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Realized Resilience After Community Flood Events: A Global Empirical Study

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Abstract:
Flooding is a major global natural hazard, with resulting disasters disproportionately affecting communities in developing countries. Enhancing community resilience is crucial for reducing flood risk, managing impacts and ultimately protecting sustainable development gains. Yet, there is little validated empirical evidence, particularly at the community scale, of the relationship between resilience characteristics before a natural hazard-event occurs and realized resilience after it. We present real-world testing of how a community's pre-flood resilience capacities influence post-flood outcomes, using actual flood events from 66 communities in seven developing countries across the world. In doing so, we applied the Flood Resilience Measurement for Communities (FRMC) approach, a validated framework and associated tool that dynamically assesses pre-flood resilience across multiple capitals to support the design of interventions for enhancing community disaster resilience. We specifically address the question how baseline community resilience, measured by 44 indicators called 'sources of resilience' influences flood impacts and post-flood outcomes that are measured across six themes (assets, livelihoods, life and health, lifelines, governance, and social norms). We observed that higher levels of natural, physical, and financial capital are associated with better post-event community outcomes and reduced flood impacts, such as the prevention of fatalities and serious injuries, the protection of public and private buildings and land, and livelihood stability. Importantly, in most cases, multiple sources of resilience worked together to influence a single outcome, highlighting the multidimensional nature of disaster resilience. Hence, our results emphasize the need for a multi-faceted and dynamic approach to building community flood resilience.

Keywords: Community Flood Resilience; Post-event Analysis; Empirical Study; Measurement Approach; Global.

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1. Introduction

Flooding is a major global hazard, with impacts from resultant disasters disproportionally borne in developing countries. In 2023 alone, floods affected approx. 32.4 million people, claimed over 7,700 lives, and caused economic losses exceeding US$ 20.4 billion, primarily in Asia and Africa (CRED 2024). Out of the 1.81 billion people directly exposed to floods worldwide, 89 percent reside in low- and middle-income countries (Rentschler et al. 2022). This higher risk and associated impacts are driven by both exposure and vulnerability factors such as poverty, poor infrastructure, social marginalization, governance challenges and other socio-economic factors (IPCC 2022a). Additionally, climate change is projected to worsen flood risk across the world via increasing extreme precipitation events and amplification of coastal flooding hazards (Seneviratne et al. 2021).

Communities generally bear the brunt of both direct and indirect consequences of disasters like those triggered by flood hazard events, yet it is also at the community level where measures to enhance resilience can be effectively implemented. Resilience and disaster resilience have been defined differently by various authors and organizations within various contexts (Cai et al. 2018; Campbell et al. 2019; Parker 2020; UNDRR 2023; Graveline and Germain 2022;). However, there is a growing consensus that disaster resilience should be understood as a multidimensional construct - a set of various capacities, capabilities, resources and characteristics - that is latent until realized by a stressor (Keating et al. 2016; Laurien et al. 2020). In this context, measuring community flood resilience and assessing community performance during and after flood events are crucial to inform planning and implementing disaster risk reduction (DRR), climate change adaptation and risk-informed sustainable development measures to minimize flood impacts and protect development gains (Tariq et al. 2021).

Disaster resilience measurement or assessment frameworks have proliferated in recent years, with new tools being developed and refined regularly (Cutter et al. 2016; Asadzadeh et al. 2017; Laurien et al. 2022; Cutter 2024). Critically however, there is a lack of empirical evidence at most scales demonstrating the validity of these measures against the impacts of actual or 'realized' disaster events. In other words, there is a lack of studies that measure the latent property of 'resilience' before an event occurs and taking the critical next step of tracking what happened in these communities as the event unfolded into a disaster. This "reality check" can only be conducted when latent resilience is measured both before (at baseline, see also Camacho et al. 2023) and after a hazard event, allowing for realized resilience to be measured in the form of disaster impacts and outcomes.

The Flood Resilience Measurement for Communities (FRMC) approach, a framework and associated tool for measuring community-level resilience to flooding has been designed to conduct such an empirical based reality check. The conceptualization of resilience underpinning the FRMC, based on a review of existing definitions and approaches, defines community flood resilience from a development-centric perspective as "the ability of a community to pursue its social, ecological, and economic development objectives while managing its flood risk over time in a mutually reinforcing way" (Keating et al. 2016). Regarding measurement of resilience, the FRMC is a standardized, multidimensional and survey-based instrument designed to empirically measure community flood resilience at various stages: baseline (T0) where latent resilience is measured, post-event where realized resilience is measured, and end-line/periodic assessments of latent resilience to track changes over time (T1, T2 and so on, see Figure 1) (Keating et al. 2016; Clark-Ginsberg et al. 2024).

Here, we present a comparative analysis of primary data on actual impacts and outcomes measured after a flood event, against the FRMC baseline (latent) resilience from 66 communities across seven developing countries around the world. By doing so, we identify which baseline indicators - called sources of resilience – are significantly related to post-flood impacts and outcomes. It should be noted that the post-event study examines a wide range of variables beyond direct damages such as number of injuries or damaged homes; it also measures indirect impacts such as outbreaks of water-borne disease, as well as the performance of critical systems and physical and livelihood recovery. It therefore provides information on how varying levels of baseline community flood resilience, as measured by the FRMC 44 sources of resilience across five capitals (5Cs), influence post-flood event impacts and outcomes, measured by the 29 indicators called 'outcome variables' across six themes, in flood-affected communities in developing countries. The main contribution of our work to the resilience literature is therefore a much needed empirical investigation of the influence of community flood resilience on flood impacts and outcomes, using a unique and global dataset.

