Geospatial tools and data for health service delivery: opportunities and challenges across the disaster management cycle

Fleur Hierink,[1,2] Nima Yaghmaei,[3] Mirjam I. Bakker,[3] Nicolas Ray,[1,2] Marc van den Homberg[4,5]

[1]GeoHealth group, Institute of Global Health, University of Geneva, Geneva, Switzerland; [2]Institute for Environmental Sciences, University of Geneva, Geneva, Switzerland; [3]KIT Royal Tropical Institute, Global Health, Centre for Applied Spatial Epidemiology, Amsterdam, The Netherlands; [4]510, an initiative of the Netherlands Red Cross; [5]Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, Enschede, The Netherlands

Abstract

As extreme weather events increase in frequency and intensity, the health system faces significant challenges, not only from shifting patterns of climate-sensitive diseases but also from disruptions to healthcare infrastructure, supply chains and the physical systems essential for delivering care. This necessitates the strategic use of geospatial tools to guide the delivery of healthcare services and make evidence-informed priorities, especially in contexts with scarce human and financial resources. In this article, we highlight several published papers that have been used throughout the phases of the disaster management cycle in relation to health service delivery. We complement the findings from these publications with a rapid scoping review to present the body of knowledge for using spatial methods for health service delivery in the context of disasters. The main aim of this article is to demonstrate the benefits and discuss the challenges associated with the use of geospatial methods throughout the disaster management cycle. Our scoping review identified 48 articles employing geospatial techniques in the disaster management cycle. Most of them focused on geospatial tools employed for preparedness, anticipatory action and mitigation, particularly for targeted health service delivery. We note that while geospatial data analytics are effectively deployed throughout the different phases of disaster management, important challenges remain, such as ensuring timely availability of geospatial data during disasters, developing standardized and structured data formats, securing pre-disaster data for disaster preparedness, addressing gaps in health incidence data, reducing underreporting of cases and overcoming limitations in spatial and temporal coverage and granularity. Overall, existing and novel geospatial methods can bridge specific evidence gaps in all phases of the disaster management cycle. Improvement and 'operationalization' of these methods can provide opportunities for more evidence-informed decision making in responding to health crises during climate change.

Correspondence: Nicolas Ray, GeoHealth group, Institute of Global Health, University of Geneva, Geneva, Switzerland.
E-mail: Nicolas.Ray@unige.ch

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Introduction

Climate change will exacerbate certain drivers of acute health crises (Alcayna *et al.*, 2022; Romanello *et al.*, 2022). Changes in the occurrence of extreme weather events have the potential to directly affect health by causing injuries and premature deaths, as well as indirectly by disrupting crucial infrastructures (McMichael, 2020; Fletcher *et al.*, 2021; Romanello *et al.,* 2022). These disruptions can lead to unsafe living conditions, limited access to healthcare, clean water, and sanitation as well as forced displacement of vulnerable populations (Kamel Boulos & Wilson, 2023). Furthermore, alterations in weather patterns can contribute to shifts in disease distribution and transmission (Fletcher *et al.*, 2021; Alcayna *et al.*, 2022; Di Napoli *et al.*, 2023). Together, these factors can trigger disasters, which are defined as serious disruptions to the functioning of a community, overwhelming local resources resulting in human, material, economic, and environmental losses (UNDRR, 2016). In these situations, evidence-informed and data-driven decision-making is important for the targeted delivery of health services. Nevertheless, there are challenges to the seamless integration of geospatial tools into the overall disaster management cycle. First, the lack of a functioning geospatial data infrastructure is a significant hurdle, characterized by the lack of up-to-date and high-quality risk-related data that can be used immediately during and postdisaster situations as a baseline and starting points. This reflects a state of poor data preparedness. Secondly, data collection during acute crises - to get an up-to-date and dynamic understanding of the operational environment and crisis impact - presents a number of challenges, such as logistical difficulties in accessing the affected areas and communities e.g., due to security concerns and infrastructure breakdowns as well as coordination difficulties given the multitude of actors involved (IASC, 2015; Colombo & Pavignani, 2017). Geospatial methodologies, encompassing geostatistical risk modelling, geographical accessibility analyses and multicritical spatial risk assessments prove instrumental in supplementing the required evidence for facilitating optimal health service delivery amid crisis situations (Haak *et al.*, 2018; Greenough & Nelson, 2019; Jabbour & Attal, 2020; Kamel Boulos & Wilson, 2023). As seen in Figure 1, the outcomes derived from these models contribute significantly across various phases of disaster management: i) Preparedness & Anticipatory Action; ii) Response; iii) Recovery: and iv) Mitigation (Klein & Irizarry, 2023). While the application of geospatial methods for health is gaining momentum, their utilization in humanitarian settings remains comparatively limited (Jabbour & Attal, 2020). To assess the current use of geospatial data in the disaster management cycle for optimizing health service delivery and to identify the key challenges associated with implementing these approaches, this paper has two primary objectives: i) to discuss four geospatial case studies, in which the authors have been directly involved, with a focus on their application within a specific phase of the disaster management cycle. Emphasis is placed on how these four papers contributed to decision-making processes in health service delivery and health system planning; ii) to present the challenges associated with integrating geospatial techniques throughout the disaster management cycle, as identified through expert discussions among the authors and a rapid scoping review (Tricco *et al.*, 2015), as well as discuss future avenues to improve the quality and utility of geospatial methods and actions that can be taken to improve them.

