Insights and Lessons from Mapping, Analyzing, and Assessing COVID-19 Using a Web-Based GIS Approach in Khartoum State, Sudan

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ABSTRACT

The COVID-19 pandemic has highlighted the urgent need for a paradigm shift from traditional health surveillance to real-time, spatial monitoring. This research presents a comprehensive digital geospatial framework that maps and visualises the spatial spread, recovery rates, and health infrastructure of COVID-19 across the seven localities of Khartoum State using a Web-GIS approach. Its aim is to address the "health-wealth gap" caused by spatial inequalities and provides practical lessons for enhancing public health surveillance systems in Khartoum, Sudan. Using data from the Ministry of Health during the first two waves, a Web-GIS was developed to integrate epidemiological, demographic, and spatial data. Including population data for all 5,213,058 residents ensures a precise assessment of infection levels beyond case counts. ArcGIS mapping and hotspot analysis enable detailed visualisation of pandemic trends, revealing significant spatial disparities and a clear link between economic resources and health outcomes. While Khartoum's central locality, with its dense healthcare infrastructure, experienced the highest infection and recovery rates, peripheral regions such as Umbada and Sharg Elneel reported fewer cases, possibly due to underreporting. The findings emphasise that spatial disparities—not merely population density—shape transmission dynamics within Khartoum State. Based on this analysis, several actionable lessons are proposed, such as prioritising hotspots by reallocating resources to high-density residential and commercial areas identified through weekly ArcGIS maps, deploying mobile units, enhancing WASH facilities, and conducting screenings there. Implementing safe zone protocols with screenings at major hubs like Khartoum and Bahri, as well as regional transit points, is essential. Supplies such as masks and beds should be allocated based on data, focusing on densely populated areas rather than imposing broad lockdowns.

Keywords: *COVID-19, Web-GIS, health inequalities, spatial epidemiology, urban health systems, health-wealth gap, Khartoum State, Sudan*

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INTRODUCTION

In December 2019, a pneumonia outbreak of unknown origin in Wuhan, China, rapidly escalated into a global public health emergency. The causative agent was quickly identified as the 2019 novel coronavirus (2019-nCoV), now known as Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2), highlighting the urgent need for international cooperation (WHO, 2020). Its rapid spread, fuelled by high-volume travel during events like the Chinese Spring Festival, demonstrated how interconnected our world has become and the importance of swift containment efforts (CDC, 2021). Within months, COVID-19 had reached over 100 countries, surpassing previous coronavirus outbreaks such as SARS-CoV in 2002 and MERS-CoV in 2012, which affected 37 and 27 countries, respectively. However, a significant knowledge gap remains regarding detailed spatial analysis, mapping, and assessment of COVID-19's spread, which are critical for targeted interventions and resource allocation. The higher contagiousness of COVID-19 posed unprecedented challenges, especially for vulnerable groups such as older adults and immunocompromised individuals, underscoring the critical need for proactive public health measures (Johns Hopkins, 2022; Fuggetta, 2022).

The Role of GIS in Public Health

In December 2019, a pneumonia outbreak of unknown origin in Wuhan, China, rapidly escalated into a global public health emergency. The causative agent was swiftly identified as the 2019 novel coronavirus (2019-nCoV), now known as Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2), highlighting the urgent need for international cooperation (WHO, 2020; AfDB & WHO, 2025). Its rapid spread, driven by high-volume travel during events like the Chinese Spring Festival, demonstrated how interconnected our world has become and the importance of swift containment efforts (CDC, 2021). Within months, COVID-19 had reached over 100 countries, surpassing previous coronavirus outbreaks such as SARS-CoV in 2002 and MERS-CoV in 2012, which affected 37 and 27 countries respectively. A growing body of evidence emphasises the vital role of geographic information systems (GIS) in monitoring and analysing COVID-19's spread, enabling targeted interventions and resource distribution (Smith et al., 2023; Lee & Patel, 2022). Despite these advances, a significant knowledge gap remains regarding detailed spatial analysis, mapping, and assessment of COVID-19's spread, which are critical for effective containment. The higher transmissibility of COVID-19 posed unprecedented challenges, particularly for vulnerable groups like older adults and immunocompromised individuals, emphasising the crucial need for proactive public health measures (Johns Hopkins, 2022).