Our paper is organized as follows. In section two, we present our research methodology by explaining the FRMC baseline resilience and post-event outcome measurement approach, dimensionality reduction and grouping of the post-event outcome variables into themes, and the testing of their validity and reliability for further analysis. We also discuss the statistical methods used, including the regression models applied in this section. In section three, we present the research results, focusing on an overview of baseline resilience of the studied communities, the flood events that impacted them, the communities' flood impacts and outcomes of the floods, and the statistical relationship between baseline 'latent' flood resilience and realized resilience at post-event. In section four, we discuss the research results in a broader context and further explore the potential influence of communities' baseline resilience on post-event outcomes. Finally, section five summarizes the findings and provides an outlook for the future.

2. Methodology

Our central research question is: how does community flood resilience, as measured by the FRMC, relate to flood impacts and outcomes after a flood event? To answer this question, we first briefly need to introduce the FRMC baseline and post-event measurement methodology.

2.1. Baseline Resilience and Post-Event Outcome Measurement Approach

The FRMC is a framework designed to empirically measure a community's flood resilience at different timesteps starting with the baseline study (see Figure 1 for the FRMC process). The baseline measurement consists of 44 sources of resilience (indicators) to assess (latent) flood resilience across five capitals (5Cs) (see Supplementary A). Each source of resilience consists of a set of data collection questions pertaining to that source that allow for grading against the source's grading rubric. The data are gathered from multiple sources: household surveys, focus group discussions, key informant interviews, and secondary sources, which allows for cross checking the information which enhances the reliability of the assigned grades. Users select the data collection methods that best suit their context. After data is collected, the sources are graded on a four-point scale from A (best practice for managing the risk) to D (significantly below good standard with potential for imminent loss), by trained resilience experts familiar with the community. The grading is based on the data collected, which is compared to the grade definitions set out in the grading rubric for that source of resilience (see Figure 1) and informed by the experts' deep knowledge of the community. Each grade can be converted to a numeric scale as follows: D=0, C=33.34, B=66.67 and A=100. This grade to number conversion allows numeric functionality such as summation and averaging. Some further basic demographic and characteristic information about each community, called here 'community characteristics' is collected as well, however this is not graded.

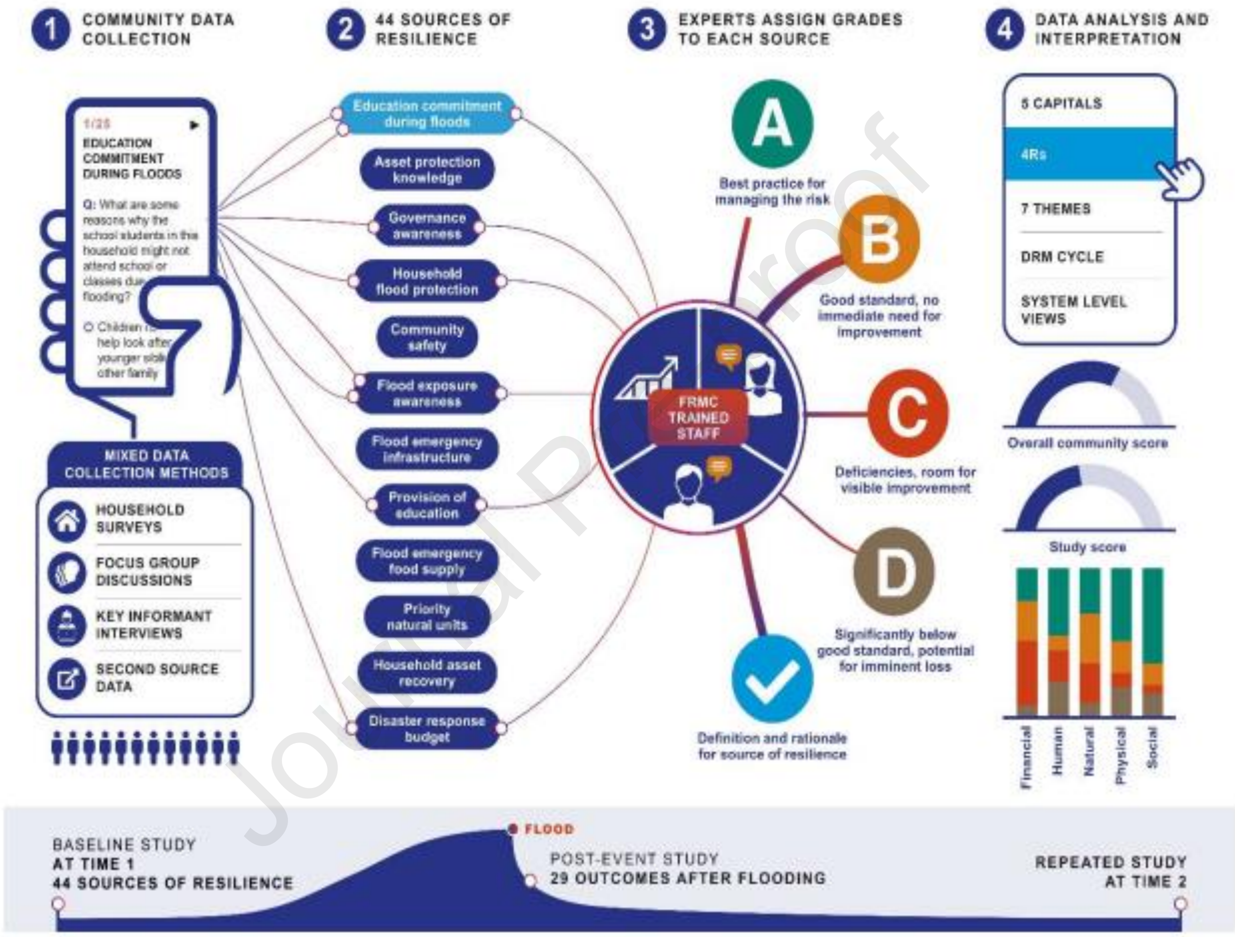

Figure 1: FRMC study design. Based on (Laurien et al. 2020)

