Pathways of resilience: a fuzzy-set qualitative comparative analysis of healthcare systems resilience to extreme weather events

AUTHORS

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ABSTRACT

Background

Increasing frequency and intensity of extreme weather events (EWEs) threaten healthcare services globally, with particularly acute risks in low-resource settings. While health system resilience is widely discussed, there is limited empirical evidence on how it is enacted in practice across complex, real-world systems, particularly beyond infectious disease contexts.

Methods

We analysed 18 case studies from diverse global contexts, examining how EWEs affected four interrelated system levels: healthcare facilities, local health systems, communities, and interconnected infrastructures. We applied fuzzy-set Qualitative Comparative Analysis (fsQCA) to identify configurations of vulnerability, adaptive capacity, and external support associated with two outcomes: service continuity and healthcare facility recovery.

Results

Four distinct resilience pathways were identified. These demonstrate that resilience emerges from cross-scale configurations rather than individual system components, with local adaptive capacity playing a key role in maintaining service continuity. Where high vulnerability across multiple system levels exceeded local capacity, resilience depended on external support, which was associated with eventual recovery but not with continuity of services. Across cases, workforce factors—including staff wellbeing, safety, and morale—were critical in shaping system response.

Conclusion

This study provides empirical evidence that health system resilience to EWEs is a multi-scalar process. The identified pathways offer practice-based insights for strengthening resilience,

highlighting the importance of cross-system coordination, planning for capacity limits and phased operational response escalation, and investing in the health workforce as a central component of effective response and recovery.

BACKGROUND

Extreme weather events (EWEs) impact healthcare systems worldwide, with the most intense effects often experienced in low-resource settings (1). Weather phenomena such as flash floods, cyclones, hurricanes and typhoons, tropical storms, droughts and heatwaves directly disrupt both the physical and organisational components of healthcare systems and often trigger secondary hazards (2). Demands for more resilient healthcare systems are therefore growing, although the concept's meaning and application remain debated (3,4). Existing research on healthcare resilience has a strong focus on infectious disease outbreaks (5), particularly COVID-19 (6) and Ebola (7). While these public health crises offer important cross-learnings for systems facing extreme weather, the nature and dynamics of disruption differ in important ways (8).

The World Health Organisation (WHO) has published an influential operational framework for building climate-resilient health systems (9). The framework defines resilient healthcare systems in line with influential scholarly definitions from the mid-2010s (10,11). A synthesised definition describes resilience as "the capacity of health systems (actors, institutions and populations) to effectively anticipate, prepare, absorb, cope, respond, recover and re-organise (or transform) when a crisis hits, to bring sustained improvements in population health despite instability". Subsequent literature has further emphasised resilience as a capability emerging from complex system interactions, particularly across formal health systems, community systems and interconnected infrastructures (4,12,13,14).

Other authors have highlighted the lack of practice-based knowledge on how health system resilience is enacted in real-world contexts (15). Research with global experts has proposed a future research agenda to enable its application in practice, including understanding how resilience operates across and between societal and health system levels, measuring systems' dynamic performance, and examining the role of governance in shaping capacity for resilience (16). Related work has explored tools to support resilience in practice, such as approaches that prompt stakeholder reflection or simulate 'real-life' disruptions to understand organisational adaptation (17). However, the effectiveness of these tools remains under-studied, and they offer limited insight into how resilience is actually configured across interacting systems during real events.

Responding to those gaps, we analyse a novel dataset of diverse global case studies examining the impacts of, and responses to, extreme weather events within district healthcare systems. The results identify four distinct resilience pathways, providing empirically grounded examples of how real-world systems respond to extreme weather disruptions across systems and scales. We conclude by discussing the implications for healthcare system strengthening and future research in this field.

METHODS

Study design

We applied a fuzzy-set Qualitative Comparative Analysis (fsQCA) to n=18 cases, a method that uses set-theoretic relations to identify causal pathways to a defined outcome of interest (18,19). We did so to answer the question: what combination of conditions leads to outcomes indicating the presence of healthcare system resilience?

Conceptual framework

To underpin this process, we first developed a ‘system of systems’ conceptual model which we used to structure our case studies and analysis process. This was done through two workshops conducted in October and November 2024 with academic partners of the “Improving business continuity for health services following extreme weather events” project (NIH 204820). Participants comprised healthcare experts from a range of disciplines including medicine, epidemiology, civil and public health engineering, sociology and business management, across five countries. Workshops used the WHO operational framework for building climate resilient health systems (9) as a foundation for discussion on how healthcare resilience works in practice in England, Malawi, Tanzania, Uganda and Vietnam.

Based on these discussions, the system of systems model was developed to include key local components such as the role transportation networks, traditional healers, and patients and family groups. Figure 1 below presents the detailed model with a nested healthcare facility at the centre. The surrounding local healthcare system connects to this facility, and comprises distributed clinics, medical supply chains, staff unions and other community-based healthcare services. We define local as equivalent to a district scale, which may have only one or multiple larger healthcare facilities (likely the case in a rural district or in an urban district, respectively). Additionally, we include the role of external support – defined as any support originating from outside the district.

