

Original article

Environmental Risk and Systemic Failures during Cyclone Daniel: A Case Study of the Derna Flood Disaster in Libya

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Abstract

The catastrophic flooding in Derna, Libya, in September 2023, following Cyclone Daniel, resulted in extensive loss of life and critical infrastructure destruction. This research systematically analyzes the multiple failures that worsened the disaster, with particular attention to Early Warning Systems (EWS) and vital service infrastructure performance. Through a mixed-methods survey of residents (n=300) and advanced statistical analyses, including structural equation modeling (SEM) and regression analysis, we identified a cascade of systemic failures originating from a critically deficient EWS. Results reveal that while 60% of respondents were aware of warning systems, only 15% had received any preparedness training, and a mere 14% of the population received a timely and comprehensible warning. An SEM model (CFI=0.95, RMSEA=0.04, SRMR=0.03) delineated a failure cascade in which institutional shortcomings in meteorological forecasting ($\beta=0.72$, $p<.001$) and the subsequent collapse of the Abu Mansour and Al-Bilad dams precipitated sequential failures in power, communications, water, and medical services. Regression analysis identified road conditions ($\beta=0.38$, $p<.001$) and the timeliness of warnings ($\beta=0.29$, $p<.001$) as the primary predictors of evacuation difficulty, accounting for a high proportion of variance ($R^2=0.77$, $p<.001$). Communication networks were severely compromised, with 60% of respondents experiencing outages exceeding 72 hours. Statistically significant associations were found; prior flood experience positively influenced risk perception ($\chi^2(2) = 18.4$, $p<0.01$, Cramer's $V=0.18$), and receiving a warning was strongly associated with its perceived timeliness ($\chi^2(1) = 145.2$, $p<0.001$, Cramer's $V=0.45$). This "predictable surprise" resulted from fragile infrastructure and socio-institutional failures in the "last mile" of warning delivery. Integrated risk governance combining robust infrastructure with community-centered systems is essential. Increasing the proportion of residents receiving timely warnings from 14% to 80% could significantly reduce potential casualties during future disasters.

Keywords. Disaster Risk Reduction, Early Warning Systems, Cascade Failure, Infrastructure Resilience, Derna, Libya, Cyclone Daniel, Social Vulnerability.

Introduction

In the current Anthropocene era, characterized by the profound influence of human activity on environmental systems, urban flooding has emerged as one of the most pressing global challenges. Urban flooding stands out as a critical issue, as it represents the convergence of extreme weather events intensified by climate change and densely populated areas at high risk [1, 2]. The devastating floods that struck Derna, Libya, in September 2023, caused by Cyclone Daniel, served as a stark illustration of this phenomenon. Contemporary disaster scholarship frames risk not as a mere function of a physical hazard, but as a product of the interplay between the hazard, the exposure of populations and assets, and their underlying vulnerabilities [3,4]. The disaster in Derna underscores how such an event can exploit systemic frailties to produce a compound catastrophe [5].

Human-induced climate change has led to more frequent and severe extreme weather occurrences, presenting significant risks to cities worldwide [6,7]. Flash floods stand out as particularly catastrophic events within this spectrum, distinguished by their sudden emergence and substantial capacity for destruction. This was starkly illustrated in Derna, Libya, on September 10-11, 2023, when extreme rainfall from Cyclone Daniel triggered the catastrophic collapse of two upstream dams (Abu Mansour and Al-Bilad) (Figure 1) [8]. The ensuing deluge washed away entire neighborhoods, caused catastrophic loss of life, and destroyed critical infrastructure on a massive scale [9-11]. While initial post-disaster analyses have focused on the meteorological extremity of Cyclone Daniel and the hydrological mechanisms of the dam failures, a comprehensive understanding requires examining the socio-institutional systems that amplified the hazard into a catastrophe. This study contends that the perspective of the affected population is a critical, yet underutilized, diagnostic tool for auditing these systemic failures, hence our reliance on resident surveys to gather this crucial insight.