The 5Cs framework, drawn from the Sustainable Livelihood Framework, developed by the Department for International Development (DFID), is one of the lenses through which the FRMC conceptualizes and assesses community flood resilience (Keating et al. 2017; Campbell et al. 2019; Pettengell et al. 2020). The 5Cs are human, social, physical, natural, and financial capital, with each of the 44 sources of resilience being assigned to one of these capitals.

- Financial capital includes the level, variability, and diversity of income sources and access to financial resources, contributing to the wealth of individuals or the community.

- Human capital involves the collective knowledge, education, skills, and health of community members, reflecting the available human resources and their ability to enhance community resilience.
- Natural capital covers the community's natural resources, such as land productivity, water availability, sustainable environmental policies and practices.
- Physical capital refers to tangible assets and infrastructure like roads, bridges, buildings, utilities, equipment, and technology that support the community's productive capacity.
- Social capital encompasses the social relationships, networks, and bonds that facilitate cooperation, idea exchange, and resource access, including trust, norms, and reciprocity within social interactions.

These 5Cs characterize and capture the community's ability to sustain and enhance the wellbeing of community members, providing a holistic picture of resilience capacities. Measuring and examining flood resilience through this lens highlights the connections and interactions between flood resilience and broader developmental goals. Within Chapagain et al. (2024) a detailed analysis of baseline community flood resilience in 292 communities across 20 developing countries and a taxonomy of community flood resilience was presented; hence, rather focusing on the baseline measurement analysis our focus will be on the post-event outcome measurement and its relationship to the baseline measurement.

If a community where baseline resilience has been measured experiences a flood event that results in a disaster for the community, a post-event study is conducted to gather information on what actually happened – how resilience realized when the flood event occurred. The post-event study uses 29 outcome variables, similar in structure to the sources of resilience (see Supplementary B). Unlike the sources of resilience, which measure the features of the community that engender resilience, the outcome variables measure the direct and indirect impacts of a flood event as well as the performance of various community sub-systems. Specifically, three of the 29 outcome variables are called "hazard trait" variables and measure the size and type of the flood; this is to collect information on and control for the size of the event when assessing impacts. There are seven "direct impact" variables, representing effects from direct contact with flood water, such as damage to homes, injuries or environmental contamination. Additionally, there are ten "indirect impact" variables, which measure the consequences of the "direct impact" variables, including ill health because of a disease outbreak, lost income because a shop is flooded, or a fuel shortage due to flooded roads. Finally, there are nine "action" variables, representing actions taken during or after a flood, such as the performance of early warning systems, support from outside the community or community members coping strategies such as taking out high-interest loans. Similar to the baseline study, questions associated with each outcome variable, except the three hazard traits indicators, are graded by experts from A to D and assigned a corresponding numeric score. The 26 graded variables span across multiple domains, including assets, livelihoods, life and health, lifelines, governance and social norms.

We want to acknowledge some inherent limitations of the qualitative grading process within the FRMC framework. Nevertheless, the framework has undergone extensive validity and reliability testing efforts to address these issues, including face validity, content validity, internal consistency and inter-rater reliability tests (see Hochrainer-Stigler et al. 2020). For example, we have shown that individual graders are consistent in their assessments across different communities, and that different graders provide consistent grades when they evaluate similar communities. We also found consistency in the grading process between raw data and graded sources of resilience. For a detailed analysis of the validation of the tool and results we refer to Chapagain et al. (2024) and will focus on the post-event analysis.

2.2. Study Communities

The FRMC baseline study was conducted in more than 292 communities in 20 developing countries from 2018 to 2022. Following the baseline resilience assessment, if a community experienced a flood disaster, a post-event study was conducted. From 2019-2023, this sequence occurred in 66 communities across seven countries (see Table 1). Therefore, our dataset for this study includes paired baseline and post-event studies from 66 communities. The largest number of communities in our dataset are from Bangladesh, followed by Vietnam, Malawi, Nepal, Senegal, Mexico and El Salvador. Together, these communities have a total population of approximately 154,000 people living in around 33,000 households.

Table 1: Post-event study descriptives

S. No.	Country	No. of Communities	Households	Population
1.	Bangladesh	32	17828	87159
2.	Vietnam	12	7145	26925
3.	Malawi	8	5837	26267
4.	Nepal	5	596	3423
5.	Senegal	4	340	3400
6.	Mexico	3	444	1491
7.	El Salvador	2	914	5370
	Total	**66**	**33104**	**154035**

Based on the baseline flood-resilience profiles, Chapagain et al. (2024) identified five distinct community clusters and related taxonomy including: Cluster 1: Rural communities with higher risk and vulnerability, and lower capacity. Cluster 2: Urban communities with poor natural & social environments. Cluster 3: Rural communities with high capacity but low income and poor physical infrastructure. Cluster 4: Less vulnerable rural communities and Cluster 5: Less vulnerable urban communities. The majority (43) of the communities in our post-event study cohort are high-risk, vulnerable, lower-capacity cluster 1 communities from Bangladesh, Malawi, Senegal, Mexico, and El Salvador. These are mostly the high flood-risk rural communities characterized by extreme poverty, low levels of women's education, and little to no influence on decisions made at higher levels. Around one-fifth (14) of the communities fall into cluster 4 communities from Vietnam and Nepal. These are generally rural communities where poverty and low female education are still prevalent but are less severe than in cluster 1 communities. These communities have some influence over decisions made at higher levels, and the flood risk is moderate. A small number of communities belong to cluster 2 from Senegal, and cluster 3 from Vietnam.