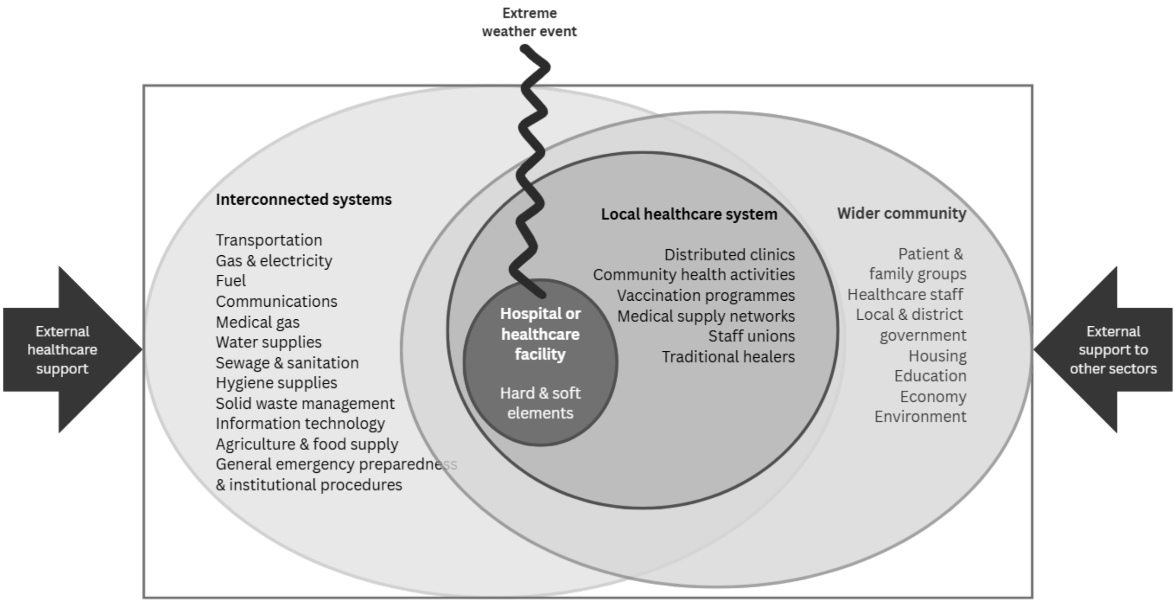

Figure 1: Conceptual healthcare systems model, showing the relations between four systems of focus in this study: central facility - comprised of hard and soft systems components - local healthcare system, wider community and interconnected systems. The jagged line represents the disruptive impacts of an event across all four systems.

Case study development

We identified case studies of healthcare systems responding to extreme weather events within the past 10 years where the impact and response were documented at the level of a specific health facility (see online supplemental information for full criteria; Tables S1 and S2). Cases were selected from a range of higher- and lower-resource settings to maximise diversity and enable cross-contextual learning.

A consistent approach was used to compile each case, following a predefined protocol and data collection proforma (see supplemental Tables S3 and S4). The first stage involved a literature review conducted by the research team, covering both grey and academic sources related to the extreme weather event. Common sources included local media reports, NGO publications, government communications, and studies on climatic or geographic vulnerability.

To validate the literature-based case studies, either a verbal interview or a written review was conducted with at least one professional who had direct experience of the event, such as a healthcare worker, facility manager, government official, or emergency responder (see supplementary S7 for interview guide). In most cases, interviews were conducted either face-to-face or online; in some instances, informants validated cases by providing written contributions to the data collection template.

A total of 27 cases were identified across 13 countries. However, not all cases were sufficiently validated for inclusion in the fuzzy-set analysis. The final set comprised 18 validated cases (see Table 1).

Table 1: List of cases with data collected (case summaries provided in Table S5). The cases in Australia and Zambia were not included in the fuzzy set Qualitative Comparative Analysis due to lack of validation and incomparable central healthcare facility, respectively.

Country	Case	Event	Validated	Number of professionals validating study
Colombia	Barranquilla, Department of Atlántico	Flooding, 2023-2024	Y	2
	Mocoa, Department of Putumayo	Flash flood inducing landslide/debris flows, 2017	Y	2
England	Norfolk, East Anglia	Extreme heat, 2022	Y	1
India	Warangal, Telangana	Flash floods, 2023	Y	3
Malawi	Mbenje, Nsanje District	Cyclone Jude, 2025	Y	3
	Nsanje District (North)	Cyclone Freddy, 2023	Y	3
	Nsanje District (South)	Cyclone Freddy, 2023	Y	4
Philippines	Dinagat Islands, Caraga Region	Super Typhoon Odette (Rai), 2021	Y	2

	Siargao Island, Caraga Region	Super Typhoon Odette (Rai), 2021	Y	1
Tanzania	Hanang, Manyara Region	Landslide, 2023	Y	1
	Ifakara, Kilombero District	Tropical Cyclone Hidaya, 2024	Y	1
	Mafia Island	Tropical Cyclone Hidaya, 2024	Y	1
Uganda	Kilembe, Kasese District	Flooding, 2020	Y	2
	Kisizi, Rukungiri District	Flooding, 2017	Y	2
	Rwangara, Ntoroko District	Flooding, 2019	Y	2
Vietnam	Huong Khe, Ha Tinh Province	Flooding, 2016	Y	2
	Huong Son, Ha Tinh Province	Heavy rains & whirlwinds, 2021	Y	2
	Tran Yen, Yen Bai Province	Heavy rains & thunderstorms, 2024	Y	2
Australia	Kimberley, Western Australia	Tropical Cyclone Ellie, 2022	N	0
Zambia	Lusaka city	Drought, 2023	Y	1

