Pathways of resilience: a fuzzy-set Qualitative Comparative Analysis of healthcare systems resilience to extreme weather events

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Coversheet statement

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ABSTRACT

Background

Increasing frequency and intensity of extreme weather events threaten healthcare services globally, with particularly intense risks to low-resource regions. Evidenced pathways for building and enacting resilience in complex health systems are under researched. Literature on resilient healthcare is dominated by infections disease outbreaks and lacks synthesised insights from weather-related disruptions and real-world practice.

Methods

This paper responds to these gaps by presenting findings from a novel dataset of 18 case studies conducted in a range of global contexts. The cases were built around understanding how extreme weather events have impacted and interacted with four interrelated systems – a central healthcare facility, local healthcare system, community and interconnected systems – building on the WHO's operational framework for climate resilience healthcare systems. The study applied a fuzzy-set Qualitative Comparative Analysis to assess the complex configuration of conditions related to two outcomes: service continuity and healthcare facility recovery state.

Results

The results demonstrated four distinct pathways through which resilience was enacted, with different configurations of vulnerability, adaptative capacity and external support. The pathways show that local adaptive capacity is crucial for ensuring service continuity during disruptive weather phenomena. Where local adaptive capacity is not present, or it is overwhelmed by the scale of the extreme weather event, external support from national and international responders can support resilience indicated by a successful final system state but not service continuity. Local experiences show the critical importance of staff wellbeing and institutional coordination for absorbing and responding to weather-related disruptions.

Conclusion

The pathways presented in this paper represent reliable modes of resilience in the dataset and provide novel insight into the gap of practice-based, locally relevant knowledge on building healthcare resilience.

INTRODUCTION

Extreme weather events (EWEs) impact healthcare 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 hard and soft components of healthcare systems and often trigger secondary hazards (2). Demands for building more resilient healthcare are growing, although the concept's meaning and application are 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 events have important cross-learnings for systems facing extreme weather, the nature of the disruptions is distinct (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 congruence with influential scholarly definitions from the mid-2010s (10,11). A synthesised definition reads: '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 emphasises the nature of resilience as an ability or capability, and how it exists in complex system interactions, particularly formal health systems, community health systems and interconnected systems (4,12,13).

Other authors highlighted the lack of practice-based knowledge (14). Research with global experts proposed a future research agenda to enable its application in practice (15). This agenda included understanding the linkages between societal and health system resilience, measuring systems' dynamic performance, and the effect of governance on the capacity for resilience. Another study reviewed learning tools used in real healthcare settings to inform and support resilience (16). Such tools are based on processes of prompting stakeholder reflection on organisational adaptations and simulating 'real life' events, yet their effectiveness remains under studied.

Therefore, an inferred knowledge gap exists in understanding how resilience unfolds in practice – particularly in places most vulnerable to the effects of EWEs – through a system of systems lens. In this article, we contribute to closing this gap by analysing a novel dataset of diverse, global case studies on the impacts and responses of district healthcare systems to extreme weather events. 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 (17,18). The results identified four resilience pathways, which we illustrated using qualitative insights from the full narrative case studies. Data collection and analysis were underpinned by the logic of the WHO framework, ensuring inter- and intra-case coherence. We conclude this study by discussing its novel implications for both theory and practice.

METHODS

This study was conducted by the RESHAPE Project consortium, funded by the UK's National Institute of Health Research (NIHR204820). It underwent ethical review at major partner intuitions in the 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).

Patients and the public are involved in other studies being undertaken by the RESHAPE Project consortium, however as this study was focused on healthcare system governance, we engaged with specifically healthcare facility managers and coordinating staff. The research presented in this paper followed a fsQCA approach, an apt method for answering the question: what combination of conditions leads to outcomes indicating the presence of healthcare system resilience?

Study design

We developed the 'system of systems' model 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. The consortium comprises 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 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.