2.3. Statistical Analysis: PCA, Consistency, Reliability and Regression Approaches

We applied a series of statistical analysis techniques to analyze the empirical data. Firstly, due to the large number of post-event outcome variables we used Principal Component Analysis (PCA) to statistically group theoretically identified post-event outcome variables into a smaller number of so-called themes. We then tested the consistency and reliability of the identified themes. Finally, we used regression analysis to test the relationship between baseline resilience and post-event outcomes according to the identified themes. Each step of the statistical analysis and techniques used is described in detail below. Because the themes identification, while interesting in its own right and discussed accordingly, is the basis for the regression analysis we present the results already in this section and fully focus on the "realized resilience" question within the results section.

2.3.1. Dimensionality reduction and validity of grouping of post-event outcome variables

We used PCA as a statistical technique to condense the vast array of variables into a smaller set of representative variables or components that collectively account for the maximum original variance (Nardo et al. 2005; James et al. 2021). Among the 29 post-event outcome variables, three are the not-graded hazard trait variables. Similarly, one of the outcome variables, "insurance payments (O29)", has all observations equal to zero and therefore no variance. Therefore, these are excluded from the PCA. We conducted a PCA on the 25 post-event outcome variables to check if the outcome variables could be represented and grouped by a smaller number of representative categories or 'themes' and identify those themes based on the empirical data. We applied a one-component PCA to identify the number of components. Through the Kaiser criterion (eigenvalue > 1), we identified six components that collectively explain 71 percent of the total variance (see Figure C1 and Table C1 in Supplementary C) (Nardo et al. 2005).

Subsequently, we conducted PCA with a varimax rotation to facilitate the interpretation of component themes (see table C2 in Supplementary C). The factor loadings of the outcome variables in the identified six components guided this process of grouping the outcome variables into post-event themes (see Table C3 in the Supplementary C for variables' factor loading to PCA components). We then undertook expert elicitation to group the outcome variables into the final six outcome themes. The themes and respective outcome variables are presented in Table 2 and explained below.

Table 2: Grouping of post-event outcome variables into themes based on PCA results and expert insights

Post-event outcome theme	Outcome variable name	Variable code
Assets	Public building and land damage	O07
	Private building and land damage	O06
	Contents and equipment loss	O08
Governance	External support	O25
	Large scale protection infrastructure performance	O09
	Property crime	O21
Life and Health	Waste management performance	O19
	Food security	O15
	Safe water	O18
	Prevention of serious injuries	O05
	Post-flood illness	O11
	Environmental contamination	O10
	Prevention of fatalities	O04

Lifelines	Flood healthcare continuity Transportation performance Communications performance Continuity of energy and fuel supply	O12 O17 O16 O20
Livelihoods	Household income stability Risky livelihoods Sale of productive assets High interest credit Continuity of education	O14 O27 O26 O28 O13
Social Norms	Mutual support Learning from flood Early warning system performance	O24 O22 O23

The post-event outcome theme **Assets** captures the damage to physical and tangible resources owned by individuals, households, and the community such as public buildings and land, private property, and the loss of personal and communal belongings and equipment due to the flood. The post-event outcome theme **Governance** assesses the effectiveness of the overall governance system before, during and following flood events to manage recovery, enhance resilience, and manage vulnerabilities. The post-event outcome theme **Life and Health** measures the well-being and health security of individuals and the community in the aftermath of the flood. This includes the community's ability to maintain public health and safety, ensuring adequate access to essential services and effective health-related responses during and after flood events. The post-event outcome theme **Lifelines** measures the resilience and functionality of critical infrastructure and services essential for the community's functioning, stability and recovery after floods. The post-event outcome theme **Livelihoods** measures the economic stability and resilience of households in the aftermath of the flood. This provides insight into how well households can sustain their economic activities, avoid detrimental financial coping strategies, and maintain access to essential services like education in the face of flooding. The post-event outcome theme **Social Norms** assesses how community members and groups provide informal support, interact and cooperate within the community during and after the flood event. It encompasses indicators such as mutual support and learning from floods.

After the grouping of post-event outcome variables into the six themes, we assessed their internal consistency and reliability using Cronbach's alpha (C-alpha). C-alpha serves as a widely used statistical tool to evaluate the degree of interrelatedness among a set of variables as a whole and their effectiveness in measuring an aggregated latent construct (Nardo et al. 2005). The results indicate that the C-alpha coefficient exceeds the acceptable threshold of 0.7 for all themes with the exception of Governance (see Table 3).

Table 3: Internal consistency and reliability test results using Cronbach's alpha for post-event outcome themes.

S. No.	Theme	C-alpha coefficient	No. of outcome variables
1.	Assets	0.75	3
2.	Governance	0.46	3
3.	Life and Health	0.80	7

4.	Lifelines	0.76	4
5.	Livelihoods	0.91	5
6.	Social Norms	0.72	3

We therefore aggregated the outcome variables into these identified themes. The Governance theme, where the internal consistency is below the threshold, contains important aspects of realized resilience, namely external support, large-scale protection infrastructure performance, and property crime. We therefore decided to keep this theme as is. This decision is supported by the fact that statistically this is the best possible grouping for these variables. Additionally, we note that the distribution of number of outcome variables is not uniform across the six themes.

