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RESEARCH

Enhancing community flood adaptation by leveraging interdependencies between resilience capitals: A global empirical analysis

Romain Clercq-Roques[1,2] · **Dipesh Chapagain**[1] · **Stefan Hochrainer-Stigler**[1]

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Abstract

Community flood resilience is defined as a multi-dimensional capacity, shaped by the dynamic interplay of social, human, financial, physical and natural capitals. Yet, previous studies and existing adaptation strategies have predominantly addressed these dimensions in isolation, neglecting the analysis of their interactions. This study contributes to the development of integrated, systems-based adaptation strategies by examining how interactions among capitals shape resilience outcomes. Drawing on Flood Resilience Measurement for Communities (FRMC) data from 293 flood-prone communities from 19 developing countries globally, this study adopts a mixed-methods design combining network analysis of covariation between capitals with a qualitative thematic analysis of stakeholder-perceived causal mechanisms linking those capitals. Our findings reveal that resilience is not simply the sum of independent capitals, but an emergent property of their interactions. Both quantitative and qualitative analysis show dense connections among capitals, with social capital found to play a central role by enabling coordination, resource mobilization, and knowledge exchange. Financial and human capitals were also found to act as foundational enablers, particularly in supporting the development and effective use of physical and natural assets. Feedback loops among capitals highlight the importance of mutually reinforcing dynamics in building adaptive capacity. These findings underscore the need for disaster risk reduction and climate adaptation strategies to move beyond siloed interventions. We advocate for integrated funding and policy frameworks that target coupled capitals, such as pairing infrastructure development with social & financial capacity-building, to leverage synergies across sectors.

Keywords Flood resilience · Community level · Social capital · Capitals interactions · Empirical analysis

Extended author information available on the last page of the article

1 Introduction

Floods are among the most pervasive and costly disasters worldwide, and their frequency, intensity, and impacts are rising due to climate and environmental change (IPCC, 2022). Worldwide, flood losses are already estimated to cost USD 90 billion annually, and are projected to rise dramatically to USD 600 billion by 2050 due to the combined effect of climate change, urban expansion, and socioeconomic growth (Alfieri et al., 2017; EEA (European Environment Agency), 2024; GHD 2022). Global warming is intensifying the water cycle, increasing extreme rainfall and amplifying both pluvial and fluvial flood risks in many regions (Seneviratne et al. 2021). Concurrently, sea-level rise and coastal subsidence are worsening flood hazards in low-lying urban and delta regions, while ecosystem degradation such as deforestation and wetland loss undermine natural flood buffers. These hazard drivers intersect with rapid urbanization and land-use change to expand flood exposure, particularly in low- and middle-income countries, where vulnerability is often highest (Winsemius et al. 2016). An estimated 1.8 billion people already live in areas exposed to once-in-100-year floods, with 89% residing in developing countries (Rentschler et al. 2022). Exposed communities face repeated flood impacts that disrupt livelihoods and erode development gains, trapping them in poverty (Chapagain et al. 2025; Hochrainer-Stigler et al., 2025; Paszkowski et al. 2024).

Addressing escalating flood risks requires integrated, cross-sectoral strategies, but current approaches often remain fragmented across sectors and governance levels, limiting their effectiveness and exacerbating vulnerability (IPCC, 2022; Kundzewicz et al. 2018). Numerous adaptation approaches have been developed, such as grey infrastructure (i.e., engineered physical interventions like flood walls), nature-based solutions (e.g. wetland restoration), social protection mechanisms (e.g. safety nets), and investments in community capacity (e.g. community based early warning systems) (Aldrich & Meyer, 2015; Sudmeier-Rieux et al. 2021). However, these strategies are typically planned and assessed in isolation by different sectors or disciplines: flood walls are planned by engineers, insurance schemes by financial actors, early warning systems by emergency services, and reforestation by environmental agencies. This fragmentation reflects a broader challenge in both policy, practice and academic communities: adaptation is often conceptualized and operationalized through isolated components rather than integrated systems (Parviainen et al. 2025). As a result, synergies and trade-offs among interventions are poorly understood (Kundzewicz et al. 2018).

In recent years, the concept of community resilience has gained prominence as a concept for designing and assessing flood adaptation strategies, thanks to the realization that the resilience of communities determines their capacity to adapt to environmental changes (Keating et al. 2017). Resilience is increasingly conceptualized as being composed of multiple capitals who all help communities absorb and adapt to disturbances (Hochrainer-Stigler et al., 2025). For example the Sustainable Livelihoods Framework (Scoones 1998), the Community Capitals Framework (Emery and Flora 2006), and the Baseline Resilience Indicators for Communities (Camacho et al. 2023) posit that a critical mass of diverse assets (human, social, financial, natural and physical) enables communities resilience. Empirical studies have confirmed the importance of each capital in isolation. For example, social capital has been found to play a critical role by fostering collective action, information and resource sharing, and social support (Aldrich 2012; Aldrich & Mayer, 2015; Dynes 2006;

Nakagawa and Shaw 2004). Human capital equips individuals with knowledge, skills, and adaptive capacities that facilitate effective decision-making, resource management, and problem-solving (Cinner & Barnes, 2019; Fabricius et al. 2007; Ford et al. 2020). Financial capital enables investments in preparedness, mitigation, and recovery efforts, and reduces vulnerability to personal ruin through e.g. insurance and social safety nets (Heltberg et al. 2009; Tariq et al., 2021). Physical capital provides critical infrastructure and services that support protection, response, and recovery (Heltberg et al. 2009; Tariq et a., 2021). Natural capital provides critical ecosystem services such as flood regulation, erosion control, and local weather regulation (Lucatello & Alcantara-Ayala, 2024; Sudmeier-Rieux et al. 2021; Vicarelli et al. 2024).

Yet, despite this multidimensional conceptualization and empirical investigations, these capitals often remain treated as independent, static, stocks to be accumulated and mobilized separately, mirroring the siloed implementation of adaptation strategies (Laurien et al. 2022). Consequently, there remains limited understanding of how these resources may reinforce or undermine one another, limiting our ability to design coherent and effective adaptation strategies (Tariq et al. 2021; Hofbauer et al. 2025).

The Flood Resilience Measurement for Communities (FRMC) is a standardized, empirically validated framework developed by the Zurich Flood Resilience Alliance to assess community flood resilience and support adaptation building. It is grounded in a multi-capital approach and evaluates 44 sources of resilience across five interdependent capital domains: human, social, physical, natural, and financial (Hochrainer-Stigler et al. 2025). Community resilience is defined as “the ability of a community to pursue its social, ecological, and economic development objectives while managing disaster risk in a mutually reinforcing way” (Keating et al. 2017). The FRMC uses household surveys, focus groups, expert assessments, and secondary data, to build a comprehensive assessment of community resilience at multiple time points, and where possible, compares these with post-event outcomes to evaluate actual resilience performance. Between 2018 and 2024, baseline and endline assessments were conducted in 293 flood-prone communities in 19 low- and middle-income countries (Hochrainer-Stigler et al. 2025).

Building on this FRMC dataset, we systematically analyse how different forms of capital interact to shape community resilience to floods. We adopt a mixed-method approach, combining quantitative network mapping of capital interactions over time with qualitative thematic analysis of mechanisms of change perceived by stakeholders, to examine how capitals co-vary and influence each other in shaping flood resilience.

This study investigates the hypothesis that community flood resilience is an emergent property of capital interdependencies rather than merely the sum of discrete capitals. By examining these interdependencies, we aim to determine whether interactions among these capitals are predominantly mutually reinforcing, to assess if specific capitals hold central roles in fostering resilience, and to identify key mechanisms responsible for those interdependencies. Doing so, we aim to provide actionable insights for integrated adaptation planning.

The remainder of the paper is structured as follows: Sect. 2 details the FRMC concept and framework as well as data and methods used, Sect. 3 presents the results, Sect. 4 discusses their implications for research and practice, and Sect. 5 provides a brief conclusion and outlook to the future.

