Flood-Resilience Priorities for Infrastructure Through Multi-Stakeholder Causal Mapping

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ABSTRACT

Urban resilience to natural hazards could make our cities less vulnerable to adverse weather events. However, the implementation of resilience actions is currently not effective, as mechanisms to facilitate collaboration among involved stakeholders are missing. This paper for the first time explores causal mapping as a method to disassemble major issues of urban resilience into a more manageable understanding, and thus identify key objectives, barriers and opportunities in thinking “resilient cities”. In this study, a cognitive-mapping-based workshop was held to elicit information from stakeholders in the remit of urban resilience to flooding. The statements and connections identified during the workshop led a consolidated map, analysed using the StrategyFinder software. This analysis highlighted barriers related to data availability, silo-based approaches and lack of funding; it also evidenced shared goals, such as the need to protect the built environment and minimise impact from flooding. Overall, causal mapping resulted a powerful analytical tool for improving understanding of the complex dynamics of urban resilience, identifying key variables and relationships, as well as eliciting information from stakeholders. Furthermore, this approach facilitated systems thinking, communication and collaboration in view of policy-making. This enhanced understanding is fundamental for advancing strategies for future planning, contributing to urban sustainability and liveability.

KEYWORDS: flood, risk, resilience, stakeholder, workshop, causal mapping, infrastructure

1 INTRODUCTION

Urban areas are becoming increasingly vulnerable to natural hazards, particularly flooding, as a result of climate change and rapid urbanisation. Flooding imposes significant economic burdens, including direct damage to infrastructure, housing, and agriculture, alongside indirect impacts such as business disruption, health consequences, and population displacement. In 2019 alone, floods accounted for over 45% of climate-related disasters globally, contributed to more than 40% of disaster-related deaths, and caused average annual losses of approximately US$40 billion. As centres of economic activity, innovation, social interaction, and infrastructure connectivity, cities play a critical role in societal functioning and sustainability (Pregnolato et al., 2021). Their importance is expected to intensify, with around 68% of the global population projected to reside in urban areas by 2050. Urban resilience has therefore become a central policy concern, reflected in the United Nations Sustainable Development Goal 11, which aims to make cities inclusive, safe, resilient, and sustainable (UN, 2015). Urban resilience refers to a city’s capacity to withstand, adapt to, and recover from shocks and stresses while maintaining essential services and safeguarding residents’ well-being (Bruneau, 2003). This concept extends beyond recovery to include proactive actions that address long-term vulnerabilities and support sustainable development. Despite growing recognition, the practical implementation of resilience strategies in urban planning remains limited and often ineffective.

One key challenge lies in the inherent complexity of cities, which consist of interconnected infrastructures, institutions, and communities (Cimellaro, 2010). Addressing urban resilience therefore requires clear identification of priorities and barriers, as well as collaboration among diverse stakeholders such as planners, policymakers, engineers, and analysts. However, resilience initiatives are frequently led by single institutions, limiting their transformative potential and reducing coordination across sectors (Elmqvist et al., 2019). This gap highlights the need for more integrated and participatory approaches to understanding and strengthening urban resilience. Understanding stakeholder perspectives is a crucial first step in developing effective resilience tools. Stakeholders often differ in their definitions, objectives, priorities, access to data, and available resources, and these differences are compounded by limited cross-organisational knowledge sharing (Cantelmi et al., 2021). A variety of methods have been used to elicit stakeholder input, including surveys, interviews, workshops, focus groups, and mixed approaches (Pacheco et al., 2018), as well as more innovative techniques such as serious games and diagnostic tools (Wehrle et al., 2022). Additional approaches include Delphi studies, storylines, and other participatory methods (de Bruijn et al., 2016).

Problem Structuring Methods (PSMs) provide a useful framework for addressing such complexity by helping groups explore and structure ill-defined problems (Ahmad et al., 2021). Within this family, Strategic Options Development and Analysis (SODA) employs cognitive or causal mapping to capture and analyse stakeholders' perceptions, objectives, and perceived causal relationships (Eden, 1989). These maps support negotiation, strategic thinking, and collective learning by making interdependencies and assumptions explicit. Cognitive and causal mapping have been widely applied across domains such as project management, health systems, supply chains, policy analysis, energy transitions, and risk perception (Ackermann et al., 2014). However, there is limited evidence of their application to urban resilience, particularly in the context of flooding (Pregnolato and Pyrko, 2022; Pregnolato et al., 2024). This study addresses this gap by applying multi-stakeholder causal mapping to explore objectives, barriers, and opportunities related to urban flood resilience in UK cities. The research investigates how causal mapping can enhance understanding, collaboration, and decision-making among stakeholders, with the aim of bridging gaps between policy intentions and practical implementation. The findings contribute to broader efforts in disaster risk reduction and urban resilience planning.