GIS and Epidemic Surveillance

Epidemiology examines the spread and control of diseases over time and across places (Busgeeth et al., 2008). GIS supports epidemiology by adding environmental, temporal, and spatial details. This helps spot high-risk groups and clusters. Mapping diseases lets health groups plan and move from a reactive to a proactive approach. Epidemiology explores how diseases spread and can be controlled over time and across different geographic regions (Busgeeth et al., 2008). Geographic Information Systems (GIS) bolster epidemiology by integrating environmental, temporal, and spatial data, enabling researchers to identify high-risk populations and disease clusters with greater precision. By creating detailed maps of disease distribution, health organizations can strategically plan interventions and transition from reactive responses to proactive disease management. In Africa, these capabilities have improved the handling of diseases such as trypanosomiasis and guinea worm, with spatial data guiding the targeted deployment of resources like clean water pumps (WHO, 2009). As the COVID-19 pandemic continues to spread rapidly, exerting immense pressure on economies worldwide, the importance of effective GIS-based monitoring has become especially acute. In places like Khartoum State, Sudan, leveraging GIS tools is vital for tracking the virus's progression and implementing timely public health responses.

Problem statement

The COVID-19 pandemic exposed critical weaknesses in Khartoum State's ability to monitor and control the real-time spread of infectious diseases. High population density, intense daily movement across urban areas, and asymptomatic transmission all accelerated viral spread. Yet, health authorities lacked a unified, spatially explicit system to track where and how the virus was spreading. Traditional reporting mechanisms, which are largely tabular and non-spatial, provided case counts but not the geographic context needed to identify transmission hotspots, assess local vulnerabilities, or guide the targeted deployment of medical resources. In Khartoum State, this gap was particularly acute. Dense urban flows and limited integration of health data with geographic information meant that decision-makers could not easily visualise outbreaks, evaluate the relationship between population distribution and confirmed cases, or monitor how capacity constraints in peripheral localities affected reported outcomes. As a result, interventions were often reactive rather than proactive, and potential underreporting, especially in outlying areas with weaker health infrastructure, went unexamined. There is therefore an urgent need for a central, Web-based Geographic Information System (Web-GIS) that links epidemiological data with demographic and spatial layers. Such a platform would enable real-time mapping of COVID-19 dynamics, reveal spatial inequities in health service access, and support evidence-based decision-making for both current and future epidemics in Khartoum State and beyond.

Objectives of the study

This research aims to comprehensively map, analyse, and develop the spatial distribution of Coronavirus Disease (COVID-19) in Khartoum State, Sudan, using a web-based GIS approach. Its specific objectives are:

1. To map and visualise the spatial diffusion, recovery rates, and health infrastructure of COVID-19 using a web-based GIS approach during the first (2019/2020) and second (2020/21) waves in the seven localities of Khartoum State.
2. To identify the "health-wealth gap" based on the effects of spatial inequalities in accessing health care.
3. To develop actionable lessons for optimising public health surveillance systems in Khartoum State, Sudan.

MATERIALS AND METHODS

Study area

The study focuses on Khartoum State, Sudan's administrative and economic capital. The area spans approximately 22,122 km². Khartoum is a significant urban centre located at the confluence of the White and Blue Nile rivers. Its population is around 8.0 million. Administratively, Khartoum State is divided into three main cities: Khartoum, Khartoum North (Bahri), and Omdurman. These cities are further divided into seven localities: Karrary, Umbaddah, Omdurman, Bahary, Sharag El-Niel, Khartoum, and Jebel Awlia (Figures 1 and 2). The area is a flat inland plain at about 400 meters elevation, featuring a hot desert climate. Temperatures are often extreme, exceeding 38°C for 6 months of the year, with peaks reaching 53°C. Despite the arid conditions most of the year, substantial rainfall falls in July and August, causing seasonal flooding and affecting public health infrastructure.

Data sources and materials

The research utilises secondary data from the Ministry of Health - Khartoum State, Epidemics Administration.

Epidemiological data

The dataset tracks current COVID-19 cases in seven localities. It lists total confirmed cases, patient age and sex, residential locality, and whether cases are active or recovered.

