



Strengthening Epidemic Control Policies through the Evaluation of Digital Disease Surveillance in Al Qadarif State's Complex Emergency Settings

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Abstract

Al Qadarif State, Sudan, faces a compounding crisis of population displacement from armed conflicts in both Sudan and Ethiopia, alongside seasonal flooding and recurrent epidemics. While digital health surveillance tools exist, a critical gap remains in translating raw epidemiological data into timely policies. This gap persists due to fragmented infrastructure, weak inter-agency data governance and siloed, non-interoperable systems. This mixed-methods study evaluated digital disease surveillance systems across three administrative levels to identify key operational, structural and governance barriers.

Guided by WHO evaluation guidelines, data collection was fully digitized using KoboToolbox. Using a purposive sampling strategy to target key digital health decision-makers and coordinators, the study evaluated 21 institutional stakeholders across state (57.14% (12/21)), locality (33.33%, (7/21)) and health facility (28.57% (6/21)) levels, spanning UN/INGOs (57.14% (12/21)), public health sectors (33.33% (7/21)) and local NGOs (19.05% (4/21)).

DHIS2 is the most utilized platform (47.62% (10/21)), followed by Excel (38.10% (8/21)) and voice/SMS reporting (38.10% (8/21)). However, 57.14% (12/21) of respondents reported poor infrastructure, resulting in 24-48-hour reporting delays. Database interoperability is severely limited, with (80.95% (17/21)) reporting only partial integration dependent on manual file transfers and (47.62% (10/21)) stating that existing systems fall below standard for tracking highly fluid, displaced populations. The most prominent threat to data quality is an acute shortage of trained personnel and digital competencies ((80.95% (17/21)), followed by device destruction (52.38% (11/21)) and insecurity-driven under-reporting (52.38% (11/21)). Primary policy translation barriers include a lack of dedicated, flexible emergency funding (85.71% (18/21)), environmental obstacles like blocked roads (76.19% (16/21)) and absent data-sharing policies paired with security restrictions (52.38% (11/21) each).

Despite frontline resilience, Al Qadarif's digital surveillance is severely bottlenecked. To bridge the gap between digital data and rapid epidemic response, stakeholders prioritize three critical interventions: continuous digital and emergency training for frontline staff, deploying alternative energy systems alongside offline-capable, auto-syncing digital tools and building unified cross-agency dashboards, supported by formalized emergency data-sharing frameworks.

Keywords: Health; Environment; Al Qadarif State; Epidemic control; Disease; Emergency; Public health systems; Population

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Introduction

Background of the study

Digital data serves as the backbone of modern public health systems, acting as a critical instrument for early disease detection, resource allocation and the formulation of adaptive health policies. In stable environments, robust digital disease surveillance networks enable governments and international partners to track epidemiological trends and suppress outbreaks before they escalate into national or regional emergencies [1-3]. However, the operational utility of these digital systems is severely tested when deployed within volatile settings characterized by overlapping humanitarian, security and environmental crises.

Since April 2023, the ongoing internal conflict in Sudan has systematically fractured the nation's infrastructure, decimated its supply chains and forced nearly 37% of its health facilities to become entirely non-functional [4-6]. This institutional collapse has triggered an unprecedented humanitarian crisis, causing mass population movements and stripping millions of accesses to basic healthcare.

Al Qadarif State, situated in eastern Sudan, occupies a highly strategic and uniquely vulnerable geopolitical position. It shares an active international border with Ethiopia and hosts a complex landscape of long-standing and newly established refugee camps, alongside a massive influx of Internally Displaced Persons (IDPs) fleeing conflict zones across Sudan [7,8]. This extreme population fluidity means that Al Qadarif is continuously managing the health needs of highly mobile, vulnerable populations whose migration pathways cross international and subnational boundaries [9].