Materials and Methods

Selection

Four case studies were selected based on direct involvement of this study's authors. Factors considered for selection were the correspondence of the case study to the different phases of disaster response and a demonstration of importance of geospatial methods in enhancing decision-making process during a disaster, with a particular focus on health service delivery and planning. The case studies were used to facilitate expert-level discussion on implementation, challenges encountered and lessons learned.

Rapid scoping review

In addition to presenting these case studies, a rapid scoping review of geospatial data used for health service delivery during disasters was conducted. This review focused on extracting and classifying the most encountered challenges and barriers in using geospatial data during disasters, as well as creating a tabular overview of the current use cases documented in the academic literature. We included articles in peer-reviewed journals publishing in English. To ensure relevance and timeliness of the literature, our inclusion criteria spanned the last decade, *i.e.* from 2013 to early 2024. This timeframe was chosen to reflect the rapid technological development of the geospatial methodology. In addition, we focused on studies related to the provision of health services or health system planning across the four phases of the disaster response cycle. We concentrated directly on articles deploying geospatial methods in a specific context and excluded review papers, meta-analyses, clinical or randomized controlled trials and short comments. Our initial search strategy (Table 1) was employed in PubMed in February 2024. Additional relevant publications were included through snowballing techniques of the reference list and searches using different search engines. Exclusion criteria were absence of geospatial methods; lack of direct association with health service delivery or health system planning, emphasis on animal health focus; absence of an implication for any of the disaster cycle phases; and absence of a disaster or climate

Table 1. Search terms and keywords utilized for conducting literature review in PubMed.

Disaster focus	("climate change"[Title/Abstract] OR "extreme weather"[Title/Abstract] OR "natural disaster"[Title/Abstract] OR "natural hazard*"[Title/Abstract] OR disaster[Title/Abstract] OR epidemic*[Title/Abstract] OR pandemic*[Title/Abstract] outbreak*|[Title/Abstract] OR earthquake*[Title/Abstract] OR wildfire*[Title/Abstract] OR cyclone*[Title/Abstract] OR hurricane*[Title/Abstract] OR storm*[Title/Abstract] OR flood*[Title/Abstract] OR tsunami*[Title/Abstract] OR drought*[Title/Abstract] or climat*[Title/Abstract] OR heatwave*[Title/Abstract] OR conflict*[Title/Abstract]) AND
Health service delivery focus	("health service"[Title/Abstract] OR "health service delivery"[Title/Abstract] OR "health*care"[Title/Abstract] OR “health care delivery”[Title/Abstract] OR “medical care” [Title/Abstract] OR “medical treatment” [Title/Abstract] OR health*[Title]) AND
Geospatial methodology focus	(geo*spatial[Title/Abstract] OR “geographic*analysis”[Title/Abstract] OR GIS[Title/Abstract] OR spatial [Title/Abstract] OR geographic*[Title]) AND
Humanitarian response phase	(humanitarian[Title/Abstract] OR crisis[Title/Abstract] OR emergency[Title/Abstract] OR *response[Title/Abstract] OR mitigation[Title/Abstract] OR prevention[Title/Abstract] OR preparedness[Title/Abstract] OR “early warning”[Title/Abstract] OR recovery[Title/Abstract]))

