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Enhancing Heatwave Resilience in the UK: Insights and Strategies from Stakeholders

Sara Mehryar, Candice Howarth

Abstract: Heatwave events are on the rise in the UK and Europe, with projections indicating increased frequency, intensity, and persistence. Despite the escalating risk, responses and adaptation strategies are lagging behind, exacerbated by a lack of comprehensive understanding of heat-related risks and effective measures. This paper addresses this gap by employing a structured approach combining Forensic Disaster Analysis with Fuzzy Cognitive Mapping (FCM) to analyse the UK's response to the heatwaves of summer 2022 that claimed 3,000 lives. 38 stakeholders from various sectors involved in the response to these heatwaves were interviewed, and their cognitive maps were developed to capture local knowledge and perceptions regarding the causes, impacts, and actions taken before, during, and after the heatwaves. Through FCM analysis, cascading effects of heatwaves and factors amplifying negative impacts are identified, along with effective and missed mitigating measures. Moreover, the study compares heat risk perceptions among different stakeholder groups, highlighting important variations in perspectives, preferences, and priorities with implications for heat adaptation policy design. The findings contribute to enhancing understanding of heatwave risks and the actions that must be taken in preparation for future heatwaves in the UK, informing more robust and holistic policymaking for heat risk reduction.

1. Introduction

Heatwaves are becoming increasingly prevalent in the UK and other European countries (Ma et al., 2020; Xu et al., 2020; Tripathy and Mishra, 2023), with projections indicating that they will become more frequent, persistent and intense in nearly all inhabited regions (Domeisen et al., 2023). Analysis by Christidis et al. (2015) shows that extremely hot summers[1], which would occur every 50 years in the early 2000s, are now expected to occur twice a decade, indicating a tenfold increase in the frequency of these events. Human contribution to the increasing frequency of heatwaves is also evidenced by studies such by Stott et al. (2004), which concludes that human influence has at least doubled the risk of a heatwave exceeding its mean threshold. Vautard et al. (2020) also show that in western Europe, the July 3-day heatwave in 2019 would have had a return period of more than 1000 years without human forcing, whereas it currently has a 50–150-year return period in the current climate.

The UK's third Climate Change Risk Assessment (CCRA3), published in 2022, identified risks to human health, wellbeing and productivity from increased exposure to heat as one of its priority risk areas (UKCCRA3, 2022). The vulnerability of UK citizens to extreme heat was evident during the 2022 summer heatwaves, with 2,985 excess deaths recorded during five heat periods over the course of the 2022 summer and more than 4000 heat-related deaths recorded in England for the entirety of 2022, the largest figure on record (UKHSA, 2023; ONS, 2023; Howarth et al., 2024). Despite their recent annual occurrence, responses to heatwaves, both individual and collective, as well as strategies for long-term adaptation, are not keeping pace with the escalating frequency of extreme heat events (Howarth et al., 2024). This lag in response and adaptation is mainly due to the lack of comprehensive knowledge and credible evidence regarding heat-related risks for various stakeholder groups and context-specific adaptation and resilience measures. Increasing frequency and intensity of heatwaves in the UK presents a new and unprecedented climate risk in comparison to historically prevalent issues such as flooding and storms. This highlights a critical knowledge gap concerning the nature, causes, and impacts of these events, as well as efforts for risk reduction, adaptation, and

[1] Anomalies relative to the 1961-1990 base period.

responses. Brimicombe et al. (2021) argue that extreme heat remains largely an invisible risk in the UK as 'silo' thinking in extreme heat research and an inherent bias in framing extreme heat only as a health sector risk hinder robust and holistic policy making for heat risk reduction. Additionally, Howarth et al. (2020) call for a step change in the UK's climate risk governance, moving from the current physical and socio-economic risk characterizations to a more inclusive approach that incorporate socially and politically defines climate risks at the local scale. They argue that this approach would better align with the impacts experienced locally and the needs of stakeholders.

In response to these challenges, this study employs a structured and systematic approach to analyse the UK's response, preparation, and risk reduction efforts following the heatwaves of summer 2022. By combining the 'Forensic Disaster Analysis' methodology with a system mapping technique called Fuzzy Cognitive Mapping (FCM), this integrated approach aims to capture the knowledge and perceptions of local stakeholders involved in the UK's response to the heatwaves in summer 2022. Specifically, it seeks to understand stakeholders' perspectives on the causes and impacts of these events, as well as the actions taken or lacking in response, preparation, and heat risk reduction.

Through the graph theory analysis used in FCM method, we identify the cascading effects of heatwaves perceived by relevant stakeholders in summer 2022, and highlight factors that amplify the negative impacts, effective mitigating measures that were implemented as well as potential mitigating measures that were missed in preparation and response to these heatwaves. FCMs are also utilized to compare heat risk perceptions among different stakeholder groups involved in the response, highlighting similarities and differences in their perspectives, preferences, and priorities.

Section 2 provides background and context for the methodologies and the case study used in this research. Section 3 elaborates on the application of the methodology, i.e., FCM combined with forensic disaster analysis approach, in the case study. Section 4 presents the results of the FCM analysis, and section 5 discusses limitations, potential future studies, and concluding remarks.

2. Background and context

Forensic disaster analysis borrows the term 'forensics' from the field of criminal investigation and applies it to study the 'root causes' of disaster events, such as disasters caused by natural hazards, industrial accidents, and infrastructure failures. Forensic analysis involves the systematic examination and interpretation of evidence to understand past events (Horvath and Meesig, 1996). It is premised on the belief that problems are best solved by attempting to correct or eliminate root causes, as opposed to merely addressing the immediately obvious symptoms (Burton, 2010). Similarly, *forensic disaster analysis* is a process of systematic and holistic analysis of a large natural hazard or human-caused event, and its causes, impacts, responses, and aftermath with the aim of understanding what happened and why it became a disaster, as well as identifying lessons learned for future risk reduction, preparedness, and response efforts (Burton, 2010; Venkateswaran et al., 2020). Typically, it employs a multidisciplinary approach, integrating social, environmental, and technical assessments by collecting and analysing various types of data. The outcome of forensic disaster analysis is expected to offer a comprehensive understanding of the event, highlighting strengths and weaknesses in response and resilience efforts, and informing future disaster risk reduction strategies (Venkateswaran et al., 2020). It often involves collaboration between government agencies, researchers, emergency responders, community organizations, and other stakeholders to ensure a thorough and objective examination of the disaster event.

Various frameworks and methodologies have been developed to structure and support the process of forensic analysis in the aftermath of a major disaster, aiming to generate insights and learnings for stakeholders involved. Among the most widely applied frameworks and tools are the Forensic Investigation of Disasters (FORIN)[2], Post-Event Review Capability (PERC)[3], Detecting Disaster Root Causes (DDRC)[4], and Near Real-Time Forensic Disaster Analysis[5] (Fraser et al., 2016; Venkateswaran et al., 2020; DKKV, 2012; Wenzel et al., 2013). Common key components of these analyses include (Mendoza and Schwarze, 2019; Ferreira et al., 2023):

1. cause determination: Investigating the underlying factors and events that led to the disaster,
2. impact assessment: evaluating the extent of the damage and loss caused by the disaster and why it had the impacts it did,
3. response evaluation: assessing the effectiveness of emergency response efforts, as well as anticipatory risk reduction and preparedness before the event, and
4. resilience and adaptation analysis: identifying strategies to enhance the resilience of communities, the environment, and infrastructure and adapt to future similar disasters.