Case study calibration into fuzzy sets

The fsQCA approach involved calibrating each case study into sets representing causal conditions and outcomes. In line with fsQCA principles, these sets were defined on a continuum from complete absence (0) to full presence (1), with intermediate thresholds used to capture partial membership. Building on our "system-of-systems" conceptual model (Figure 1), we assess each case study in terms of the four systems of focus: a central facility, a local healthcare system, the wider community, and interconnected systems. We then assigned membership sets in terms of the relative vulnerability and adaptative capacity within each subsystem during the extreme weather response. Definitions used were informed by the WHO climate resilient healthcare framework and wider resilience literature (5, 14) and specific definitions at each level are given in Table 2 but in summary: vulnerability was defined as the combined exposure and sensitivity of a system to an extreme weather event, as reflected in the degree of disruption experienced; and, adaptive capacity referred to the demonstrated ability of a system to prepare for, respond to, and adjust to these disruptions, including both pre-event preparedness and in-event and post-event response. An additional two causal sets were added related to the role of external or humanitarian support beyond the core systems in our conceptual model. Two outcome sets were used – (i) service continuity; (ii) final system state; again, these were informed by the WHO climate resilient healthcare framework and wider resilience literature (5, 14). Here, we note that service continuity can be considered an outcome indicating "robustness" meaning the ability of the health system to withstand pressure without significant changes in functionality (19). Whereas, final system state is an outcome more associated with interpretations of "resilience" associated with how well the system recovers from adverse conditions and disruption (19). These set definitions were iterated into their final form by following a calibration process and using the collaborative workshops to ensure adjustments were appropriate across contexts. This process led to the final definitions and thresholds of 10 causal condition sets and two outcome sets, as shown below in Tables 2, 3 and 4 (with additional detail in Table S6).

Table 2: The final 10 causal conditions and their definitions as used in our fuzzy set Qualitative Comparative Analysis. Calibration thresholds and respective sub-definitions are detailed in Table S5).

Label	Causal condition	Set definition
V1	Vulnerability of central healthcare facility	The combined exposure of the facility to extreme weather and its sensitivity – demonstrated by the hard and/or soft system impacts – during the EWE of focus in the case study.
V2	Vulnerability of the local healthcare system	The combined exposure of the healthcare system to extreme weather and its sensitivity during the EWE of focus in the case study.
V3	Vulnerability of the community	The combined exposure of the community (the people served by the facility and local healthcare system) to extreme weather and its sensitivity during the EWE of focus in the case study.
V4	Vulnerability of the interconnected systems	The combined exposure of the community (including power, water and telecoms utilities and transportation) to extreme weather and its sensitivity during the EWE of focus in the case study.
A1	Adaptive capacity of the central healthcare facility	The demonstrated response to the impacts of the EWE at the facility level. Both the preparedness prior to the event (including aspects of emergency planning, protocols and early warning alerts) and the timeliness of response during and after the event, indicate capacity to absorb and adapt to disruptions.

A2	Adaptive capacity of the local healthcare system	The demonstrated response to the impacts of the EWE at the healthcare system level. Both the preparedness prior to the event and the timeliness of response during and after the event, indicate capacity to absorb and adapt to disruptions.
A3	Adaptive capacity of the community	The demonstrated response to the impacts of the EWE at the community level. Both the preparedness prior to the event and the timeliness of response during and after the event, indicate capacity to absorb and adapt to disruptions.
A4	Adaptive capacity of the interconnected systems	The demonstrated response to the impacts of the EWE at the interconnected systems level. Both the preparedness prior to the event and the timeliness of response during and after the event, indicate capacity to absorb and adapt to disruptions.
HH	Humanitarian (or external) support to healthcare	The extent of support provided to the central healthcare facility and the local healthcare system from sources external to the district. This includes mobilisation of healthcare staff, supplies and infrastructure (e.g. field hospitals, cholera treatment facilities, psychosocial support) from other districts or regions in the country (national humanitarian responders) and from other countries (international humanitarian responders).
OH	Humanitarian (or external) support to sectors other than healthcare	The extent of support provided to the community, interconnected systems, or other non-health related sectors from sources external to the district. This includes food, shelter, water, sanitation, nutrition, livelihoods, electricity and communications from other districts or regions in the country and from other countries.

Table 3: Calibrated set definitions and threshold descriptions for service continuity outcome.

Outcome set (i)	Set threshold	Description
Continuity of healthcare service delivery during and immediately after the EWE.	1	Essential functions of the central healthcare facility continued, with some minor disruptions to peripheral elements of the healthcare facility. These disruptions were able to be recovered quickly. Patients did not experience any significant disruption.
	0.67	There were some minor disruptions to essential functions of the central healthcare facility, but patient facing services were protected as far as possible - usually staff were affected via changing work patterns or facility accessibility issues. Remedial measures were taken to quickly to return to service continuity and subsequently all other disruptions were addressed in due course.
	0.33	There were major disruptions to the continuity of core healthcare service provision. Essential functions of the system and facility were heavily disrupted during and after the event. Staff and patients were substantially affected.
	0	Healthcare service delivery was completely halted during the event – there was no continuity. Service delivery did not resume for weeks or months afterwards.