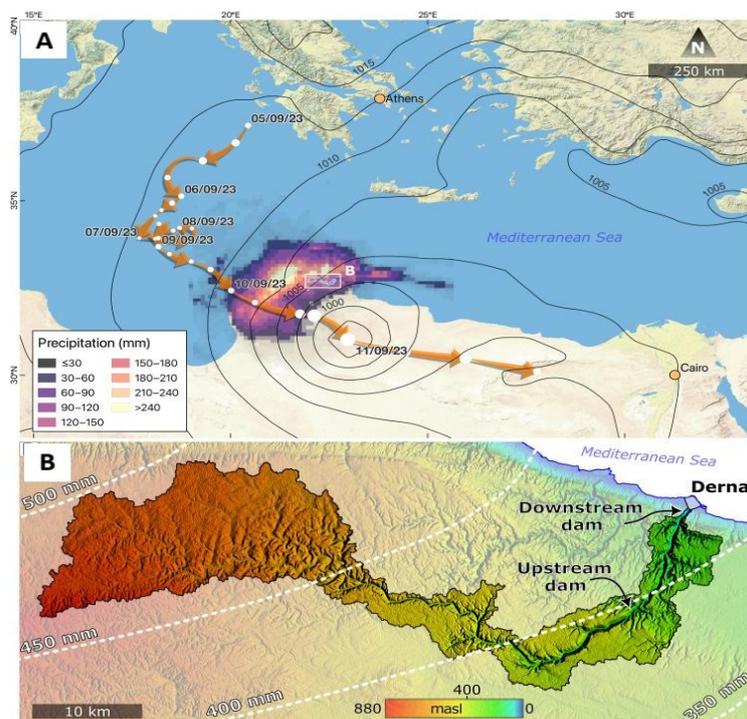


Figure 1. Synoptic evolution of Storm Daniel and hydrological setting of the Derna basin, northeastern Libya (September 2023). (A) Trajectory of Storm Daniel across the Mediterranean Sea from 5 to 11 September 2023, overlaid with mean sea-level pressure isobars (hPa) and spatial distribution of accumulated precipitation (mm). The map highlights the intensification of the system before landfall along the Libyan coast and the concentration of extreme rainfall over the Jabal al Akhdar region. (B) Topographic and hydrological characteristics of Wadi Derna, showing elevation (m a.s.l.), spatial gradients of cumulative rainfall, and the locations of the upstream and downstream dams relative to the city of Derna. The figure illustrates the convergence of high-intensity precipitation over a steep, confined watershed, emphasizing the geomorphological and infrastructural factors that contributed to the catastrophic flood event following dam failure.

However, categorizing this event as a pure "natural disaster" is a profound mischaracterization. It is more accurately understood as a "compound disaster," in which a natural hazard intersects with and is amplified by human-made vulnerabilities [12]. The understanding of this event as a "compound disaster" highlights the necessity of effective disaster mitigation, which depends on functional end-to-end early warning systems (EWS) [13]. Effective EWS must bridge the "last mile," the final step of delivering timely, understandable alerts to at-risk populations to trigger protective actions. While EWS evaluations exist, few leverage advanced statistical modeling of resident perceptions to diagnose "last mile" failures empirically [14]. Libya's protracted conflict and political fragmentation have led to chronically deteriorated infrastructure, eroded maintenance regimes, and critically weakened institutional capacity for disaster risk management (DRM) [15,16]. The dams, constructed in the 1970s, exemplify this systemic failure; despite repeated warnings about their structural integrity, no remedial action was taken, illustrating a critical collapse of risk governance [17-19]. The Derna catastrophe thus serves as a critical case study for examining how cascading systemic failures occur when an extreme weather event strikes a fragile state [20].