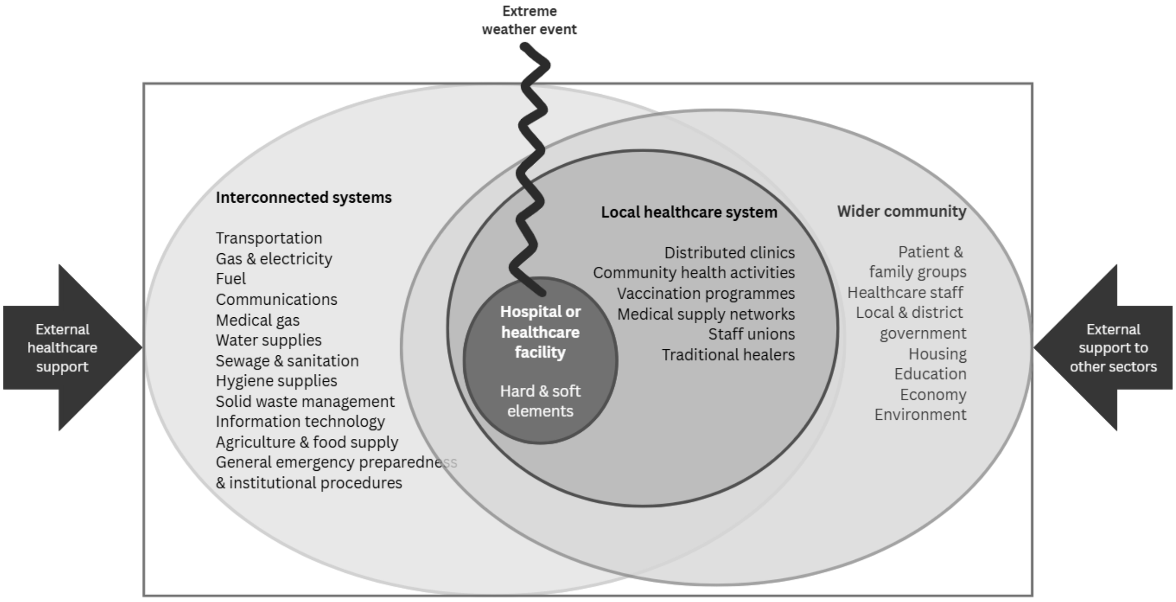

Figure 1: Conceptual healthcare systems model, showing the relations between four systems of focus in this study: central facility - comprised of hard and soft systems components - local healthcare system, wider community and interconnected systems. The jagged line represents the disruptive impacts of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

Case compilation

Case studies were identified based on a set of criteria (detailed in online supplemental Tables S1; S2) designed to ensure both data comparability and recall memory of key informants. Selection was therefore based on an EWE and central healthcare facility meeting these criteria, as well as the availability of documentation and key contacts. A range of cases from higher resource to lower resource settings were selected designed to maximise case diversity and cross-contextual learnings. Given the focus of this research was low resource setting, most cases are based in such settings.

A total of 27 cases were identified across 13 countries, including the five partner countries, although not all cases were validated sufficiently for inclusion in the fuzzy-set analysis, shown below in Table 1. A consistent approach was taken to compiling a case following a set protocol and data collection proforma (shown supplemental (Tables S3; S4). The first stage involved a literature review by the research team of grey and academic documentation of the EWE. Common literature types included local media articles, NGO reports, government announcements, and studies on climatic or geographic vulnerability.

To validate the literature-based case study, verbal interview or written document review by at least one professional with direct experience of the event, such as healthcare workers, facility managers, government officials or emergency responders, was required. In most cases an interview was conducted, either face-to-face or online, but in some instances, informants validated cases by providing written contribution to the data collection table. The total number of validated cases included in the final analysis was n=18.