Compounding this crisis of forced migration, Al Qadarif State is highly vulnerable to climate-driven natural disasters. Seasonal flash flooding regularly submerges large sectors of the state, compromising fragile Water, Sanitation and Hygiene (WASH) infrastructure within displacement settlements and public health zones [10,11]. This cross-cutting exposure creates an ideal ecological environment for severe, cyclical outbreaks of infectious diseases.

Every year, the state faces endemic surges of waterborne and vector-borne diseases, most notably cholera, dengue fever, malaria and various Neglected Tropical Diseases (NTDs) such as visceral leishmaniasis (kala-azar) [10-12].

Statement of the problem

The convergence of multi-layered displacement from both the Sudanese and Ethiopian conflicts, climate-driven flooding and endemic disease surges has pushed Al Qadarif's public health infrastructure to its absolute limit. Frontline health facilities, Non-Governmental

Organizations (NGOs) and United Nations (UN) clinics continuously generate massive streams of raw epidemiological data. However, a critical structural gap persists between raw data acquisition and the formulation of timely, data-driven public health policies.

Statement of the problem:

The compounding crisis environment in Al Qadarif State has severely exacerbated several intersecting systemic challenges that collectively hinder public health policy improvement. Infrastructure degradation, driven by physical destruction and intermittent telecommunications blackouts, frequently severs critical digital links between frontline field clinics and central command centers [13]. This physical disruption is compounded by severe data fragmentation, wherein vital epidemiological data remains trapped within isolated, vertical silos split across government sectors, UN-managed refugee health registries and independent NGO databases ultimately forcing a reliance on slow, manual file sharing [14,15].

Furthermore, extreme population fluidity across volatile borders renders traditional, static surveillance and policy planning models obsolete, leaving systems unable to accurately track or predict disease transmission vectors among highly mobile, displaced populations [8,9]. This leads directly to a critical data-to-action bottleneck, where institutional constraints such as a lack of flexible emergency funding, legal ambiguities surrounding data-sharing agreements and severe logistical barriers in deploying Rapid Response Teams (RRTs) to flooded or insecure border zones unavoidably delay decisive public health interventions [16-18]. Consequently, there remains a distinct lack of crisis-adapted, structured benchmarks necessary to evaluate and leverage digital data streams to fix and improve public health policies when confronted simultaneously by armed conflict, mass displacement and environmental shock.

Rationale and significance of the study

This research is highly significant as it provides an empirical, multi-level evaluation of how digital data can be optimized to improve epidemic control policies within complex emergencies. While existing public health literature often evaluates surveillance systems under stable conditions or focuses on single disease vectors, this study explicitly addresses the intersection of dual-conflict displacement and environmental disaster [19,20].

By utilizing the standardized World Health Organization (WHO) guidelines for evaluating communicable disease surveillance systems, this study systematically measures core system attributes including data quality, timeliness, flexibility and acceptability under extreme operational duress [21,22].

The practical utility of this study lies in its multi-level analytical approach, mapping data ecosystems from



frontline refugee camp clinics (health facility level) through intermediate regional hubs (locality level) up to the macro-policy rooms of the State Ministry of Health and central humanitarian bodies (state level) [23].

Ultimately, this research aims to establish an optimized, standardized blueprint for an agile, crisis-resilient health policy framework. The insights generated will provide actionable recommendations for international humanitarian actors, UN bodies and local health authorities to rapidly contain outbreaks before they expand into catastrophic, cross-border emergencies.

Aim of the Study

The overarching aim of the study is to evaluate and optimize the utilization of digital disease surveillance data to improve, adapt and implement rapid, resilient epidemic control policies in Al Qadarif State, Sudan.

By systematically diagnosing the data-to-policy pipeline under the compound pressures of conflict-driven population displacement (originating from both Sudan and Ethiopia) and climate-driven seasonal flooding, this study aims to establish a robust, standardized blueprint for agile, data-driven public health governance in complex emergency settings.