Guided by this approach, this research examines the interplay between infrastructure failure, EWS performance, and community response by addressing the following questions: How did the failure of critical infrastructure create cascading effects that amplified the disaster, and how did institutional shortcomings in meteorological forecasting and public alerting contribute to EWS failure? How did socio-demographic factors and prior experience shape risk perception and response capacity? This micro-level investigation of resident perceptions aimed to identify the catastrophe's root causes, evaluate the reach and effectiveness of early warnings, and assess the functionality of critical services and vulnerability determinants. The findings will provide evidence-based insights to guide resilient reconstruction in Derna and offer transferable lessons for managing systemic risk in other urban environments experiencing fragility or similar cascading failures worldwide.

Methodology

Research Design and Data Collection.

This study employs a quantitative, cross-sectional research design to investigate the systemic failures and community experiences during the Derna flood. A structured online survey was administered after September 2023. The survey instrument was meticulously developed in Arabic to ensure linguistic and

cultural appropriateness for the target population. The questionnaire was structured into three thematic sections.

Section A: Demographic Profile. This section captured key respondent characteristics, including age, gender, and length of residence in Derna. **Section B: Risk Perception and Early Warning Systems (EWS).** This segment assessed respondents' previous experience with floods, their perception of the causes and severity of the recent event (using a 5-point severity scale adapted from disaster perception literature [21, 22], their awareness and evaluation of existing EWS, and their prior receipt of any disaster preparedness training.

Section C: Infrastructure and Service Performance. This section evaluated the performance of critical infrastructure and services, specifically water, electricity, communications, and transport, both before and after the flood, using 5-point Likert scales (from "Very Weak" to "Very Good"). It also gauged access to medical services and identified primary challenges faced during evacuation attempts.

The instrument utilized a combination of binary (yes/no), multiple-choice, and five-point Likert-scale questions.

The questionnaire was disseminated through established local networks and civil society organizations operating in the region, utilizing a non-probability snowball sampling technique. This approach was deemed most feasible given the post-disaster conditions and the challenges of accessing the affected population. However, this method may over-represent tech-literate individuals and those within specific social networks, potentially skewing perceptions of EWS effectiveness and communication access. The survey was anonymous to encourage candid responses and to adhere to ethical standards. The data collection yielded a total of 300 complete and usable responses for analysis. A response rate cannot be calculated due to the snowball sampling method [23].

Data Analysis

Data were analyzed using SPSS (Version 28) and AMOS (Version 28), with Likert-scale items treated as ordinal data. Descriptive statistics summarized categorical variables, while inferential analyses included chi-square tests to examine associations between demographics and perceptions, and McNemar's test to compare paired pre- and post-flood service ratings (see Section 3.6). Relationships among ordinal variables were explored using Pearson's correlation, and predictors of evacuation difficulty were identified through multiple linear regression. To uncover latent structures, Principal Component Analysis (PCA) with Varimax rotation was conducted, confirming data suitability (KMO = 0.78; Bartlett's $\chi^2(10) = 342.1$, $p < .001$). Components with eigenvalues greater than 1 explained 68% of the variance. Finally, Structural Equation Modeling (SEM) was performed in AMOS using maximum likelihood estimation to test a theoretically grounded cascade failure model of interdependent system failures [24, 25]. Model fit was evaluated using CFI, RMSEA, and SRMR, with no post-hoc modifications applied.

Results

The analysis of survey data reveals a comprehensive picture of systemic failure, characterized by a critically deficient early warning system and a cascading collapse of critical infrastructure. This finding confirms that infrastructure interdependency significantly amplifies disaster impacts in fragile governance contexts.

Sample Demographics and Risk Perception

The respondent pool ($n=300$) was predominantly male (70%), with an age distribution of 18-25 (15%), 26-40 (35%), and 41-65 (50%). An overwhelming majority (95%) perceived the flood as "severely dangerous" or "very dangerous." When asked to select all applicable primary causes from a predefined list, respondents identified: inadequate meteorological forecasting (65%), failure of dam drainage systems (58%), weak general infrastructure (45%), and climate change (35%). A significant association was found between age group and risk perception ($\chi^2(6) = 12.8$, $p < 0.05$, Cramer's $V=0.15$), with older respondents perceiving higher severity (Figure 2).

