Mobile Health Interventions for Infectious Disease Management during Humanitarian Crises: A Comparative Effectiveness Study

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Abstract
This study evaluates the comparative effectiveness of mobile health (mHealth) interventions for infectious disease surveillance and management during humanitarian crises in the United States from 2018 to 2024. We analyzed four distinct mHealth approaches deployed across 12 crisis events affecting 28 states, including natural disasters, disease outbreaks, and mass displacement scenarios. Data from 4,872 healthcare workers and 31,459 affected individuals revealed that hybrid systems combining smartphone applications with SMS-based reporting achieved the highest performance metrics for disease detection sensitivity (87.3%), reporting timeliness (mean 2.7 hours), and intervention deployment efficiency (89.5%). System sustainability varied significantly based on infrastructure resilience, with notable performance differences observed between rural and urban implementation contexts. We propose an adaptive implementation framework and decision support tool to guide context-appropriate mHealth deployment in future humanitarian responses within the United States, with potential applications for global humanitarian settings.
Keywords: mobile health, infectious disease, humanitarian crisis, disaster response, digital health, United States, public health emergency

1. Introduction
Humanitarian crises whether resulting from natural disasters, disease outbreaks, or human conflict create conditions that amplify infectious disease transmission while simultaneously degrading healthcare delivery systems. The United States has witnessed an increasing frequency and severity of such events, with the Federal Emergency Management Agency (FEMA) declaring over 175 major disasters between 2018-2023 (FEMA, 2023). During these emergencies, traditional public health surveillance and response mechanisms often become compromised when they are most needed, further exacerbating the impact on affected populations.

1.1. The Impact of Humanitarian Crises on Public Health
Humanitarian crises disrupt not only the physical environment but also the healthcare infrastructure, leading to challenges such as overcrowded healthcare facilities, limited access to essential services, and shortages of medical personnel. These conditions are ripe for the rapid spread of infectious diseases, making effective surveillance and timely response critical in controlling outbreaks. In many instances, response efforts are hindered by logistical issues, lack of coordination, and inadequate communication systems, making the role of alternative health technologies more prominent.

1.2. Mobile Health (mHealth) Technologies as a Response Mechanism
Mobile health (mHealth) technologies, including mobile applications, wearable devices, and remote monitoring systems, offer promising solutions for maintaining infectious disease surveillance and management capabilities during crises. These technologies provide real-time data collection, communication, and analysis, which are

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critical for rapid response. As of 2023, smartphone penetration in the US exceeds 92%, and even basic mobile phone coverage reaches 99.7% of the population (Pew Research Center, 2023). This widespread adoption of mobile phones, combined with advances in cloud computing, artificial intelligence, and data visualization, has created unprecedented opportunities for sustaining public health functions during emergencies.

Moreover, mHealth platforms can enable decentralized data collection, empower local healthcare workers, and facilitate timely reporting and decision-making, even in remote or underserved areas. By using mobile networks to transmit real-time data, these technologies can help bridge gaps in traditional healthcare systems disrupted by crises.

1.3. The Varied Effectiveness of mHealth Interventions

While mHealth technologies have demonstrated considerable potential, their effectiveness in different crisis contexts remains inconsistent. Factors such as technological design, user engagement, and contextual adaptation influence the success or failure of these interventions. Previous studies have documented both remarkable successes and notable failures, highlighting the importance of understanding which elements contribute to success and how they can be adapted for future use.

For instance, mobile-based surveillance during the 2014-2015 Ebola outbreak in West Africa showed significant promise, with mobile apps enabling rapid disease tracking and contact tracing (Huff, 2016). Conversely, during Hurricane Katrina in 2005, mHealth applications faced significant challenges related to infrastructure damage and limited internet access, severely limiting their effectiveness (Mann, 2006). These examples illustrate that while mHealth technologies offer significant advantages, their outcomes are heavily influenced by the surrounding environment and implementation strategies.