2 METHODOLOGY

This study applies cognitive (causal) mapping, to examine how multiple stakeholder groups perceive urban infrastructure resilience to flooding (Eden, 1989). A structured workshop was used to elicit stakeholders' views on key objectives, barriers, opportunities, and the causal relationships between them. Participants worked in separate groups to develop individual causal maps, which were later consolidated into a single composite map and analysed using StrategyFinder software (Web-1).

Causal mapping is a participatory, co-creation method that supports collaboration, shared understanding, and capacity building among diverse stakeholders (Marana et al., 2019). It has been successfully applied in complex sectors such as aviation (Ahmad et al., 2021) and was selected here for its ability to explicitly represent causal relationships and support emergent strategy development through an active process of collective sense-making (Pyrko et al., 2019). A causal map represents a system as a network of statements (nodes) connected by directed links that indicate "may-lead-to" relationships. This graphical representation enables the exploration of problem complexity, interdependencies, and patterns that are often difficult to capture through linear methods (Eden, 2004).

In this study, cognitive mapping was conducted in two stages (Fig. 1). First, four separate causal maps were developed by different stakeholder groups during the workshop. Second, these maps were merged into a single composite map following a structured four-step procedure adapted from previous studies (Ahmad and Xu, 2021): identifying overlapping concepts, integrating additional causal links, preserving the internal structure of each group's map, and interpreting the final consolidated map. Interpretation focused on identifying macro-themes, goals, feedback loops, and isolated concepts that could inform actionable strategies (Marana et al., 2019). The analysis of the composite map relied on established structural properties of causal maps (Eden, 2004)], including causal links, central or "potent" nodes, clusters of related concepts, reinforcing or undermining feedback loops, and directional features such as "tails" (triggers) and "heads" (end goals). StrategyFinder supported this process by providing both graphical visualisation and quantitative analytics, such as link density and identification of critical nodes and cycles.

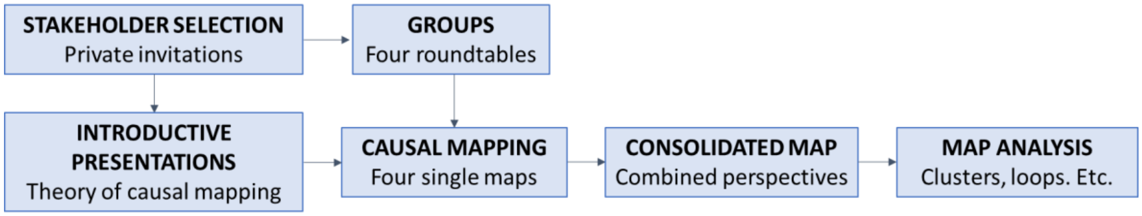

Figure 1: Graphical summary of the methodology

Primary data were collected during a one-day workshop held on 30 November 2021 in Bristol, UK. The overarching question guiding the exercise was: "How can infrastructure resilience to flooding be improved in urban environments?", grounded in participants' professional experience. Twenty-three stakeholders took part, representing policymakers, researchers, practitioners, and private-sector actors. The workshop combined introductory sessions with a facilitated causal mapping exercise, in which participants worked in diverse groups to reflect on challenges and goals related to urban flood resilience. The resulting causal maps provided a structured representation of stakeholder knowledge and perceptions, forming the basis for subsequent analysis and discussion.

3 RESULTS

During the workshop, four stakeholder groups independently developed causal maps that captured key objectives, gaps, and causal relationships related to urban infrastructure resilience (Fig. 2).