Table 4: Calibrated set definitions and threshold descriptions for final system state outcome.

Outcome set (ii)	Set threshold	Description
Final state of the local healthcare system, measured by proxy as the final state of the central healthcare facility including a temporal dimension.	1	The final state of the central healthcare facility was: ▪ A transformed facility that was upgraded in its hard and/or soft system components and operated more effectively than it did before the event. After the event, learnings were integrated into protocols, procedures and/or construction. ▪ A facility that returned to the same state it was in as before the event, provided it was functioning effectively. It is expected that in these cases the 'bounce back' time will be relatively short for an effective system.
	0.67	The final state was a healthcare facility that recovered to the same as before the event, if it had previously operated well (relative to context), but with some minor issues around consistency of service delivery.
	0.33	The final state was a facility that was functioning but providing inconsistent services. It is likely that in these cases the bounce back time is long and draw out. This could look like either: ▪ A facility that returned to the same state as before the event, if it previously had major issues in delivering core healthcare services.

		▪ A functional facility but one that was in substantially worse state than it was before the event.
	0	The final state after the event was the complete collapse of the central healthcare facility.

Data analysis

Using Ragin's fsQCA software V4.1 two analyses were conducted, the first with outcome (i) and second with outcome (ii). Analyses involved evaluation of all possible logical combinations of causal conditions associated with the outcome, using Boolean minimisation. Each of our two chosen outcomes is indicative of what a resilient system could look like during an EWE – (i) service continuity – and in the months or years after when recovery is considered (locally) to have occurred – final state. Following convention, data analysis results were produced for complex pathways, whereby only logically coherent fsQCA "solutions" based on the data reported are shown, as well as parsimonious pathways whereby logical minimisation helps identify the simplest possible pathways. In practical terms, this analysis shows which combinations of factors tend to come together in real-world cases to enable healthcare systems to maintain services and recover effectively after extreme weather events.

RESULTS

Results were generated by analysing the fuzzy set scores for each case study, shown in Table 5 below. Four pathways of resilience that meet fsQCA consistency threshold conditions were found (see Table 6). The standard threshold used in fsQCA is 0.8, which indicates that 80% of the time that configuration of causal conditions is present, the outcome is also present. Visual representation of the pathways is shown below in Figure 2. For each of these pathways, the fsQCA associates one or more cases that closely align with the configuration of causal conditions and outcome presence. The pathway or configuration is based on the theoretical definitions for each condition and outcome, applied to the real cases through fuzzy scoring and subsequent qualitative comparative analysis. In the following sub-sections, we qualitatively describe the four pathways using these examples from the cases most closely configured to each theoretical pathway.

Table 5: Final fuzzy-set scores from the fourth scoring round.

Case	Causal condition score										Outcome score	
	V1	V2	V3	V4	A1	A2	A3	A4	HH	OH	(i) Continuity	(ii) Final state
1_Colombia, Barranquilla	0.55	0.67	0.7	0.88	0.8	0.5	0.5	0	0	0	0.9	1
2_Colombia, Mocoa	0.9	1	1	0.95	0.15	0	0	0.15	1	0.8	0.2	1
3_England, Norfolk	0	0.15	0.3	0.15	1	0.67	0.67	1	0	0	1	1
4_India, Warangal	0.67	0.75	1	0.67	1	1	0.33	0.67	0	0	0.67	1
5_Malawi, Mbenje	0.85	1	0.8	0.67	0	0	0.33	0	0.33	0.2	0	0
6_Malawi, Nsanje (south)	0.67	1	1	1	0.33	0.33	0.2	0	0.67	0.67	0.33	0.4
7_Malawi, Nsanje (north)	0.67	1	1	1	0.67	0.33	0.33	0	0.67	0.4	0.9	0.67
8_Philippines, Dinagat	0.95	1	1	1	0	0.67	0	0.33	1	1	0.1	0.5
9_Philipines, Siargao	0.67	1	1	1	0.2	0.67	0	0.2	1	1	0.33	1
10_Tanzania, Ifakara	0.5	0.8	0.8	0.67	0.67	0.33	0	0.2	0.8	0.33	1	1

11_Tanzania, Katesh	0.5	0.9	1	0.67	0.5	0	0	0.33	0.8	0.67	1	1
12_Tanzania, Mafia	0.5	0.8	0.9	0.67	0.67	0.6	0.2	0.33	0.33	0.33	0.85	1
13_Uganda, Kilembe	1	0.8	1	1	0	0	0.1	0.1	0.5	0.35	0	0.2
14_Uganda, Kisizi	0.5	0.5	0.5	0.67	0.33	0.33	0.67	0.5	0.2	0.2	0.33	0.4
15_Uganda, Rwangara	1	1	0.33	1	0	0	0	0	0.5	0.4	0	0.5
16_Vietnam, Huong Khe	0.67	0.9	1	0.9	0.67	0.5	0.5	0.67	0.67	0.5	0.2	0.75
17_Vietnam, Huong Son	0.67	0.8	0.9	0.75	0.67	0.67	0.5	0.5	0.67	0.4	0.33	0.67
18_Vietnam, Tran Yen	0.8	0.9	0.9	1	0.67	0.5	0.2	0.33	0.67	0.6	0.6	0.8