2.3.2. Correlation and regression analysis

The next phase of empirical analysis included the examination of the correlation coefficients between the 44 sources of baseline resilience and community characteristics, with the 25 post-event outcome variables. This step allowed us to explore the relationship between baseline resilience and post-event outcomes at the level of specific sources of resilience and outcome indicators, providing a foundation for interpreting the subsequent regression results. We then conducted a Generalized Linear Regression Model (GLM) analysis to ensure the model remained robust even if the assumptions of the classical Ordinary Least Squares (OLS) regression were not met. We tested two variants of the GLM: the first used Gaussian distribution with the default identity link function, i.e. $E(Y) = X\beta$ where $Y \sim N(X\beta, \sigma^2)$. The second variant also used a gaussian distribution but with a logarithmic link function, i.e. $log(E(Y)) = X\beta$ so $E(Y) = e^{X\beta}$ and $Y \sim N(e^{X\beta}, \sigma^2)$.

Both models performed similarly, with the identity link function performing marginally better in several cases. Importantly, the coefficients from both model variants exhibited consistent signs and effects. We therefore decided to use the model with the identity link function (presented below) due to its relative simplicity and (importantly) more intuitive nature.

$$E(Y) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + \epsilon$$

In this regression model, E(Y) is the expected value of the dependent variable Y. In our study, the dependent variables include post-event outcome themes (Assets, Governance, Life and Health, Lifelines, Livelihoods, and Social Norms), and direct flood impacts (total fatality and total injury). The coefficient β_0 is the intercept, and β_1, β_2, … , β_k are the regression coefficients associated with explanatory variables X_1, X_2,…..X_k. These explanatory variables are the baseline 5Cs (financial, physical, natural, social and human capital).

In the IPCC risk framework, risk is conceptualized as a function of the interaction between hazard, exposure and vulnerability (IPCC 2022b). The 5Cs of community flood resilience capture the vulnerability aspects of this framework. To account for hazard and exposure, we included the flood return period as an indicator of hazard intensity, and flood-exposed population as an indicator for exposure – both hazard trait variables in the post-event study, as additional explanatory variables in the regression model. The term ϵ represents the error term, which captures the variability in Y not explained by the linear combination of the explanatory variables. At first, we fitted the full model for each dependent variable (see Supplementary D). We then applied a stepwise model selection process to identify the best subset of predictors for each dependent variable based on the Akaike Information Criterion (AIC). The stepwise model selection process evaluates models by iteratively adding or removing predictors and selects the model that minimizes the AIC, thereby balancing model fit with model complexity (i.e. number of predictors) (James et al. 2013). Afterwards, the best performing models were evaluated using a LASSO model to control for collinearity and highly colinear variables were removed (Tibshirani 1996). The results of the best models are presented and discussed in detail in the results section next.

3. Results

In order to provide appropriate background and context for our findings, we first provide and discuss an overview of the communities' baseline flood resilience levels, floods experienced by the communities and their impacts, outcomes and communities post-event performance, and finally the relationship between baseline flood resilience (latent resilience) and post-event outcomes (realized resilience).

3.1. Overview of estimated communities' baseline flood resilience levels

For the majority of the 66 communities, FRMC baseline average capital grades were measured at the lower end ranging from deficiencies and room for visible improvement (C grade) to significantly below good standard with a potential for imminent loss (D grade) across all capitals, except for human capital (see Figure 2 and Table E1 in Supplementary E). Human capital baseline grades range up to good standard with no immediate need for improvement (B grade). The average capital score is highest for human capital at 44. This relatively higher score in human capital is mainly due to the community's higher awareness of flood exposure and future flood risk. Nevertheless, other aspects of human capital, such as the first aid knowledge, and education commitment during floods, remain low.

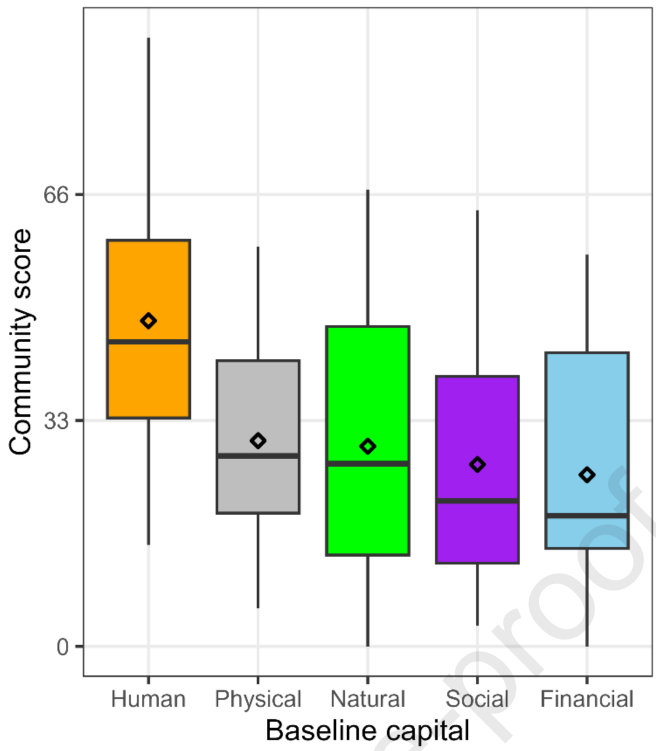

Figure 2: Distribution of communities' baseline aggregated capital scores.