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

Set definition

Building on the concepts included in stage 3 of the WHO framework (9), we selected an initial 16 causal condition sets, based upon the concepts of exposure, sensitivity, adaptive capacity, and the additional element of external (or humanitarian) support, across the four system levels (Figure 1). Three outcome sets were proposed – (i) service continuity; (ii) final system state; (iii) time taken to reach final state, based on stage 5 in the WHO framework and wider resilience literature (5, 19). All sets were initially defined based on theoretical concept definitions, aligning to the fsQCA approach. For example, exposure of the central healthcare facility was defined from 0 – a complete absence of exposure to 1 – total exposure to the EWE.

Set definitions were iterated into their final form by following the calibration process and using the collaborative workshops to ensure adjustments were appropriate across contexts (18). This process led to exposure and sensitivity conditions being consolidated into an overarching vulnerability condition, and the external support variables being consolidated into two broad sets: healthcare-specific external support and support provided to other sectors. Additionally, the three outcome sets were reduced by merging (ii) the final state and (iii) the time taken to reach the final state. The consolidation process for causal condition and outcome sets was carried out to ensure an optimal number of sets for insightful/successful analysis. Overall, this 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 (further threshold definitions can be found 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.

Set scoring

Fuzzy scoring is based on fsQCA principles that a condition or outcome will exist between complete absence (0) and presence (1). Each set is defined by establishing the thresholds of 0 and 1, as well as intermediary thresholds, commonly 0.33 and 0.67 (18, 20, 21). The process of scoring took place over four rounds. The first round was conducted by the researchers responsible for each case study, based on theoretical set definitions and training sessions on scoring, both by the first author. The subsequent rounds 2, 3 and 4 were completed by the first author. These rounds involved (2) reviewing and repeating all scores to ensure a consistent approach, (3) consolidation of the initial causal conditions and outcomes, and (4) adjusting scores relative to the dataset based on calibrated set definitions.

Scoring incorporated the magnitude of the EWEs and temporal elements, to enable comparability between diverse cases. This is described in the set threshold definitions in Tables 3, 4 and S6. Since the method uses set definitions calibrated to the dataset, descriptions of response time and event magnitude are contextual and scaled relative to the characteristics of the 18 cases.

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. 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.

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, making them salient across the dataset, detailed in Table 6. Visual representation of the pathways is shown below in Figure 2. In the following sub-sections, we qualitatively describe the four pathways using 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