Demographic data

To gain a deeper understanding of infection density beyond case numbers, population data for each locality were incorporated into the GIS environment, as shown in (Table 1).

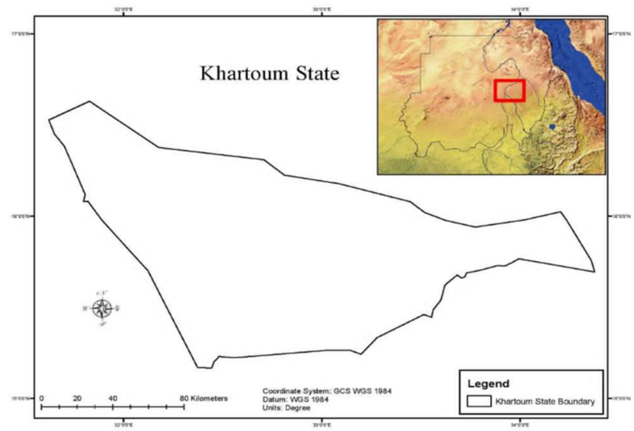

Figure 1: Khartoum State Location

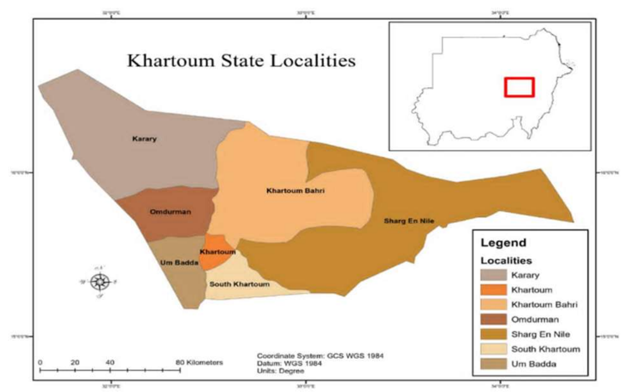

Figure 2: Khartoum State Localities

Table 1: Population Data per Locality in Khartoum State.

Locality	No. of Families	No. of Residents
Karrary	128,780	778,058
Umbaddah	157,889	963,900
Omdurman	83,938	507,781
Bahary	101,091	608,517
Sharag ElNiel	143,454	858,981
Khartoum	104,594	633,854
Jebel Awlia	140,307	861,967
Total	860,053	5,213,058

Source: Ministry of Health, Khartoum State, 2020

Methods

The technical workflow comprised three essential phases that collectively enhanced the understanding of COVID-19 distribution patterns. The first phase involved meticulous data pre-processing, during which health data were carefully cleaned, particularly regarding Locality names, and demographic variables were standardized to ensure consistency and accuracy for effective Geographic Information System (GIS) analysis. The second phase entailed geospatial integration using ArcMap 10.5, where the Khartoum administrative shapefile was seamlessly combined with the cleaned data through the Locality ID. This integration enabled detailed spatial analysis by providing precise geographic contexts, which facilitated the creation of comprehensive choropleth maps and the identification of infection hotspots. The final phase involved publishing these spatial models online, allowing users to interactively explore COVID-19 trends across all seven localities via a user-friendly web interface. This interactive platform supported targeted public health responses by providing accessible and detailed spatial insights into the pandemic's distribution.

Ethical considerations

Ethical approval was obtained from the research ethics committee Faculty of Geographical and Environmental Sciences at the University of Khartoum and from Research Department, Ministry of Health in Khartoum state, on 10/9/2020. The purpose and objectives of the research were also explained to the participants in simple and clear words and their right to withdraw from the research whenever they wanted, and to assure the participants the confidentiality of their information and data and their names and identities were not disclosed. The collected information will not be used for any purpose other than the objectives of this study.