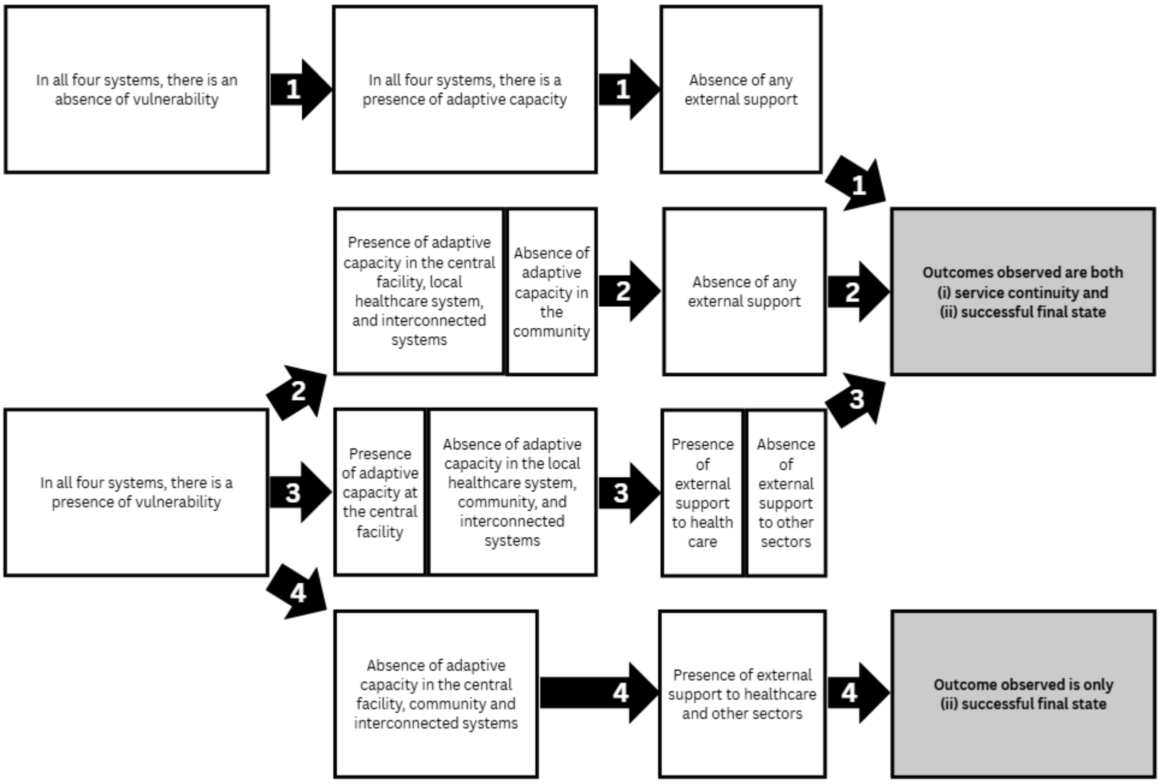

Figure 2: Four resilience pathways resulting from the fuzzy set Qualitative Comparative Analysis. Pathways 1, 2 and 3 all hold for both outcomes (i) & (ii), whereas pathway 4 holds only for outcome (ii).

Table 6: Prevalence and frequency of pathway occurrence across the dataset. Raw coverage represents the share of the outcome set that is covered by that pathway, for example 13.7% of the presence of outcome (i) within the dataset is explained by pathway 1. Consistency refers to the degree to which the cases with the outcome also have the pathway. The standard value for a reliable pathway is a consistency score of 0.8 (18, 20).

Pathway	Outcome indicator (i) service continuity		Outcome indicator (ii) successful final state	
	Raw coverage	Consistency	Raw coverage	Consistency
1	0.137	1	0.093	1
2	0.274	0.948	0.196	1
3	0.386	0.963	0.272	1
4	N/A	N/A	0.433	0.876

Pathway 1: Low vulnerability and high local capacity

Pathway 1 is characterised by low vulnerability, with the four conditions relating to vulnerability all being coded as absent in the healthcare facility, healthcare system, community and interconnected systems (~V1, ~V2, ~V3, ~V4), at the time of the extreme weather event. It is also characterised by high adaptive capacity in all four systems, demonstrated by the presence of the conditions relating to adaptive capacity (A1, A2, A3, A4). Additionally, no external support from beyond the district (or equivalent) boundaries was provided to the healthcare systems or other sectors (~HH, ~OH).

This pathway represents a scenario where systems are robust in the face of a hazard and can cope with the level of disruption they face without external support. It is exemplified in the case study of a hospital in Norfolk, England, during a heatwave in 2022. During this event, temperatures were recorded in the late 30s (°C), with the highest recorded at 40.3°C (remaining the highest temperature recorded to date in England at time of writing, late 2025) approximately 30 miles away from the facility. At the hospital, the key informant described adaptive capacities during the event as a combination of multiple small actions. An important focus of these actions was staff morale and wellbeing, which were lower than normal due to the unusually high heat for the context. Healthcare staff faced the same heat impacts as people in the wider community, including poor sleep, resulting in lower concentration and more mistakes, dehydration and risk of urinary tract infections. Low morale and higher irritability also meant that problems escalated more quickly than usual, and higher staff absences were noted due to illness and people being less willing to work extra hours.