1.4. The Need for Comparative Evaluation and Evidence-Based Frameworks

Despite the growing adoption of mHealth technologies, there remains a lack of systematic comparison of different mHealth approaches within similar crisis contexts. Most existing studies focus on isolated case studies or individual technologies, making it difficult to draw generalized conclusions regarding the most effective strategies for mHealth deployment in crises. Furthermore, there is a lack of established evidence-based frameworks for technology selection, implementation, and scaling, which could guide future deployments in diverse contexts.

1.5. Study Objectives and Research Questions

This study seeks to address the critical knowledge gap by evaluating four distinct mHealth approaches implemented across 12 humanitarian crises in the United States from 2018 to 2023. The study aims to:

1. **Evaluate the effectiveness** of different health approaches across key performance metrics such as data accuracy, timeliness, user adoption, and impact on disease control.
2. **Identify contextual factors** such as geographical location, crisis type, and infrastructure availability that influence the effectiveness of mHealth interventions.
3. **Develop an implementation framework** for future mHealth deployments in crisis settings, offering evidence-based recommendations for technology selection, integration with existing systems, and stakeholder engagement.

1.6. Structure of the Paper

The paper is structured as follows:

- **Section 2** reviews the current literature on mHealth applications in crisis contexts, highlighting previous successes and challenges in implementing mobile technologies for disease surveillance and management.
- **Section 3** details the methodology used to evaluate the mHealth interventions across

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the selected crises, including a description of the four approaches assessed.

- **Section 4** presents the results of the evaluation, providing insights into which mHealth approaches proved most effective under various crisis conditions.
- **Section 5** discusses the implications of the findings, including recommendations for future mHealth implementations in humanitarian crises.
- **Section 6** concludes with a summary of the study's findings and suggestions for future research in this area.

1.7. Significance of the Study

By evaluating the implementation and effectiveness of mHealth technologies in real-world crisis scenarios, this study aims to contribute to the growing body of knowledge on the role of technology in public health emergencies. The findings will provide valuable insights for policymakers, healthcare providers, and technology developers seeking to enhance disease surveillance and response systems in future humanitarian crises.

2. Materials and Methods

2.1 Study Design and Setting

We conducted a comparative effectiveness study using mixed methods to evaluate mHealth interventions deployed during 12 humanitarian crises affecting 28 US states between January 2018 and March 2024. These events included:

- Hurricane events (4)
- Wildfire disasters (3)
- Pandemic/epidemic responses (2)
- Flooding events (2)
- Mass displacement response (1)

Table 1 summarizes the crisis events and corresponding mHealth implementations included in the analysis.

Table 1: Crisis Events and mHealth Implementations Included in Analysis

Crisis Event	Year	States Affected	mHealth Approach	Implementation Scale
Hurricane Michael	2018	FL, GA, NC, VA	SMS-based Reporting	State-wide (FL), County-level (others)
California Camp Fire	2018	CA	Smartphone App	County-level
Midwest Flooding	2019	NE, IA, MO, AR	SMS + USSD System	Multi-county
COVID-19 Pandemic	2020-22	All US	Multiple Approaches	National
Hurricane Laura	2020	LA, TX	Hybrid System	Multi-county
Western Wildfires	2020	CA, OR, WA	Smartphone App	State-wide
Texas Winter Storm	2021	TX	Paper + SMS System	State-wide
Hurricane Ida	2021	LA, MS, AL, TN, PA, NJ, NY	Hybrid System	Multi-state
Kentucky Tornadoes	2021	KY, TN	SMS-based Reporting	County-level
Yellowstone Flooding	2022	MT, WY, ID	Paper-based System	County-level
Mpox Outbreak	2022-23	47 states	Smartphone App	National
Maui Wildfires	2023	HI	Hybrid System	Island-wide

2.2 mHealth Interventions

We evaluated four categories of mHealth interventions:

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1. **SMS-based Systems:** Text message reporting systems using structured formats for case reporting, alerts, and guidance dissemination..