(a) (b)

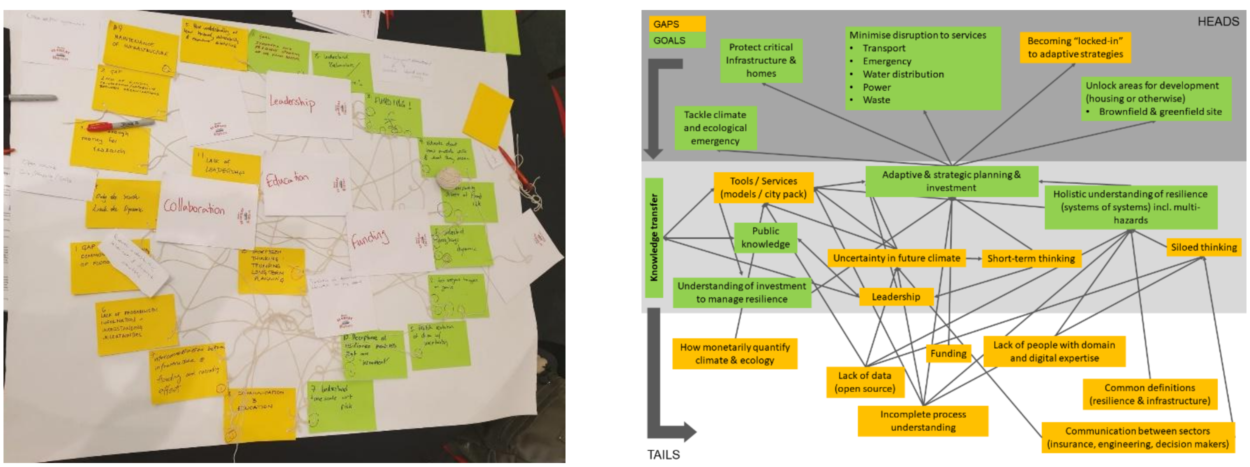

Figure 2: Example of (a) hard copy map produced during the workshop in one of the roundtables; (b) elaborated map, obtained from the hard copy.

In total, 88 statements were elicited, almost evenly split between goals and gaps (see Table A1 in Appendix A). These group-level maps were subsequently integrated into a single consolidated causal map following a structured harmonisation process, in which similar statements were merged and all causal links retained. The consolidated statements were categorised into four thematic clusters: Data; Technical and Technological Knowledge; Leadership and Relationships; and Modelling and Tools. They were further classified according to structural properties such as: heads, tails, and central nodes.

The largest proportion of statements related to Modelling and Tools (34.5%), followed by Leadership and Relationships (28%), Technical and Technological Knowledge (25%), and Data (12.5%). This distribution reflects the areas that stakeholders considered most salient when discussing urban resilience. The consolidated map was implemented and analysed using StrategyFinder, allowing a system-level interpretation of the complex interdependencies among issues, goals, and enabling factors.

Analysis of the consolidated map began with the identification of central nodes (statements with the highest number of incoming and outgoing connections) highlighting priority areas for stakeholders. Five central priorities emerged: developing adaptive and strategic planning and investment, producing tools and services, maintaining clear communication with citizens, assessing future flood risk using high-resolution climate data, and training staff to use models and interpret outputs. These priorities were distributed across all four thematic clusters, underscoring the multi-dimensional nature of urban resilience.

Further examination revealed that staff training and flood risk assessment function primarily as enabling actions (tails), while strategic planning and public communication represent end goals (heads). The development of tools and services plays a pivotal intermediary role, translating staff capability and data into actionable adaptation strategies. Sub-map analyses showed that staff skills are essential for producing and communicating information, while tools and risk assessments underpin effective strategic planning. Notably, none of the central nodes appeared exclusively as heads or tails, indicating that the core of resilience lies in the processes and interactions between elements rather than isolated starting points or endpoints.

Head statements represented the desired outcomes of resilience efforts, including protecting critical infrastructure and homes, minimising disruptions to essential services, unlocking safe areas for future development, and developing a shared vision of resilience. These outcomes collectively reflect stakeholders' overarching aim of safeguarding the built environment and supporting safer, more robust urban systems. Conversely, tail statements captured the drivers and constraints shaping resilience pathways, such as data scarcity, limited funding, short-term thinking, lack of shared definitions, community engagement challenges, and uncertainty in returns on resilience investments. Addressing these drivers was identified as a necessary first step in any effective resilience strategy.