Actions the facility took to respond included making adaptive changes to uniform policy to allow shorts, informing staff to keep windows shut to regulate temperatures, and providing ‘tangible’ good-will gestures, such as free drinks and ice creams. Otheractions, such as longer staff breaks, were described by the key informant as unrealistic and unpopular, because they would cause staff to finish shifts later. While there is a standard operating procedure policy document or 'adverse weather policy' at most hospital trusts in England, specific actions are adaptive and facility dependent. For example, some reported strategies include delayed discharge of high-risk patients, shifting surgery times to early morning, and selecting lower-risk patients for surgery. However, the facility in this case did not have the internal flexibility to employ such strategies due to consistent high demand for services – routine medical care 'just has to happen'.

Pathway 2: High vulnerability, with local capacity in formal systems

In contrast, pathway 2 is characterised by high vulnerability within all four systems of interest (V1, V2, V3, V4), meaning that there is significant exposure and sensitivity to the extreme weather event. Adaptive capacity is split between an absence of adaptive capacity in the local community, but a presence of adaptive capacity within the three more formal systems – central facility, local healthcare system and interconnected systems (A1, ~A2, A3, A4). In this identified pathway, there is no external support provided to healthcare or other sectors, demonstrating again a situation of local resilience (~HH, ~OH).

This pathway is demonstrated most closely in the case conducted at a hospital in Warangal, India, during a flash flood event in 2023. The hospital was in a low-lying area on the outskirts of Warangal city, adjacent to some low-income, informal neighbourhoods. Due to the rapid expansion of the city, drainage infrastructure was reportedly not complete in this area. In July 2023, after three days of heavy rain, an external-facing wall in the hospital compound was damaged, reportedly by people living beside it with the motivation of alleviating substantial flooding in their neighbourhood. The broken wall released large volumes of water into the hospital grounds and submerged most of the facility's ground floor.

The response by the hospital mobilised both the facility's internal resources and connected them to the surrounding healthcare system. Due to the large size of the hospital, they were able to shift many patients to higher floors and move critical patients to nearby facilities, with local farmers aiding in transportation across flooded access roads. Shifting of patients to other hospitals and to the upper floors of the hospital had to happen without any power supply as the floods had destroyed the powerlines and the power generatorcould not function due to inundation. Other facilities in the area were also vulnerable to flooding, but the larger facilities had flood protections and were not as badly affected as the central hospital due to the damaged wall. The interconnected systems in the area were repaired quickly, but the hospital also quickly restored its own boreholes and generators, which provided multiple options for power and water continuity.

In contrast, in the community, the slum neighbourhoods were reportedly 'washed away' by the floods, but many people received healthcare from the hospital, as it provided free and affordable services. Increased numbers of patients arriving with conditions such as skin and eye diseases, fevers, colds and injuries. The community faced serious impacts and did not benefit from the protections of its own, independent resilience – due to many complex contextual and political factors – but many community members received support from the hospital in the short-term. After the incident the hospital invested heavily in providing the stormwater drainage systems to avoid future flooding.

The formal systems in this pathway had sufficient capacity to respond and adapt to the event, despite high exposure, leading to the presence of both outcomes (i) service continuity and (ii) final system state. This implies that if three out of the four systems have strong adaptive capacity, then local resilience can exist. It may also suggest that the community – often comprised of more informal networks – can be bolstered by connecting to stronger formal systems.

Pathway 3: Healthcare-specific capacity and external support

Resilience pathway 3 is characterised by four vulnerable systems (V1, V2, V3, V4), with local adaptive capacity at the central healthcare facility, although not in the local healthcare system, community or interconnected systems (A1, ~A2, ~A3, ~A4). In contrast to the first two pathways, it also has some external support to healthcare but not to other sectors (HH, ~OH). This pathway demonstrates a strong healthcare strand, combining health-focused support and adaptive capacity, can be a resilient pathway.

Pathway three is exemplified in Nsanje (north), Malawi, during Cyclone Freddy in 2023. The case study location is highly exposed to floods and cyclones, and the four systems of interest were sensitive to the event. The hospital itself demonstrated some effective strategies to respond, but in the wider healthcare system, community and interconnected systems, there were limited adaptive capacities. Many homes, livelihoods, roads and other infrastructures were damaged, and repairs took a long time (relative to the dataset).

At the hospital, a particularly important adaptive strategy was the medical staff collaborating with community health workers to respond to cholera outbreaks and provide outpatient care. After the event, an emergency meeting was called, and a community needs assessment was conducted to plan a targeted response. Staff distributed chlorine for water treatment, provided education on hygiene for diarrhoea and malaria prevention, and conducted daily assessments to prevent outbreaks, effectively preventing disease spread and reducing hospital admissions. An NGO provided direct medical supplies and personnel assistance, including nurses and clinicians on one-year contracts, helping to reduce waiting times.

The hospital itself escaped major damage in the event, and essential services were able to continue, but soft systems disruptions persisted for one year, such as the stocking of medical supplies. These ongoing disruptions were partly attributed to hospital staff being frequently required to go out into the local community and to travel to help other communities affected by

Cyclone Freddy. The final state was a system operating as before the event, although this took approximately a year to achieve due to nearby communities with low adaptive capacities and high healthcare needs.