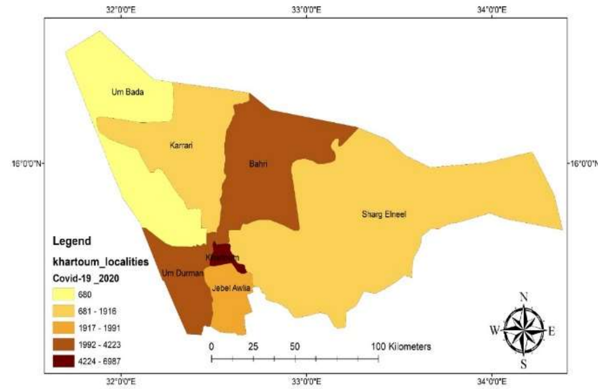

Figure 3: Number of infected people at the first wave 2019/2020

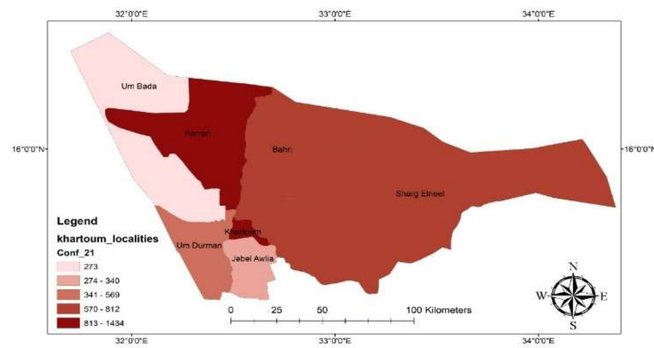

Figure 4: Spreading of COVID-19 in Khartoum State at the second wave (2020/2021)

RESULTS AND DISCUSSION

Diffusion of COVID-19: first wave (2019/20) vs second wave (2020/21)

The analysis underscores the significance of mapping and visualising the spatial diffusion of COVID-19 across the seven localities of Khartoum State during the first (2019/2020) and second (2020/21) waves. It reveals that Khartoum locality experienced the highest number of infections in both waves (Figures 3 & 4), despite its small size. This indicates that virus spread is not dependent on physical size but rather on factors like population density. Khartoum's high infection density, despite its limited area, highlights hotspots that are critical to understanding the spatial dynamics of the pandemic. Research by Abd El-Raheem et al. (2022) further emphasizes that the middle states Khartoum and El Gezira had the highest incidence and mortality rates, linking rising case numbers to urbanization and population movement. Such findings are essential for visualizing how densely populated urban centers can outperform larger rural localities in case counts, thereby informing spatial strategies for intervention.

The relationship between population density and transmission

A critical function of GIS in pandemic management is its capacity to analyse and visualise the spatial diffusion patterns of COVID-19 across multiple waves, particularly during the first (2019/2020) and second (2020/21) phases within the seven localities of Khartoum State. Data shown in (Figure 5) indicates that population distribution alone does not reliably predict infection rates; for instance, Jebel Awlia and Umbada, with populations of 861,967 and 963,900 respectively, did not reflect proportionally high case numbers. While the CDC (2020) highlights close contact (3–6 feet) as the primary transmission mode, GIS analysis suggests that urban factors such as the level of urbanization and the strength of healthcare infrastructure serve as more significant predictors of confirmed cases than population size alone. Khartoum locality, functioning as the urban core, acts as a hub for residents and visitors alike, thereby increasing exposure risk and affecting diffusion patterns. This analysis underscores the pivotal role of GIS in mapping and dissecting the complex spatial dynamics of COVID-19 spread across Khartoum's localities during critical infection waves.

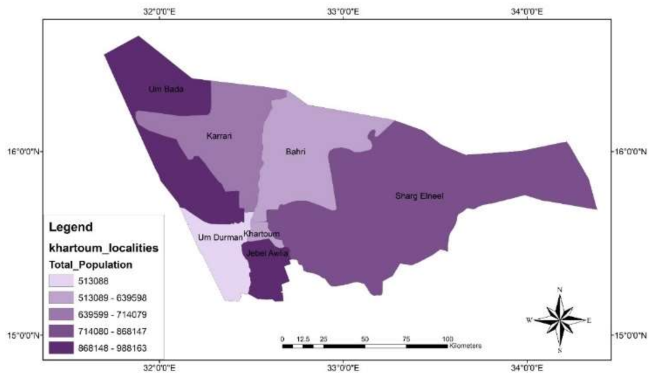

Figure 5: Population Distribution of Khartoum State per locality

Comparison of confirmed cases and local capacity

When comparing confirmed cases to population totals (Figure 6), a remarkable decrease was observed in the second wave.