Thematic cluster analysis provided further insight. The Modelling and Tools cluster emerged as the most complex and influential, containing two central nodes and closely aligning with final resilience goals. This cluster highlighted the importance of impact modelling, real-time warning systems, climate information, and policy tools for reducing disruptions and enhancing asset protection. It also revealed how modelling activities can help address data gaps by generating new, decision-relevant information. The Data cluster emphasised challenges related to data availability, resolution, accessibility, and management, reinforcing the need for improved data practices to support risk assessment.

The Technical and Technological Knowledge cluster underscored the dominance of knowledge-related issues, particularly the need to understand physical processes, risk components, and modelling outputs. Staff capacity and skills were identified as critical enablers, highlighting training as a priority intervention. The Leadership and Relationships cluster focused on communication with citizens, community engagement, cooperation across institutions, funding, and leadership. Together, these elements point to the importance of trust, shared understanding, and coordinated governance in delivering resilience.

Overall, the analysis shows that urban resilience emerges from interconnected processes involving data, knowledge, tools, leadership, and community engagement, rather than from isolated actions.

4 DISCUSSION

This study investigated how causal mapping can support improved decision-making and collaboration among multiple stakeholders to strengthen resilient infrastructure in UK cities. By applying causal mapping in a multi-stakeholder workshop, the research captured and analysed the mental models of participants from different professional backgrounds involved in urban resilience. The approach enabled the identification of key objectives, barriers, and opportunities related to urban resilience to flooding, while recognising that results are context-specific and influenced by participant composition and facilitation dynamics (Lami and Todella, 2019).

The study highlights both methodological considerations and practical insights. While the workshop format is flexible and adaptable to different contexts, the authors note the importance of careful stakeholder selection, facilitation, and post-workshop validation to improve reliability and learning outcomes (Ahmad and Xu, 2021). Disseminating findings to participants for feedback was identified as particularly valuable for enhancing ownership, reflection, and cross-disciplinary learning (Tavella and Papadopoulos, 2017). Feedback from participants confirmed that causal mapping was engaging, accessible, and effective in supporting systems thinking, networking, and shared understanding, reinforcing evidence from earlier studies (Ackermann and Eden, 2005).

From an urban resilience perspective, the study demonstrates the value of causal mapping as a novel method for engaging stakeholders in a field characterised by complexity and multi-disciplinarity. The resulting composite map revealed four operational thematic clusters (data, technical and technological knowledge, leadership and relationships, and modelling and tools) which are not explicitly identified in existing resilience frameworks. Key challenges included data limitations, siloed working practices, and insufficient funding, while shared goals focused on protecting the built environment and minimising flood impacts, consistent with prior research (Godschalk, 2003).

Importantly, the analysis highlighted staff skills, capacity building, and knowledge transfer as central drivers of urban resilience, alongside community engagement and leadership. These findings suggest that resilience strategies should prioritise training, institutional collaboration, and public involvement, complementing policy-focused approaches in the literature (Ahmad and Xu, 2021). Overall, the study shows that causal mapping effectively supports visualisation, systems thinking, communication, and collaboration, offering a practical foundation for developing holistic and integrated urban resilience strategies (Sharifi and Yamagata, 2016).

5 CONCLUSION

The limited implementation of resilience measures in urban planning highlights the need for platforms that foster stakeholder collaboration. Problem Structuring Methods (PSMs), particularly causal (cognitive) mapping, offer a way to structure complex challenges into manageable components. This study identifies three gaps: limited effectiveness of current resilience measures, lack of applications of cognitive mapping in urban resilience, and underuse of multi-level cognitive mapping. It investigates how causal mapping can improve understanding of barriers and opportunities for collaborative decision-making. A stakeholder workshop was conducted to develop group cognitive maps, later integrated into a consolidated multi-level map and analysed using established indicators. Key barriers included limited data availability, siloed practices, and insufficient funding, while shared goals focused on protecting the built environment and reducing flood impacts. The findings demonstrate that causal mapping supports systems thinking, communication, and collaborative strategy development, offering practical guidance for strengthening urban resilience planning.

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APPENDIX A

Table A1. List of statements, and relative assigned theme. Colour legend: Data - yellow; Technical and technological knowledge - green; Leadership and relationships - blue; Modelling and tools - orange.