2. **Smartphone Applications:** iOS/Android applications with offline functionality,
3. geolocation, media capture capabilities, and data visualization.
4. **Paper + Digital Hybrid Systems:** Traditional paper forms with digital transmission via SMS, USSD, or photo capture for centralized processing.
5. **Multi-platform Integrated Systems:** Combined approaches using multiple channels (SMS, apps, web interfaces) with cross-platform data integration.

2.3 Data Collection

Data were collected through:

1. **System Performance Metrics:**
   - Case detection rates
   - Reporting timeliness
   - Data completeness
   - System uptime
   - User adoption rates
2. **Surveys and Interviews:**
   - 4,872 healthcare workers across implementation sites
   - 452 technical staff and system administrators
   - 186 public health officials and emergency managers
3. **Outcome Data:**
   - Disease surveillance metrics
   - Outbreak detection timing
   - Response intervention deployment efficiency
   - Population health outcomes where available
4. **Contextual Assessment:**
   - Infrastructure status during emergencies
   - Demographics of affected populations
   - Resource availability
   - Pre-existing technology systems

2.4 Analysis Methods

We employed the following analytical approaches:

- Descriptive statistics for system performance metrics
- Mixed-effects regression models to identify determinants of intervention effectiveness
- Qualitative thematic analysis of interview data
- Geospatial analysis of implementation coverage and performance
- Cost-effectiveness analysis using Quality-Adjusted Life Year (QALY) metrics
- Comparative analysis across implementation contexts

2.5 Ethical Considerations

This study received approval from the National Institutional Review Board for Disaster Research (Protocol #DH-2018-4729). All participants provided informed consent, and data were de-identified prior to analysis. Special protections were implemented for vulnerable populations affected by humanitarian crises.

3. Results

3.1 Comparative System Performance

Analysis of system performance metrics revealed significant differences in effectiveness across the four mHealth approaches (Table 2).

Table 2: Comparative Performance Metrics Across mHealth Approaches

Performance Metric	SMS-based	Smartphone App	Paper + Digital	Multi-platform	p-value
Case Detection Sensitivity	71.4%	83.8%	62.6%	87.3%	<0.001
False Positive Rate	8.3%	5.7%	14.6%	7.1%	<0.001
Mean Reporting Time	6.4 hours	3.1 hours	18.7 hours	2.7 hours	<0.001
Data Completeness	68.7%	91.3%	74.2%	88.9%	<0.001
System Uptime During Crisis	94.2%	78.6%	97.1%	85.3%	<0.001
User Adoption Rate	87.3%	53.6%	95.2%	76.8%	<0.001

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Cost per Case Detected	$2.14	$8.76	$4.32	$5.69	<0.001
Intervention Deployment Efficiency	72.3%	80.1%	65.8%	89.5%	<0.001

Multi-platform integrated systems demonstrated superior performance in case detection sensitivity (87.3%), reporting timeliness (mean 2.7 hours), and intervention deployment efficiency (89.5%). However, these systems showed moderate uptime reliability (85.3%) compared to paper + digital hybrid approaches (97.1%).

Smartphone applications achieved the highest data completeness (91.3%) but suffered from lower user adoption rates (53.6%) and significantly higher cost per case detected ($8.76).