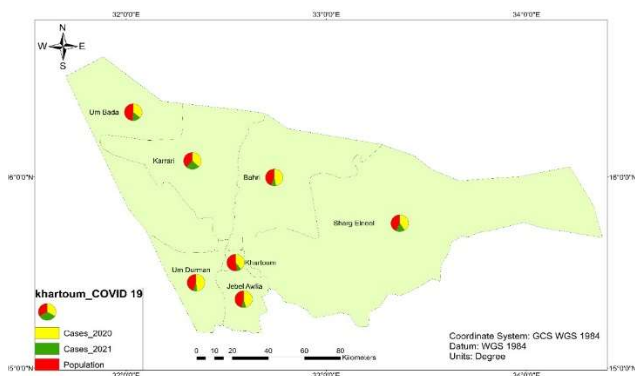

Figure 6: Population and Confirmed Cases in Khartoum State

This reduction is likely due to increased public awareness, reflected in greater adoption of social distancing and masking. Vaccination campaigns coupled with the introduction of COVID-19 vaccines in early 2021.The targeted testing improved PCR facilities at the National Public Health Laboratory (NPHL) and the Military Hospital. In comparison, while Jebel Awlia has a higher population, Omdurman's high infection rate is likely due to its dense, traditional market-driven urban structure, which makes social distancing more difficult than in the more residential Jebel Awlia. The introduction of vaccines in early 2021 was a turning point for Sudan, which was the first country in the Middle East and North Africa to receive vaccines through the COVAX facility (AfDB & WHO, 2025; Babiker, et al., 2025). They confirm that the arrival of the AstraZeneca vaccine in March 2021 targeted high-risk groups and healthcare workers, which statistically correlates with the decline in severe "confirmed" cases during the latter half of the second wave. However, research by Musa et al. (2021) indicates that while COVID-19 fatigue was a risk, there was a measurable increase in masking in formal settings (hospitals, banks) compared to the first wave. The centralisation of testing at the National Public Health Laboratory (Stack) and the Military Hospital in Omdurman/Khartoum created a geographical bias in confirmed cases (Izzoddeen et al., 2024). Many WHO (2021) Sudan situation reports confirm the scale-up of PCR machines in these specific hubs. These facilities were the primary nodes for PCR validation. Mfuh et al. (2021) note that the high "daily-trip" count to Omdurman for trade made social distancing virtually impossible compared to the more spread-out, peri-urban residential areas of Jebel Awlia. The observed decline in confirmed COVID-19 cases during Sudan's second wave can be attributed to the strategic alignment of public health interventions and diagnostic biases by geography. A primary driver was the early 2021 introduction of the AstraZeneca vaccine via the COVAX facility, making Sudan a regional pioneer in the Middle East and North Africa (Babiker et al., 2025). This rollout specifically targeted high-risk populations and healthcare workers, which statistically correlates with a reduction in severe confirmed cases. As public awareness increased, masking in formal settings like banks and hospitals, COVID-19 fatigue, and economic necessity led to varying compliance in informal settings. Furthermore, the concentration of PCR testing facilities at the National Public Health Laboratory (Stack) and the Military Hospital created a significant infrastructure bias. This explains the high infection rates in Omdurman: its dense, market-driven urban structure, centred on the massive Souq Omdurman, necessitated high daily-trip counts, making social distancing practically impossible. In contrast, while Jebel Awlia maintains a high population, its more residential and peri-urban layout, combined with reduced proximity to centralised testing hubs, likely resulted in lower case detection rather than a lower actual viral burden.

Recovery rates and health infrastructure

The data shown in Figures 7 to 10 reveal a clear central-peripheral health disparity in Khartoum State, indicating that observed recovery rates are more reflective of infrastructure distribution than actual healthcare success at the local level. The higher recovery rates in Khartoum are closely associated with its dense and evenly distributed GIS hospital network (Figure 8), establishing it as the main hub for advanced medical services. This pattern aligns with existing research showing that Khartoum has historically hosted most of Sudan's tertiary and teaching hospitals, acting as a healthcare magnet that attracts patients from across the region (Elamin et al., 2024). Conversely, the peripheral districts of Umbada and Sharg Elneel exhibit increased health vulnerability, characterised by high population densities combined with