context. The titles and abstracts were screened for initial inclusion. Selected articles were then classified by country, disaster phase, disaster type according to the EM-DAT classification (EM-DAT, 2024) and reported data limitations. The challenges associated with integrating geospatial techniques throughout the disaster management cycle were categorized according to the seven distinct groups under the data supply dimension of the data ecosystem framework developed by van den Homberg and Susha (2018), which addresses structuredness of data; degree of access; timeliness; content of data; content accuracy; source reliability; granularity; and spatial coverage (Van Den Homberg & Susha, 2018). While the general findings from the scoping review will be discussed in the Result section, the primary focus of the discussion will be on interpreting and dissecting the various challenges that emerged from the expert discussions and publications.

Case studies

Each of the case studies presented here corresponds to one of the phases of disaster management: i) preparedness & anticipatory action; ii) response; iii) recovery; and iv) mitigation as given by Klein & Irizarry (2023). The preparedness phase focuses on ensuring that people, countries or regions have the necessary tools, plans, equipment and information to respond effectively to potential hazards before they escalate or occur. Anticipatory action involves taking proactive measures and conducting analyses ahead of predicted hazards to minimize their potential impact on vulnerable populations. The response phase addresses immediate and short-term needs to alleviate the impacts of a disaster. The recovery phase involves restoring and rebuilding while enhancing community resilience. The mitigation phase, on the other hand, involves implementing strategies to reduce or eliminate long-term risks and impacts of future disasters.

Case study i: preparedness

In Sudan, a network of Emergency Obstetric and Newborn Care (EmONC) facilities was established by the Ministry of Health with the support of the United Nations Population Fund to maximize access for the population within two-hour travel time. To address the potential challenges of water security in these facilities, exacerbated by climate change, and to ensure the preparedness of healthcare providers, particularly in drought-prone regions, Simonin *et al.* (2023) developed a geospatial composite Drinking Water Security Index (DWSI) at three levels: i) 1-km^2 grid cells, ii) facility catchments and iii) State level. Using spatial indicators about i) water quality; ii) accessibility; iii) continuity; and iv) availability and quantity, the composite DWSI was calculated temporally for two time periods: i) a historical range from 1970 to 2006 and ii) a future time frame (2020-2050) using five different climate scenarios. The analysis revealed that nearly 19 million people are served by facilities with the lowest DWSI. Alarmingly, this number is expected to surge 60% by 2030. Understanding the current state of water security in facilities, and its potential evolution in the coming decades due to climate change, provides important insights into the current state and sustainability of the health system. This assessment aids in pinpointing areas that require urgent attention to ensure the delivery of quality healthcare under water-secure conditions.