Pathway 4: High vulnerability, low adaptive capacity and extensive external support

Pathway 4 holds for outcome (ii) successful final state – defined as either transformation of the central facility or a return to stable and effective functionality. This pathway does not hold for outcome (i) the continuity of core healthcare services during an EWE. It is characterised by a presence of vulnerability in all four systems (V1, V2, V3, V4) and an absence of adaptive capacity in the central facility, the community and the interconnected systems (~A1, ~A3, ~A4). Causal condition A2 'adaptive capacity of the local healthcare system' is not included in the pathway as either present or absent; that is, within the Boolean minimisation the outcome occurs regardless of whether A2 is present or absent within this configuration. External support to both healthcare and other sectors is present (HH, OH).

This pathway is exemplified in four cases: Mocoa, Colombia; Siargao, Philippines; Dinagat, Philippines; Nsanje District (south), Malawi. All cases comprise systems and communities vulnerable to EWEs, with limited adaptive capacity relative to the vulnerability of the hazard they faced. In all cases, the repair and restoration of the central facility, local healthcare clinics, and interconnected systems depended heavily on the external support provided by national and international humanitarian responders. Similarly, the health and wellbeing of the community was reliant on external support, most acutely in the immediate days and weeks following an event.

This pathway is not robust in terms of service continuity as many facilities experienced heavy disruptions to infrastructure, staff, medical supplies or patient demand to an extent far beyond local capacity to 'bounce back' and adapt. In most cases, external support coordinated at the national or local level was present. In Mocoa, responders set up community health clinics to take pressure off the local facilities. In the Philippines, national emergency responders set up field hospitals and cholera units in Dinagat and Siargao, which enabled local staff to conduct outreach in communities and rural areas.

The successful final state after external support had been provided was either a return to normal functionality for effective systems, or transformation. In Mocoa and Siargao, transformation of the central facility was achieved – after multiple years, the hospital was substantially upgraded. In both cases, plans had been made for the upgrades prior to the EWE but only enacted after the event. These were the main examples of major 'transformation' in the dataset.

Simplified pathways

As well as full (complex) pathways, fsQCA also finds parsimonious pathways comprising the most simplified ways of indicating an outcome. Table 7 below shows that for both outcomes, the adaptive capacity of the central facility (A1) was a common causal condition. For outcome (ii), humanitarian healthcare support (HH) was also a highly common causal condition in pathways to a successful final state.

Table 7: Parsimonious pathways for outcomes (i) and (ii)

Causal conditions	Outcome indicator (i) service continuity		Outcome indicator (ii) successful final state		Cases indicated
	Raw coverage	Consistency	Raw coverage	Consistency	
A1	0.815	0.855	0.646	1	England, Norfolk; India, Warangal; Colombia, Barranquilla; Malawi, Nsanje (north); Tanzania, Ifakara; Tanzania, Mafia; Vietnam, Huong Khe; Vietnam, Huong Son; Vietnam, Tran Yen
HH	N/A	N/A	0.652	0.857	Colombia, Mocoa; Philippines Dinagat; Philippines, Siargao; Tanzania, Katesh; Malawi, Nsanje (south); Vietnam, Huong Khe; Vietnam, Huong Son; Vietnam, Tran Yen

DISCUSSION

The fsQCA results reveal four distinct pathways through which healthcare system resilience unfolds in practice, with different configurations of vulnerability, adaptive capacity and external support across the four system levels. Our findings provide empirical support for the widely asserted but rarely operationalised claim that health system resilience is inherently multi-scalar (14). Rather than single-level determinants, resilience outcomes emerge from specific cross-scale configurations of vulnerability and adaptive capacity. These configurations reveal partial substitutability across levels: weaknesses at one scale (e.g. community capacity) can be offset by strengths at others (e.g. facility or system-level capacity). The fuzzy-set approach has enabled us to identify these specific, evidenced pathways through which resilience is assembled across systems and scales.

By analysing two different outcomes, three pathways were found to support healthcare service continuity during an EWE, all characterised by the presence of local adaptive capacity within formal healthcare systems. Pathway four did not hold for service continuity but did for the second outcome of interest—successful final state. In this pathway, local capacity sufficient to be robust to the magnitude of the event was not present; although service continuity was not maintained, a well-functioning final system state was still achieved. A key insight from this dynamic is the presence of an implicit threshold beyond which local systems are not robust and therefore unable to sustain resilience autonomously. This suggests that in settings characterised by high multi-system vulnerability, resilience depends on the mobilisation of external support, meaning that resilience is not simply a property of local systems, but a function of their position within wider support networks. However, humanitarian support is not typically conceptualised as integral to resilience, which is often associated with internal capacity and the ability of local systems to cope with disruption (21). Yet, we see this type of resilience – characterised by an external intervention – as aligned with the ‘resilience-by-intervention’ concept, proposed as an alternative to ‘resilience-by-design' (22). These terms, developed by Mahoney and colleagues in the context of food supply chain management (22), mean in practical terms that 'resilience-by-design' builds internal self-sufficiency to handle disruptions autonomously, while 'resilience-by-intervention' relies on external emergency relief to rescue a system when it fails. We see both dynamics within our dataset and, at a practical level, our findings align with the need for coordination and phased escalation across scales when local capacity is exceeded during disasters (23).