In addition, forensic disaster analysis adopts a holistic and systemic approach, integrating multidimensional aspects of risk and resilience. It is typically conducted within a short period after a disaster, but not immediately, to avoid disrupting response activities. This timing leverages the fresh memory of the event among key stakeholders.

Fuzzy Cognitive Mapping is a computational modelling technique used to represent and analyse complex systems (Papageorgiou and Salmeron, 2012; Özesmi and Özesmi, 2004; Mourhir, 2021). It is depicted through signed and directed graphs, comprising nodes and weighted interconnections. Nodes represent the variables or concepts within the system (e.g., temperature or public trust), and weighted connections represent the *'causal relationships'* among these concepts (Kosko, 1986). These relationships are weighted with fuzzy values ranging from −1 to +1, where negative values close to −1 represent a strong negative influence, positive values close to +1 illustrate a strong positive connection, and values close to 0 mean that there is a weak relationship between the linked concepts (Carvalho, 2013). Representing causal relationships is an important aspect of FCM as participants provide quantification for connections based on their perception of the cause-and-effect relationships among concepts—i.e., how interrelated concepts affect one another and provide feedback (Singh and Chudasama, 2017).

FCM has been successfully used in a wide range of disaster studies, including assessments of flood risk and resilience (Mehryar and Surminski, 2022; Romero-Lankao and Norton, 2018), community preparedness to cyclone (Singh and Chudasama, 2017), coastal vulnerability to erosion (Ahmed et al., 2018), air pollution (Anezakis et al., 2016), and water scarcity and drought (Mehryar et al., 2017; Mehryar et al., 2020). This method is increasingly employed in managing environmental challenges and disaster risks due to its ability to 1) capture stakeholders' knowledge, perceptions, and beliefs for evidence-based decision-making, and 2) model complex and hard-to-model qualitative and subjective concepts and their causal relationships (Singh and Chudasama, 2021; Gray et al., 2019).

FCMs are often developed through participatory processes, encompassing individual interviews or focus group discussions (Gray et al., 2015; Voinov et al., 2018) which leverage the context-specific knowledge and experiences of local stakeholders to model and understand complex systems. This is particularly valuable for addressing scientifically unknown aspects of the system, such as those

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1 developed by International Council for Science (ICSU), International Social Science Council (ISSC), and United Nations International Strategy for Disaster Reduction (UNISDR).
3 developed by Zurich Flood Resilience Alliance.
4 by the German Committee for Disaster Reduction (DKKV)
5 Developed by the Centre for Disaster Management and Risk Reduction Technology (CEDIM)

lacking reliable data (Mehryar et al., 2017; Ballesteros-Olza et al., 2022). Moreover, FCMs serve as a mental modelling technique to delineate how individuals perceive and reason about complex problems, along with their various priorities and preferences in decision-making (Hamilton et al., 2019; Mehryar and Surminski, 2022; Mehryar et al., 2020; Yang and Zhen, 2020). It, therefore, can facilitate inclusive and holistic decision-making processes by including such heterogeneities in perceptions, preferences, and priorities. The semi-quantitative aspect of FCMs allows for formalizing the knowledge in a logical framework and translating narratives and qualitative data collected during interviews into semi-quantitative models (Singer et al., 2017). Additionally, the causal relationships represented by FCMs are employed to model the interdependencies and dynamic interactions among components of a system (Romero-Lankao and Norton, 2018) and identify components that can be leveraged to enhance the overall function of a system (Rölfer et al., 2022; Singh and Chudasama, 2021).

FCMs can be analysed using graph theory or social network analysis techniques (Schuerkamp and Giabbanelli, 2022; Mago et al., 2013), such as analysing *indegree*, *outdegree*, *centrality*, *closeness*, *betweenness*, and *eigenvector* degree of nodes. The selection of the analysis depends on the type of system and the research questions. The 'indegree' represents the sum of weights of links entering the node, while the 'outdegree' signifies the sum of weights of the links exiting the node. Indegree and outdegree indicate the extent to which a node is impacted by and impacts other nodes, respectively. 'Centrality' is the sum of indegree and outdegree, representing a measure of the relative importance of the nodes in FCM analysis. The greater the centrality, the greater the potential for that node to affect change in the whole map/system. Therefore, centrality C(V) is calculated as follows:

$$C(V) = \sum (id(V) + od(V))$$

where id(V) and od(V) are the indegree and outdegree of node V, respectively.

Combining FCM with Forensic Disaster Analysis: In this paper, we demonstrate conducting a forensic disaster analysis with the FCM technique to facilitate structured learning and systematic knowledge gathering in the aftermath of a specific disaster. Given the urgency of forensic disaster analysis post-event, it's essential to employ a systematic yet flexible method to collect a wide range of data from different sectors and perspectives, analyse it, and draw meaningful conclusions that represent both the majority and the heterogeneity of experiences, making them suitable for policymakers.

FCM offers a structured approach for collecting data and analysing response and preparedness in the aftermath of disasters, integrating diverse knowledge, experiences, and observations to develop a unified understanding. Instead of focusing solely on isolated aspects, FCM enables a systemic approach by identifying and mapping the interconnections and causal relationships between various variables involved in disaster risk and response, providing a holistic perspective. Additionally, it translates qualitative data from interviews into quantitative and visualized models, facilitating easier comparisons of findings across different geographies and groups of stakeholders.

Hence, the structure of this study is grounded in a forensic disaster approach, centring on a specific disaster and aiming to identify root causes, impacts, effective actions and gaps in managing the disaster. It involves interviews guided by only a few questions and aims to derive insights for future similar events. The data collection and analysis are then conducted using FCM, which adopts a forensic approach, facilitating a deeper analysis process.

Case study: During the summer of 2022, the UK experienced five heatwave periods, marked by unprecedented temperatures exceeding 40°C in England (Howarth et al., 2024). In July 2022, the UK government declared a national emergency following the Met Office's first ever red extreme heat warning and the first level 4 alert heatwave (Met Office, 2022). At the time of these events, the UK's heatwave definition and alert system relied on a threshold temperature criterion. A heatwave would be declared when a location experienced a period of at least three consecutive days with maximum temperatures meeting or exceeding a heatwave temperature threshold (McCarthy et al., 2019). These thresholds varied by UK county, ranging from 25°C to 28°C, calculated using the 1991-2020 climatology of daily maximum temperature at the mid-point of the meteorological summer (15 July) (Met Office, 2022). However, in 2023, the UK Health Security Agency (UKHSA) and Met Office introduced a new heat-health alert system based on impacts. This system, running over a period from 1 June to 30 September each year, determines temperature thresholds based on the epidemiological evidence of the relationship between temperatures and mortality, observed impacts across the health and social care system during adverse weather episodes in the last decade, and the long-term weather trends of each region of England (UKHSA and Met Office, 2023).