2 Methodology

2.1 The FRMC framework and tool

This study uses a mixed-method approach to analyse community resilience to floods, contrasting qualitative and quantitative data collected through the FRMC, a framework and tool developed by the Zurich Climate Resilience Alliance and implemented in 293 flood-prone communities from 19 countries (Albania, Bangladesh, Bolivia, Cambodia, El Salvador, Jordan, Kenya, Malawi, Nepal, Mexico, Montenegro, Mozambique, Nicaragua, Peru, Philippines, Senegal, South Sudan, Vietnam, Zimbabwe) between 2018 and 2024, allowing for an assessment of resilience changes over time. While the broader FRMC framework includes post-event outcome assessments (depicted in Fig. 1), this study relies exclusively on baseline and endline studies conducted to analyse resilience capacities. Baseline and endline studies used the same method, indicators and were conducted in the same communities.

The Zurich Climate Resilience Alliance is a multi-stakeholder partnership that strengthens community resilience to floods through research, policy engagement, and interventions (Laurien et al. 2020). The Alliance includes NGOs, research institutions, and the private sector. Resilience is conceptualised as multidimensional and encompassing social, human, natural, financial, and physical capitals, aligning with social-ecological resilience theories (Folke 2006), and emphasizing preparedness, adaptation, and long-term transformation. Operating in flood-prone regions in sub-Saharan Africa, Latin America, Asia, and Europe, the Alliance assesses community resilience to climate hazards with the FRMC and co-develops locally tailored resilience-building interventions with local communities and other stakeholders (Laurien et al. 2020).

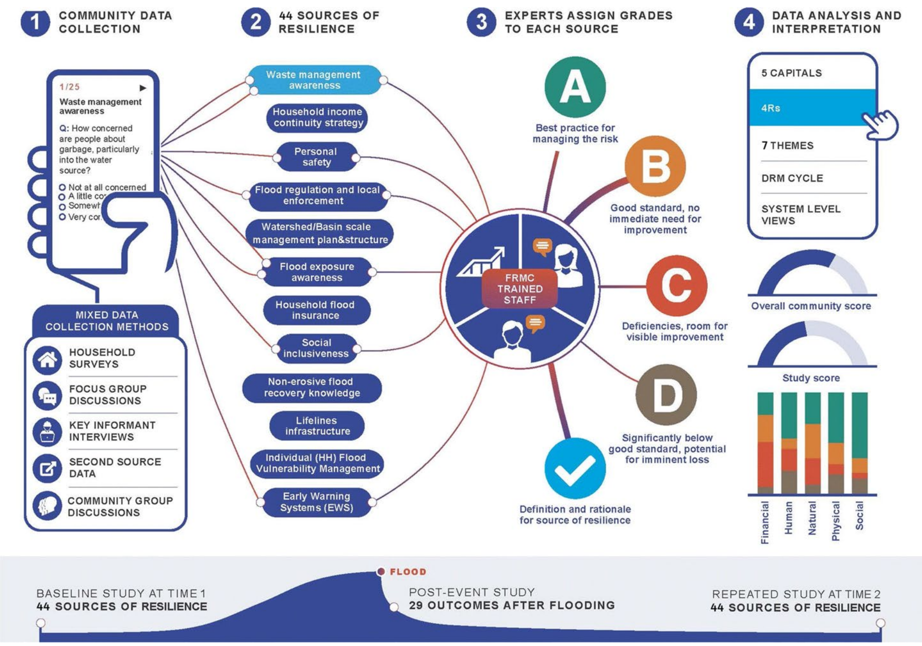

Fig. 1 FRMC data implementation process. Based on Laurien et al. (2020)

A cornerstone of the Alliance's work is the FRMC, which holistically assesses resilience using qualitative and quantitative data (Laurien et al. 2020). The FRMC methodology has evolved over time to reflect improved understanding of resilience and expanding climate risks. Launched in 2013, the original Flood Resilience Measurement Tool (FRMT) assessed over 80 potential sources of resilience across five capitals, and was empirically tested in over 100 communities. This provided extensive feedback which informed the development of a revised "NextGen" FRMC, on which this study relies. This NextGen FRMC was deployed between 2018 and 2024, focusing on 44 core indicators to improve usability and comparability while retaining theoretical depth. Since 2025, the methodology has been revised a third time to encompass multiple climate hazards, in what is now called the Climate Resilience Measurement for Communities (CRMC). This CRMC is currently being deployed, and data not yet available.

This study uses data from the "NextGen" FRMC. In partnership with communities, implementing teams conducted structured baseline and endline studies in the same communities between 2018 and 2024, assigning resilience grades to 44 resilience indicators (Table 1). The FRMC categorizes each of the 44 resilience indicators into one of five capitals (Table 1), allowing to gain a finer understanding of determinants of resilience in communities across space and time. Each capital is measured as the average value of its constituent sources. The data collection and grading were participatory, involving local stakeholders (community members, local government officials, and other relevant actors) to ensure that evaluations and plans were informed by local knowledge and priorities.

For the baseline and endline assessment, the FRMC dataset encompasses 293 communities across 19 countries, representing a total estimated community population of approximately 0.7 million people. Data were collected from 16,946 households and focus groups, key informants, and secondary data sources, as well as grades assigned to each of the sources of resilience.

After completion of the endline study, an additional qualitative assessment was conducted to understand causes of changes in community resilience. Implementing teams assessed what led each of the 44 indicators to decrease, increase, or remain stable. This evaluation process was collaborative, involving discussions with local stakeholders and among implementing teams. In particular, teams aimed to understand the extent to which NGO interventions, local actors' actions, community actions, and contextual factors impacted grades.

2.2 Data analysis

This study adopts a mixed-methods design. Quantitative and qualitative data were collected concurrently through the FRMC framework, then analysed separately, and later integrated to provide a more comprehensive understanding of capital interactions (Creswell and Plano Clark 2017), as described in Fig. 2. We conducted a quantitative analysis of FRMC grade through correlation network mapping to assess whether statistically significant co-variations between resilience capitals were observable. We conducted a complementary qualitative thematic analysis of stakeholder-perceived causal mechanisms shaping interactions between capitals.

This mixed-method approach allowed to capitalize on their complementary strengths: a quantitative analysis of FRMC data to identify generalizable patterns from a large global

Table 1 The 44 sources of resilience in the FRMC and their categorization into 5 capitals

Code	Capital	Source Name
F01	Financial	Household asset recovery
F02	Financial	Community disaster fund
F03	Financial	Business continuity
F04	Financial	Household income continuity strategy
F05	Financial	Risk reduction investments
F06	Financial	Disaster response budget
F07	Financial	Conservation budget
H01	Human	Evacuation and safety knowledge
H02	Human	First aid knowledge
H03	Human	Education commitment during floods
H04	Human	Flood exposure awareness
H05	Human	Asset protection knowledge
H06	Human	Future flood risk awareness
H07	Human	Water and sanitation awareness
H08	Human	Environmental management awareness
H09	Human	Governance awareness
N01	Natural	Natural capital condition
N02	Natural	Priority natural units
N03	Natural	Priority managed units
N04	Natural	Natural resource conservation
N05	Natural	Natural habitat restoration
P01	Physical	Flood healthcare access
P02	Physical	Early Warning Systems (EWS)
P03	Physical	Flood emergency infrastructure
P04	Physical	Provision of education
P05	Physical	Household flood protection
P06	Physical	Large scale flood protection
P07	Physical	Transportation interruption
P08	Physical	Communication interruption
P09	Physical	Flood emergency food supply
P10	Physical	Flood safe water
P11	Physical	Flood waste contamination
P12	Physical	Flood energy supply
S01	Social	Community participation in flood related activities
S02	Social	External flood response and recovery services
S03	Social	Community safety
S04	Social	Community disaster risk management planning
S05	Social	Community structures for mutual assistance
S06	Social	Community representative bodies
S07	Social	Social inclusiveness
S08	Social	Local leadership
S09	Social	Inter-community flood coordination
S10	Social	Integrated flood management planning
S11	Social	National forecasting policy & plan

sample and a complementary qualitative analysis to contextualize the dynamics and processes underpinning those patterns. In more detail, the quantitative analysis used community grades for the 44 sources of resilience from baseline and endline surveys.