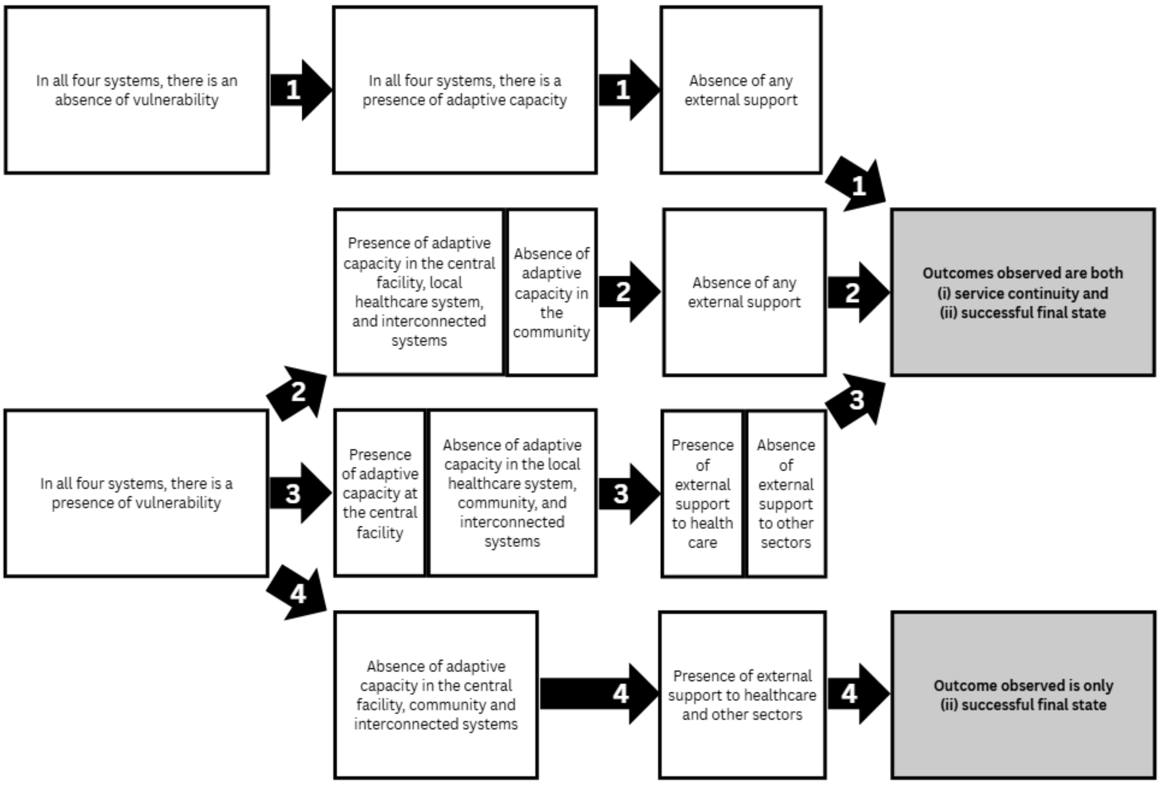

Figure 2: Four resilience pathways resulting from the fuzzy set Qualitative Comparative Analysis. Pathways 1, 2 and 3 all hold for both outcomes (i) & (ii), whereas pathway 4 holds only for outcome (ii).

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 (Ragin, 2008).

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 absent (~V1, ~V2, ~V3, ~V4). 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 is provided to healthcare or other sectors (~HH, ~OH). This pathway acts as one type of theoretical scenario where systems can cope with disruption without external support.

For each pathway, the fsQCA associates one or more cases that closely align with the configuration of causal conditions and outcome presence. Pathway one 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 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. Other actions, 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 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

Pathway 2 is characterised by high vulnerability within all four systems of interest (V1, V2, V3, V4). The adaptive capacity is split between an absence of adaptive capacity in the 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). No external support is provided to healthcare or other sectors, demonstrating again a situation of local resilience (~HH, ~OH). The formal systems in this pathway have sufficient capacity to respond and adapt to the event, 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.

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 director 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 completely destroyed the powerlines as the power generator also could 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 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 was not afforded the protections of its own, independent resilience – due to many complex contextual and political factors – but many received support from the hospital in the short-term. Subsequent to the incident the hospital invested heavily in providing the stormwater drainage systems to avoid future flooding.

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). 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.

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. 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. 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 conducive to 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

Pathways and outcomes

The fsQCA results described in the previous section reveal four distinct pathways through which healthcare system resilience unfolds in practice, with different configurations of vulnerability, adaptative capacity and external support. The four pathways are not proposed as universal or applicable in all contexts, but they are reliable and consistent configurations of causal conditions correlating to the chosen outcomes within our diverse dataset.

By analysing against two different outcomes, three pathways were found to hold for healthcare service continuity during an EWE, all characterised by the presence of local adaptive capacity in formal healthcare systems. Pathway four did not hold for service continuity but it did for the second outcome of interest – successful final state. Local capacity relative to the event magnitude was not present in this pathway and, although service continuity was not supported, a well-functioning final system state was possible.

These findings correlate with recent literature arguing that resilience is not only an outcome but an ability or capability (4,13). Our two fsQCA outcomes did not directly show the presence or absence of resilience, but rather they indicated whether a broader resilience existed across multiple causal conditions and systems throughout the pathway. While adaptive capacities and outcome state were commonly associated with resilience in our findings, the role of contextual vulnerability and external support also contributed.