On 19 July 2022, a record temperature of 40.3°C was documented at Coningsby, Lincolnshire. Additionally, seven weather stations across England recorded temperatures equal to or surpassing 40°C, with an additional 30 stations registering temperatures at or above 39°C (Met Office, 2022). During five heat periods that look place over the course of summer 2022 (16–19 June; 10–25 July; 30 July–5 August 8–17 August; 23–25 August), almost 3,000 heat-related excess deaths were recorded in England (UKHSA, 2023). Further experimental analysis indicates that for the whole of 2022, more than 4,500 people died in England due to high temperatures, the largest annual figure on record (ONS, 2023).

The heatwave experienced in the UK in July 2022 was a 1-in-1,000-year event, made 10 times more likely by anthropogenic climate change (Zachariah et al., 2022). Research by the Met Office (Christidis et al., 2020) suggests that exceeding 40 °C anywhere in the UK in a given year occur approximately every 100-300 years at present, however, without mitigating greenhouse gas emissions, this frequency could decrease to 3.5 years by 2100. Hence, heatwave periods (whether defined by new or old criteria) are projected to become more likely as our climate continues to change. 2022 was the warmest year on record for the UK, with 2023 being the second warmest (Met Office, 2024), and the 10 hottest years in the UK have all occurred since 2002. Hence summer 2022 was not an isolated anomaly but a consequence of a warming trend. The UK is not prepared to manage the impacts of extreme heat (Howarth et al., 2024) and we must learn lessons from the summer 2022 heatwaves to fill important gaps in knowledge, responses and governance on extreme heat.

3. Application of methods to case study

Immediately following the summer 2022 heatwaves, a stakeholder mapping process was undertaken by researchers of this project to identify relevant sectors and stakeholders involved in the UK's response to heatwaves. Over 65 stakeholders were approached from four main areas: government, first response, utilities, and civil society. Subsequently, 38 semi-structured interviews were conducted over a 3-month period in Autumn 2022. The responsible organizations identified in the stakeholder mapping included local councils, regional climate change agencies, the environment agency, the UK health security agency, fire brigades, ambulance services, water and energy companies, Transport for London/North, schools, the Met Office, and the British Red Cross. We interviewed stakeholders from most of these key sectors and organizations from local, regional, and national levels (table 1). Our sample also included representatives from London and Manchester at the local level, the Yorkshire and Humber region at the regional level, and England at the national level. These areas were selected as they were particularly affected by the heatwave in 2022 with temperature records broken in many of these locations (Met Office, 2022).

Table 1: Number of participants per location, organization type, and category of stakeholders.

Nr of participants per location	Nr of participants per organization type	Nr of participants per category of stakeholders defined in this study
England = 9 London = 12 Manchester = 8 Yorkshire and Humber = 9	Met office = 4 Governmental departments =2 British Red Cross = 3 Local authority = 10 Fire Brigade = 2 Ambulance service = 2 Transportation = 2 Water utility = 4 Public health = 2 Research institute = 2 Environment agency = 2 Farmers association = 1 Resilience forum = 2	Government = 18 First response = 9 Utilities = 4 Civil society = 7

3.1. Interviews and mapping sessions

All interviews were conducted online by two researchers and lasted approximately 60 minutes each. We utilized the online software 'Mental Modeler' to create maps in real time (Gray et al., 2013). During the interviews, a screen displaying the Mental Modeler interface was shared with participants and while one researcher facilitated the discussion, the other created the maps and asked clarifying questions regarding components of the maps. This approach facilitated map verification and validation by allowing interviewees to view the nodes and connections, ensuring that the maps accurately reflected their thoughts. We conducted interviews until we achieved data saturation for each location, meaning we gathered enough information to establish a shared narrative and draw conclusions from the participants' FCMs with a number of interviews providing similar insights.

During the interviews participants were asked four broad questions:

1. Tell us about your experience of the 2022 summer heatwaves (15-17 June, 16-19 July, 9-15 August). How did it affect [name of city] and your environment? (impact in FCM)
2. What makes heat risk and its impacts worse for your city? (causes/exacerbators in FCM)
3. What went well? What were the strengths in response to the heatwave? (actions taken/strengths in FCM)
4. What didn't go so well? What were the challenges or weaknesses? (Gaps/Inactions in FCM)

Each question led to a discussion with participants, allowing them to share their experiences and observations. Impacts, exacerbating factors, actions, and gaps were captured from stakeholders' responses to respective questions, and integrated into the map as new nodes linked to the focal point, 'extreme heatwave'. Often, additional clarifying questions were posed after the initial inquiries to encourage participants to identify further relationships among the concepts. For instance, if a participant mentioned "increasing vulnerable population" in response to the second question, we would encourage them to consider how vulnerability influences the impacts of a heatwave, prompting them to mention other connections, for example, to "underlying health conditions" or "poor housing conditions". In this way, the networks were constructed within the online tool by one of the interviewers, who consistently verified them with participants.

After defining the whole network, participants were asked to assign a weight to the connections to show the degree of importance of each concept. They were first asked to weigh the connections from the focal node to impact, exacerbator, actions, and gaps separately and then to provide a weight for each of the interconnections. A 5-point Likert scale was used to weight the connections, which are equivalent to ‘very low’, ‘low’, ‘medium’, ‘high’, and ‘very high’ in the linguistic value system.

3.2. Post-processing FCMs

All the visual maps created in Mental Modelers can be exported in the form of adjacency matrices in which the concept/nodes are listed on the vertical and horizontal axes on a spreadsheet. The weight of connections, as assigned by participants, are shown by the values in the cells of the adjacency matrices. These values should be normalized between −1 and +1 within the adjacency matrices.

Homogenization and aggregation: In this step, the concepts gathered from separate interviews and coded into individual FCMs are homogenized. This involves identifying concepts with similar meaning but different wordings and establishing common terminology. It includes concepts with minor spelling variations, e.g., ‘people behaviour’ and ‘human behaviour’, alongside concepts that can be grouped under an overarching concept depending on the study’s required level of detail, e.g., ‘heatwave warning’, ‘early warning system’, and ‘forecasting heatwave’ can be merged into ‘forecasting & early warning system’. This process reduces the number of concepts in combined FCM visualizations and ensures a unified understanding of concepts and connections across individual maps (Olazabal et al., 2018). However, it is crucial to document all original concepts for further analysis, especially when comparing FCMs from different stakeholder groups.

The individual homogenised maps were then aggregated into a single map. The simple matrix addition function is used for aggregation process, in which the values of connections that appear in more than one map is the mean value. Similar to the approaches in (Mehryar and Surminski, 2020) and (Olazabal et al., 2018), the standard deviation and coefficient variations were also calculated but did not provide any different result than the mean value in our analysis.

Condensation: The process of condensation involves less important or relevant concepts being eliminated in the aggregated FCM based on ‘centrality degree’ (as described in section 2) and ‘consensus degree’[6]. We established a minimum consensus degree of 3 for a concept to be included, meaning it had to be identified by at least three stakeholders. Additionally, a minimum centrality degree of 1.90 was set, representing 10% of the largest centrality degree in the aggregated FCM. These conditions were interrelated, allowing a concept identified by fewer than three maps to still be included if it ranked in the top 10 in terms of centrality degree. This flexibility acknowledges the significance of a concept, even if identified by only one or two stakeholders, particularly if they recognized numerous linkages between that concept and other components of the system. Similarly, a concept with a centrality of less than 1.90 but included in more than 10 maps was considered to have substantial agreement and was not excluded.

