance. AI, machine learning, and data analytics are being integrated into GIS platforms to automate processes, predict disease trends, and derive actionable insights from vast datasets. Mobile health applications and wearable devices equipped with location-tracking capabilities contribute to real-time data collection, continuously monitoring individual health behaviours and identifying potential health risks (Chan, Estève, Fourniols, Escriba, & Campo, 2012; Kheirkhahan et al., 2019; Park & Han, 2023).

4.1. Applications of GIS in Disease Surveillance

Geographic Information Systems have emerged as indispensable tools in disease surveillance, offering a spatial lens through which health professionals can analyze, monitor, and respond to the complex dynamics of diseases. The applications of GIS in disease surveillance span a wide spectrum, from tracking infectious diseases to monitoring environmental factors that influence health outcomes. This section delves into the multifaceted applications of GIS in disease surveillance, exploring its role in tracking disease spread, environmental health monitoring, emergency response, and surveillance of non-communicable diseases.

GIS plays a pivotal role in tracking and monitoring infectious diseases, offering a comprehensive view of outbreaks' spatial distribution and temporal trends. During an infectious disease outbreak, GIS facilitates the creation of real-time maps that display the geographic spread of cases, helping health authorities identify hotspots and allocate resources efficiently. The ability to overlay demographic and environmental data on these maps enables a more nuanced understanding of the factors influencing disease transmission. For example, during the H1N1 influenza pandemic in 2009, GIS was employed to map the spread of the virus and identify vulnerable populations (Abdalla et al., 2011; J. Wang, Xiong, Yang, Peng, & Xu, 2010). Health officials could prioritize vaccination efforts and implement targeted interventions in high-risk areas by integrating data on population density, healthcare infrastructure, and socioeconomic factors. This spatial intelligence proved crucial in mitigating the impact of the pandemic (Christaki, 2015).

GIS extends its reach into environmental health monitoring, enabling the integration of environmental data with health outcomes. By mapping environmental factors such as air quality, water quality, and land use, health professionals can identify potential environmental determinants of diseases and assess their spatial distribution. This application is particularly relevant in understanding the impact of environmental exposures on public health. For instance, GIS has been utilized to study the spatial distribution of vector-borne diseases like malaria and Lyme disease, where environmental conditions influence the prevalence of certain vectors (Jamison, Tuttle, Jensen, Bierly, & Gonser, 2015; Kitron, 1998). Researchers can identify high-risk areas and implement targeted vector control measures by overlaying disease incidence maps with environmental data. GIS also aids in monitoring the impact of environmental pollution on health, facilitating the identification of areas with elevated disease risks.

GIS technology is a cornerstone in emergency response and preparedness, providing a spatially informed approach to managing health crises. During natural disasters, disease outbreaks, or other emergencies, GIS facilitates the rapid collection, analysis, and visualization of spatial data to inform decision-making. Real-time mapping of affected areas helps emergency responders prioritize interventions, allocate resources, and coordinate efforts effectively (Blum, Eichhorn, Smith, Sterle-Contala, & Cooperstock, 2014). In the aftermath of the 2010 earthquake in Haiti, GIS played a crucial role in coordinating the response efforts (Goggins, Mascaro, & Mascaro, 2012; Kawasaki, Berman, & Guan, 2013). By mapping affected areas and healthcare facilities, responders could identify gaps in coverage and deploy resources strategically. GIS also contributed to disease surveillance by tracking the spread of infectious diseases in the post-disaster environment.

Beyond infectious diseases, GIS is increasingly being applied to the surveillance of non-communicable diseases (NCDs) such as cardiovascular diseases, diabetes, and cancer. GIS helps identify patterns of disease prevalence, access to healthcare resources, and socioeconomic factors contributing to NCD risk. By visualizing these factors spatially, health professionals can develop targeted prevention and intervention strategies. For example, GIS has been employed in mapping the prevalence of cardiovascular diseases in urban areas, revealing spatial disparities in risk factors such as access to healthy food and opportunities for physical activity. This information informs the development of community-based interventions and urban planning strategies to create environments that promote cardiovascular health (Kroll, Phalkey, & Kraas, 2015; Saleem et al., 2021).

4.2. Challenges and Limitations of GIS in Public Health Surveillance

While Geographic Information Systems offer unprecedented capabilities in enhancing public health surveillance, several challenges and limitations must be acknowledged to ensure their effective and responsible use.

One of the foremost challenges is the quality and compatibility of data. GIS relies heavily on accurate and up-to-date data, and inconsistencies or inaccuracies in data sources can compromise the reliability of analyses (Jakovljević, Govedarica, & Álvarez-Taboada, 2019). Integrating diverse datasets, especially those from different sources and formats, poses a challenge. Variability in data standards and the need for constant updates require meticulous data management to maintain the integrity of GIS applications in public health (Campo, 2012).