Case study ii: anticipatory action

Humanitarian organizations have implemented 70 frameworks

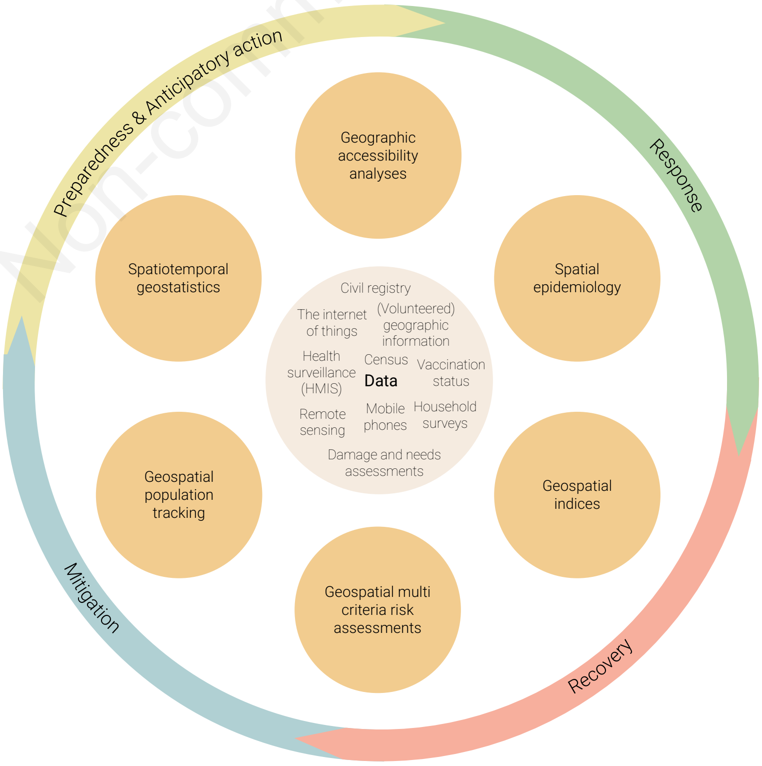

Figure 1. Overview of the data and geospatial methods used during the different phases of disaster management.

for anticipatory action mostly focused on natural hazards, with little attention to epidemics. In a recent study, Hierink *et al.* (2022) developed a tailored epidemic risk index for the Philippines to assist local humanitarian organizations, particularly the Philippines Red Cross, in deploying prevention measures against recurrent dengue outbreaks of all viral strains. The geospatial epidemic risk index was developed based on two key dimensions: Hazard & Exposure and Vulnerability & Coping Capacity. Key indicators were first selected for each dimension, then normalized and aggregated at the provincial level. Subsequently, the public epidemiological data were adjusted to account for potential underreporting of disease cases. This correction included an estimate of relative differences in underreporting based on geographic accessibility to healthcare. The modelled risk index varied between 0.43 and 0.69 in all regions of the Philippines, using a scale of 0 to 1. The results showed a robust correlation between the calculated dengue risk and conventional epidemiologic measures, such as dengue incidence ($p = 0.002$). The findings affirm that the modelled epidemic risk index serves as a robust indicator of sub-national dengue disease patterns demonstrating its suitability for conducting disease risk assessments when timely epidemiological data are unavailable. These metrics can guide targeted control measures, including strategic initiatives, such as anti-mosquito spraying efforts or the removal of breeding sites.

Case study iii: response and recovery

Tailored data products such as maps play a crucial role in prioritizing response efforts and planning for long-term recovery operations. Hierink *et al.* (2020) collaborated with the United Nations Children's Emergency Fund (UNICEF) to model the travel time of children under-five to the nearest functional health facility following the impact of cyclones Idai and Kenneth in Mozambique in 2019. Using AccessMod V.5.6.30, geospatial factors, including roads, rivers, lakes, flood extent, topography and land cover were incorporated and overlaid with health facility coordinates considering non-functionality due to damages and high-resolution population data. This allowed the derivation of accessibility coverage estimates at 30-m resolution under various