In the formal language, concept V was excluded in the aggregated FCM if:

$$((Co(V) < 3) AND\ (C(V) < 9.00))\ OR\ ((C < 1.90)\ AND\ (Co(V) < 10))$$

[6] That is the number of individual maps including each node, i.e., number of participants identified that node.

Where Co(V) and C(V) are consensus degree and centrality degree of concept V.

3.3. Grouping

Five aggregated FCMs were developed. One combined the entire 38 individual FCMs, representing the holistic system map, while the other four combined FCMs from stakeholder groups including central and local government, civil society, utility services, and first responders, separately. The stakeholder group FCMs offer insights into the diverse sector-specific perceptions and observations of those involved in responding to the summer 2022 heatwaves in the UK.

3.4. analysing aggregated FCMs

The causal relationships identified in FCMs represent interdependencies among the components of a system and enable a system analysis that extends beyond evaluating individual system components in isolation. In this study, we employed consensus degree, indegree, outdegree, and centrality degree analysis to provide insights into the "importance" of nodes based on their direct and indirect influence on other nodes within the system.

- Consensus degree shows the number of individual maps including each node, i.e., number of participants who identified that node, which represents level of agreement among stakeholders.
- Outdegree represents the extent to which a node is affecting other nodes of the system, either positively or negatively.
- Indegree represents the extent to which a node is affected by other nodes of the system. Centrality indicates the degree to which a node is affected by and/or affects other nodes.
- Centrality degree is the sum of indegree and outdegree, and it can be high due to a high indegree, a high outdegree, or both. In the FCMs of this study, 'impact' nodes with high centrality typically have high indegree and low outdegree, as they primarily receive effects from other nodes. This high centrality reflects the significant cascading effects of heatwaves, involving sequential or successive impacts stemming from an initial event. Conversely, 'action' and 'gap' nodes with high centrality tend to have high outdegree but low indegree, as they mainly affect 'exacerbators' and 'impacts' of heatwaves. Therefore, their high centrality signifies their crucial role as actual mitigators or potential mitigators of the negative effects of heatwaves. However, 'exacerbators' with high centrality exhibit both high indegree and high outdegree, as they both receive effects from other exacerbators, impacts, and actions, and strongly influence 'impact' nodes and other 'exacerbators'. Thus, the high centrality of exacerbators indicates their pivotal role as amplifiers of the negative effects of heatwaves (table 2).

Table 2. implication of high centrality for each category of FCM nodes and their indegree-outdegree proportion

nodes	Outdegree and indegree of high centrality nodes	High centrality nodes
impact	High indegree, low outdegree	Cascading effects
exacerbator	Equal indegree and outdegree	Amplifiers
Actions taken	High outdegree and low indegree	Actual mitigators
Inactions/ gaps	High outdegree and low indegree	Potential mitigators

4. Results

Table 3 represents the 47 concepts elicited during the 38 interviews (after homogenization and condensation) and their 'indegree', 'outdegree', and 'centrality degree', along with the 'consensus degree'. The latter demonstrates the number of individual FCMs including each concept, representing the number of stakeholders who identified each concept as impact, exacerbator, actions, or gaps.

4.1. Initial analysis - consensus degree

Analysis of the aggregated FCM reveals that the primary impacts of the 2022 heatwaves, conveyed by a significant number of stakeholders, include '*health issues*' (n=97%), '*wildfire'* (n=52%), and '*low productivity*' (n=31%) – n indicates the percentage of stakeholders that identified each impact factor. Health issues discussed by stakeholders included heat-related death and pre-existing health problems that were made worse by heatwaves (e.g., for elderly and vulnerable populations) as well as health problems for healthy people (e.g. due to exposure to high temperatures through their employment, being pregnant etc.). In addition, numerous instances of wildfires were observed across the UK during the heatwaves, with over half of the stakeholders attributing the severity, frequency, and spread of these wildfires to heatwave events. One of the first response stakeholders mentioned that "*what was very different about these wildfires is they happened across several days [and] consecutively, so the fires were burning at the same time…. firefighting is physically very difficult, and you do need a rest … Normally if you fight a fire, you must take the rest of the day off and you're not typically sent out to fight another fire, but some of these firefighters weren't given a rest, because the Fire Brigade couldn't afford to let fires burn without being attended*." Many stakeholders also highlighted the impacts of the heat on productivity as a significant impact, encompassing productivity in outdoor jobs particularly exposed to heatwaves, as well as productivity in home or office settings with inadequate ventilation and cooling options.

'*Social-economic and spatial vulnerability*' (n=57%) was mentioned by the largest number of participants as an important exacerbator of the heatwave in the UK, followed by '*heat-vulnerable buildings*' (n=50%) and '*underlying health conditions'* (n=42%). Prolonged heat can lead to the emergence of new vulnerable populations, such as individuals with underlying health conditions, pregnant women, rough sleepers, and workers directly exposed to heat (e.g., road workers, builders, farmers, etc.), who may not be considered vulnerable under other circumstances but become so during heatwaves. In addition, stakeholders discussed that most buildings in the UK are not equipped to deal with heatwaves and lack adequate ventilation and cooling, and often efforts ensuring buildings are warm in the winter are prioritised over efforts to reduce overheating in warmer months. Over-heating in buildings exacerbates health issues for vulnerable populations in care homes and affects productivity in schools and workplaces.

Among the actions taken in response to heatwaves '*public messaging*' was the most commonly mentioned (n=57%), followed by '*forecasting and early warning system*' (n=31%), and '*emergency response*' (n=28%). Many participants across all sectors praised the effectiveness of forecasting and early warning systems, which facilitated timely alerts and messages to key organizations and residents. Some participants also mentioned that the deployment of the 'heat alert systems' was considered a success – warning processes worked well and had noticeably catalysed action. However, it was acknowledged that while there was widespread awareness about the severity and timing of the heatwaves among the public, there was a lack of communication regarding mitigation measures that individuals could take to reduce their exposure and vulnerability to the heat. Additionally, there was recognition that organizational communication lacked clarity and context specificity in terms of advice and protocols. A government stakeholder highlighted efforts in communication, stating: "*we did a lot of communication in a very short space of time … some kind of simple messaging based on national guidance, but making it a bit more local and then disseminating that through our own wide range of stakeholders and networks and channels*".

Table 3. 47 nodes of aggregated FCM after homogenization and condensation. The rows are colour coded to represent impact (blue), exacerbator (orange), action (yellow), and gap (green) concepts. Bold numbers show the top 10 ones per each column of indegree, outdegree, and centrality.