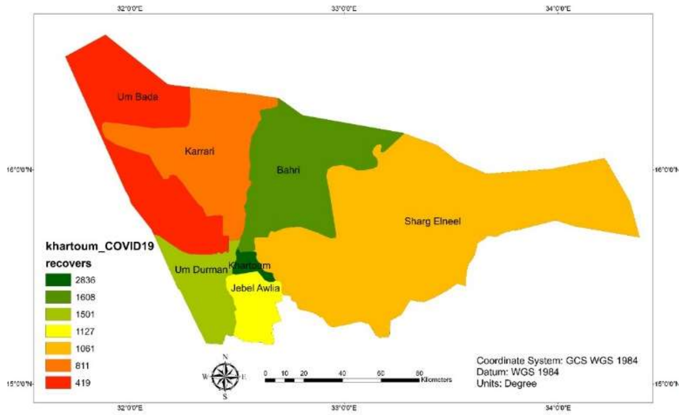

Figure 7: Recovery cases in Khartoum State

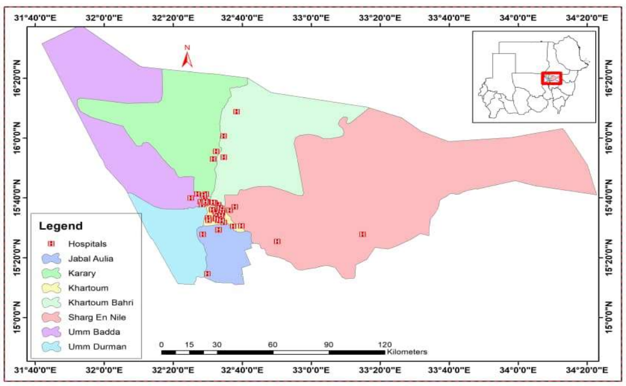

Figure 8: Hospitals Distribution in Khartoum State

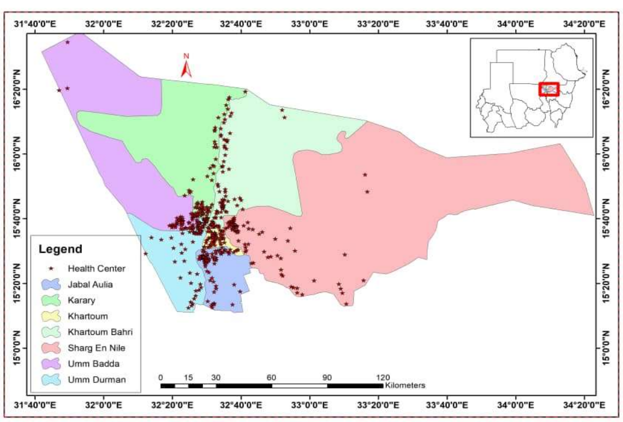

Figure 9: Health Centre Distribution in Khartoum State

limited facilities, which causes systemic reporting biases. Due to their limited capacity to treat complex cases, patients in these areas often bypass local primary centres, seeking care directly at central hospitals where specialist staff and medicines are available (Mohamed Ali, 2007). As a result, recovery data are recorded at central facilities rather than local districts, creating an artificial undercount

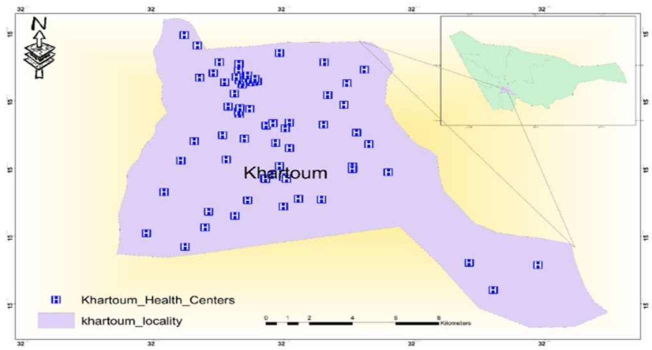

Figure 10: Health centre distribution in Khartoum Locality

of rural health performance. Recent assessments also reveal that this centralised concentration of health resources became a systemic weakness during the 2023–2024 conflict, as the closure of central hospitals left high-population peripheral areas with few alternatives (HSARA, 2025). This spatial imbalance demonstrates that, within the Sudanese context, recovery metrics are heavily influenced by geographic access to tertiary care infrastructure rather than genuine improvements in community health.