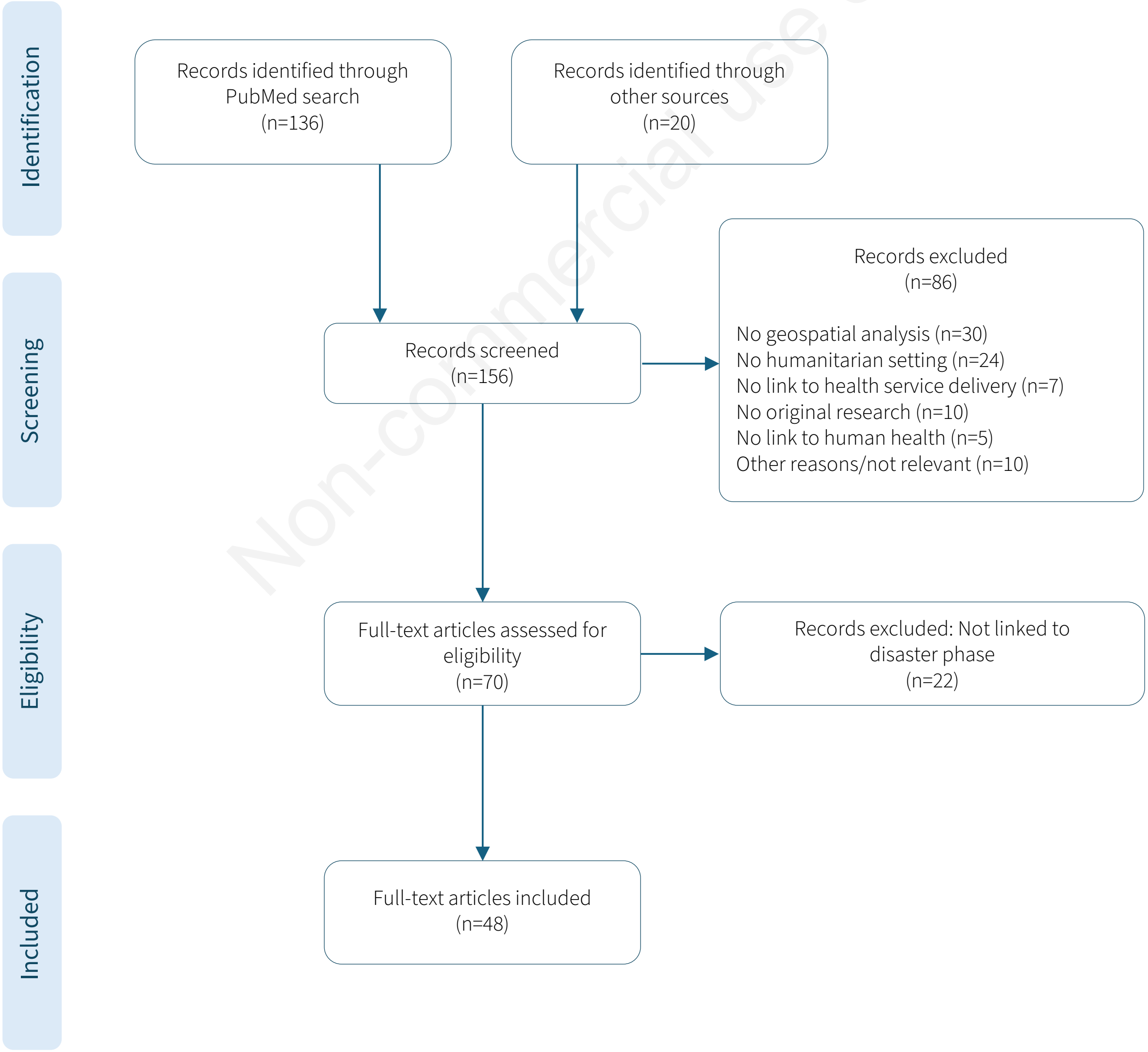

Figure 2. Flow diagram of article inclusion and exclusion in scoping review.

pre- and post-cyclone travel scenarios. The findings highlighted a substantial decrease in accessibility coverage in cyclone-affected districts attributed to factors such as reduced travel speeds, barriers to movement, road constraints and non-functional health facilities. Specifically, in Idai-affected districts, accessibility coverage dropped from 78.8% to 52.5%, affecting 136,941 children under-five. Modelling geographic accessibility in the aftermath of a disaster enhances our comprehension of spatial variations in geographical healthcare access and can guide the targeting and prioritization of scarce resources. Our findings highlight the potential for integrating accessibility modelling into early disaster response efforts, contributing valuable insights for discussions on health system recovery.

Case study iv: recovery and mitigation

In the direct aftermath of an emergency response, it is important to support countries and regions in longer term recovery efforts and build resilience. During the COVID-19 pandemic, services of Tuberculosis (TB) care and prevention programs were severely disrupted with the number of people newly detected falling globally by 18% in 2020 (World Health Organization, 2021). The mapping and analysis for tailored disease control and health system strengthening (MATCH) approach (Royal Tropical Institute (KIT), 2018) was developed to identify disparities in spatial and temporal epidemic trends while accounting for local variations in risk profiles, access to care and program performance gaps using routine surveillance, health systems and population data. Based on geospatial analysis and validation, interventions were tailored to the local area and responsive to specific needs. MATCH was first applied in Bangladesh through comparing the predictions of the best fitting spatial model with the observed case notification rate in each of the 484 upazilas (district sub-units)