Resilience in practice

Humanitarian support is not often considered integral to resilience, as the resilience concept is associated with high internal capacity and the ability of local systems to cope with disruption (22). However, in our dataset external support was integral to resilience: only three cases did not have external support present. This is not an ideal resilience scenario – in cases where external support was relied upon, service continuity was not often present – but in practice it is a common occurrence and demonstrably can lead to a successful final state of the healthcare facility.

In our analysis, we treated exposure as how exposed a local system was to the expected EWEs in that region. No cases indicated that local facilities would prepare for catastrophes beyond what was expected in that context. As EWEs become increasingly intense, there is a question around whether local healthcare systems should prepare for all extreme scenarios, or whether connecting with national and international support systems can be an effective and realistic pathway of resilience for exposure to extraordinary events.

Our research highlights the critical role of healthcare staff (medical and non-medical), both the essential role they play in keeping disrupted systems functioning and the burden they are asked to absorb. Staff morale, wellbeing, and physical and mental health are concerns (can also be conceived as system 'bottlenecks') during EWEs. Cases show that the impacts of extreme weather on staff members' homes and families would often restrict their ability to work, and this combination of personal and professional disruption had compound effects on wellbeing. Healthcare systems that continued to function during EWEs always relied on staff working longer hours due to higher patient and operational demands. In practice, local and humanitarian staff play a vital role in healthcare system adaptive capacities. Innovative technologies, such as serious games, have potential for reducing the demands on personnel/human resources during system shocks (16).

Limitations

The complexity of healthcare system resilience to EWEs creates some challenges around comparability of case studies. FsQCA is an apt approach for simplifying this complexity into common configurations of causal conditions and outcomes. The simplification naturally limits the nuanced detail retained in the general pathways, but they are useful for drawing out ways in which combined systems work together to maintain core functionality and produce a successful final state.

Some methodological limitations were faced due to the highly localised nature of the data and the breadth of focus of the four systems of interest. As such, the central healthcare facility was positioned as a lens on the other three systems. This resulted in the most detailed information collected pertaining to the facility. Further, outcome indicator (ii) uses the facility as a proxy for the healthcare system's final state, which will be imperfect. In most cases, distributed healthcare clinics or programmes were found to be less resilient than the central facility.

Validation through key informant interview was designed to ensure case studies were reflective of real impacts and response to the EWE, and to reduce bias in the literature reporting which at times were influenced by disaster politics, for example the purpose of an NGO report may be to demonstrate positive impact to funders. Identifying key informants with local knowledge of the healthcare system and EWE of interest was challenging in some cases. As such, not all cases developed from the literature were able to be validated, which led to some being excluded from the main analysis. We purposively collected information on infrastructure services and hospital physical structures. However, this data was often not available or comparable. The range of included EWE types is also limited by access to data, although we attempted to include a diversity of weather events.

CONCLUSIONS

This study applied a fsQCA to 18 in-depth case studies of healthcare system resilience to EWEs. A range of global contexts were included, with most cases conducted in low resource settings where vulnerability to weather-related disruptions is often higher. A few higher resource cases were also included to increase the diversity and cross-learnings in the dataset. We contribute to the gap in practice-based knowledge of how healthcare system resilience unfolds after extreme weather disruptions. Using a system of systems conceptual model, this research shows some of the multiscale dynamics that shape resilient outcomes. This helps to ground the rich theoretical literature in this space and provides strategic insights to healthcare professionals wishing to build resilience in their local setting.

Building on this study, future research is needed on how different conditions and complex systems come together to produce resilience in practice. Important areas for greater attention are the role of staff and institutions in absorbing the impacts of extreme weather. Investigations into the role of physical infrastructure - including specific locations and structural characteristics of buildings – is another promising avenue for understanding practical pathways for building local resilience. Engineering fields have developed more quantitative measures of concepts such as vulnerability which could be adapted into this health systems field (23), but integrating knowledge from technical and social disciplines remains a challenge in practice. Finally, as globalisation and international humanitarian support become less secure, the importance of national and local capacity in responding to extreme weather disruptions are even more pressing.

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