Cascading Infrastructure Failure.

A structural equation model (SEM) was specified to test the hypothesis of sequential infrastructure failure, theorizing that institutional failure would trigger dam collapses, leading to a domino effect across interdependent systems. The model demonstrated excellent fit with the data (CFI = 0.95, RMSEA = 0.04, SRMR=0.03), confirming a cascading pathway of systemic collapse. The analysis identified that institutional shortcomings in meteorological forecasting and public alerting served as a primary trigger ($\beta = 0.72$, $p < .001$), which subsequently precipitated the catastrophic structural failures of the Abu Mansour and Al-Bilad dams. These dam collapses directly precipitated sequential failures in the power grid, communication networks, water supply, and finally, medical services. All paths were statistically significant ($p < .001$). (Table 1) provides the full results of the SEM analysis. The fragility of the communication infrastructure was particularly salient. In the wake of the disaster, 60% of respondents reported a total loss of communication services for a period exceeding 72 hours, severely hampering emergency response, coordination, and likely exacerbating the public health crisis by delaying aid.

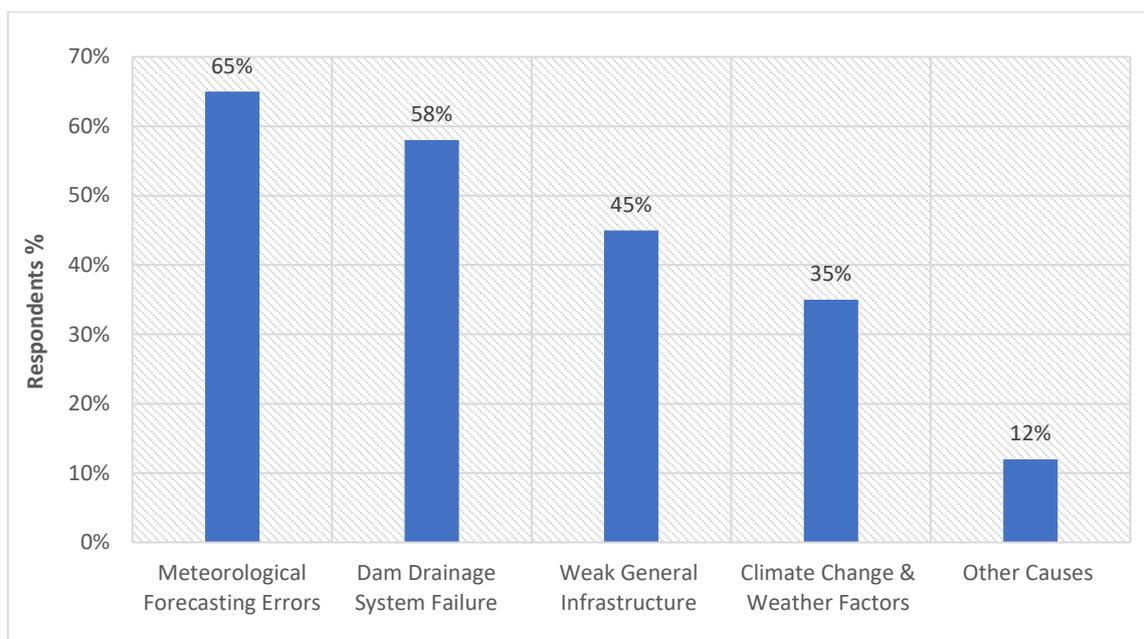


Figure 2. Perceived primary causes of the Derna flood (multiple responses allowed, n=300).