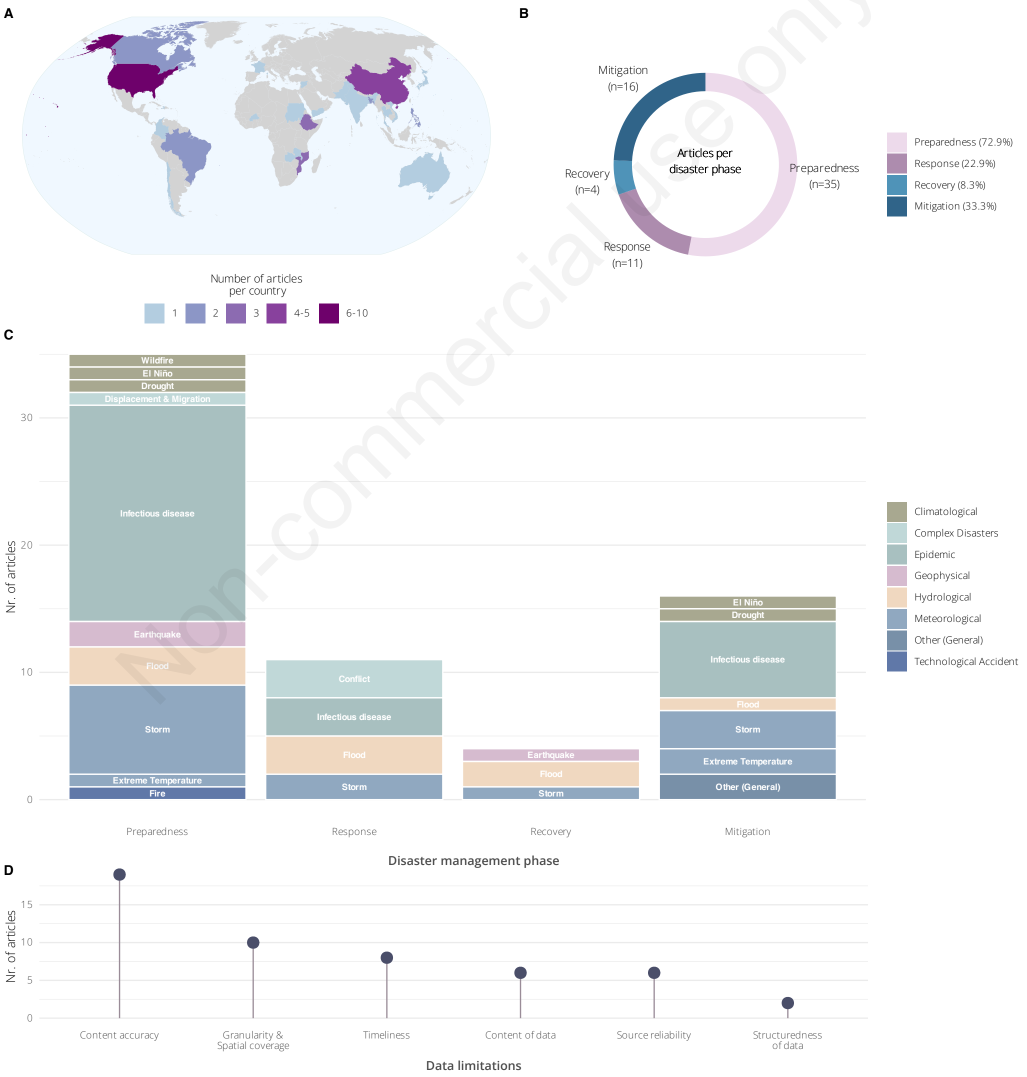

Figure 3. Overview of the scoping review results representing the number of studies conducted by **A**) geographic focus, **B**) disaster phase, C) disaster type & disaster phase, and D) mentioned data limitations as categorized by the framework from van den Homberg & Susha (2018). Some of the studies touched upon more than one of the disaster phases or limitations, resulting in some double counting and percentages totaling more than 100%.

included in the analysis. Areas with low TB case notification rates, high poverty, low TB testing rates and poor TB treatment outcomes were identified to likely have TB under-detection (Rood *et al.*, 2018). In the aftermath of COVID-19 in Lesotho, MATCH was used to geo-optimize TB care services, which were studied through examination of spatial variations and gaps. Local health care needs were identified and interventions strategized to find missing people with TB in a post-COVID-19 setting (Soothoane et al., 2023). MATCH can also be used in the mitigation phase to identify areas with highest vulnerability to reduced access to health services during disasters.