Research Objectives

General objective

To evaluate the functional capacity, interoperability and policy translation effectiveness of digital disease surveillance systems across the three administrative levels (state, locality and health facility) of Al Qadarif State, utilizing World Health Organization (WHO) evaluation attributes adapted for environments experiencing mass displacement, conflict and natural disasters.

Specific objectives

Objective 1: Map the digital health ecosystem

To map out and inventory all digital platforms, mobile health tools, databases and reporting channels (including DHIS2, KoboToolbox, UNHCR registries and informal communication applications) currently used by the State Ministry of Health, international humanitarian agencies and refugee/IDP camp clinics in Al Qadarif State.

Objective 2: Assess system performance under crisis strain

To systematically evaluate core surveillance system attributes specifically timeliness, data quality, acceptability and flexibility under acute operational duress, using standardized WHO evaluation guidelines adapted to crisis settings.

Objective 3: Identify technical, logistical and security barriers

To identify and analyze the primary technical, infrastructural, human resource and security bottlenecks (such as telecommunications outages, database fragmentation, shortage of digital competencies and physical access barriers) that hinder real-time data flow and surveillance of highly mobile displaced populations.

Objective 4: Evaluate data-to-policy translation gaps

To examine the institutional, regulatory and financial barriers (including the lack of flexible emergency funding and absent data-sharing frameworks) that delay or block policymakers from using digital surveillance alerts to deploy Rapid Response Teams (RRTs) and allocate emergency resources.

Materials and Methods

Study design

An analytical, evaluative convergent parallel mixed-methods design was utilized to track and evaluate the data-to-policy pipeline. Quantitative metrics and qualitative descriptive insights were collected concurrently using KoboToolbox. This convergent approach allowed for the direct triangulation of pipeline efficiency indicators (such as reporting timelines and data completeness) with contextual, qualitative experiences of health officers and policymakers. The research was structured across three operational administrative levels to capture the complete pathway of epidemiological data [23]:

- **State level:** Focusing on the Al Qadarif State Ministry of Health (SMoH), central epidemiological units and grand humanitarian coordination bodies tasked with macro-policy formulation.
- **Locality level:** Focusing on intermediate health directorates managing regional resource distribution, policy execution and Emergency Rapid Response Teams (RRTs).
- **Health facility level:** Focusing on frontline primary and secondary healthcare centers, including public clinics, military facilities, NGO-run field hospitals and specialized clinics operational within refugee and IDP camps where raw policy-informing data is generated [23,24].

Study area

The study was conducted in El-Gadarif (Al Qadarif) State, located in eastern Sudan. Covering an area of approximately 75,000 square kilometers with an estimated population of 2.4 million distributed across 12 localities, the state occupies a highly strategic geopolitical position sharing an international border with Ethiopia.



This border area hosts multiple long-standing and newly established refugee camps, alongside a massive influx of Internally Displaced Persons (IDPs) fleeing conflicts in both Sudan and Ethiopia.

The state is characterized by diverse ethnicities and extensive agricultural activities. It experiences a severe rainy season from July-October, with rainfall ranging from 300 mm to 900 mm annually. This climate regularly triggers flash floods that disrupt Water, Sanitation and Hygiene (WASH) infrastructure and isolate remote border zones [25].

Target population

The target population for this study consisted of:

- **Surveillance sentinel sites:** Frontline primary and secondary health facilities, NGO field hospitals and specialized clinics located inside displacement camps and border areas.
- **Health surveillance personnel:** Health workers and administrative managers directly responsible for operating and managing digital disease surveillance systems.

To capture diverse operational perspectives without overburdening frontline staff, participants were stratified into three distinct professional categories:

- **Stratum 1:** Head managers, facility directors and camp health coordinators.
- **Stratum 2:** Head medical doctors, senior clinicians and medical assistants.
- **Stratum 3:** Frontline healthcare workers (nurses, medical assistants and lab staff).