Density		**Total Nr. Factors**	**Total Nr. Connections**	
0.033557934		47	149	
Concepts	**Outdegree**	**Indegree**	**Centrality**	**nr of maps including each node**
extreme heatwaves	12.78	40.60	53.38	38
social-economic & spatial vulnerability	**5.67**	**9.00**	**14.67**	**22**
health issues	1.00	**12.44**	**13.44**	**37**
wildfire	1.30	**10.89**	**12.19**	**20**
drought	3.70	**7.75**	**11.45**	6
public messaging	**8.10**	1.80	**9.90**	**22**
internal heatwave plan	**7.20**	2.70	**9.90**	**10**
transport disruption	1.20	**8.29**	**9.49**	7
pressure on first response sector	1.90	**7.47**	**9.37**	6
heat-vulnerable buildings	2.51	**6.60**	**9.11**	**19**
awareness of heat risk and protection measures	4.50	4.50	**9.00**	**11**
forecasting and early warning	**8.10**	0.00	8.10	**12**
public education and training	**7.20**	0.90	8.10	8
assessing impacts of heatwave	**7.20**	0.90	8.10	7
emergency response	**5.40**	2.70	8.10	**11**
heat-specific plan	**5.40**	2.70	8.10	6
increased water demand	1.45	**6.45**	7.90	6
emotional & practical support for vulnerable population	2.70	**5.20**	7.90	5
lack of perception of heatwave as a risk	4.10	3.60	7.70	3
non-adaptive behaviour	3.90	3.60	7.50	**11**
heat vulnerability assessment	**6.30**	0.90	7.20	**11**
coordination & collaboration among response groups	**5.40**	1.80	7.20	6
resources and capacity for emergency services	**5.40**	1.80	7.20	5
health risk for first-responders	1.80	5.07	6.87	3
low productivity	1.90	4.53	6.43	**12**
heat risk prevention	3.60	2.70	6.30	**10**
perception of heatwave as a risk	**5.40**	0.90	6.30	4
reservoir and groundwater level drop	1.60	3.90	5.50	4
post-covid social networks	4.50	0.90	5.40	4
preparation planning for response	4.50	0.90	5.40	4
retrofitting existing buildings	3.60	0.90	4.50	**11**
experiential learning	4.50	0.00	4.50	4
lack of planning for heat preparedness activities	0.70	3.60	4.30	3
heat-vulnerable transport	2.30	1.80	4.10	3
flexible working	3.60	0.00	3.60	3
communication and coordination	0.90	2.70	3.60	4
lack of culture of heat	1.80	1.80	3.60	2
lack of awareness on heat risk & protection measures	0.77	2.70	3.47	5
pressure on water treatment and distribution	0.00	3.45	3.45	4
climate change	3.08	0.00	3.08	7
learning from the past organizational responses	1.80	0.90	2.70	4
water distribution planning	1.80	0.90	2.70	4
national hot weather protocol	1.80	0.90	2.70	3
urban heat island effect	0.85	1.80	2.65	**12**
natural environment and biodiversity deterioration	0.00	2.40	2.40	4
underlying health conditions	2.26	0.00	2.26	**16**
pressure on health system	0.50	1.53	2.03	4
noisy and unsafe locations	1.20	0.70	1.90	3

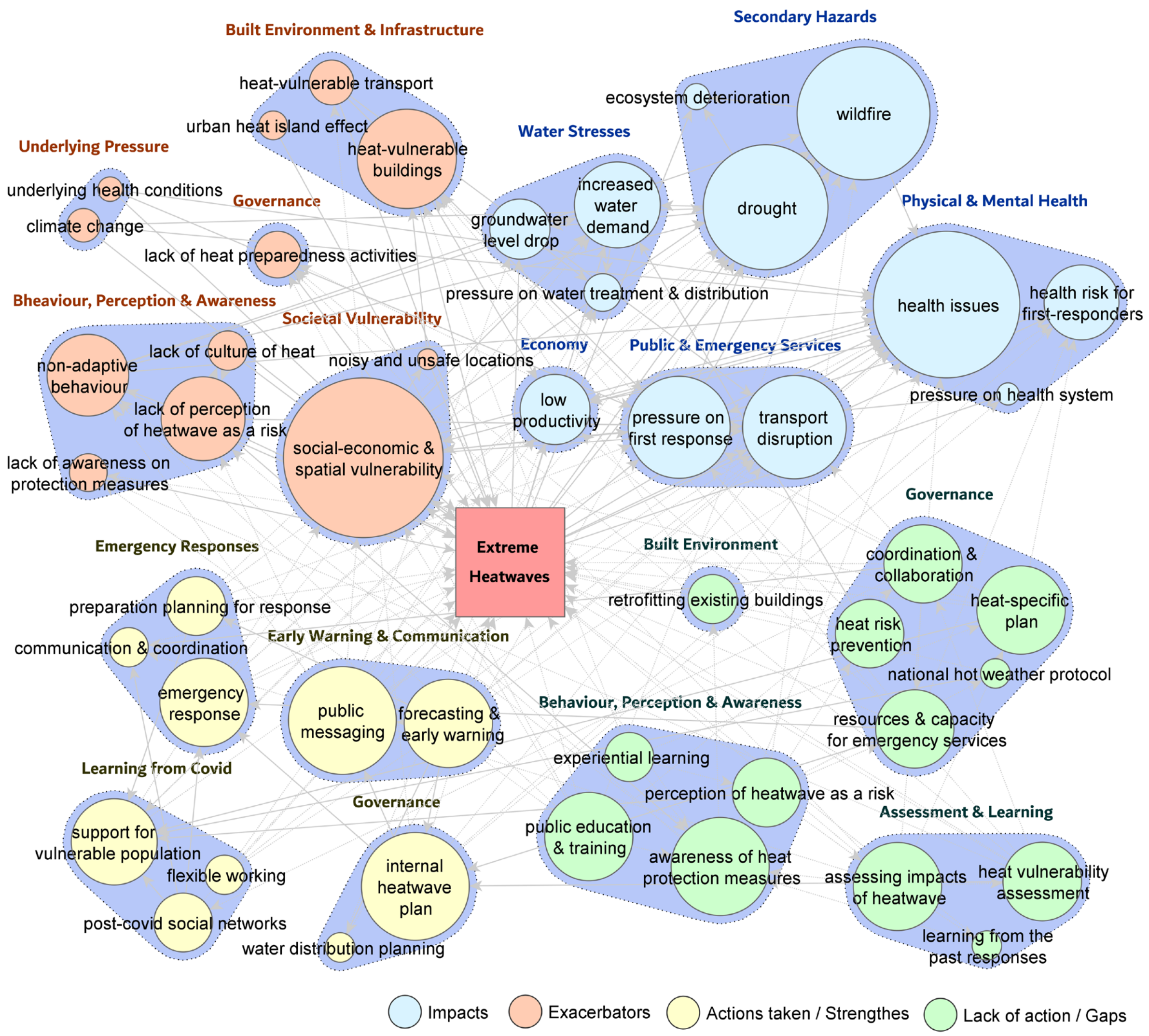


Figure 1: Aggregated FCM of all stakeholders. Th size of nodes represents centrality degree which is the sum of indegrees and outdegrees for each node. Largest impact nodes = main cascading effects, largest exacerbator nodes = main amplifiers, largest action nodes = main actual mitigators, and largest lack of action/gap nodes = main potential mitigators.

Overall, swift and efficient 'emergency responses', including drought and water emergency response by utility companies, as well as heat, fire, and severe weather emergency responses by first response sectors and governments, were acknowledged by the majority of stakeholders. However, concerns were raised regarding the adequacy of emergency response resources, capacities, and plans for prolonged periods of heatwaves in the future. Stakeholders identified many different inactions and gaps in preparation and response to heatwaves, with a low degree of consensus. However, the lack of '*retrofitting existing buildings*', '*heat vulnerability assessment*', and '*awareness of heat protection measures*' were among the most commonly mentioned gaps, identified by 28% of stakeholders.