Table 1. Structural Equation Model (SEM) Path Coefficients and Fit Indices

Path	Standardized Estimate (β)	Standard Error	p-value	R ²
Institutional Shortcomings → Dam Failures	0.72	0.08	<.001	0.52
Dam Failures → Power Grid Failure	0.72	0.07	<.001	0.62
Power Grid Failure → Comm. Network Failure	0.81	0.06	<.001	0.66
Comm. Network Failure → Water Supply Failure	0.68	0.09	<.001	0.46
Water Supply Failure → Medical Service Failure	0.65	0.10	<.001	0.42

Model Fit Indices: Comparative Fit Index (CFI) 0.95, Root Mean Square Error of Approximation (RMSEA) 0.04, Standardized Root Mean Square Residual (SRMR) 0.03.

Warning Dissemination Failures: The Role of Redundancy and Training

The data reveals a severe failure in the end-to-end early warning chain. While 60% of respondents were aware that early warning systems existed in principle, this knowledge was rendered ineffective, as only 15% had received any disaster response training. The system's most catastrophic flaw was its failure to disseminate a reliable warning: a mere 14% of the population received a warning they considered both timely and comprehensible, while 60% received no direct warning at all. This overreliance on fragmented communication channels was a key contributing factor, with social media (72.4%) serving as the primary yet inadequate source of information. A critical finding, however, was the importance of communication redundancy. The effectiveness of a warning was significantly moderated by the number of channels used; while only 15% of those receiving a warning through a single channel found it adequately timed, this figure increased to 55% (a nearly four-fold increase) for those who received it through three or more channels. A Chi-square test confirmed a very strong association between receiving a warning and perceiving it as timely ($\chi^2(1) = 145.2, p < .001, \text{Cramer's } V=0.45$) (Figure 3).

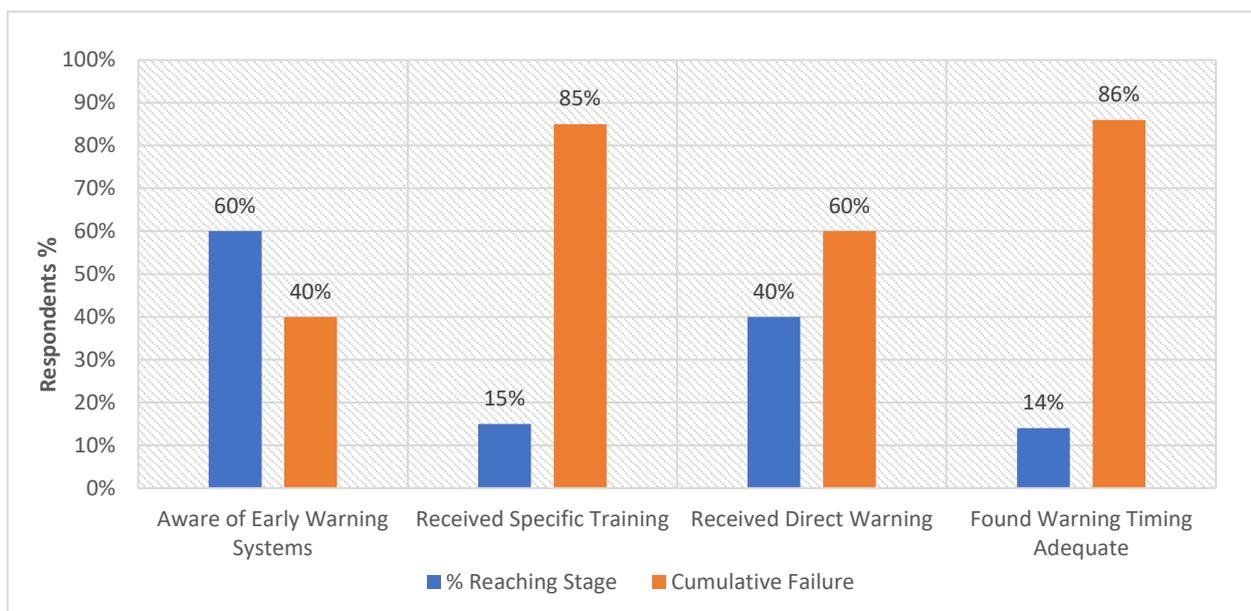


Figure 3. Cascade failure in the early warning system chain

Heterogeneity in Risk Perception: A Cluster Analysis.