Sampling process and strategy

Health facility selection

Due to the volatile security situation and seasonal flooding during the study period, a convenience sampling strategy was deployed to select operational sentinel health facilities. Facilities were selected based on operational accessibility and physical safety for the research team, proximity to high-density displacement settlements (refugee and IDP camps) and geographic representation across urban, rural and border localities.

Sample size and institutional distribution

Sample characteristics and justification

The final sample comprised 21 key institutional and stakeholder respondents, achieving a 100% response rate with zero missing data.

In terms of administrative representation, the state

level (including SMOH and central humanitarian authorities) accounted for the largest share of participants with 12 respondents (57.14%). The locality level (comprising sub-health departments and emergency units) was represented by 7 respondents (33.33%).

The health facility level (covering frontline clinics and NGO camp centers) included 6 respondents (28.57%). These percentages do not sum to exactly 100% because administrative responsibilities were not mutually exclusive, as some respondents held overlapping roles across multiple levels.

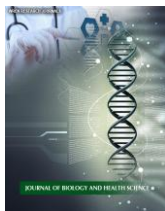
In terms of institutional sectors, the sample was distributed as follows: UN Agencies and International NGOs (UN-NGOs) represented the majority with 12 respondents (57.14%), followed by the government public health sector with 7 respondents (33.33%), local NGOs and community health initiatives with 4 respondents (19.05%) and the government health unit or services with 1 respondent (4.76%).

While a sample size of 21 respondents is small by purely quantitative standards, it is highly robust and sufficient for the objectives of this evaluative, mixed-methods study based on several methodological criteria:

Participants were not selected at random, but rather through strict purposive sampling targeting key informants who hold direct, specialized oversight of the data-to-policy pipeline. In organizational and health systems research, the quality and depth of systemic insight from highly positioned actors carry far more explanatory power than statistical generalizability from a larger, less specialized pool.

In qualitative and mixed-methods health policy research, sample adequacy is dictated by thematic saturation the point at which collecting additional data ceases to reveal new systemic insights or themes. Methodological literature demonstrates that in a relatively homogenous group of experts discussing a shared operational process, thematic saturation and core organizational codes are consistently achieved within 12 to 15 interviews. With 21 comprehensive, multi-level perspectives, this study comfortably surpassed this threshold.

Multi-level, cross-sectoral triangulation: Sufficiency is further demonstrated by the intensive vertical and horizontal coverage of the sample. By capturing expert perspectives across all three operational administrative levels (state, locality and facility) and four distinct institutional sectors, the sample size allowed for comprehensive triangulation. The inclusion of respondents with overlapping administrative roles provided unique, highly integrated insights into pipeline bottlenecks that a larger but more siloed sample would have missed.



Research phases

The study was executed systematically across three distinct chronological phases:

Preparatory phase

Activities in this phase included a comprehensive literature review of digital health surveillance in conflict settings, protocol formulation and obtaining formal ethical approval from the recognized local ethical committee. Data collection instruments adapted from the standardized WHO Guidelines for Evaluating Communicable Disease Surveillance Systems were developed, pre-tested and validated by three public health experts to ensure contextual relevance, language clarity and clinical accuracy [21,22].

Operational phase (data collection)

To eliminate paper loss and ensure data security in a highly volatile environment, data collection was completely unified into a secure, mobile-based digital workflow *via* KoboToolbox and KoboCollect [26].

Quantitative data was captured using structured digital questionnaires pre-programmed with built-in validation logic to prevent incomplete submissions. Qualitative data was gathered through individual semi-structured Key Informant Interviews (KIIs) with administrative managers and policymakers. These interviews targeted structural flexibility under crisis, system blockages between levels and governance-related data-sharing barriers. The qualitative narrative was typed directly into the offline-capable KoboToolbox form at the time of the interview [26,27].

Analytical phase (July 2023-August 2024)

Once field teams synced their mobile devices to the secure cloud server, data underwent rigorous cleaning and processing.