4.2. Deeper analysis - interdependencies

Cascading effects: As discussed, analysing interdependencies in FCMs provides insights at the system-level, as emergent patterns or phenomena may arise from the interactions between individual components.

Figure 2 illustrates the interconnectedness of components within each category. It reveals that 'health issues', the most significant impact of heatwaves cited by participants (with highest centrality degree among impact factors), stem not only from the direct effects of the heatwave but also from cascading effects such as 'transportation disruption', 'pressure on first response', 'wildfire', and 'water and air pollution', all triggered or exacerbated by heatwaves. All these impact factors have the top centrality degree, identifying them as the most significant cascading effects of heatwave. These impacts significantly amplify the indirect effects of heatwaves on other system components.

Figure 2. Interconnections among significant (A) cascading effects, (B) amplifiers, (C) actual actions (left) and potential actions (right), and other nodes of FCM. Blue: Impacts, Orange: Exacerbators, Yellow: Actions taken/Strengths, Green: Lack of action/Gaps.

Another interesting finding is that although 'drought', 'transport disruption', and 'pressure on first response sector' are not predominant impacts mentioned by a large number of stakeholders, they rank among the top 10 nodes with high centrality (Table 3 and Figure 1). This is mainly due to the fact that these three factors are strongly affected by other factors of the system and can trigger subsequent events or hazards, even though they are not recognized as the most important direct impact of heatwaves. Drought, for example, when triggered by extreme hot weather, can lead to wildfires, drops in groundwater levels, decreased crop production, and increased water demand, as identified by stakeholders and shown in Figure 2. These can then lead to further damage, destruction, and loss of life, amplifying the overall impact of heatwaves. Pressure on first responses and transport disruption can also affect and be affected by all these compounding and cascading hazards such as drought, wildfires, air pollution, and health issues.

Amplifiers: Similarly to the consensus degree, *'socio-economic vulnerability*' and *'heat-vulnerable buildings*' received the highest centrality degree, representing the most significant amplifiers of heatwave impacts. Stakeholders identified vulnerability issues as external amplifiers for various cascading effects of heatwaves, including 'health issues', 'wildfires', 'pressure on first response and health systems', and 'health risks for responders' (see figure 2.B). Participants emphasized that socio-economic vulnerability worsened health issues during heatwaves by limiting access to resources like cooling, exacerbating pre-existing conditions, increasing social isolation, exposing individuals to occupational hazards, and worsening housing conditions, which consequently, placed additional pressure on first responders and health services. Additionally, spatial vulnerability impeded healthcare access and humanitarian or first-response support, further exacerbating health issues, as highlighted by one of the participants. Furthermore, stakeholders' observations indicate that vulnerability has amplified the risk of wildfires and their consequences, particularly among economically vulnerable populations living in poor building conditions.

Various mitigation measures were identified by stakeholders that can potentially protect vulnerable populations from the impacts of heatwaves but are currently lacking. These measures include the development of 'heat vulnerability assessments' and their dissemination to first response and voluntary sectors to identify 'at-risk' groups. These include individuals aged over 65, pregnant women, homeless individuals, as well as those working in heat-vulnerable environments such as offices, schools, emergency services, and occupations that entail direct exposure to heat. Other crucial mitigation measures include the development of 'heat-specific plans' tailored to vulnerable populations and their needs, as well as enhancing 'communication channels' with targeted vulnerable groups. Additionally, heat-vulnerable buildings were identified as significant contributors to low productivity and health issues during heatwave events. However, gaps in long-term preservation measures hinder investments in heat-resilient buildings and the retrofitting of existing structures.

Contrary to the consensus degree, behavioural and perceptual factors such as *'non-adaptive behaviour*' and *'lack of perception of heat as a risk*' emerge as significant factors in amplifying the impacts of heatwaves. According to stakeholders who identified these factors, public perceptions and behaviours have contributed to various cascading effects of heatwaves such as wildfires, drought, transport disruption, health issues, and increased water demand (figure 2.B). Examples of such behavioural and perceptual issues include a lack of awareness and adherence to barbecue regulations in green areas during heatwaves, increased reliance on public transport for travel to beaches and cooler locations, lack of awareness and utilization of available cooling systems (when they were available), and workers being excessively exposed to heat while performing their duties. Stakeholders attributed these behaviours to a general lack of perception of heatwaves as a risk and a lack of awareness regarding measures for heat protection and emphasized the need for better heat risk communication, trainings, and educational campaigns (figure 2.B - left). This includes enhancing education through public campaigns to improve awareness of water conservation and safety during heatwaves, particularly in rural areas where risks of wildfires and wild swimming are prevalent. They also stressed the need for effective engagement efforts tailored to specific audiences, as well as actively listening to community feedback to improve heat response strategies. Increasing the visibility of heat risks through communication channels was identified as a key factor in enhancing overall heat responses.

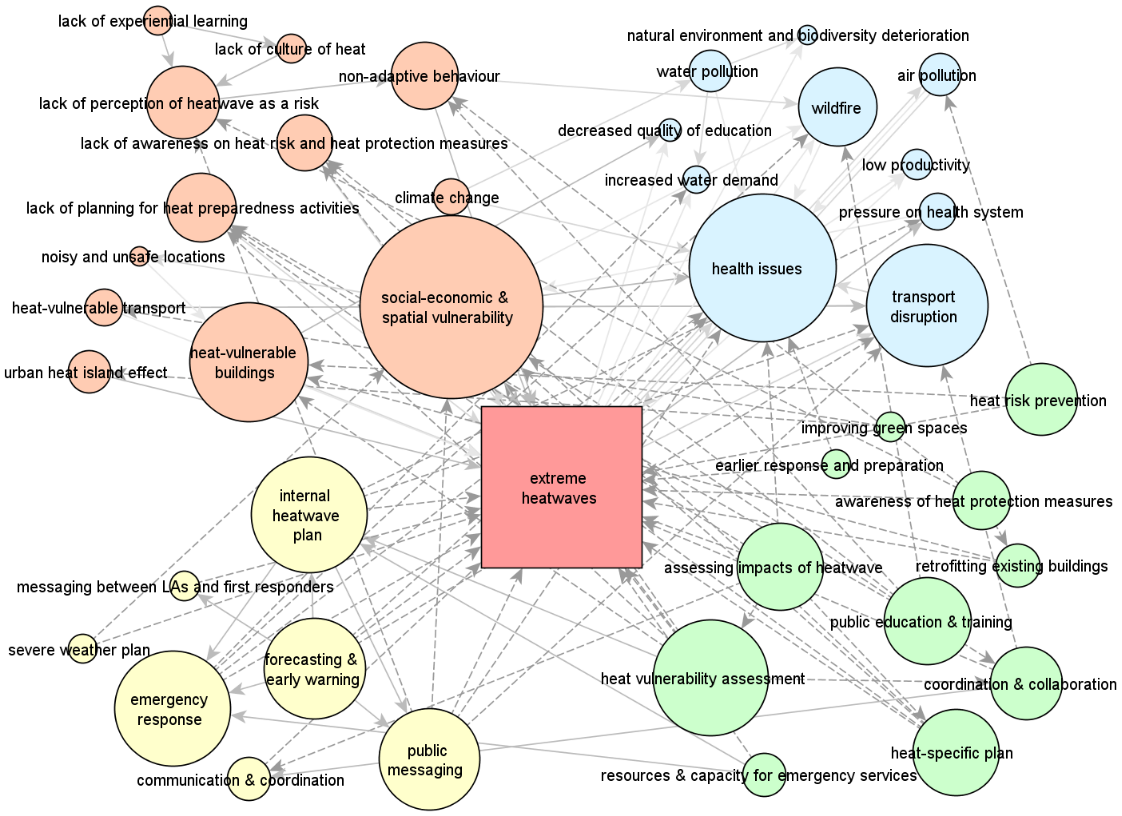
Actual and potential mitigators: The *'internal heatwave plan'* emerges as the most impactful mitigation action observed by stakeholders, followed by *'public messaging'* and *'forecasting and early warning systems*'. This highlights the effectiveness of context-specific heat plans, although they are not available across all organizations and sectors. Entities equipped with such plans reported significant benefits in facilitating prompt and efficient responses. For example, water services utilized these plans to manage reservoir and groundwater levels, reducing pressure on water treatment and distribution systems. Similarly, transport and health services utilized heat plans to improve coordination, communication, and capacity management in order to address anticipated pressures early on. The early 'forecasting and early warning system', followed by rapid 'messaging and communication' of predicted heatwaves were found to be extremely helpful and well-timed by stakeholders from all sectors. This advance notice allowed them to activate their emergency plans, ensure they had sufficient capacities to respond, and adjust plans and procedures as necessary. See figure 2.D-left for the mitigating effects of 'public messaging' on other factors.