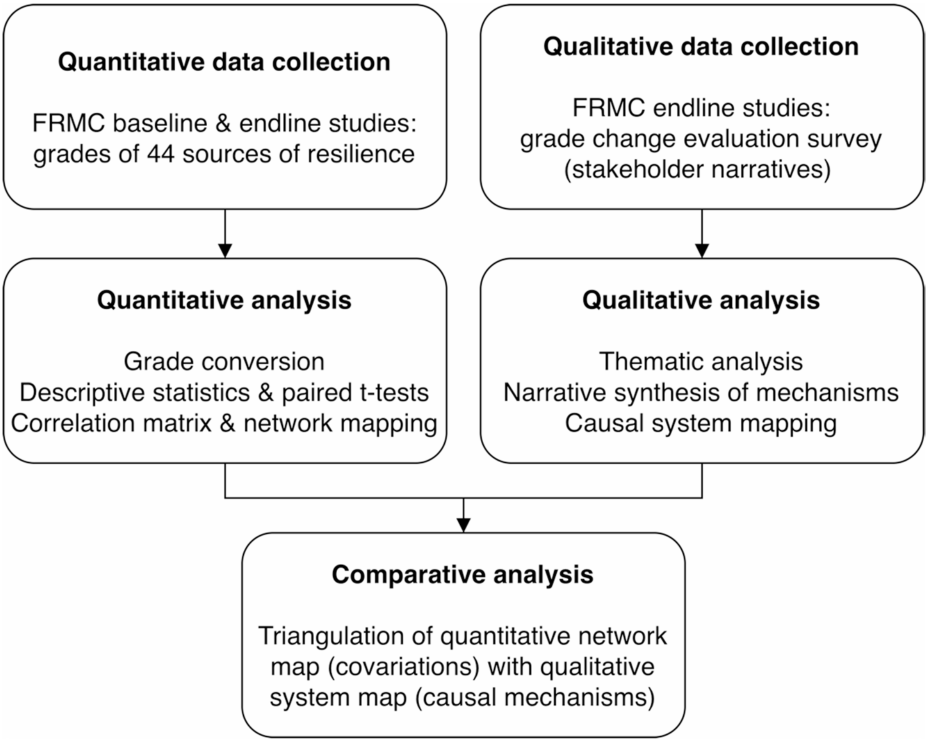

Fig. 2 data sources and analytical strategy. Quantitative and qualitative data from FRMC studies were first analysed independently, before being contrasted in a comparative analysis

All sources of resilience were graded on a scale from A to D, converted to numerical values (A = 100, B = 66.6, C = 33.3, D = 0) to facilitate numerical aggregation. The numerical scores for relevant sources within each capital (Supplementary 1) were then averaged to generate an overall score for each capital. The methodology behind this grading system, including its validity and reliability, is detailed in Laurien et al. (2020) and Chapagain et al. (2024).

At the beginning, descriptive statistics were calculated for each of the five capitals for the FRMC baseline and endline surveys to provide insights into the distribution and central tendencies of resilience scores at both time points. We then conducted paired t-tests for each capital to assess whether the differences in mean scores between baseline and endline were statistically significant. Then, we conducted a correlation network analysis to explore the interrelationships among the five capitals. Data from the baseline and endline surveys were combined under the assumption that the relationships among capitals remain stable over time, as separate correlation analysis for the baseline and endline produced similar results. Pairwise Pearson correlation coefficients were calculated across the dataset to capture linear co-variations among capital scores. These coefficients were used to construct an undirected weighted network, with nodes representing the five capitals and the weight and darkness of edges indicating the strength of correlations. The network was visualized using a force-directed layout displaying the structure of interrelationships among capitals. Finally, we performed a second-level correlation analysis among the 44 underlying sources of resilience to help reveal which specific sources drove the capital-level co-variations (Supplementary 1.3).

To complement this quantitative analysis, we conducted a thematic analysis of qualitative data of stakeholder-reported mechanisms having caused changes in grades between baseline and endline, providing insights on mechanisms driving interrelationships among capitals. Following Clarke and Braun's (2013) six-step method, we first organized data in capitals, resilience sources and countries, before immersing ourselves in the data through repeated reading to gain familiarity with it and identify key patterns. We then generated codes for distinct mechanisms and extracted relevant quotes to illustrate mechanisms and enhance transparency in the analytical process. Next, we structured the results into a narrative, categorizing mechanisms by capital. The result section provides a concise narrative synthesis of the mechanisms, and the supplementary information provide a detailed description enriched with quotes (Supplementary 2). The final phase of the qualitative analysis involved constructing a causal diagram mapping the mechanisms and the connections between capitals. To synthesize the results of the thematic analysis and visually represent the interconnections between capitals, a causal loop-based system map was constructed. We used causal statements describing how specific mechanisms (e.g., community savings groups) linked one capital to another. These statements were then translated into directed edges between capitals, forming a network of perceived influence. This approach draws on established principles from systems thinking to provide an empirically grounded model of stakeholder-informed pathways of resilience (Barbrook-Johnson and Penn 2022).

As a final analytical step, we integrated quantitative and qualitative data. The network map showing quantitative correlations between grade changes, and the system map showing mechanisms perceived by stakeholders to generate interactions between capitals, were compared to identify similarities and differences, providing a richer understanding of interactions between capitals. We present the similarities and differences in the result section and assess their implications in the discussion section.

3 Results

The analysis of the FRMC data provides a comprehensive view of the interactions between capitals and how they impact community resilience. The results are presented in 4 sections. First, we briefly present the overall quantitative changes in community grades and the network map based on the correlations between capitals. Second, we present a system map of perceived interaction between capitals, developed from qualitative data. Third, we provide a narrative synthesis of the mechanisms presented in the system map. Finally, we compare the network map and system map.

3.1 Resilience score changes and network map

The assessment of community flood resilience scores across the five capitals (5Cs) revealed a notable improvement from the baseline to the endline assessment (Table 2). Most communities experienced significant progress in all five capitals, with social capital showing the highest increase in median score (36.37 to 63.64), financial capital increasing from 28.58 to 42.86, human capital increasing from 51.85 to 66.67, natural capital increasing from 33.34

Table 2 Descriptive statistics of community resilience scores across the 5 capitals in baseline and endline assessments

Capitals	Baseline					End-line				
	Mean	SD	Median	Min	Max	Mean	SD	Median	Min	Max
Financial	29.92	17.36	28.58	0.00	85.72	42.08	22.00	42.86	0.00	95.24
Human	51.44	15.98	51.85	11.11	88.89	66.78	13.92	66.67	25.93	96.30
Natural	35.86	15.82	33.34	0.00	86.67	47.56	17.70	46.67	6.67	100.00
Physical	36.19	15.00	36.12	5.56	80.56	49.31	14.77	47.23	11.11	80.56
Social	35.26	17.00	36.37	3.03	78.79	59.83	17.00	63.64	9.09	87.88

to 46.67, and physical capital showing the lowest increase, from 36.12 to 47.23. Paired t-test results confirmed that these changes were statistically significant for all five capitals at the $p < 0.05$ level.

We do not discuss these grade changes in detail and refer to Hochrainer-Stigler et al. (2025) for a detailed analysis and focus here on interdependencies which were not presented yet. The network map (Fig. 3), based on the correlation matrix among the five capitals (Supplementary 1.3), reveals varying strengths of interconnections between capitals giving rise to community flood resilience. A detailed heat-map between the 44 sources of resilience composing the 5 capitals (Supplementary 1.2) and a narrative synthesis of these interactions (Supplementary 1.3) shows a more granular picture of these interdependencies.