The lowest average score is for financial capital, at only 19. Community grades are low in their financial capacity, such as business and household income continuity after floods, household asset recovery, community disaster funds, and risk reduction investments. Average scores for physical, natural and social capitals stand at 28, 27 and 21, respectively. The low grade in physical capital is due to deficiencies in basic supplies (food, safe water, sanitation, and energy) during floods, poor functioning of the utility infrastructure and facilities (health, transportation, communication, and education), and a lack of early warning and emergency response infrastructure. The physical status and services of natural resources are also poor in these communities, with limited natural resource management efforts, leading to low natural capital. While there is some level of mutual assistance and solidarity, community participation, inclusiveness, and local leadership are limited, resulting in low social capital. External flood response and recovery efforts are also inadequate.

3.2. Floods experienced by communities and their impacts

Data from the 66 post-event studies shows that flash floods and river floods were the two most common types of floods encountered by the communities (see Figure E1(a) in Supplementary E). However, a few communities also experienced surface flooding. Around half of the flood events (30) encountered by the communities were estimated to be one-in-two-year return period floods (see Figure 3). Additionally, ten communities experienced an estimated one-in-five-year return period flood, another ten communities experienced one-in-ten-year return period flood, 15 communities experienced one-in-25-year return period flood, and one community even experienced a one-in-50-year return period flood. Notably, the communities affected by the severe 50- and 25-year return period floods were primarily located in Bangladesh, with some also in Vietnam and Nepal.

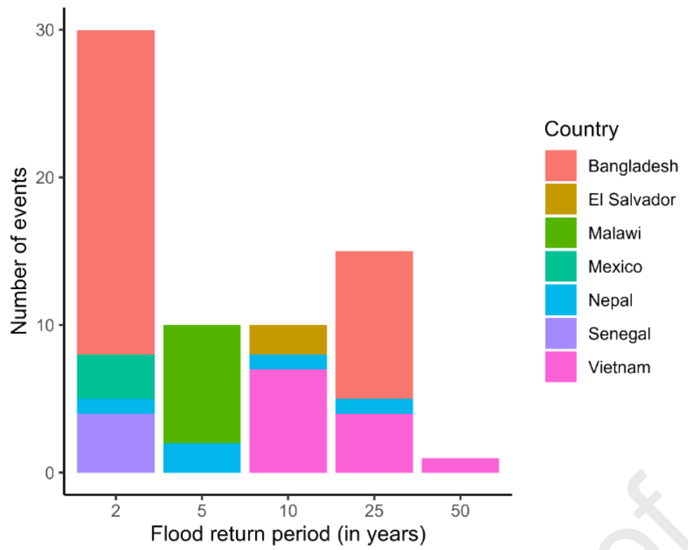

Figure 3: Return period of flood event experienced by the communities.

In the majority of cases, the floods assessed in the post-event studies impacted more than 80 percent of the community (see Figure E1(b) in Supplementary E). Together, due to these flood events it was reported that 53 men died and 1,729 were injured, 29 women died and 1,316 were injured, and 68 children died and 863 were injured. The majority of fatalities occurred in the poorer, rural communities (cluster 1) in Bangladesh and Malawi with a few also in Vietnam (see Figure E2(a) in Supplementary E). Similarly, the majority of serious injuries occurred in Bangladesh, Senegal and El Salvador (see Figure E2(b) in Supplementary E).

3.3. Understanding Communities post-event performance

In most communities, performance during flood events across all six themes falls below good standard level (B to C), with the Livelihoods theme falling significantly below good standard (C to D grade) (see Figure 4 and Table E2 and Figure E3 in Supplementary E). The highest average score of 44 is observed in the Governance and Social Norms themes. In the Governance theme, relatively better (B-C) performance is mainly due to no increases in theft and looting during and after floods (A), and the accessibility of at least some external assistance for response and recovery by most community members in need (C). However, communities lacked large-scale protective infrastructure or existing infrastructure failed to provide adequate flood protection (D). Despite suboptimal performance level (C), factors such as learning from flood experiences, mutual support, and early warning system (EWS) performance, while not reaching good standards, were also not significantly below this threshold in the majority of communities. This helped to maintain the average Social Norms score at a moderate level.

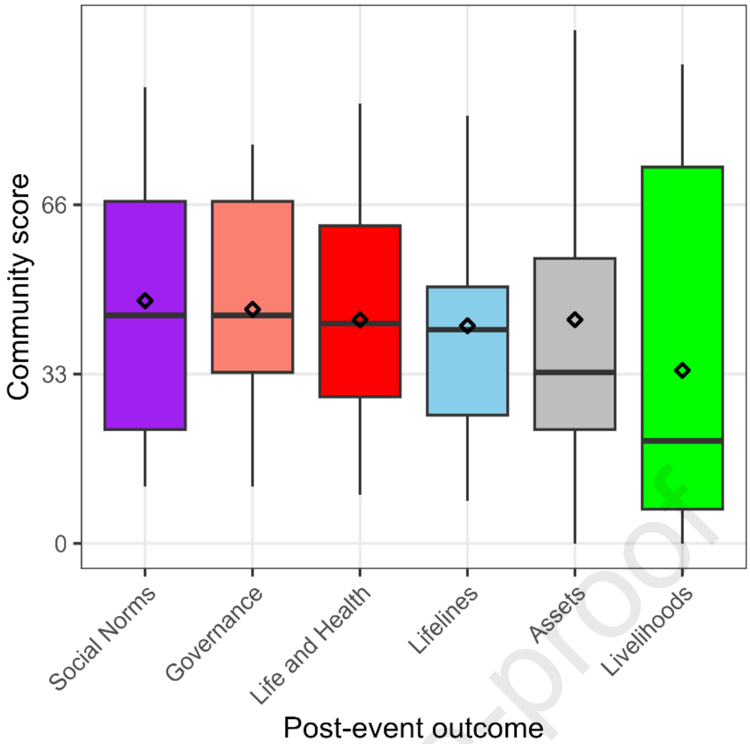

Figure 4: Distribution of communities' theme grades for post-event assessment.