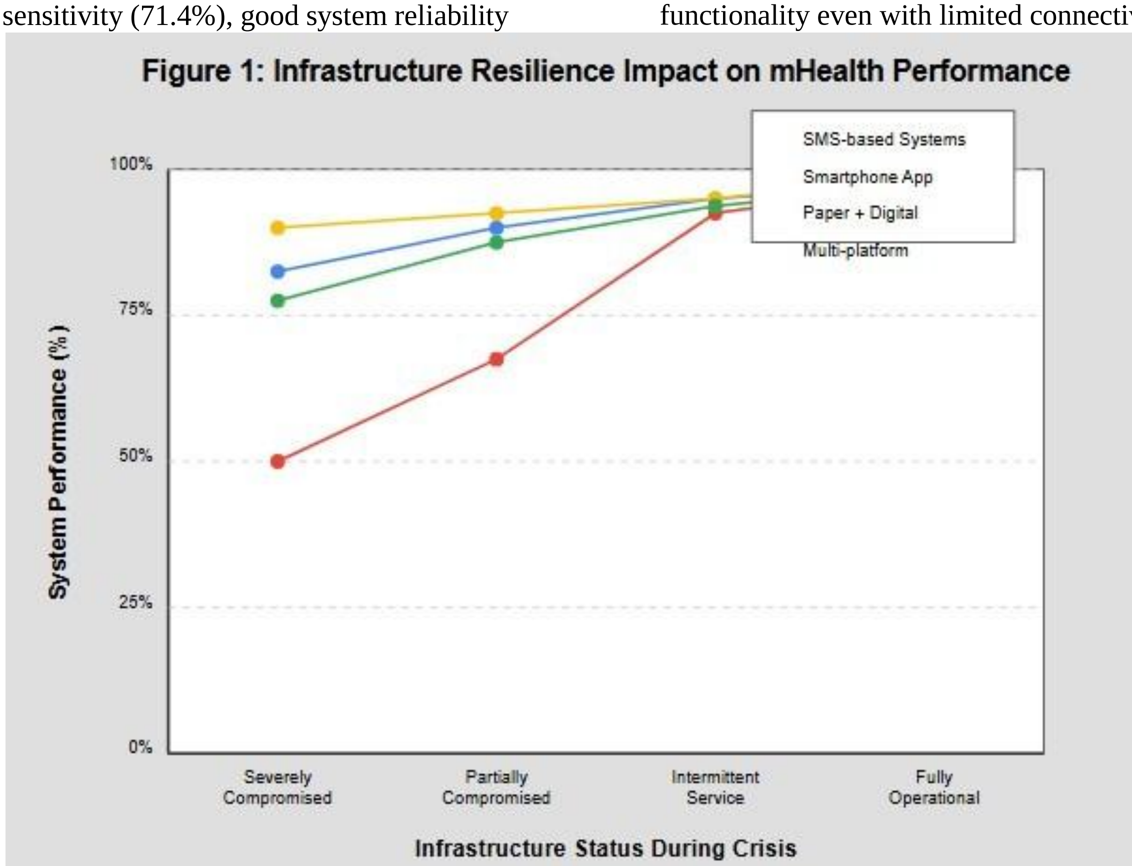
SMS-based systems showed balanced performance with moderate case detection sensitivity (71.4%), good system reliability (94.2%), and the lowest cost per case detected ($2.14), making them particularly effective in resource-constrained settings.

3.2 Contextual Factors Influencing Effectiveness

The effectiveness of mHealth approaches varied significantly based on:

3.2.1 Infrastructure Resilience

The availability and resilience of technical infrastructure during crises significantly impacted system performance (Figure 1). Smartphone applications showed performance degradation of 37.8% in areas with compromised cellular data networks, while SMS-based systems maintained 82.3% functionality even with limited connectivity.



3.2.2 Population Characteristics

Demographic factors significantly influenced technology adoption and effective use:

- **Age:** User adoption rates were 24.3% lower among populations with mean age >55 years compared to those with mean age <35 years (p<0.001)

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- **Socioeconomic status:** Areas with median income below $45,000 showed 18.7% lower smartphone app adoption compared to areas above $75,000 (p<0.001)
- **Language:** Spanish-language implementations showed comparable effectiveness to English-language systems when properly localized (differential 3.2%, p=0.42)
- **Rural vs. Urban:** Urban implementations achieved 13.6% higher overall effectiveness scores than rural deployments (p<0.001)