In more detail, social capital emerged as a central source in the communities surveyed, with strong and positive correlations to all other capitals. Physical capital showed strong positive correlations with financial, human, and social capital, but it did not exhibit a significant relationship with natural capital. Financial capital was strongly linked to physical and social capital, while its correlations with human and natural capital were weaker. Human capital was strongly correlated with physical and social capital and had weaker associations with financial and natural capital. Finally, natural capital had comparatively weaker ties to other capitals remained an integral part of the network, contributing to the broader system of capital interactions. Overall, the five resilience capitals were found to be deeply intercon-

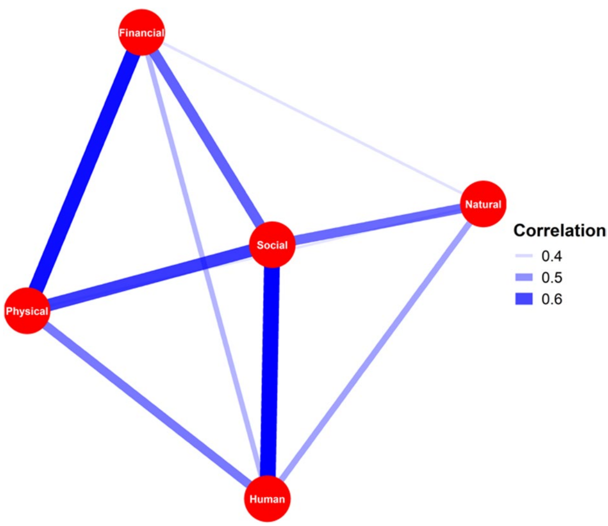

Fig. 3 Capital interaction network map based on the correlation matrix. Note: Thicker and darker edges represent stronger interactions between capitals, and capitals with many strong relationships appear closer together

nected, forming a system where improvements in one capital were often accompanied by improvements in others.

3.2 Systems mapping

While quantitative data of grade changes allowed to build a network map exploring quantitative covariations between capitals, qualitative data of stakeholder-reported mechanisms of grade changes allowed us to conduct a detailed narrative analysis of the causal mechanisms perceived to generate interactions between capitals, as well as to synthesize these interactions into a system map (Fig. 4) providing a complementary picture to the quantitative network map.

This system map displays the mechanisms identified and how they connect the five capitals to create an integrated whole. Social capital appears particularly connected, having the highest number of direct links to other capitals (11 outward links, 4 inward links). Many of those are toward human capital, which also has numerous links to other capitals (4 outward links, 7 inward links). Financial capital is also highly connected (4 outward links, 7 inward links). On the contrary, physical (3 outward links, 5 inward links) and natural capitals (3 outward links, 3 inward links) display fewer links to other capitals. Specific mechanisms (in white boxes) are presented in the remainder of the result section.

3.3 Interactions synthesis

In this section, we provide a narrative synthesis of the qualitative data, detailing the stakeholder-reported mechanisms that drive interactions between the five capitals. Rather than statistical covariation, this section focuses exclusively on the perceived causal pathways generating these links. This section explains how the mechanisms connect the five capitals into an interdependent system, where investments in one lead to improvements in others and deficiencies in one can constrain resilience. Due to its importance, a focus on social capital was given. A more expansive synthesis and supporting quotes are presented in the supplementary information (Supplementary 2).

3.3.1 Social capital

Social capital emerged as a particularly influential capital, with stakeholders considering that it impacted other capitals through numerous mechanisms. Social capital was found to influence human capital through formal and informal groups playing key roles in disseminating disaster risk reduction (DRR) knowledge, organizing training activities, and fostering collective action (such as rescue operations, or waste management preventing disease outbreaks during floods). Social cohesion also helped reduce antisocial behaviours, such as theft or exploitation, especially during or after crises. Greater equality and inclusion of women and minorities were also considered to improve their access to education and DRR knowledge and skills, thus improving their human capital. In addition, social capital was considered to influence financial capital, through mutual support mechanisms (such as gifts, loans, and remittances from relatives) which enabled asset recovery without harmful coping strategies such as selling livestock. Community groups were found important by sharing

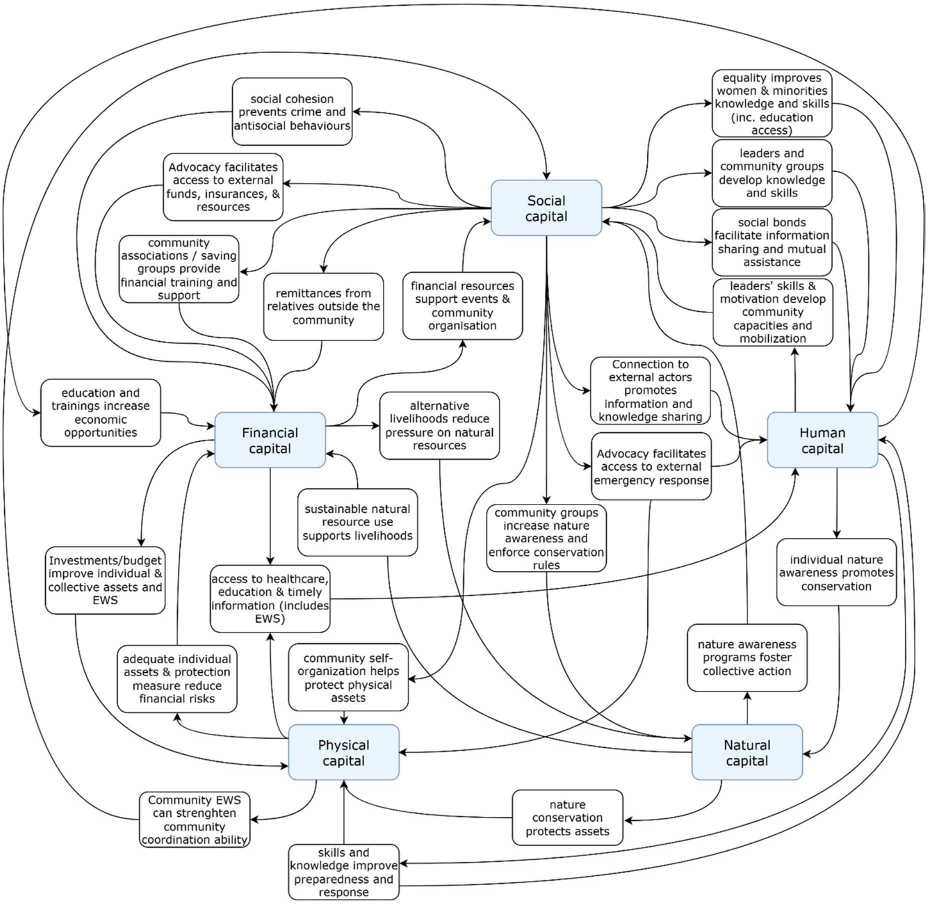

Fig. 4 System map of mechanisms and capitals. Capitals (in blue boxes) are connected via mechanisms (in white boxes). Arrow heads indicate the direction of impact. For example, community association and saving groups (social capital) can provide financial training and loans (financial capital)

financial advice, sharing knowledge of risk reduction strategies, and providing information about formal schemes such as insurance or financial relief.

Furthermore, social capital was considered to enhance physical capital by supporting the development and maintenance of protective infrastructure. Community cohesion and coordination allowed residents to mobilize internal assets (e.g. labour, tools) and gain access to external resources through advocacy, enabling the construction and upkeep of dykes, drainage systems, and other DRR infrastructure. Social ties also supported the establishment of effective community-based early warning systems. Social capital was also considered to support natural capital by promoting awareness of environmental issues and mobilizing collective action for protection and restoration. Community norms, local planning, and partnerships with external actors helped implement conservation and nature-based solutions.

Interestingly, social capital not only influenced many other capitals but was influenced by other capitals as well (Fig. 4). Human capital, particularly leadership skills and DRR knowledge, enabled effective cooperation and collective action. Community leaders were essential in organizing preparedness and promoting inclusive governance. Financial capital supported community events and planning activities that strengthened social cohesion; its absence, however, often strained social relations. In some cases, financial hardship following disasters eroded trust and led to increased antisocial behaviours, weakening the community's social fabric. For more detailed discussions we refer to Supplementary 2.5.