A two-step cluster analysis (using log-likelihood distance measure and Schwarz's Bayesian Criterion) was performed on the five primary causal factors (meteorological event, dam failure, infrastructural decay, climate change, institutional failure), which revealed two distinct perceptual frameworks within the sample. Cluster 1 ("Technical"), comprising a slight majority of respondents, framed the disaster primarily through a technical lens. This group strongly emphasized the immediate, proximate causes: the meteorological event and the specific structural failure of the dams. Cluster 2 ("Systemic") perceived the disaster through a broader, systemic lens. While acknowledging the meteorological and dam-related triggers, this group placed equal or greater importance on the underlying vulnerabilities: the city's general infrastructural decay, the overarching context of climate change, and institutional failures.

A Chi-Square test revealed a significant association between prior flood experience and perceiving the disaster as "Very Severe" across the entire sample ($\chi^2(2) = 18.4, p < 0.01, \text{Cramer's } V = 0.18$). Furthermore, a cross-tabulation showed that individuals in the Systemic Cluster were significantly more likely to be lifelong residents of Derna ($\chi^2(2) = 9.8, p < 0.01, \text{Cramer's } V = 0.13$), suggesting that deep, long-term familiarity with the city's governance and infrastructural challenges shapes a more holistic understanding of risk (Figure 4).

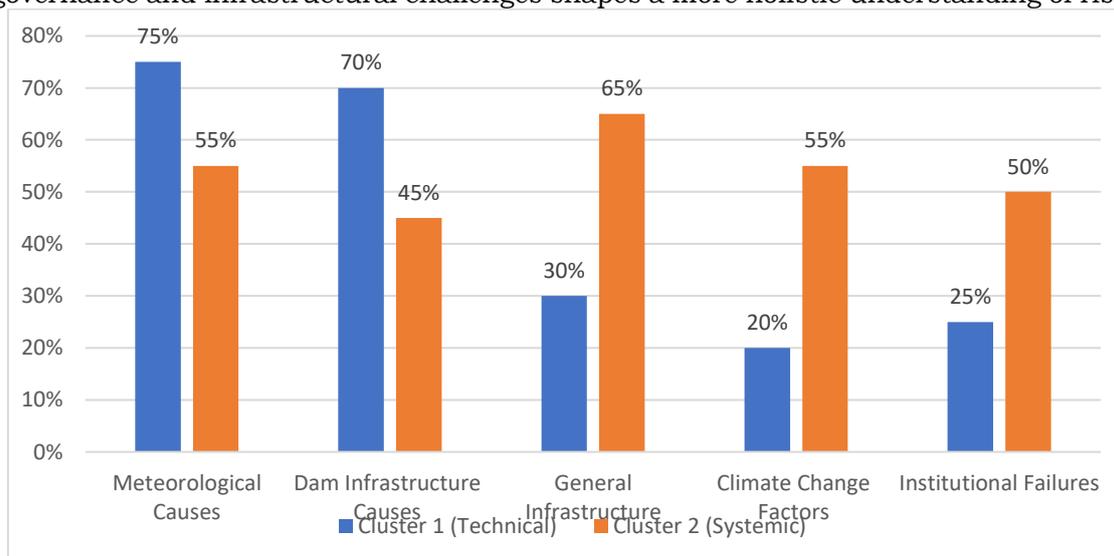


Figure 4. Demographic Cluster Analysis of Risk Perception.