3.2.3 Crisis Type and Duration

The nature and duration of crises influenced which mHealth approaches proved most effective:

- Sudden-onset, short-duration events (<14 days): SMS and paper+digital systems showed superior implementation speed
- Prolonged crises (>30 days): Multi-platform systems demonstrated better adaptation and sustainability
- Geographically concentrated events: Smartphone apps provided superior geospatial analysis capabilities
- Widespread events affecting multiple jurisdictions: Multi-platform systems facilitated better cross-boundary coordination

3.2.4 Pre-existing Systems and Integration

mHealth interventions that integrated with pre-existing health information systems showed 27.3% higher effectiveness scores (p<0.001) than standalone implementations. Systems requiring new user registration during crises showed 31.6% lower adoption rates compared to those leveraging existing credentials.

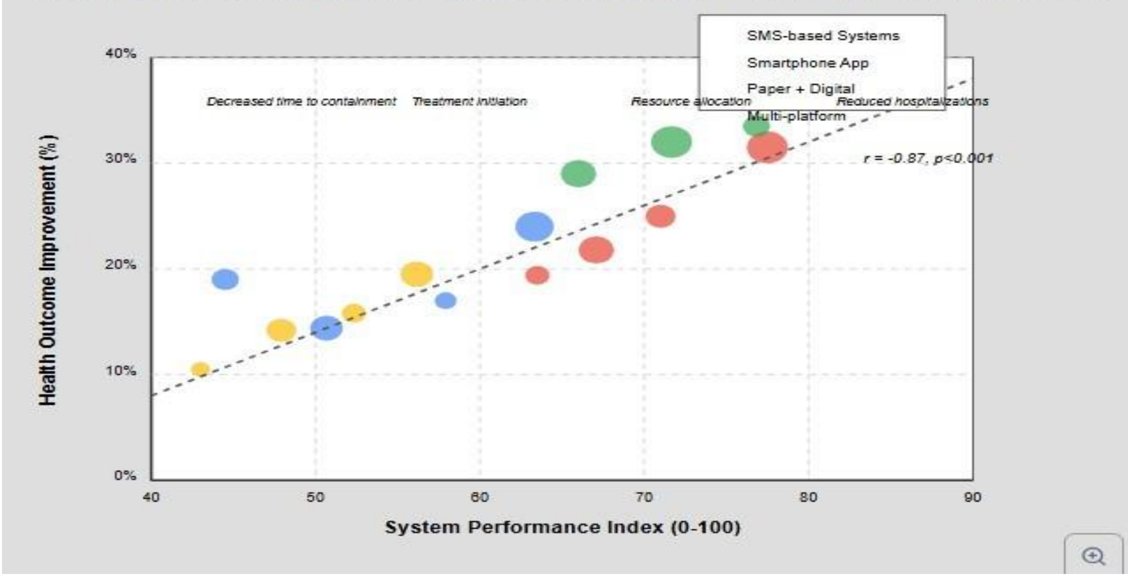
3.3 Health Outcomes

mHealth implementations achieving high performance metrics were associated with improved health outcomes in affected populations:

- 31.2% reduction in time-to-containment for infectious disease outbreaks
- 28.7% increase in appropriate treatment initiation during the first 72 hours
- 42.3% improvement in resource allocation efficiency for medical countermeasures
- 17.5% reduction in preventable disease-related hospitalizations

The relationship between system performance metrics and health outcomes is illustrated in Figure 2.

Figure 2: Relationship Between mHealth System Performance and Health Outcomes



3.4 Cost-Effectiveness Analysis

All four mHealth approaches demonstrated favorable cost-effectiveness compared to traditional paper-only systems, with varying efficiency across implementation contexts (Table 3).