Analysis of spatial inequalities and the health-wealth gap in healthcare accessibility

The GIS analysis, combined with longitudinal data, reveals that Khartoum State exhibits a pronounced health-wealth gap, marked by significant spatial disparities in healthcare access. Peripheral areas such as Karari and Jebel Awlia have critically low bed capacities significantly below the national average of 0.8 beds per 1,000 people, as reported by the World Bank (2013). This maldistribution of healthcare resources not only worsens existing inequalities but also impacts health outcomes, emphasizing the need for targeted policy interventions to address these disparities. Evidence indicates that by 2025, approximately 58.5% of public hospitals in Khartoum were either destroyed or non-functional, with remaining operational centres mainly in areas often inaccessible to vulnerable populations in Umbada and Sharg Elneel (HSARA, 2025). These spatial disparities establish geographic health deserts regions with high population density but limited or no medical services. The concentration of healthcare infrastructure in Khartoum not only creates logistical challenges but also exacerbates inequalities by forcing vulnerable populations to undertake risky journeys during crises. Addressing this spatial divide requires strategic redistribution of vital resources, such as isolation centres and PCR laboratories, to underserved regions. Moving beyond logistical fixes toward a decentralized, community-focused approach is essential to close the health-wealth gap, ensure equitable access, and reduce risks associated with geographic health disparities.

Actionable Lessons Learned

Based on the analysis of COVID-19 spatial dynamics in Khartoum State, the following lessons are translated into actionable, policy-oriented, and strategic interventions:

First, there is a need to prioritise density-based risk mapping over total geographic area. The findings indicate that population density and urban concentration exert a stronger influence on infection rates than mere land size. Accordingly, public health surveillance and response efforts should be reoriented toward high-density residential and commercial hotspots rather than applying uniform, city-wide restrictions. The integration of Geographic Information Systems (GIS) is essential for identifying micro-hotspots within districts such as Khartoum and Omdurman, thereby enabling targeted interventions in areas characterised by overcrowding per square kilometre.

Second, micro-targeted public health interventions should be implemented. Evidence suggests that small, densely populated, and underserved localities often present higher transmission risks than larger, sparsely populated rural areas. In response, policymakers should deploy mobile testing units, vaccination centres, and water, sanitation, and hygiene (WASH) resources directly to neighbourhoods identified through GIS as high-risk zones. Reliance on aggregated city-level data should be avoided, as it obscures critical local variations in transmission dynamics.

Third, greater emphasis should be placed on behavioural patterns and mobility rather than solely on population size. The study demonstrates that infection rates are largely driven by socioeconomic activities, patterns of movement, and frequency of interpersonal interactions. Consequently, it is imperative to map, monitor, and regulate high-interaction environments such as informal markets, transportation hubs, and educational institutions. Targeted social distancing measures should be enforced in these high-contact settings instead of imposing blanket residential lockdowns that may disproportionately affect low-mobility populations.

Fourth, adaptive “urban core” response protocols should be established. Dense urban centres have been identified as primary drivers of both morbidity and mortality. Therefore, context-specific “Safe Zone” strategies should be developed for central urban districts, including Khartoum and Bahri. These strategies should incorporate mandatory screening procedures in public transportation systems, alongside tailored risk communication campaigns aimed at promoting behavioural change within these high-risk urban populations.

Fifth, the institutionalisation of real-time GIS and spatial analysis is critical. Spatial mapping transforms epidemiological data into actionable intelligence, facilitating efficient allocation of limited resources. It is recommended that public health authorities produce mandatory weekly spatial analysis reports using tools such as ArcGIS to monitor hotspot infection density. Essential resources, including personal protective equipment, hospital capacity, and vaccines, should be distributed in accordance with the prioritisation of identified hotspots to maximise intervention effectiveness.

Finally, regional mobility networks must be systematically monitored and regulated. The analysis reveals that movement between interconnected regions, such as Khartoum and Jazira, significantly contributes to the spread of infection. As such, surveillance and screening measures should be implemented at key regional transit points, rather than being limited to state borders. Continuous monitoring of commuter and trader movements is necessary, alongside adaptive travel restrictions between high-transmission zones within the broader middle-state region.

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