3.3.2 Human capital

Human capital, encompassing individual knowledge, skills, education, and health (Cinner & Barnes, 2019), was considered central to enhance agency and reduce vulnerability. It contributed to resilience across multiple domains. For example, it was indicated by the interviews to support financial capital as greater skills and training allowed for livelihood diversification, enabling households to buffer shocks and maintain income during floods. DRR education additionally helped reduce asset losses by encouraging proactive behaviour and implementing protective measures, reducing risks of losses. These mechanisms were thought to similarly protect physical capital. Human capital was also thought to support natural capital protection by increasing awareness of the ecological functions of forests, wetlands, and rivers. In contrast, lack of awareness was considered to hinder conservation policies implementation.

As social capital, but to a lesser extent, human capital was also found to be influenced by other capitals. Social capital was essential to mobilize communities and organize capacity building and information sharing events. Financial capital was considered key to education access, with flood related financial losses causing children to leave school and take on household responsibilities. Physical capital helped safeguard education and healthcare access by maintaining transport routes, communication systems, and public infrastructure during crises. Effective communication networks were also considered key to distribute DRR information and timely alerts. More details are available in Supplementary 2.2.

3.3.3 Financial capital

Financial capital was also found important by enabling improvements in all other capitals but also requiring social and human capitals to be mobilized effectively. Regarding social capital, financial resources were found necessary to organize community events and flood management meetings that strengthened coordination, and to support community participation in those events. Conversely, financial hardship was considered to undermine social cohesion, at times leading to antisocial behaviours. Financial capital was considered necessary to maintain access to education and healthcare, core components of human capital. Regarding physical capital, dedicated budgets allowed for investments in infrastructure building and maintenance, including roads, culverts, and embankments. Both individual and collective risk reduction efforts depended on available funds, either through community pooling or advocacy for external funding. Financial capital was also considered to impact natural capital, with poverty sometimes leading to unsustainable practices such as deforestation. Conversely, investment in sustainable livelihoods could reduce pressure on ecosystems.

Financial capital was also shaped by other capitals. Social capital provided community financial safety nets and improved access to institutional support. Human capital increased income-generating capacity and reduced exposure to losses via vocational training and DRR awareness. Physical capital, for example dykes, protected assets and ensured economic continuity. Natural capital, when sustainably managed, could provide income through ecosystem services, but its degradation could lead to trade-offs between short-term financial gains and long-term flood risks. See Supplementary 2.1 for more details.

3.3.4 Natural capital

Natural capital was reported to be efficient for protecting both physical infrastructure and individual assets through nature-based DRR solutions (NBS) such as vegetative buffers, floodplains, and riverbank stabilization. However, NBS were reported to not always be sufficient on their own and were sometimes damaged by extreme events such as cyclones. Financial capital, e.g. through community budgets, enabled restoration activities and supported transitions to sustainable livelihoods. As indicated in the previous paragraph, trade-offs between financial and natural capitals could occur through the degradation of natural capital for short-term income.

As shown in Fig. 4, natural capital was supported by social capital through raised awareness, coordinated conservation actions, and enforcement of environmental rules. Social groups at various levels were considered important to protect and restore natural capital: community groups through self-organization, local and regional State authorities through regulation adoption and enforcement, and bridging organizations (such as NGOs) to connect and support them. Human capital, through knowledge of regulations and knowledge of the importance of natural capitals, further supported protective and restorative actions. See Supplementary 2.3 for more details.

3.3.5 Physical capital

As stated in the paragraphs above, physical capital was considered important to reduce flood exposure of, and impact to, collective and individual assets, and to persons, thus protecting financial and human capitals. Physical capital, through community based early warning systems was also considered to support social capital by building community coordination capacities. Physical capital supported the delivery of response services and maintained access to education, healthcare, and income generating activities. Physical capital was considered to depend on financial capital, which funded investments in individual and collective assets construction and maintenance, and on social and human capitals, necessary to identify and coordinate appropriate actions. NBS, as part of natural capital, also contributed to physical protection, though with limitations. (See Supplementary 2.4).

3.4 Comparative analysis

In this section, we systematically integrate the quantitative correlation network (Fig. 3) with the qualitative system map (Fig. 4) to triangulate our findings. By comparing these distinct datasets and analyses, we map the statistical covariations established in Table 2 against the specifical causal mechanisms outlined by stakeholders.

Comparing the network map showing quantitative correlations between grade changes and the system map showing mechanisms perceived by stakeholders to generate interactions between capitals reveals many similarities and some differences. A key result is that both maps similarly give a central role to social capital, highly correlated to other capitals (Fig. 3) and connected through a high number of mechanisms (Fig. 4).

Most of these connections originate from the social capital and are directed toward other capitals. Both maps show similarly strong connections between social and human capitals, highlighting their interdependence. A third similarity is that both maps show strong links between social and financial capitals.

Overall, both maps converge in showing tight integration between social, human and financial capitals, with mechanisms going in all directions, hinting at potential feedback loops. Conversely, both maps show comparatively little connection between human and financial capital, and between human and physical capital. Both maps also show that the natural capital had the least connections to other capitals in FRMC data. While some capitals are more connected than others, both maps show that all capitals are connected.

However, the system map (qualitative, Fig. 4) differs from the network map (quantitative, Fig. 4) by not displaying as strong a direct link between social and physical capitals. While the system map does not show a strong direct link, indirect links through other capitals are visible, in particular through the financial and human capitals (Fig. 4.), which are strongly correlated to both social and physical capitals in the network map (Fig. 3). We assess other non-obvious and complex links, as well potential explanations for similarities and differences between qualitative and quantitative results, in the discussion.

4 Discussion

In this study, we used the FRMC framework and tool to analyse how the resilience of 293 flood-prone communities across 19 countries was shaped by interaction between capitals. We found that a web of mechanisms tightly connected the five capitals. Flood risk adaptation is commonly operationalized through siloed strategies targeting individual resilience components (e.g. physical capital), but our study suggests that approaches ignoring interactions between capitals risk missing opportunities for synergy or, conversely, generating unintended trade-offs (Ward et al. 2022). As such, our results support recent calls for integrated, systems-based adaptation planning that links physical, ecological, social and institutional domains (Folke et al. 2021; Parvianien et al. 2025; Hofbauer et al. 2025).

Resilience score changes indicate that community resilience improved overall, with social capital seeing the highest increase (Table 2). While our study focused on capital-level interactions, previous studies of FRMC data provide insights on sources having contributed most to resilience improvement. Sources related to governance and coordination, such as inter-community collaboration, disaster risk management planning, and alignment with national forecasting systems (Table 1), were found to play a particularly important role, thanks to their association with reduced property crime and increased external support during and after floods (Chapagain et al. 2025). Additionally, sources linked to social cohesion and human capital, such as mutual assistance, inclusiveness, and community participation (Table 1), were found especially important in flood-related injuries reduction, while preparedness measures (Table 1) were found important for both injuries and fatalities reduction (Guimaraes et al. 2025). Nevertheless, these findings did not isolate a dominant source, rather, they indicate that resilience depends on the combined effects of multiple sources. Below, we develop on those interactions.

While our results show a tightly connected network, they also underline the centrality of social capital. Quantitative results indicate that social capital was strongly correlated to other capitals, indicating that communities with higher trust, cohesion, and collaboration (sources S1 to S11, Table 1) also tended to have better outcomes in other areas (Fig. 3 and Supplementary 1). Qualitative results showed social capital to be a key enabling factor, facilitating coordination and the mobilization of critical assets (financial, physical and natural, but also labour, knowledge and skills; Fig. 4). These functions enabled communities to build, maintain and access internal and external resources, and utilize them efficiently (Fig. 4 and Sect. 3.3, see also Adger 2003; Aldrich and Meyer 2015). Our quantitative results (Fig. 3 and Supplementary 1.3) corroborate previous empirical studies identifying social capital as foundational to community resilience (Aldrich 2012; Cutter et al., 2008, Islam, 2024). Furthermore, our qualitative results (Fig. 4 and Sect. 3.3) extends our understanding by suggesting mechanisms and feedback loops through which social capital can interact with other capitals. Both quantitative and qualitative results highlight in particular the strong links between social and human capital (Figs. 3 and 4, Sect. 3.3.1 and Supplementary 1.3).