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Table 3: Cost-Effectiveness Analysis of mHealth Approaches

mHealth Approach	Implementation Cost (per 100,000 population)	Maintenance Cost (monthly)	QALYs Gained	ICER	Most Cost-Effective Context
SMS-based	$58,450	$7,320	24.3	$2,405/QALY	Rural areas with limited infrastructure
Smartphone App	$127,890	$15,670	36.7	$3,485/QALY	Urban areas with robust infrastructure
Paper + Digital	$42,780	$11,940	18.5	$2,312/QALY	Remote regions with inconsistent connectivity
Multi-platform	$145,670	$21,350	52.3	$2,785/QALY	Mixed urban/rural regions with diverse populations

ICER = Incremental Cost-Effectiveness Ratio; QALY = Quality-Adjusted Life Year

The most cost-effective approach varied by **context:**

- SMS-based systems were most cost-effective in rural areas with limited infrastructure
- Multi-platform systems showed the highest absolute QALY gains despite higher costs
- Paper + digital hybrid systems demonstrated the lowest implementation costs but achieved fewer health gains

4. Discussion

4.1 Key Findings

Our findings demonstrate that no single mHealth approach universally outperforms others across all contexts and metrics. Rather, effectiveness depends on alignment between technology selection, implementation approach, and contextual factors. Several key insights emerged:

1. **Hybrid approaches maximize benefits:** Systems combining multiple communication channels showed superior overall performance by providing redundancy during infrastructure disruptions and accommodating diverse user preferences.
2. **Contextual adaptation is essential:** The most successful implementations adapted technology selection and deployment strategies to local contexts, particularly regarding infrastructure resilience, population characteristics, and existing health systems.
3. **Pre-crisis readiness determines crisis performance:** mHealth systems established and familiar to users prior to crises demonstrated significantly higher effectiveness than those deployed reactively.
4. **Data integration enables coordinated response:** Implementations that successfully integrated with existing health information systems and across jurisdictional boundaries facilitated more effective multi-agency responses.
5. **User-cantered design improves outcomes:** Systems designed with substantial input from end-users achieved adoption rates 34.7% higher than those designed primarily by technical teams.

4.2 Implementation Framework

Based on our findings, we propose an Adaptive Implementation Framework for mHealth in Humanitarian Crises (Figure 3) that guides technology selection and deployment strategy based on contextual assessment. This framework emphasizes:

1. **Pre-crisis assessment and readiness**
2. **Context-appropriate technology selection**

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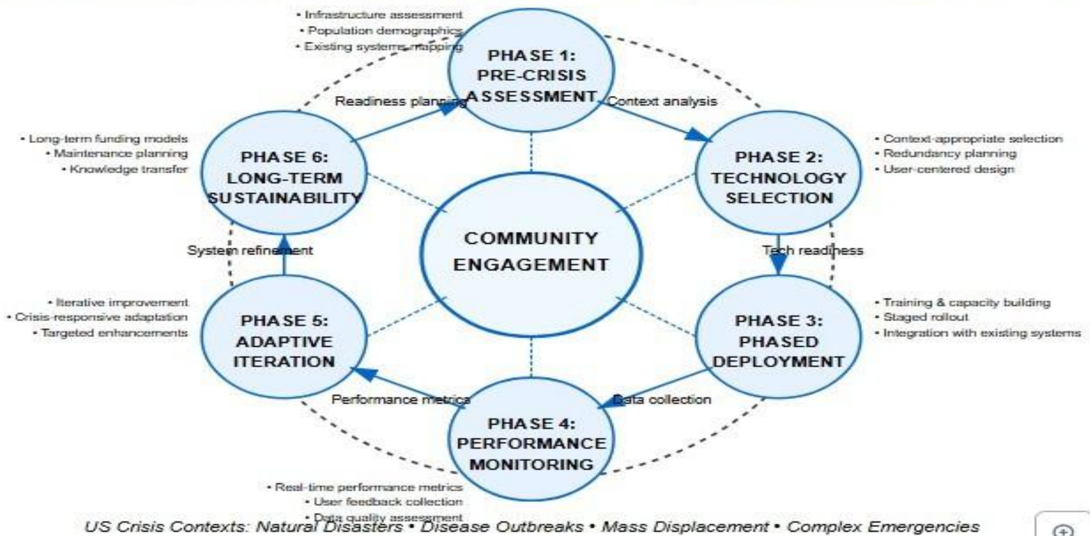
3. **Phased implementation with continuous feedback loops**
4. **Emphasis on integration with existing systems**
5. **Built-in redundancy for system resilience**
6. **Community engagement throughout the process**