The Life and Health theme has an average score of 43. Major challenges persist in post-flood situations with the management of illness, food security, access to safe water, and environmental contamination falling below good standard (C). Waste management performance was significantly below good standard (D). Nevertheless, these communities were able to significantly prevent fatalities and serious injuries, albeit for the annual to medium return period events mentioned. The average community score for the Lifelines theme is 42. The performance and continuity of healthcare, communications, and transportation systems during and after the flood events were below good standard in the majority of communities. Energy and fuel supply showed relatively better performance compared to other lifeline outcome variables. Flood damage to public and private buildings and land was high, but the loss of contents and equipment was low. Overall, the average score of the Assets theme is 33. Community performance in the Livelihoods theme is the lowest among all themes, with an average score of only 20. All outcome variables contributing to the Livelihoods theme, including risky jobs after floods, high interest credit, continuity of education, household income stability, and sale of productive assets, fell below or strongly below good standard.

3.4. Relationship between baseline flood resilience and post-event outcomes

Some first indications of the relationships between latent resilience and realized resilience can be found by looking at the correlation between the 44 sources of baseline resilience and the 25 post-event outcome variables (Supplementary F). The majority of coefficients are positive and significant, suggesting that baseline resilience sources are correlated with reduced flood impacts. Moreover, post-event impacts and outcomes correlate with multiple resilience sources, which is expected given that we consider resilience as a latent multidimensional construct. It is interesting to note that post event outcomes variables learning from flood (O22), external support (O25), and risky livelihoods (O27) are all negatively correlated with community population size. In other words, post-event performance in these outcome variables tend to be worse in more populated or larger communities than in the smaller communities.

Next, we present the results of the regression analyses to elucidate the influence of baseline capitals, flood return period, and exposed population on post-event outcome themes (Table 4). In the regression models, the explanatory variables are: the five baseline capitals (5Cs), which represent the community's latent flood resilience before the flood; flood return period, which represents the scale of the flood hazard, and; population, which represents the exposure of the community to the flood hazard. The dependent variables are the community's performance across the six post-event outcome themes. Overall, the models demonstrate a significant fit and explain 40 to 80 percent of the variance in post-event outcomes.

Table 4: Regression results for baseline capital grades on post event outcome themes.

	Assets		**Governance**		**Life and Health**		**Lifelines**		**Livelihoods**		**Social Norms**	
Predictors	*Estimates*	*p*	*Estimates*	*p*	*Estimates*	*p*	*Estimates*	*p*	*Estimates*	*p*	*Estimates*	*p*
(Intercept)	-3.89	0.521	32.39	**<0.001**	13.02	**0.001**	28.36	**<0.001**	-22.19	**<0.001**	29.63	**<0.001**
Financial Capital	0.40	**0.048**	0.71	**<0.001**					0.43	**0.016**	-0.50	**0.003**
Physical Capital	0.83	**0.001**			0.47	**<0.001**	1.23	**<0.001**	0.58	**0.012**		
Natural Capital	0.29	0.077	-0.33	0.090	0.66	**<0.001**	0.39	**0.016**	0.74	**<0.001**	0.66	**<0.001**
Social Capital			0.41	**0.040**								
Human Capital							-0.72	**<0.001**	0.22	0.148		
Flood Return Period	0.51	0.062	-0.74	**0.003**							1.40	**<0.001**
Population					-0.00	0.132			-0.00	0.126		
Observations	66		66		66		66		66		66	
R^2	0.592		0.421		0.736		0.409		0.790		0.470	
AIC	574.325		565.290		505.037		575.823		556.765		567.399	

Post-event outcome theme average grades as dependent variables and community resilience (baseline 5Cs), hazard scale (flood return period) and exposure (community population) as explanatory variables. [Best performing models based on AIC]

The regression results show that, after controlling for other explanatory variables, baseline financial and physical capitals are statistically significant to the 5 percent confidence level, and natural capital is statistically significant to the 8 percent confidence level, with positive associations with post-event outcomes in the Assets theme. A one-unit increase in physical and financial capital grades is correlated with better post-event Assets outcomes by 0.8 and 0.4, respectively. Social and human capitals did not exhibit a significant association with Asset theme outcomes.

Similarly, post-event Governance outcomes displayed a positive and significant relationship with baseline financial and social capital. A one-unit increase in financial and social capital grades is correlated with better post-event governance outcomes by 0.7 and 0.4 respectively. However, the flood return period had a statistically significant negative relationship with Governance outcomes, where a one-unit increase in flood return period is correlated with worse post-event governance outcomes of 0.7. Natural capital displayed a negative relationship with Governance outcomes (at the 9 percent confidence level). Physical and human capitals were not significantly associated with the Governance outcomes.

Regarding Life and Health outcomes, we found a positive and significant relationship with baseline natural and physical capitals. A one-unit increase in both natural and physical capital grades is correlated with better post-event life and health outcomes by 0.7 and 0.5 respectively. Financial, social and human capitals did not show a significant association to life and health outcomes.