Our findings suggests that the human capital of community leaders and champions (in particular their leadership, inclusion, and advocacy skills; Fig. 4 and Sect. 3.3.1) can impact communities' ability to coordinate internally and mobilize external actors, developing bonding, bridging and linking capital. Previous studies of resilience in social-ecological systems, had similarly found that community leaders and champions played key roles of structuring inter-individual and inter-group cooperation (Burch et al. 2014; Chaffin et al. 2016; Westley et al. 2013; Muwafu et al. 2024). Our findings extend these studies by suggesting that, conversely, social capital could also reinforce human capital by fostering information exchange and knowledge & skill development (Sect. 3.3.1-2), possibly generating mutually reinforcing dynamics. Our findings further indicate that human capital might, in turn, reinforce other capitals, by e.g. improving environmental awareness and knowledge of appropriate measures to protect physical and financial capital (Sect. 3.3.2). This hints at interdependencies between individual and collective agency, thought to be an important determinant of resilience (Cinner and Barnes 2019; Westley et al. 2013).

Our results further suggest that physical capital can improve social capital through community-based early warning systems, which are categorized within physical capital in the FRMC (Sect. 3.3.1 & 3.3.5, and Fig. S2). These flood-focused organizations improve communities' coordination abilities and link between community members through information sharing and trainings (Bajracharya et al. 2021; Marchezini et al. 2017). More generally, our analysis indicate that physical and natural capital could play structurally different roles from other capitals. Both physical and natural environment require careful design to reduce risks, something which requires knowledge, coordination abilities, and financial resources, thus underlining the foundational role of human, social and financial capital (Sect. 3.3). Quantitative results also point at positive correlations between financial and physical capitals (Fig. 3 ad S2), which qualitative results indicate could be due to a mutually reinforcing dynamic between the two: improvements in financial capital facilitate investment in infrastructures and protective measures, reducing exposure and vulnerability of collective and individual assets, thus mitigating financial losses and allowing further investments (Fig. 4).

Social and financial capitals have been argued to play critical and interdependent roles in resilience-building: social networks need material resources to act upon (Muwafu et al. 2024), and financial resources need competent institutions and networks to be utilized efficiently (Aldrich and Meyer 2015; Partelow 2020). In the communities studied, we found that strong social capital facilitated financial training, community support, and access to financial resources (Sect. 3.3.1 & Supplementary 1.3). Conversely, financial capital allowed to finance community coordination events and structures (Sect. 3.3.3 and Supplementary 1.3). More generally, financial capital appears as an enabler of other capitals when channelled through effective social networks (Himes-Cornell et al. 2018; Warner et al. 2007). The interdependency between social and financial capital suggests that investing in both simultaneously may yield synergetic outcomes, improving all capitals and overall community resilience.

One somewhat surprising result was that natural capital appeared less connected to other capitals in our analysis (Figs. 3 and 4). This contrasts with a growing body of literature highlighting that natural capital can provide critical protective functions such as flood regulation and erosion control, and can improve financial capital through sustainable natural resource use (Aloscious et al. 2025; Hankin et al. 2021; Lallemant et al. 2021; Manes et al. 2024). A recent study additionally found that the five capitals, in particular social and human capitals, influenced the adoption of nature-based solutions (Sandilya and Goswami 2024). Our results may be due to multiple factors. Context-specific synergies and trade-offs could have averaged to lower overall correlations: in some of our communities, exploiting natural resources (e.g. for charcoal production) provided short-term financial gains but degraded long-term protective functions, weakening overall resilience (Sect. 3.3.4). Conversely, previous studies had found that conservation policies had sometimes negatively impacted communities by depriving them of income sources and of natural resources (Dowie 2009; Neudert et al., 2016; Ward et al. 2018). Recognizing and managing these potential trade-offs and capitalizing on synergetic effects would thus be important. In addition, the time needed for improvements in natural capital to benefit other capitals may exceed the time between baseline and endline surveys and may thus not be reflected in the data. Finally, our results could also be due to the under-representation of natural capital in stakeholders' narratives and its under-prioritisation in NGO interventions. The implication is that integrating nature-based solutions into community resilience strategies remains a challenge. Ensuring that natural capital is valued and invested in alongside other capitals will be important for truly comprehensive adaptation strategies.

While using a comprehensive quantitative dataset and rich qualitative insights, the study has several limitations, highlighting avenues for future research. First, our data focuses on community-level dynamics, and we did not systematically account for broader dynamics, such as country and global trade (Conevska 2021), or macroeconomic dynamics (Mochizuki et al. 2014), which likely influence local resilience but remain often missing in resilience studies (Bene et al., 2014; Brown 2014). Multi-scale research linking community and macro-level mechanisms would provide a more holistic view. Second, the two to three years interval between baseline and endline surveys may be too short to see the full effects of resilience-building, especially for longer term interventions (e.g. ecosystem restoration or social norm change). Longer-term studies would be needed to observe sustained resilience trajectories and delayed outcomes. Third, our results reflect average patterns across 293 communities in 19 countries. Because our current analysis aggregates data at a global scale, it reveals overall patterns but does not explicitly differentiate between communities with potentially varied profiles (Chapagain et al. 2024), such as rural and urban communities where the relative importance of physical and natural capital may differ. Future research should disaggregate these settings to uncover context-specific capital interdependencies. Such information can then be related to risk assessment approaches (de Moel et al. 2015) for estimating direct and indirect risks (Botzen et al. 2019) for different risk bearers or respective systems (Hofbauer et al. 2025).

Our study provides actionable insights to communities and policymakers for transitioning from siloed disaster risk reduction to integrated, system-based adaptation. Our results suggest that social capital acts as functional enabler, and community-based policies should prioritize strengthening local governance and mutual assistance network as foundational to technical interventions. The feedback loops identified between capitals, particularly between financial and human capitals, suggest that 'bundled' interventions targeting multiple capitals would be more effective. For example, providing financial safety nets with concomitant human capital training would mitigate immediate loss while building long-term adaptive capacity. Similarly, policies should prioritize programs pairing infrastructure development with social and financial capacity building to improve community capacities to manage and maintain their infrastructures. The links identified between financial hardship and the erosion of social trust, and with the erosion of natural capital, underscore the need for policies that facilitate access to emergency funds and insurance, preventing reinforcing feedback loops (spiral down effects) were asset and livelihood loss lead to worsening resilience. Our results suggest that preventing this requires multi-level approaches: developing communities' own capacities, through e.g. mutual assistance networks, and developing communities' advocacy capacities, for instance with skilled leaders and champions.

We suggest several important avenues to future enquiry. First, the assessment of longer-term dynamics. The 2–3 years interval between baseline and endline studies may not have captured dynamics playing over longer periods, such as the full benefits of natural capital restoration. Future studies in the same communities may provide important additional evidence. Second, disaggregating between community types, as resilience mechanisms and correlations might differ between, for instance, urban and rural communities. Future studies should assess whether social capital plays such a central in urban communities, and whether the relative weight between social and other capitals, in particular human, financial and physical, shifts in densely populated centres compared to villages with potentially stronger social tissues. Third, assessing multiple scales, as local resilience is inherently nested with regional, national and global economic and policy environments. Future studies should investigate how the various layers of administrative and political governance institutions support or hinder community capitals and overall resilience.

5 Conclusion

This study aimed to inform adaptation planning by uncovering how different types of capital reinforce or constrain each other in supporting community flood resilience. Building on the FRMC framework and dataset, we systematically analysed how different forms of capital interact to shape community resilience to floods, using a mixed-method approach. This study advances the understanding of community adaptation to global environmental change by conceptualizing flood resilience not as the sum of independent assets, but as an emergent property of dynamic interactions among social, human, financial, natural, and physical capitals.