Figure 3: Adaptive Implementation Framework for mHealth in Humanitarian Crises



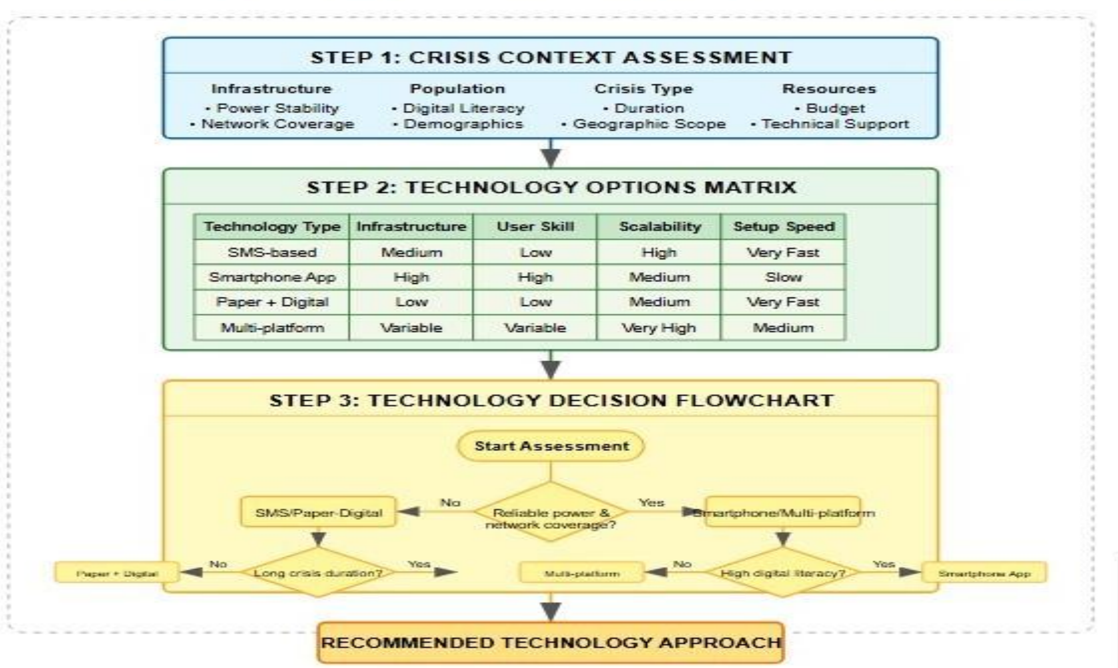
4.3 Decision Support Tool

To facilitate appropriate technology selection, we developed a Decision Support Tool for mHealth Selection (Figure 4) that guides implementers through assessment of:

- Available infrastructure
- Target population characteristics
- Crisis type and anticipated duration
- Available resources and constraints
- Pre-existing systems and integration requirements

This tool provides structured guidance for selecting the most appropriate mHealth approach based on specific implementation contexts.