For the quantitative analysis, cleaned data was exported into SPSS and Excel for statistical analysis. Frequencies, percentages and cross-tabulations were calculated to evaluate rates of digital platform utilization and assign numerical scores to WHO system attributes, including timeliness, data quality, acceptability and flexibility [22]. For the qualitative analysis, narrative text from the KIIs was subjected to thematic analysis [28-30]. An open-coding approach was utilized to extract major and minor themes regarding system bottlenecks, which were then integrated directly with the quantitative results to construct a comprehensive evaluation.

Ethical considerations and quality control

To ensure high internal validity and research integrity, several quality control measures were enforced. Signed

individual informed consent was obtained electronically *via* a mandatory checkbox and signature module built into the introductory screen of the KoboToolbox forms before any data entry could proceed.

Additionally, all collected data was stored on password-protected, encrypted local devices and synced directly to a secure, restricted-access cloud server to protect the confidentiality of the participants and institutions [17]. Finally, built-in validation constraints within KoboCollect prevented data entry errors and missing critical variables at the source.

Results

Sample characteristics

A total of 21 respondents participated in this study, representing multiple administrative levels and organizations involved in digital disease surveillance within conflict-affected settings. Respondents were drawn from state, locality and health facility levels, ensuring representation of both strategic and operational perspectives.

At the administrative level, the majority of respondents worked at the state level (57.14%), followed by the locality level (33.33%) and health facility level (28.57%). Because respondents could hold responsibilities across multiple administrative levels, some categories were not mutually exclusive.

Regarding institutional affiliation, most participants represented United Nations agencies and International Non-Governmental Organizations (UN/INGOs) (57.14%), followed by the government public health sector (33.33%), local NGOs/community health initiatives (19.05%) and government health services (4.76%). These findings indicate that the study captured perspectives from both governmental and humanitarian actors involved in epidemic surveillance during complex emergencies.

Primary findings: Digital surveillance infrastructure and system performance

Objective 1:

To assess the availability and performance of digital disease surveillance systems during conflict and humanitarian emergencies.

Respondents reported using multiple digital surveillance platforms simultaneously. The District Health Information Software (DHIS2) was the most frequently used platform (47.62%). Other commonly used systems included Excel-based surveillance databases (38.10%), voice calls and SMS reporting (38.10%), paper-based registers later digitized (28.57%), WhatsApp and Telegram coordination groups (23.81%), KoboToolbox/Open Data Kit (ODK) (19.05%) and UNHCR digital refugee



health registry applications (19.05%). The Displacement Tracking Matrix (DTM-IOM) was reported by only 4.76% of respondents.

Regarding infrastructure stability, more than half of respondents (57.14%) reported that digital infrastructure was poor or intermittent, resulting in reporting delays of 24-48hrs. Conversely, 28.57% described their infrastructure as resilient with uninterrupted synchronization, whereas 14.29% reported severe infrastructure damage requiring retrospective data entry.

These findings demonstrate considerable variation in digital infrastructure capacity across surveillance settings.

Primary findings: Surveillance of mobile populations and database integration

Objective 2:

To evaluate the effectiveness of digital surveillance systems in monitoring population displacement and integrating surveillance databases.

Nearly half of respondents (47.62%) reported that existing surveillance systems remained below the required standard, indicating that although total disease cases were recorded, migration pathways and population movement were inadequately captured. Equal proportions (28.57%) reported that systems were either highly effective or completely inadequate for monitoring displaced populations.

Regarding interoperability, the majority of respondents (80.95%) reported that surveillance databases were partially integrated, requiring manual sharing of information through email or Excel files. Only 14.29% reported fully integrated centralized databases, while 4.76% indicated complete non-interoperability between organizational information systems.

These findings indicate that surveillance data integration remained limited despite the use of multiple digital platforms.