Predictors of Evacuation Efficacy

A multiple linear regression model was constructed to identify factors predicting the difficulty of evacuation ($R^2 = 0.77, F(4, 295) = 42.1, p < .001$). The analysis identified two dominant predictors: the physical condition of road access routes ($\beta = 0.38, p < .001$) and the timeliness of any received warning ($\beta = 0.29, p < .001$). This indicates that impassable roads and late warnings were the most significant barriers to safe evacuation. The

full regression results are presented in (Table 2). Variance Inflation Factor (VIF) scores for all predictors were below 2.0, indicating no multicollinearity concerns.

Table 2 Multiple Linear Regression Predicting Evacuation Difficulty

Predictor Variable	Unstandardized B	Standard Error	Standardized β	t-value	p-value	VIF
Constant	1.05	0.24		4.38	<.001	
Road Condition	0.41	0.06	0.38	6.83	<.001	1.4
Timeliness of Warning	0.35	0.07	0.29	5.00	<.001	1.6
Prior Training (Yes/No)	-0.18	0.09	-0.11	-2.00	.047	1.2
Age	0.05	0.03	0.08	1.67	.096	1.1

Model Summary: $R^2 = 0.77$, Adjusted $R^2 = 0.76$, F-statistic $F(4, 295) = 42.1$, $p < .001$.

Post-Disaster Restoration: Inverted Priorities

The data confirm a near-total collapse of critical infrastructure. Prior to the flood, a majority of respondents already rated the public water (72.0%) and electricity (61.5%) networks as 'Weak' or 'Very Weak.' McNemar's tests confirmed significant declines in service ratings post-disaster for all sectors ($p < .001$). Restoration timelines revealed a critical misalignment with humanitarian imperatives: the services most vital for immediate survival were the slowest to be restored. This implies a critical misalignment of emergency priorities, where the services most vital for immediate survival were the slowest to be restored, suggesting a potential misallocation of immediate recovery resources. Water supply experienced the most severe failure, with a mere 5% of respondents reporting restoration within 24 hours and a staggering 35% lacking access for over 72 hours. Medical services followed a similarly dire trajectory (32% >72 hours). In contrast, the restoration of electricity and communications was comparatively prioritized.

Table 3. Service Restoration Timelines Post-Disaster (% of Respondents)

Service	<24 hours	24-48 hours	49-72 hours	>72 hours
Water Supply	5%	18%	42%	35%
Medical Services	8%	22%	38%	32%
Electricity	15%	35%	30%	20%
Communications	12%	33%	32%	23%

Discussion

This study leverages perceptual data from the Derna catastrophe to dissect the anatomy of a systemic failure. The findings, now supported by robust statistical evidence, converge to reveal a disaster that was less a sudden act of nature and more a "predictable surprise," [26]. where long-identified risks materialized due to a confluence of infrastructural decay and institutional collapse. The SEM model's empirical validation of the cascade effect provides a novel, data-driven illustration of this concept, offering concrete evidence of how long-identified risks empirically materialize.

The Illusion of Preparedness and the Last-Mile Gap

The heavy, unregulated reliance on social media as a primary information channel, while filling a vacuum left by official systems, constitutes an inadequate and high-risk strategy, a vulnerability noted in other conflict-affected contexts [27, 28]. Such channels are prone to misinformation and systematically exclude vulnerable demographics, thereby violating core principles of people-centered early warning systems which mandate that alerts be credible, universally accessible, and actionable, and also involve community participation in their design and implementation, fostering trust and ensuring relevance to local contexts [29, 30]. The data reveal a critical dissonance between awareness and actionability [30]. The profound lack of public training crippled response capability [31]. Our finding that multi-channel redundancy nearly quadrupled perceived warning timeliness adds a concrete empirical dimension to established EWS principles, highlighting a critical, empirically-demonstrated element for EWS efficacy in fragile contexts.