Our analysis drew on a rich empirical dataset collected through the Flood Resilience Measurement for Communities (FRMC) framework from 293 flood-prone communities in 19 low- and middle-income countries (Laurien et al. 2020). The FRMC captures both qualitative and quantitative data on resilience across five capitals. This unique dataset allowed us to explore not only the presence or absence of resilience components, but also the ways in which they co-occur, reinforce, or constrain one another. We can therefore provide empirical and conceptual contributions to current efforts to design integrated multi-sectoral adaptation strategies. To investigate these interdependencies, we adopted a mixed method combining a quantitative network mapping of capital interactions with a system mapping of stakeholder-perceived causal mechanisms. This approach is a key innovation of this study, providing a more holistic understanding of the structure and dynamics of capital interactions.

We conceptualized resilience as an emergent property of capital interactions, allowing us to advance resilience theory by moving beyond static, additive conceptions of capital toward a systems-based perspective grounded in empirical evidence. Our results also contribute to the development of more integrated and effective flood adaptation strategies, and are relevant to the broader challenge of achieving the Sustainable Development Goals (SDGs) in a context of global environmental change.

We find that resilience emerges through a web of capitals interactions, on which resilience-building interventions should capitalize. This implies that focusing on one capital or several capitals in isolation would be misguided, and that identifying local strengths can be as important as identifying local vulnerabilities: stronger capitals could be mobilized to reinforce weaker capitals. Additionally, our results indicate that social and financial capitals play key and complementary roles and that they should be addressed jointly. Moreover, we found that improvements in physical and natural capitals were dependent upon strong human, social, and financial capitals, as they require knowledge, coordination abilities, and financial resources. This calls for integrated adaptation strategies leveraging these interactions, opening pathways to more coherent, efficient, and locally grounded adaptation strategies (Hofbauer et al. 2025). We suggest that community resilience is best addressed through 'bundled' interventions, such as pairing physical infrastructure with financial and human capacity building, to leverage reinforcing feedback loops and prevent potential 'spiral-down' effects from asset and livelihood loss. Future research should address long-term temporal dynamics, particularly regarding natural capital restoration, while disaggregating mechanisms across diverse community types (e.g., urban vs. rural) and assessing the role of multi-level governance in supporting local adaptive capacities.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

References

Adger WN (2003) Social capital, collective action, and adaptation to climate change. Econ Geogr 79(4):387–404

Aldrich DP (2012) Building resilience: Social capital in post-disaster recovery. University of Chicago Press

Aldrich DP, Meyer MA (2015) Social capital and community resilience. Am Behav Sci 59(2):254–269

Alfieri L, Bisselink B, Dottori F, Naumann G, de Roo A, Salamon P, Wyser K, Feyen L (2017) Global projections of river flood risk in a warmer world. Earths Future 5(2):171–182. https://doi.org/10.1002/2016EF000485

Aloscious A, Artuso M, Moghadam S (2025) Nature-Based Solutions for Flood Mitigation: The Case Study of Kochi. Sustainability. https://doi.org/10.3390/su17051983

Bajracharya S, Khanal N, Nepal P, Rai S, Ghimire P, Pradhan N (2021) Community Assessment of Flood Risks and Early Warning System in Ratu Watershed, Koshi Basin. Nepal Sustainability 13:3577. https://doi.org/10.3390/SU13063577

Barbrook-Johnson P, Penn AS (2022) Participatory Systems Mapping. Systems Mapping. Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-031-01919-7_5

Béné C, Newsham A, Davies M, Ulrichs M, Godfrey-Wood R (2014) Resilience, poverty, and development. J Int Dev 24(5):521–536

BotzenWW,Deschenes O, Sanders M (2019) The economic impacts of natural disasters: A review of models and empirical studies. Rev Environ Econ Policy 13(2):167–188. https://doi.org/10.1093/reep/rez004

BrownK(2014) Global environmental change I: A social turn for resilience? Prog Hum Geogr 38(1):107–117. https://doi.org/10.1177/0309132513498837

Burch S, Shaw A, Dale A, Robinson J (2014) Triggering transformative change: a development path approach to climate change response in communities. Clim Policy 14(4):467–487. https://doi.org/10.1080/14693062.2014.876342

Camacho C, Bower P, Webb RT, Munford L (2023) Measurement of community resilience using the Baseline Resilience Indicator for Communities (BRIC) framework: A systematic review. International journal of disaster risk reduction

ChaffinB,Garmestani AS, Gunderson LH, Beson H, Angeler M, Arnold DG, Cosens CA, Craig B, Ruhl RK, Allen JB, C. R (2016) Transformative environmental governance. Annu Rev Environ Resour 41:399–423. https://doi.org/10.1146/annurev-environ-110615-085817

Chapagain D, Hochrainer-Stigler S, Velev S, Keating A, Hyun JH, Rubenstein N, Mechler R (2024) A taxonomy-based understanding of community flood resilience. Ecol Soc 29(4):e36. https://doi.org/10.5751/ES-15654-290436

Chapagain D, Hochrainer-Stigler S, Velev S, Keating A, Mechler R (2025) Realized resilience after community flood events: A global empirical study. Int J Disaster Risk Reduct 118:105246. https://doi.org/10.1016/j.ijdrr.2025.105246
Cinner J, Barnes M (2019) Social dimensions of resilience in social-ecological systems. One Earth 1
Clarke V, Braun V (2013) Teaching thematic analysis: Overcoming challenges and developing strategies for effective learning. Psychol 26(2):120–123
Conevska A (2021) International Cooperation and Natural Disasters: Evidence from Trade Agreements. Int Stud Quart. https://doi.org/10.1093/ISQ/SQAB065
Creswell JW, Plano Clark VL (2017) Designing and conducting mixed methods research
Cutter SL, Barnes L, Berry M, Burton C, Evans E, Tate E, Webb J (2008) A place-based model for understanding community resilience to natural disasters. Glob Environ Change 18(4):598–606
de Moel H, Jongman B, Kreibich H et al (2015) Flood risk assessments at different spatial scales. Mitig Adapt Strateg Glob Change 20:865–890. https://doi.org/10.1007/s11027-015-9654-z
Dowie M (2009) Conservation refugees: The hundred-year conflict between global conservation and native peoples. The MIT Press. https://doi.org/10.7551/mitpress/7532.001.0001
Dynes RR (2006) Social capital: Dealing with community emergencies. Homel Secur Affairs 2(2):1–26
EEA (European Environment Agency) (2024) Economic losses from weather- and climate-related extremes in Europe. Accessed 10.08.2025. https://www.eea.europa.eu/en/analysis/indicators/economic-losses-from-climate-related?activeAccordion=546a7c35-9188-4d23-94ee-005d97c26f2b
Emery M, Flora C (2006) Spiraling-Up: Mapping community transformation with community capitals framework. Community development
Fabricius C, Folke C, Cundill G, Schultz L (2007) Powerless Spectators, Coping Actors, and Adaptive Co-managers: a Synthesis of the Role of Communities in Ecosystem Management. Ecol Soc 12(1):29
Folke C (2006) Resilience: The emergence of a perspective for social–ecological systems analyses. Glob Environ Change 16(3):253–267
Folke C, Polasky S, Rockstrom J, Galaz V, Westley F, Lamont M, Scheffer M, Osterblom E, Carpenter S, Chapin F, Seto K, Weber E, Crona B, Daily G, Dasgupta P, Gaffney O, Gordon L, Hoff H, Levin S, Lubchenco J, Steffen W, Walker B (2021) Our future in the Anthropocene biosphere. Ambio 50:834–869
Ford J, King N, Galappaththi E, Pearce T, McDowell G, Harper S (2020) The resilience of indigenous peoples to environmental change. One Earth 2
GHD (2022) Aquanomics: The economics of water risk and future resiliency. GHD
Guimaraes et al (2025) The effect of community resilience and disaster risk management cycle stages on morbi-mortality following floods: an empirical assessment. Nat Hazards Earth Syst Sci. https://doi.org/10.5194/nhess-25-3803-2025
Hankin B, Page T, McShane G, Chappell N, Spray C, Black A, Comins L (2021) How can we plan resilient systems of nature-based mitigation measures in larger catchments for flood risk reduction now and in the future? Water Secur. https://doi.org/10.1016/j.wasec.2021.100091
Heltberg R, Siegel PB, Jorgensen SL (2009) Addressing human vulnerability to climate change: Toward a 'no-regrets' approach. Glob Environ Change 19(1):89–99
Himes-Cornell A, Ormond C, Hoelting K, Ban N, Koehn Z, Allison E, Larson E, Monson D, Huntington H, Okey T (2018) Factors Affecting Disaster Preparedness, Response, and Recovery Using the Community Capitals Framework. Coastal Manage 46:335–358. https://doi.org/10.1080/08920753.2018.1498709
Hochrainer-Stigler S, Keating A, Velev S et al (2025) Assessing Community Resilience: Validating a Universally Applicable Flood Resilience Measurement Framework and Tool. Int J Disaster Risk Sci. https://doi.org/10.1007/s13753-025-00652-3
Hofbauer B, Einhäupl P, Hochrainer-Stigler S et al (2025) Just Systems or Justice in Systems? Exploring the Ethical Implications of Systemic Resilience in Local Climate Adaptation. Int J Disaster Risk Sci. https://doi.org/10.1007/s13753-025-00653-2
IPCC, Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O (2022) : Climate Change 2022: Impacts, Adaptation and Vulnerability. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., https://doi.org/10.1017/9781009325844
Islam MS, Fishermen (2024) using social-ecological resilience adapting coastal disasters. Mitig Adapt Strateg Glob Change 29:17. https://doi.org/10.1007/s11027-024-10110-y
Keating A, Campbell K, Mechler R, Magnuszewski P, Mochizuki J, Liu W, Kundzewicz ZW (2017) Disaster resilience: What it is and how it can engender a meaningful change in development policy. Dev Policy Rev 35(4):635–663
Kundzewicz Z, Hegger D, Matczak P, Driessen P (2018) Opinion: Flood-risk reduction: Structural measures and diverse strategies. Proc Natl Acad Sci 115:12321–12325. https://doi.org/10.1073/pnas.1818227115