In terms of gaps and challenges, 'public awareness of heat risk and protection measures' were associated with many exacerbator and impact factors, followed by 'public education and training'. Lack of 'assessing the impacts of heatwave' and 'learning from the past responses' were also mentioned as the second category of the most important gaps.

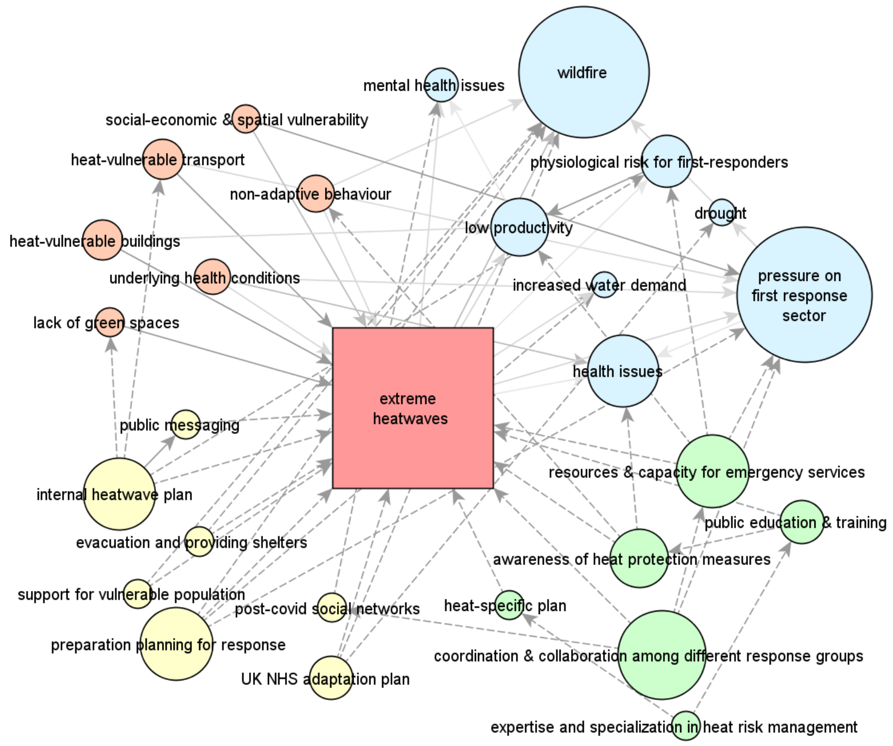
4.3. FCMs of stakeholder groups

Comparing FCMs from different stakeholder groups reveals both similarities and differences in how various sectors perceive the impacts and exacerbators of heatwaves. These variations can lead to diverse preferences and priorities in planning and preparing for future heatwaves which should be considered in an inclusive adaptation planning. Additionally, it highlights that each stakeholder group has limited observations and perspectives on the entire system. Therefore, integrating these diverse viewpoints can result in the emergence of new and holistic knowledge, encompassing various aspects of the system.

Our analysis indicates that during the interviews, first responders and utility service providers tended to focus more on discussing and providing input on the impacts of heatwaves and actions taken to mitigate these impacts (see impact nodes and inputs from action nodes to impact nodes in Figure 3.B and 3.C) rather than on exacerbators and actions. In contrast, government members were able to discuss and provide details on exacerbators and strategies to mitigate them (see exacerbators and inputs from gap nodes to exacerbators in Figure 3.A). This difference can be attributed to the expertise and job responsibilities of first responders and utility service providers, who regularly deal with the immediate impacts of such climate risks on society. Meanwhile, policymakers and government members are tasked with addressing the root causes of disasters and planning measures to reduce or eliminate them.



A. FCM of government members



B. FCM of first responders

Figure 3A & 3B. Aggregated FCMs of government members and first responders.