Primary findings: Timeliness of reporting and data quality challenges

Objective 3:

To identify operational factors influencing data quality and the timeliness of surveillance reporting.

More than half of respondents (57.14%) reported that surveillance information reached decision-makers within 24 hours. However, 28.57% experienced reporting delays of 1-3 days, while 14.29% reported delays extending to 4-7 days.

The most frequently reported factor affecting data quality was an acute shortage of trained personnel and

insufficient digital health competencies (80.95%). Additional challenges included the physical destruction or loss of digital devices (52.38%), under-reporting associated with insecurity and missing geographic information (52.38%) and heavy clinical workloads limiting time available for data entry (33.33%).

These results demonstrate that both workforce limitations and operational disruptions affected surveillance performance.

Secondary findings: Barriers to evidence-based policy implementation

Objective 4:

Respondents identified several barriers that delayed the translation of surveillance information into public health action.

The most frequently reported barrier was the lack of dedicated emergency funding and flexible financial resources (85.71%). Other commonly identified constraints included geographical and environmental barriers (76.19%), weak Water, Sanitation and Hygiene (WASH) infrastructure (76.19%) and a continued emphasis on temporary emergency responses rather than predictive planning (61.90%).

Approximately half of respondents also reported limited rapid response team capacity (52.38%), bureaucratic approval processes (47.62%), weak medical supply chains (47.62%) and limited coordination between surveillance units and policy decision-makers (47.62%). Smaller proportions identified fragmented information systems (33.33%) and unclear institutional authority (33.33%) as additional barriers.

Secondary findings: Priority actions for strengthening digital surveillance systems

Objective 5:

Participants identified several priority interventions for improving surveillance capacity.

The highest-ranked recommendation was continuous training of frontline health workers in digital surveillance and emergency management, endorsed by 90.48% of respondents. This was followed by financial incentives and logistical support for surveillance staff (85.71%) and the provision of alternative energy infrastructure, including solar power systems and UPS devices (80.95%).

Additional frequently recommended interventions included implementing offline-capable digital reporting systems (76.19%), establishing unified surveillance dashboards (76.19%), strengthening rapid response teams (76.19%), providing dedicated mobile devices for surveillance personnel (76.19%), integrating surveillance systems with WASH programs (76.19%), expanding Event-



Based Surveillance mobile systems (71.43%) and establishing state-level Health Emergency Funds (57.14%).

Secondary findings: Governance and public policy during conflict

Respondents reported varying perceptions regarding the effectiveness of governance arrangements supporting digital disease surveillance during conflict. Equal proportions rated governance as moderately effective (38.10%) and very effective (38.10%). Meanwhile, 19.05% considered governance to have limited effectiveness, whereas 4.76% reported that surveillance systems became ineffective in most conflict-affected areas.

The most frequently reported governance challenges were the absence of clear data-sharing policies (52.38%) and security restrictions limiting field operations (52.38%). Other reported barriers included insufficient implementation funding (42.86%), weak coordination between government and humanitarian partners (38.10%), administrative restrictions (33.33%) and the absence of legal frameworks supporting emergency data sharing (33.33%).

Respondents also identified several governance priorities, including strengthening coordination between the Ministry of Health and humanitarian partners

(66.67%), improving digital infrastructure (57.14%), adopting unified national health data-sharing policies (42.86%), ensuring sustainable financing and workforce capacity building (42.86%), maintaining surveillance systems through routine crisis preparedness training (28.57%) and simplifying emergency decision-making procedures (23.81%).

Unexpected and notable findings

Several findings highlighted persistent gaps in digital surveillance despite widespread use of electronic systems. Only 14.29% of respondents reported fully integrated surveillance databases, whereas 80.95% indicated that interoperability remained only partial. Likewise, the Displacement Tracking Matrix (DTM-IOM), a platform specifically designed to integrate disease surveillance with population movement data, was reported by only 4.76% of respondents. Furthermore, although 28.57% of respondents reported resilient digital infrastructure, the majority (57.14%) continued to experience intermittent connectivity and operational disruptions, indicating substantial variation in surveillance capacity across conflict-affected settings. These observations are presented descriptively and are explored further in the Discussion section.