The integration of personal health information into GIS raises ethical concerns regarding privacy and data security. Balancing the need for detailed spatial information with the protection of individual privacy is a complex task (Adebukola, Navya, Jordan, Jenifer, & Begley, 2022; Maduka et al., 2023; Okunade, Adediran, Maduka, & Adegoke, 2023). Striking the right balance is crucial to prevent unauthorized access, use, or disclosure of sensitive health data. Geographic disparities in GIS technology and infrastructure access present challenges, particularly in resource-limited settings. Developing countries may face hurdles in establishing the necessary technological infrastructure and providing training for personnel. This digital divide could hinder the widespread adoption of GIS in public health surveillance, limiting its potential impact on a global scale.

The complexity of GIS analyses may pose a challenge for non-specialists in public health. Interpreting spatial patterns, statistical analyses, and complex models requires a certain level of expertise. Ensuring that public health professionals possess the necessary skills to understand and interpret GIS outputs is essential for the effective utilization of this technology. Implementing and maintaining GIS technology can be resource-intensive. Costs associated with software, hardware, training, and data collection may strain the budgets of public health agencies, particularly in low-resource settings. Securing ongoing financial support for GIS initiatives is crucial to sustain their effectiveness. GIS applications often operate at specific temporal and spatial scales, limiting their ability to capture dynamic changes or address issues at finer scales (Agarwal, 2002). This limitation can impact the detection of rapidly evolving disease outbreaks or the identification of localized health disparities.

Addressing these challenges requires a comprehensive and collaborative approach. Strategies include investing in data quality assurance, implementing robust privacy measures, expanding access to GIS technology, providing training for professionals, and developing standardized protocols for data integration. By navigating these challenges, the integration of GIS in public health surveillance can continue to evolve as a valuable tool for understanding and addressing complex health issues.

4.3. Future Directions and Innovations in GIS Applications for Public Health Surveillance

The future of GIS applications in public health surveillance promises exciting advancements and innovations that will further enhance our ability to monitor, analyze, and respond to health challenges. Several key directions and innovations are expected to shape the landscape of GIS in public health.

Integration with Emerging Technologies: The synergy between GIS and emerging technologies, such as Artificial Intelligence (AI) and machine learning, is poised to revolutionize public health surveillance. AI algorithms can process vast datasets, identify complex patterns, and predict disease trends with unprecedented accuracy. Machine learning models integrated into GIS platforms can automate data analysis and decision-making processes, providing real-time insights for more proactive and responsive public health interventions.

Enhanced Spatial and Temporal Resolution: Future developments in GIS technology are likely to improve spatial and temporal resolution, allowing for more precise mapping and monitoring of health-related phenomena. High-resolution satellite imagery, improved GPS accuracy, and advancements in remote sensing technologies will contribute to a more detailed understanding of disease dynamics and environmental factors influencing public health.

Mobile Health and Wearable Devices: Integrating GIS with mobile health applications and wearable devices will play a significant role in real-time data collection and monitoring. These technologies enable continuous tracking of individual health behaviours, movement patterns, and environmental exposures. By incorporating this real-time data into GIS platforms, health professionals can gain insights into population health trends and identify potential health risks more efficiently.

Geospatial Big Data Analytics: The increasing volume of geospatial data, often called geospatial big data, presents both opportunities and challenges. Future innovations will focus on developing advanced analytics tools capable of processing and analyzing large-scale datasets. This will allow for more in-depth spatial analyses, uncovering subtle patterns and relationships that were previously difficult to discern.

Community Engagement and Participatory GIS: Future GIS applications in public health will likely emphasize community engagement and participatory approaches. Involving communities in the mapping and monitoring of health-related information empowers individuals to contribute valuable insights. It enhances the relevance and accuracy of spatial data.

Global Collaboration and Standardization: To address global health challenges effectively, future directions in GIS for public health will involve increased collaboration and standardization of data and methodologies. Establishing common standards for data collection, sharing, and analysis will facilitate cross-border collaboration and the development of a global GIS infrastructure for public health surveillance.

5. Conclusion

The integration of GIS into public health surveillance has evolved into a transformative force, offering a dynamic and spatially informed approach to understanding, monitoring, and responding to health challenges. Through a historical exploration, it is evident that GIS has progressed from rudimentary mapping techniques to sophisticated technologies, becoming an indispensable tool in disease surveillance.

GIS has demonstrated its efficacy in tracking infectious diseases, monitoring environmental health, facilitating emergency response, and surveilling non-communicable diseases. It provides a platform for visualizing complex spatial data, identifying patterns, and informing evidence-based decision-making. The applications of GIS extend beyond traditional boundaries, contributing to a holistic understanding of the intricate interplay between health outcomes and environmental, socio-economic, and demographic factors. However, challenges such as data quality, privacy concerns, and resource constraints must be navigated to harness the potential of GIS in public health surveillance fully. Future directions and innovations, including the integration with emerging technologies, improved spatial resolution, and community engagement, hold promise for addressing these challenges and advancing the field.

In conclusion, GIS stands at the forefront of a data-driven and proactive era in public health surveillance. As technological advancements continue, the marriage of GIS with public health is poised to lead us into an era where precision, efficiency, and inclusivity converge to foster healthier communities globally. Embracing these innovations will be paramount in ensuring the continued success of GIS applications in shaping the future of public health surveillance.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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