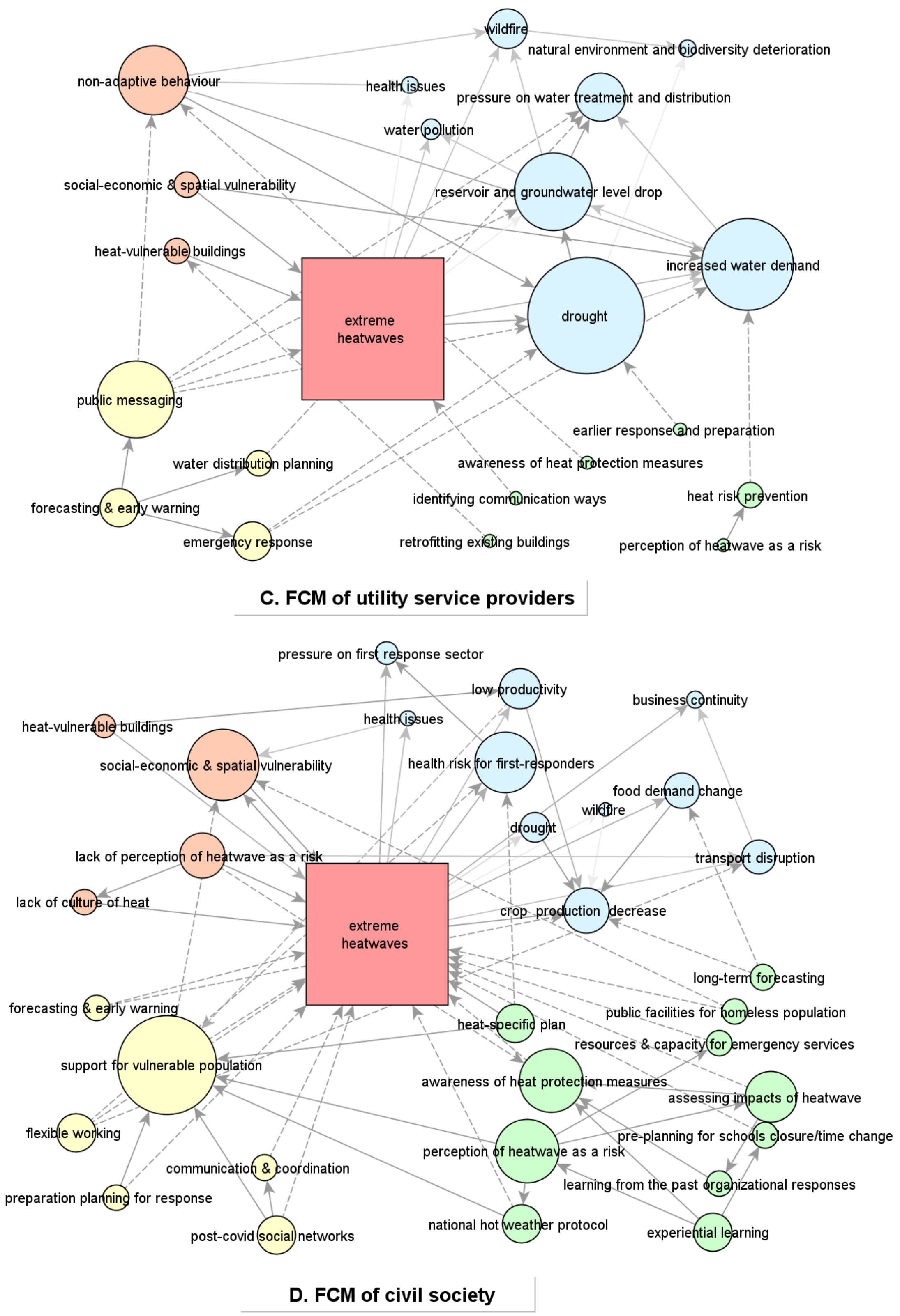


Figure 3C & 3D. Aggregated FCMs of utility providers and civil society.

Furthermore, local and national government representatives identified ‘health issues’ and ‘transport disruption’ as the primary impacts of the summer 2022 heatwave (fig 3.A), whereas first responders emphasized ‘wildfire’ and ‘pressure on the first response sector’ as the most significant impacts (fig 3.B) and utility service providers predominantly cited water-related stresses such as ‘drought’, ‘groundwater level drop’, and ‘increased water demand’ as the main impacts of heatwaves (fig 3.C). While government representatives would rely on available data and reports from the 2022 heatwaves to discuss their impacts, first responders and utility service providers elaborated on their on-the-ground experiences and observations of the impacts. For example, first responders were mainly concerned that operational and strategic on-the-ground resources to respond to the extreme heat were severely stretched, with the ambulance and fire services under “severe pressure”. They mentioned that resources, funding, and capacity were inadequate given the severity of the event and felt there was overall a lack of preparedness which led to avoidable impacts. Utilities stakeholders particularly highlighted the role of drought as a compounding factor, which added pressure to the water sector precisely at the time when public demand for water surged. This contrasts with observations from other sectors, where drought, water stresses, and pressure on natural and food systems are less emphasized. However, this may indicate that these impacts could manifest more prominently in society in the future, given that they are currently managed by utility sectors. As articulated by utility stakeholders, the prospect of more severe and prolonged periods of heatwaves presents increasing challenges for utilities in effectively addressing water and food supply issues, potentially leading to broader societal implications if proactive measures are not taken.

Civil society members emphasized the effective role of providing ‘support to vulnerable populations’ in mitigating negative impacts of heatwaves in summer 2022 (figure 3.D) as they were the most in contact with vulnerable populations during the heatwave periods. These included offering both practical and emotional support for rough sleepers, the elderly, and individuals with underlying health conditions. In some cases, networks established during the Covid19 pandemic to reach out to and support those most vulnerable were accessed and utilised to reach out to those groups during the heat events. In contrast, utility providers found early and effective ‘communication and messaging’ to be the most effective action during this period (figure 3.C), which enabled them to implement precautionary measures and manage demand-supply balance. Government members, however, identified ‘emergency response’ and ‘internal heat plans’ as the most effective components of their heatwave response, acknowledging that heat plans were not available across all sectors and organizations (figure 3.A). However, government stakeholders argued that responses to heat were often reactive and limited to emergency management measures. They underscored the necessity of developing a comprehensive strategy to integrate heatwave preparedness into year-long planning, making it a standard practice rather than a crisis-driven response. Additionally, they emphasized the importance of balancing both long-term and short-term considerations in addressing heat-related challenges effectively.

5. Discussion and conclusion

This study offers a comprehensive analysis of the UK's response to the 2022 heatwaves, employing a structured approach that combines the 'Forensic Disaster Analysis' methodology with Fuzzy Cognitive Mapping (FCM) to capture local stakeholders' insights. The heatwaves of 2022 highlighted the urgent need for proactive measures to address climate change risks, as they caused significant impacts on public health, infrastructure, and the economy.

Stakeholders identified primary impacts such as health issues, wildfires, and transportation disruptions, with further analysis revealing the interdependencies between these factors, resulting in cascading effects. Socio-economic vulnerability, inadequate building standards, and behavioural factors like non-adaptive behaviour were identified as the most significant exacerbators of the heatwave impacts. Stakeholders emphasized the importance of public messaging and awareness campaigns to improve heat risk communication and community engagement.

Effective mitigation measures, including forecasting and early warning systems, were highlighted, but gaps in public awareness and learning from past responses remain challenges for future preparedness. Concerns were also raised about resource adequacy for prolonged heatwaves, with stakeholders identifying gaps in preparation and response, particularly regarding building retrofitting and heat vulnerability assessments.

The study revealed variations in perceptions and priorities among stakeholder groups, underlining the importance of inclusive adaptation planning. Overall, the findings emphasize the need for proactive and integrated approaches to heatwave preparedness, informed by both short-term emergency responses and long-term mitigation strategies. Coordinated action across sectors, learning from past experiences, and addressing critical knowledge gaps are essential to building resilience and protecting vulnerable communities from increasingly frequent and severe heatwaves.

It is important to note that the FCMs in this study primarily reflect the observations and experiences of individuals during the summer 2022 heatwaves. As a result, the impacts, exacerbating factors, actions, and gaps discussed and depicted in the maps are constrained to those encountered during that specific timeframe. However, participants also noted other factors that, while not as prominent during the observed period, could pose significant challenges in the future without mitigation measures. For instance, concerns were expressed regarding the potential impacts of heatwaves on mental health and well-being, the natural environment, food production, and supply chains, particularly with more extreme and prolonged heat events. In addition, while FCMs excel in co-producing knowledge and representing various preferences and perceptions, they may not fully capture outliers' perspectives in the aggregate maps. For example, concerns raised by schools' representatives regarding the quality of education affected by extreme heat may not be adequately represented.

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