Lallemant D, Hamel P, Balbi M, Lim T, Schmitt R, Win S (2021) Nature-based solutions for flood risk reduction: A probabilistic modeling framework. One Earth. https://doi.org/10.1016/j.oneear.2021.08.010
Laurien F, Hochrainer-Stigler S, Keating A, Campbell K, Mechler R, Czajkowski J (2020) A typology of community flood resilience. Reg Envriron Chang 20(1):e24. https://doi.org/10.1007/s10113-020-01593-x
Laurien F, Martin JGC, Mehryar S (2022) Climate and disaster resilience measurement: Persistent gaps in multiple hazards, methods, and practicability. Clim Risk Manage 37:e100443. https://doi.org/10.1016/j.crm.2022.100443
Lucatello S, Alcántara-Ayala I (2024) Sustainable Synergy: Strengthening disaster risk reduction in Latin America and the Caribbean through nature-based solutions. Int J Disaster Risk Reduct. https://doi.org/10.1016/j.ijdrr.2024.104860
Manes S, Vale M, Pires A (2024) Nature-based solutions potential for flood risk reduction under extreme rainfall events. Ambio. https://doi.org/10.1007/s13280-024-02005-8
Marchezini V, Trajber R, Olivato D, Muñoz V, Pereira F, Luz A (2017) Participatory Early Warning Systems: Youth, Citizen Science, and Intergenerational Dialogues on Disaster Risk Reduction in Brazil. Int J Disaster Risk Sci 8:390–401. https://doi.org/10.1007/s13753-017-0150-9
MochizukiJMR, Hochrainer-Stigler S, Keating A, Williges K (2014) Revisiting the ‘disaster and development’ debate – Toward a broader understanding of macroeconomic risk and resilience. Clim Risk Manage 3:39–54. https://doi.org/10.1016/j.crm.2014.05.002
Muwafu SP, Rölfer L, Scheffran J et al (2024) A framework for assessing social structure in community governance of sustainable urban drainage systems: insights from a literature review. Mitig Adapt Strateg Glob Change 29:42. https://doi.org/10.1007/s11027-024-10136-2
Nakagawa Y, Shaw R (2004) Social capital: A missing link to disaster recovery. Int J Mass Emergencies Disasters 22(1):5–34
Neudert. R, Ganzhorn JU, Watzold F (2016) Global benefits and local costs – The dilemma of tropical forest conservation: A review of the situation in Madagascar, environmental conservation
Partelow S (2020) Social capital and community disaster resilience: post-earthquake tourism recovery on Gili Trawangan, Indonesia. Sustain Sci 16:203–220. https://doi.org/10.1007/s11625-020-00854-2
Parviainen J, Hochrainer-Stigler S, Cumiskey L, Bharwani S, Schweizer PJ, Hofbauer B, Cubie D (2025) The Risk-Tandem Framework: An iterative framework for combining risk governance and knowledge co-production toward integrated disaster risk management and climate change adaptation. Int J Disaster Risk Reduct 116:105070
Paszkowski A, Laurien F, Mechler R, Hall J (2024) Quantifying community resilience to riverine hazards in Bangladesh. Global Environmental Change
Rentschler J, Salhab M, Jafino BA (2022) Flood exposure and poverty in 188 countries. Nat Commun 13:3527. https://doi.org/10.1038/s41467-022-30727-4
Sandilya J, Goswami K (2024) Effect of different forms of capital on the adoption of multiple climate–smart agriculture strategies by smallholder farmers in Assam, India. Mitig Adapt Strateg Glob Change 29:30. https://doi.org/10.1007/s11027-024-10112-w
Scoones I (1998) Sustainable rural livelihoods: A framework for analysis. IDS working paper no 72, Institute of Development Studies, Sussex, UK
Seneviratne SI, Zhang X, Adnan M, Badi W, Dereczynski C, Di Luca A, Ghosh S, Iskandar I, Kossin J, Lewis S, Otto F, Pinto I, Satoh M, Vicente-Serrano SM, Wehner M, Zhou B (2021) Weather and climate extreme events in a changing climate. in climate change 2021: The physical science basis. contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 1513–1766 https://doi.org/10.1017/9781009157896.013
Sudmeier-RieuxK,Arce-Mojica T, Boehmer H et al (2021) Scientific evidence for ecosystem-based disaster risk reduction. Nat Sustain 4(9):1–8. https://doi.org/10.1038/s41893-021-00732-4
Tariq H, Pathirage C, Fernando T (2021) Measuring community disaster resilience at local levels: An adaptable resilience framework. Int J Disaster Risk Reduct 62(2021):102358
Vicarelli M, Sudmeier-Rieux K, Alsadadi A, Shrestha A, Schütze S, Kang M, Leue M, Wasielewski D, Mysiak J (2024) On the cost-effectiveness of Nature-based Solutions for reducing disaster risk. Sci Total Environ 174524. https://doi.org/10.1016/j.scitotenv.2024.174524
WardC,Stringer LC, Holmes G (2018) Protected area co-management and perceived livelihood impacts. J Environ Manage 228:1–12. https://doi.org/10.1016/j.jenvman.2018.09.018
Warner K, Bouwer L, Ammann W (2007) Financial services and disaster risk finance: Examples from the community level. Environ Hazards 7:32–39. https://doi.org/10.1016/j.envhaz.2007.04.006

Westley FR, Tjornbo O, Schultz L, Olsson P, Folke C, Crona B, Bodin Ö (2013) A theory of transformative agency in linked social-ecological systems. Ecol Soc 18(3):27
Winsemius H, Aerts J, van Beek L et al (2016) Global drivers of future river flood risk. Nature Clim Change 6:381–385 (2016). https://doi.org/10.1038/nclimate2893

Authors and Affiliations

Romain Clercq-Roques[1,2] · Dipesh Chapagain[1] · Stefan Hochrainer-Stigler[1]

✉ Romain Clercq-Roques
roques@iiasa.ac.at

✉ Stefan Hochrainer-Stigler
hochrain@iiasa.ac.at

Dipesh Chapagain
chapagain@iiasa.ac.at

1 International Institute for Applied Systems Analysis, Laxenburg, Austria

2 London School of Hygiene & Tropical Medicine, London, United Kingdom