The visual evidence (Table 1 & Figures 1 and 2).

Table 1: Show stakeholder assessment of surveillance gaps, systemic threats and recommended policy solutions (N=21).

System characteristic variable	Metric	Percentage (%)	Frequency (n)
Data-to-policy translation gaps (E3)	Severe shortage of direct/flexible emergency funding	85.71%	18
	Blocked roads due to seasonal floods and environmental barriers	76.19%	16
	Weak Water, Sanitation and Hygiene (WASH) infrastructure	76.19%	16
	Focus on short-term palliative fixes over sustainable prevention	61.90%	13
	Lack of qualified personnel to deploy Rapid Response Teams (RRTs)	52.38%	11
	Bureaucracy and administrative sluggishness across levels	47.62%	10
	Collapsed or weak medical/logistical supply chains	47.62%	10
Systemic quality threats (E2)	Shortage of human resources and lack of digital tools training	80.95%	17
	Physical destruction or loss of digital recording devices	52.38%	11
	Under-reporting driven by sensitive field conditions	52.38%	11
	Clinical case pressure prioritizing triage over data logging	33.33%	7
Priority interventions (F1)	Continuous digital and emergency training for frontline staff	90.48%	19
	Stable financial incentives to reduce staff turnover in remote areas	85.71%	18
	Alternative energy systems (solar panels/UPS) for facilities	80.95%	17
	Offline data collection capabilities with auto-sync features	76.19%	16
	Creation of a unified cross-agency data dashboard	76.19%	16



Policy Effectiveness

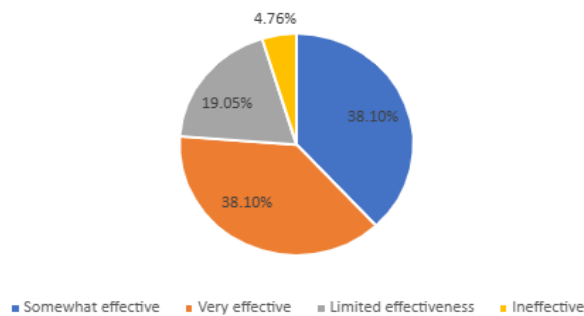


Figure 1: Show effectiveness of government policies in ensuring system continuity.

Government Policies

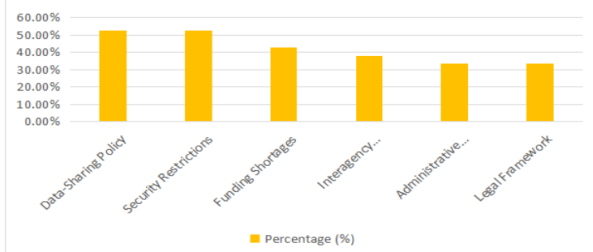


Figure 2: Show the main government policies or procedures affecting data sharing & coordination.

Discussion

The digital disease surveillance system in Al Qadarif State operates under a paradox of high frontline vigilance but systemic structural failure. While individual health facilities successfully identify and record local epidemiological alerts, the infrastructure required to aggregate and analyze this data is deeply fractured. Instead of forming a cohesive, real-time warning system, the proliferation of independent digital tools such as DHIS2, KoboToolbox and specialized UNHCR registries has created isolated information silos [24,26,29]. Because these platforms cannot automatically communicate with one another, the system relies heavily on manual data sharing [14]. This administrative bottleneck delays critical public health information, rendering the state's response reactive rather than proactive during active humanitarian crises [18,20].