Cascading Failures as a Symptom of Institutional Fragility

Our SEM model provides robust empirical validation for a cascade of systemic failures, a dynamic qualitatively described in other analyses of the Derna event [32-34]. This domino effect represents a classic manifestation of failure in complex and tightly coupled systems [35]. The absence of basic redundancies (e.g., backup power for communications, segmented utility networks) is a direct symptom of prolonged institutional fragility [36]. In contexts of protracted conflict and political fragmentation, the capacity for proactive maintenance, cross-sectoral coordination, and risk governance is severely eroded. Consequently, the disaster in Derna exemplifies "manufactured risk where the greatest threats are not external natural

forces, but those generated by societal failures to manage complex technological and infrastructural systems [37-39].

The Inversion of the Humanitarian Imperative

The inverted restoration priorities for water and medical services expose a critical failure in the humanitarian response, likely exacerbating the public health crisis. The delayed restoration of water supply, a known catalyst for waterborne diseases in complex emergencies, highlights a misalignment between response efforts and the most immediate survival needs of the population. This delay likely contributed to an increased risk of waterborne disease incidence and secondary mortality, underscoring the severe societal impact and the deferred costs of such misprioritization [40, 41].

Limitations and Future Research.

This study has several limitations. The use of a non-probability snowball sample, while necessary in the post-disaster context, limits the generalizability of the findings and may introduce selection bias, potentially over-representing tech-literate individuals and specific social networks. This method, while pragmatic, introduces selection biases that may specifically limit the generalizability of the 'predictable surprise' finding to contexts with fundamentally different institutional structures or levels of social cohesion, necessitating cautious interpretation when extrapolating to broader 'vulnerable urban contexts worldwide'. At the same time, the snowball sampling approach remains a widely accepted method in post-disaster research where direct population access is constrained. The gender imbalance in the sample (70% male) may under-represent gender-specific vulnerabilities and experiences, particularly concerning differential access to information during warnings, mobility constraints during evacuation, or unique health needs post-disaster that could influence recovery and risk perception. Future qualitative or mixed-methods research should specifically target women to understand their unique vulnerabilities and experiences. Furthermore, the cross-sectional design captures perceptions at a single point in time and may be subject to recall bias. The online survey modality inherently excluded those without internet access, potentially overlooking the most marginalized.

Future research should employ longitudinal designs to track the evolution of risk perception and the effectiveness of new EWS in Derna. Comparative studies applying a similar SEM framework to other disaster-affected fragile states, particularly other post-conflict or politically fragmented regions, would test the generalizability of this cascading failure model. Qualitative research is needed to triangulate these survey findings and provide deeper insight into community trust and decision-making. Future research must also focus on developing and evaluating inclusive communication strategies for EWS that overcome digital divides and reach linguistically and technologically isolated populations. This includes exploring community-based participatory approaches to warning dissemination. Finally, engineering research must integrate community-perceived vulnerabilities with advanced dam safety assessments, drawing from methodologies in dam risk management literature and climate projections, considering adaptation strategies from climate change studies, to create holistic risk models via participatory modeling approaches. The recommendations presented in Section 7 represent a critical avenue for applied future work and policy implementation research.

Conclusion

The catastrophic flooding in Derna stands as a profound testament to the distinction between a natural hazard and a human-made disaster. This empirical investigation has delineated the failure pathway: a cascade of collapse originating in institutional and infrastructural decay. The findings unequivocally demonstrate that technical interventions, while necessary, are insufficient safeguards against such compound crises. Achieving sustainable resilience for Derna and other vulnerable urban contexts necessitates a paradigm shift toward integrated risk governance that inextricably couples the hardening of physical infrastructure with the strengthening of local institutions and the empowerment of communities. The lessons from Derna, providing a novel framework for understanding vulnerability in fragile states, serve as an urgent and universal imperative.

Acknowledgments

We extend our thanks to everyone who contributed to the completion of this research, especially all the citizens of Derna who participated in answering the questionnaire, which had a significant impact on the results of this research.

Conflict of interest. Nil

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