At a more granular level, the research highlights the critical role of healthcare staff (medical and non-medical), both in sustaining disrupted systems and in absorbing the burden of response. Recent scholarship has identified the health workforce as a central component of climate and disaster resilience, with system performance contingent on staff capacity, wellbeing, and ability to operate under stress (24). Our study supports this, with qualitative vignettes across cases demonstrating how staff morale, wellbeing, and physical and mental health become critical constraints during EWEs. Impacts on staff members’ homes and families frequently restricted their ability to work, with this combination of personal and professional disruption compounding pressures on wellbeing. Healthcare systems that maintained functionality during EWEs consistently relied on staff working longer hours in response to increased demand. In practice, both local and humanitarian staff are integral to healthcare system adaptive capacity, and the maintenance of service continuity often depended on the goodwill and morale of frontline workers. Measures to support and sustain the workforce are therefore likely to be a key component of resilience building.

In considering the limitations of the study, validation through key informant interviews was used to ensure that case studies reflected real impacts and responses, and to reduce potential bias in the literature, which can be influenced by factors such as reporting incentives. However, identifying suitable informants with detailed local knowledge proved challenging in some cases, meaning not all cases could be validated and some were excluded from analysis. We also purposively collected data on infrastructure systems and healthcare facility characteristics, though these data were often limited or not comparable across cases. The range of EWE types included was similarly constrained by data availability, despite efforts to ensure diversity.

We also note that the complexity of healthcare system resilience to EWEs creates challenges for comparing case studies. By using fsQCA, we sought to structurally analyse this complexity through identifying common configurations of causal conditions and outcomes. However, this necessary simplification limits the nuanced detail captured in the generalised pathways, and the analysis allows us to claim only that the four pathways are those evidenced within our dataset; other resilience pathways likely exist in practice. Consequently, conditions that appear uniform or neutral across certain pathways—such as the role of community adaptive capacity in the pathways —should not be viewed as analytically irrelevant. Unlike conventional quantitative methods, configurational approaches do not require conditions to exert an independent effect. We retained the community system within our analysis primarily due to its central relevance to our theoretical framework. While our current pathways do not show the community level independently driving the final outcomes, it is likely still exerting a configurational influence by interacting with the other systems. Isolating the influence of community-level factors may require a broader study with a larger sample of cases.

Building on this study, further research is needed to better understand how different conditions and complex systems interact to produce resilience in practice. In particular, greater attention should be given to the role of staff and institutional dynamics in absorbing the impacts of extreme weather. Investigation into the role of physical infrastructure—including the location and structural characteristics of healthcare facilities—also represents an important avenue for future work. Engineering disciplines have developed more quantitative approaches to concepts such as vulnerability, which could inform health systems research (25), though integrating technical and social perspectives remains a key challenge. Finally, in a context where globalisation and international humanitarian support may become less predictable, strengthening national and local capacity to respond to extreme weather events is likely to become increasingly important.

CONCLUSIONS

This study applied fsQCA to 18 case studies of healthcare system responses to extreme weather events across diverse global contexts. Using a system-of-systems approach, the findings show that resilience emerges from specific cross-scale configurations of vulnerability and adaptive capacity spanning facilities, local health systems, communities, and interconnected infrastructures. These results demonstrate how resilience is assembled across levels in practice, with strengths in some parts of the system partially compensating for weaknesses in others, and point to the need for deliberate investment in cross-scale coordination rather than isolated system improvements.

The analysis also identifies a threshold dynamic in which locally available capacity becomes insufficient when vulnerability is high across multiple system levels, requiring external support to enable resilience outcomes. Notably, such support is more closely associated with recovery than with maintaining service continuity, suggesting limits to what can be sustained once systems are overwhelmed and the importance of planning for timely escalation. Across cases, the ability to respond was also strongly shaped by the actions and endurance of healthcare workers, highlighting workforce capacity as a critical and sometimes under-recognised component of resilience. Together, these findings position health system resilience as a multi-scalar and human-mediated process, underscoring the need to strengthen local capacities, embed systems within wider networks of support, and prioritise the workforce as central to effective preparation for and response to increasingly severe shocks.

DECELARATIONS

ETHICAL APPROVALS

All interview participants provided informed consent to take part in the study. The study underwent ethical review at major partner intuitions in the research consortium and national committees where relevant, with approval codes: University of Leeds (EPS FREC - 2025 1843-3136), University of East Anglia (ETH2324-2246), Hanoi University of Public Health (413/2024/YTCC-HD3), Mbarara University of Science and Technology (MUST-2024-1764; UNCSTHS5370ES), Mwanza Intervention Trials Unit (NIMR/HQ/R.8a/Vol.IX/4818), and Kamuzu University of Health Sciences (P.08/24-0984). All procedures performed in this study involving human participants were conducted in accordance with the ethical standards of the institutional research committees and with the 1964 Declaration of Helsinki and its later amendments.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

The datasets used and analysed during the current study are available from the corresponding author on reasonable request. Data summaries of each case study are provided in the Supplementary Information files.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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AUTHOR CONTRIBUTION STATEMENT

RES, JB, PH[3], EZS, and PH[1] were involved in the conception of the work. All authors were involved in the research design through two collaborative workshops. All authors were involved in the data collection. RES, PH[1], FGA, JB, TTTH, SAK, WL, DM, FM, SM, JN, MN, SP, YMS contributed to data analysis and interpretation. RES drafted the article with input from PH, and all authors contributed to critical revision and final approval of the article.

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