Statement	Theme	Note
1 to work with lack of data	Data	Tail
2 to quantify climate and ecology	Technical and technological knowledge	Tail
3 to gather funding	Leadership and relationships	-

4 to work in a condition of incomplete process understanding	Technical and technological knowledge	Loop B
5 to keep data open-source	Data	-
6 to cope with little funding	Leadership and relationships	Tail
7 to have staff with domain and digital expertise	Technical and technological knowledge	-
8 to lack of common definitions on resilience and infrastructure	Technical and technological knowledge	Tail
12 to communicate among sector (insurance, engineering, policy, etc.)	Leadership and relationships	-
13 to understand investments in resilience management	Technical and technological knowledge	-
14 to possess public knowledge	Technical and technological knowledge	Loop A
15 to produce tools/services (e.g., models, city pack)	Modelling and tools	Central node
16 to develop adaptive and strategic planning and investments	Modelling and tools	Central node
17 to account for uncertainty in future climate	Modelling and tools	-
18 to provide leadership among all players	Leadership and relationships	Loop A
19 to think in short terms	Leadership and relationships	Tail
20 to think in longer-terms	Leadership and relationships	-
21 to overcome siloed-thinking	Leadership and relationships	-
22 to account for a holistic understanding or resilience, e.g., system of systems and multi-hazards	Technical and technological knowledge	-
23 to tackle climate and ecological emergency	Modelling and tools	Head
24 to protect critical infrastructures and homes	Modelling and tools	Head
25 to minimise disruptions to services (transport, water, power, waste)	Modelling and tools	Head
26 to develop adaptive strategies	Modelling and tools	Head
27 to unlock "safe" areas for development (housing or otherwise), also in the future	Modelling and tools	Head
28 to transfer knowledge across sectors and institutions	Technical and technological knowledge	Loop A
29 lack of data integration across different systems	Data	-
30 to increase accuracy while limiting computing resources	Modelling and tools	-
31 to develop real-time warning system	Modelling and tools	Loop B
33 to manage inter-dependency of infrastructure	Modelling and tools	-
35 to work with lack of real-time dynamic data (e.g. flood outputs)	Data	-
36 to use technology to optimise transport system during flooding	Technical and technological knowledge	-
37 to define a business case for adaptation (e.g., blue-green infrastructure)	Modelling and tools	-
38 to include climate information into planning process	Modelling and tools	-
40 to model different parts of the network	Modelling and tools	-
41 to assess future flood risk using high resolution climate data	Data	Central node
42 to improve public awareness to flood risk	Leadership and relationships	-

43 to deliver risk information to cities	Leadership and relationships	-
44 to maintain clear communication with citizens	Leadership and relationships	Central node
45 to map safe zones of the city	Modelling and tools	-
46 to develop methods based on limited data	Data	-
47 to improve protection of assets	Modelling and tools	-
48 to deliver best-value plans for flood risk management authorities	Modelling and tools	Head
49 to use appropriate databases for data of ecosystem services	Data	Tail
50 to develop a societal mindset on infrastructure issues	Leadership and relationships	-
51 to engage the wider community	Leadership and relationships	Tail
52 to develop and share a consistent common language	Modelling and tools	-
53 to develop standards and rules	Modelling and tools	-
54 to understand the interlink among hazard, vulnerability and exposure	Technical and technological knowledge	Loop B
55 to improve/optimise infrastructure maintenance	Modelling and tools	-
57 to improve cooperation among organisations	Leadership and relationships	-
58 to consider the interaction among infrastructure, flooding and casualty effects	Technical and technological knowledge	-
59 to gather funding for research	Leadership and relationships	-
60 to deal with lack of leadership	Leadership and relationships	-
61 to train staff to use models and understand outputs	Technical and technological knowledge	Central node
62 to pair data resolution and uncertainty	Data	-
63 to develop a shared vision	Leadership and relationships	Head
64 to understand the drivers of flood risk	Technical and technological knowledge	-
65 to understand the risk timescale	Technical and technological knowledge	Head
66 to educate the general public	Leadership and relationships	-
67 to update/keep records of flood happenings	Technical and technological knowledge	Head
68 to accept resilience measure whose return is uncertain	Technical and technological knowledge	Tail
69 to conduct research	Technical and technological knowledge	-

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