Scoping review results

Our PubMed search term strategy yielded 136 unique publications. Additionally, 20 supplementary studies were found manually through PubMed, search engine queries and snowballing techniques (Figure 2 and Annex I). After screening the initial pool of articles, 86 were excluded due to lack of relevance in the title and abstract. In addition, 22 studies were not directly related to phases of disaster management. In total, 48 geospatial studies implied health and health service delivery throughout at least one of the disaster management phases. Some studies touched upon more than one disaster phase (n=18) resulting in some double counting in Figure 3 and percentages totalling more than 100%. Geographically, the United States was represented in 8 studies, followed by China (Figure 3A). By regional categorization according to the World Bank Group (2024), sub-Saharan Africa was represented in 12 studies followed by East-Asia & Pacific (n=11) and North-America (n=10). Studies conducted in East-Asia & Pacific, Sub-Saharan Africa and Latin America & the Caribbean were more focused on infectious disease outbreaks (n=5, n=4 and n=3), studies in North-America on storms (n=4) and studies in the Middle East & North Africa on conflict (n=2). Most studies (n=35) applied geospatial tools for Preparedness & Anticipatory Action (Figure 3B), particularly for forecasting disease outbreaks (Figure 3C). The second most represented disaster phase was mitigation (n=16), with studies aimed at improving health system adaptation and building resilience. The coverage of geospatial methods used in the direct response and recovery phase of a disaster remained limited.

Unfortunately, the power of geospatial tools for enhancing health service delivery in disaster settings is constrained by data limitations. Analysis of all included articles reveals that 19 studies cited content accuracy as hindrances to reliable analysis outcomes, while 10 publications identified limitations in the granularity or spatial coverage of geospatial data. Challenges related to underreporting, data timeliness, non-standardized formats and access to population data in disaster settings were also noted (Figure 3D).

Discussion

With respect to disaster management, geospatial tools provide invaluable support to decision makers throughout the cycle (Greenough & Nelson, 2019; Jabbour & Attal, 2020). This review found that these tools were notably more used in the preparedness and mitigation phases, a trend reflecting the challenges of conducting and prioritizing research during ongoing disasters and underscoring the importance of prioritizing operational research. This trend also highlights that operational organizations often prioritize the development of actionable geospatial data products for internal reporting and activities rather than peer-reviewed publications. Additionally, several challenges to the effective use of geospatial tools in disasters came to light during our review, as well as several solutions actively being used to address these challenges.

The most cited challenge to the use of geospatial data was content accuracy, an observation indicating that the data do not accurately reflect reality (Figure 3D). This issue can for example stem from underreporting of diseases or missing data points. The second most frequently reported challenge was the granularity of the data and spatial coverage, indicating that data are often released at aggregated scales, which also increase the risk of the modifiable area unit problem (MAUP). Finally, limited timeliness or outdated data sources was also often highlighted (Figure 3D). Other, less frequently mentioned limitations, as categorized under the data supply dimension from the framework developed by van den Homberg & Susha (2018), included source reliability as well as type of content and structuredness of the data (Van Den Homberg & Susha, 2018).

Content accuracy of the data - underreporting

Addressing gaps in health incidence data and mitigating underreporting of cases require concerted efforts to improve reporting mechanisms. In numerous countries, disease notification relies on passive surveillance systems within health facilities, which are often not publicly shared. Several studies in the scoping review addressed the issue of underreporting and underestimations in true incidence data. The study conducted by Warsame *et al.* (2021) used satellite imagery to identify new burial sites in Somalia, new information enabling the calculation of excess mortality during the COVID-19 pandemic, which was needed as no epidemiological data were available. In addition, Hierink *et al.* (2022) used a distance decay method to address the underreporting of dengue incidence in the Philippines, an approach accounting for the decreasing probability of reported dengue cases with increasing travel time to health facilities.