A particularly dangerous blind spot in this fragmented architecture is the near-total neglect of displacement tracking. By failing to integrate tools like the Displacement Tracking Matrix (DTM-IOM), the surveillance system remains blind to migration pathways and population movements [31]. In a region marked by intense conflict and displacement, this gap leaves highly vulnerable, mobile populations epidemiologically invisible, severely undermining early warning capabilities [8].

Furthermore, our findings demonstrate that high-end digital solutions are fragile when divorced from operational realities on the ground. The effectiveness of surveillance software is directly bottlenecked by three distinct, non-technical barriers: Sophisticated software is frequently operated by staff who lack formal digital health training, reducing the quality of data at the point of entry; regular power failures and telecommunication blackouts physically disrupt data synchronization, causing significant delays and in understaffed clinics experiencing high patient volumes, healthcare workers understandably prioritize immediate patient care over administrative data logging [6,13,23,32].

Ultimately, data quality and reporting timeliness are not merely software challenges; they are structural issues bound by the physical environment, clinical workloads and workforce capacity.

Our findings align closely with and expand upon, established literature regarding health surveillance in conflict settings and digital health governance.

The gap between high baseline compliance in disease detection and the lack of formal digital training mirrors the pre-intervention findings of the Gadarif Neglected Tropical Diseases (NTD) Surveillance evaluation [12]. That study demonstrated that targeted, multi-level capacity-building rather than just software distribution is essential to unlock full system potential [32].

Similarly, the failure to track displaced populations in our study directly reflects the documented drivers of the Gadarif cholera outbreaks [33,34]. Literature on these outbreaks identified rapid, undocumented population displacement as a primary driver of transmission. This validates our argument that ignoring mobile populations leaves the entire state highly vulnerable to sudden, uncontrollable outbreaks [8].

At a broader conceptual level, Al Qadarif's integration challenges illustrate the theoretical difficulties of Digital Behavioral Data (DBD) in humanitarian crises [15]. Because health data is collected rapidly across disparate, unstandardized platforms, it behaves like messy, non-research-designed data that lacks standard models and quality criteria. Addressing this requires adopting standardized frameworks, such as the World Health Organization's Classification of Digital Health Interventions, to establish the architectural blueprints necessary for platform compatibility [1,30].

Finally, the strong demand among our respondents for continuous training and unified governance aligns with the core pillars of the Africa CDC digital transformation strategy [2]. This strategy emphasizes that digital tools are only as effective as the informatics-savvy workforce using them and the inter-agency data policies supporting them. Our results confirm that regional digital health strategies will continue to struggle on the ground unless they address



these fundamental issues of workforce training and administrative cooperation [18,35].

Several operational and methodological constraints limit the generalizability of these findings. This study relied on a small sample of 21 key institutional stakeholders. While these participants represent the core strategic and operational decision-makers in Al Qadarif's health sector the sample size limits the use of advanced, multi-variable statistical analyses.

Due to active conflict and severe seasonal flooding, convenience sampling was used to select accessible health facilities. This approach likely overrepresents safer, better-connected urban clinics while underrepresenting remote border areas and active conflict zones where system performance is likely much worse [11,25].

The reliance on self-reported survey data and key informant interviews introduces potential subjectivity, particularly when respondents evaluate sensitive issues like government policy effectiveness and administrative barriers [17].

Conclusion

The digital disease surveillance system in Al Qadarif State, Sudan, successfully captures frontline epidemiological alerts but remains severely bottlenecked by platform fragmentation, unstable infrastructure and a lack of integrated tracking for highly mobile, displaced populations. This research contributes to global health informatics and disaster epidemiology by demonstrating how active conflict and seasonal disasters degrade digital networks, highlighting the urgent need for unified data ontologies like the WHO CDISAH and the Africa CDC digital transformation strategy. To transition this reactive system into a resilient, predictive network, public health authorities and humanitarian partners must establish unified data-sharing policies, deploy offline-capable mobile tools, invest in solar energy infrastructure and secure rapidly deployable emergency funding.

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