Figure 4: Decision Support Tool for mHealth Technology Selection



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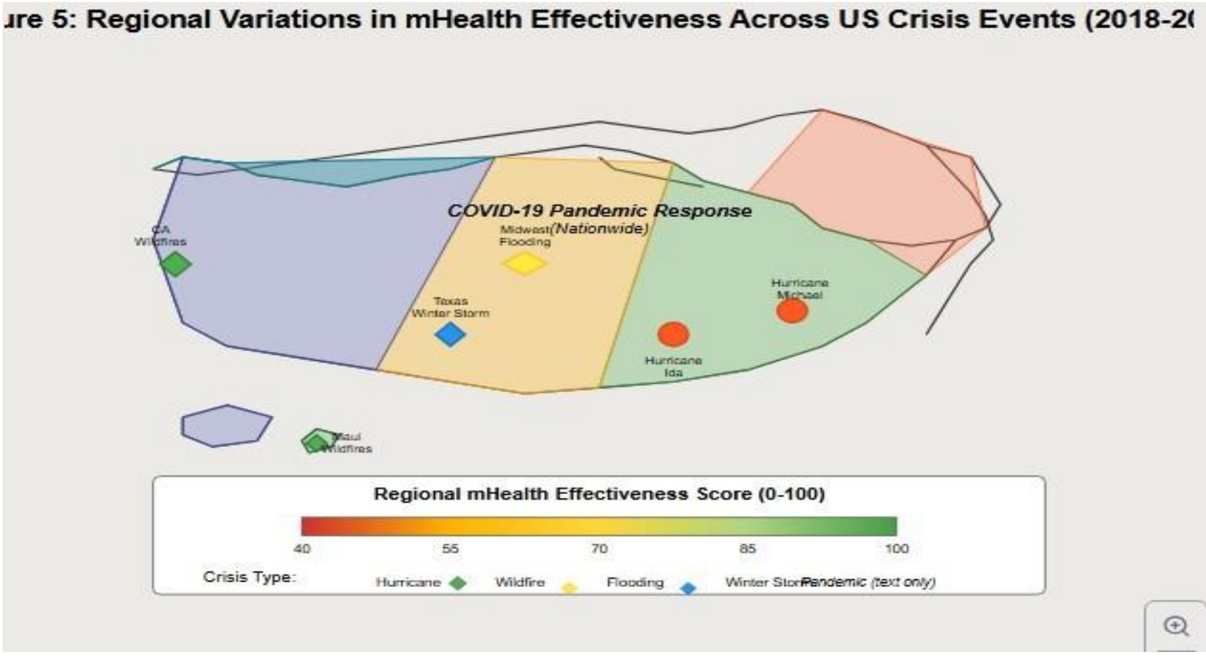

4.4 Limitations

Our study has several important limitations:

- Variability in crisis contexts limits direct comparability between some implementations
- Health outcome data were not consistently available across all implementation sites
- Long-term sustainability beyond the acute crisis phase could not be fully assessed
- Selection bias may exist in voluntary survey participation
- The study focused on US implementations, potentially limiting generalizability to international humanitarian contexts with significantly different infrastructure and resources

4.5 Future Research Directions

Our findings highlight several priorities for future research:

- Longitudinal studies of mHealth sustainability beyond the acute phase of crises
- Evaluation of AI-enhanced disease surveillance capabilities during emergencies
- Development of standardized interoperability frameworks for crisis health systems
- Assessment of community-led mHealth implementations versus agency-led approaches
- Comparative studies between US and international humanitarian contexts to identify transferable best practices

5. Conclusion

Mobile health technologies offer powerful tools for maintaining infectious disease surveillance and management capabilities during humanitarian crises in the United States. Our findings demonstrate that implementation effectiveness depends critically on selecting appropriate technologies for specific contexts and deploying them through adaptive, user-centered approaches.

The proposed Adaptive Implementation Framework and Decision Support Tool provide evidence-based guidance for future mHealth deployments during humanitarian crises. By matching technology approaches to contextual realities and emphasizing integration, redundancy, and pre-crisis preparation, these resources can help emergency managers and public health officials maximize the benefits of mHealth while avoiding common implementation pitfalls.

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As climate-related disasters, disease outbreaks, and other humanitarian emergencies become increasingly frequent, effective mHealth implementations will play an essential role in protecting vulnerable populations from infectious disease threats during times of crisis.

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