Granularity and spatial coverage

Geospatial health data often show inadequate spatial and temporal coverage as well as insufficient granularity. Frequently, datasets are reported at aggregated administrative levels and captured at specific points in time. This challenges decision-making utility, as targeted resource allocation may require information at a more highly granular administrative level (van den Homberg *et al.*, 2017; Van Den Homberg *et al.*, 2018). In studies conducted by Simonin *et al.* (2023) and Hierink *et al.* (2022), these challenges introduced outcome uncertainties. For example, Simonin's creation of a water security index for Sudan faced a notable obstacle with data reporting water supply at the state level for the years 2010 and 2014, with one dataset predating South Sudan's independence. Moreover, the state-level granularity significantly impacts pixel-level predictions and prevents disaggregation between rural and urban situations (Simonin *et al.*, 2023). Hierink *et al.* (2022) demonstrated the creation of a dengue risk index using publicly available incidence data at administrative boundary level 1. However, a higher data granularity would have contributed to easier decision-making.

Data timeliness

Humanitarian actors face difficulties in obtaining timely and detailed post-disaster data. The collection, storage and use of data are often characterized by diverse groups and challenged by security issues and logistical constraints leading to inefficiencies and delays. For example, Hierink *et al.* (2020) demonstrated that although satellite imagery data on flood extents and road damage were available within a week of the disaster, critical information requiring ground validation, such as the operational status of health facilities, took nearly a month to gather. This delay in obtaining updated health facility data is not uncommon. Mroz *et al.* (2023) also highlighted that the data they used for health facilities were often more than a decade old, introducing a strong and significant uncertainty into their assumptions. These examples underscore the broader issue of data timeliness, particularly with regard to health infrastructures. To address this, proactive measures - such as preparing and verifying the coordinates of health facilities before a disaster - are essential for enabling faster, more accurate data collection and integration in the aftermath of a crisis.

Data structuredness

A further challenge is the lack of standardized and structured data formats. For example, maps are often provided in pdf format, while logistic cluster updates are presented as images rather than shapefiles or raw data. In addition, different definitions are used in various damage and needs assessments, a fact that contributes to confusion regarding impact and inefficiency during the response. Harmonization of data formats and definitions is critical for interoperability and seamless integration of geospatial data into disaster responses (Jones *et al.*, 2022).

In Hierink *et al*. (2020), it was pointed out that the publication of road closures was limited to pdf maps, where historical versions were removed when updates became available, a fact preventing a temporal analysis of the evolution of road closures. To analyze road damages, manual digitization was necessary, involving a visual comparison between OpenStreetMap data and published maps. In parallel to the development of standardized data formats, Nelson *et al.* (2020) highlighted the lack of a structured process for analyzing gender vulnerability in refugee settlements in Bangladesh. Despite the monitoring of standard indicators that are critical to understanding gender vulnerability, these indicators are not publicly available, highlighting a gap in transparent and accessible data analysis procedures.

Conclusions

Geospatial methodologies hold immense promise for health service delivery in disasters. They could drive development, yet their full potential is curtailed by several challenges. Addressing these gaps involves prioritizing data literacy and preparation in countries, ensuring that essential baseline data is readily accessible when disaster strikes.

This review highlights the dearth of research on critical topics such as migration, water security and health, conflict and health as well as climate change and extreme temperatures. While infectious diseases, particularly in the context of COVID-19, have received substantial research attention, emerging issues, such as heat waves and extreme temperatures, which are increasingly relevant in the era of climate change, remain underexplored. Additionally, there is a noted scarcity of articles examining the response and recovery phases of disasters, indicating a crucial area for future research. While acknowledging the inherent difficulties in studying these phases, efforts to investigate and address their complexities are essential for advancing disaster response and recovery.

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Online Supplementary Materials

Overview of scoping review results (excel table).