The post-event Lifeline outcomes exhibited a positive and significant association with baseline natural and physical capitals, a significant negative association with human capital, and no significant association with financial or social capital. A one-unit increase in physical and natural capital is correlated with better post-event Lifelines outcomes by 1.3 and 0.4 respectively. Interestingly, our analysis finds that a one unit increase in human capital is correlated with a reduction in post-event Lifelines outcomes by 0.7.

Post-event Livelihood outcomes demonstrated a positive and significant relationship with baseline financial, natural, and physical capitals. A one-unit increase in natural, physical and financial capital is correlated with better post-event Livelihood outcomes by 0.7, 0.6, and 0.4 respectively. Social and human capital did not show a significant association with Livelihood outcomes.

Finally, post-event Social Norms outcomes showed a significant positive association with baseline natural capital but a negative relationship with financial capital. A one-unit increase in natural capital is correlated with better post-event Social Norms outcomes by 0.7, whereas a one-unit increase in financial capital is correlated with worse post-event social norms by 0.5. Additionally, the flood return period had a statistically significant positive relationship with social norms; a one-unit increase in flood return period is correlated with better post-event Social Norms by 1.4 grades. Social and human capital were not significantly associated with Social Norms outcomes.

Table 5: Regression results for capitals on fatalities in events.

	Total Fatality		**Total Injury**	
Predictors	*Estimates*	*p*	*Estimates*	*p*
(Intercept)	4.91	**<0.001**	113.04	**<0.001**
Physical Capital	-0.09	**0.039**		
Social Capital	-0.06	0.058	-1.53	**0.017**
Natural Capital			-1.23	**0.048**
Flood Return Period	0.19	**<0.001**	2.90	**<0.001**
Observations	66		66	
R^2	0.413		0.461	
AIC	341.049		725.714	

Flood impacts (total fatality and total injury) as dependent variables and community resilience (baseline 5Cs) and hazard scale (flood return period) as explanatory variables. Population as *indicator of exposure was also included but dropped in this selected model due to no significant explanatory power [best performing models based on AIC]*

We also investigated the influence of baseline resilience (5Cs), flood return period, and exposed population on two individual outcome variables in the post-event theme Life and health: fatalities and injuries (Table 5). Physical capital showed a statistically significant negative association with total flood related fatality (at the 5 percent confidence level), as did social capital (at 6 percent confidence level); the other capitals (financial, natural, and human) did not exhibit a significant relationship with total fatalities. Both social and natural capital displayed a statistically significant negative relationship with flood-related injuries. The flood return period variable had a positive association with both total fatalities and total injuries, as expected.

4. Discussion: Resilience in action

The analysis further supports the validity of the FRMC measurement framework. That is, higher resilience levels as measured by the FRMC baseline study are associated with significantly lower impacts from floods across the board. Communities with higher natural, physical, and financial capitals generally perform better across most post-event outcome themes. Social capital shows influence in relation to the Governance outcome theme. In many cases, we find that multiple sources of resilience act together to influence a single outcome variable, which in turn highlights the multidimensional nature of disaster resilience. For example, sources like risk reduction investment, early warning systems (EWS), large scale flood protection, flood emergency food supplies, community safety measures, and inter-community flood coordination have a beneficial effect across multiple outcome variables. Consequently, as these sources of resilience show multiple benefits in terms of mitigating flood impacts, they could be considered cornerstones of community disaster resilience and high priorities for investment in strengthening resilience. We now discuss further findings based on our statistical analysis presented in results section.

Natural Capital refers to indicators used to measure the physical state of a community's natural resources and the services they provide, along with strategic management efforts aimed at environmental sustainability. We observed that communities with higher natural capital performed better in post-event assets, life and health, lifelines, livelihood, and social norms outcome themes. We can infer from the results that investment in sustainable natural resource management has helped to physically protect the community - public and private buildings and land - from flood damage. The communities stronger in their natural capital also show higher post-event livelihood outcomes, particularly income stability, minimizing the sale of productive assets, less reliance on high-interest credit, and less uptake of risky livelihoods as a coping strategy. Higher natural capital also positively relates to post-flood life and health outcomes, it is correlated with lower serious injuries, less post-flood illness outbreaks, and better food security and water safety. This is supported by a statistically significant negative relationship between total injuries and natural capital. This finding of a positive association supports previous studies which describe the positive role of ecosystem services in supporting income stability, well-being, and community safety (Brookhuis and Hein 2016; Belle et al. 2017).

Physical Capital is measured through indicators associated with essential supplies and systems (such as food, safe water, sanitation, and energy), utility infrastructure (such as health, transportation, communication, and educational facilities), and early warning systems and emergency response infrastructure. The results indicate that higher community physical capital is statistically significantly related to post-event assets, life and health, lifelines, and livelihoods outcomes. The flood protection infrastructure may reduce the damage to private and public buildings and land, and also decrease the loss of contents and equipment during floods. Large-scale flood protection infrastructure and emergency food and safe water supplies reduce flood-related fatalities, post-flood illnesses, improve food and safe water supply, and waste management performance during and after floods. This is also indicated in our analysis by a statistically significant negative relationship between total fatalities and physical capital. Better flood healthcare access, flood energy supply and flood emergency infrastructure in the community could have resulted the continuity of essential lifelines and services, particularly healthcare, energy and fuel supply, and communication during and after floods. Higher physical capital is also positively correlated with post-event livelihood outcomes, particularly the continuity of education, minimizing the sale of productive assets, and reducing risky livelihoods. Together, the positive correlation between natural and physical capital and outcomes across most post-event themes strongly implies there is value in mixing nature-based solutions (NBS) together with traditional grey infrastructure for flood risk management (Browder et al. 2019; Vojinovic et al. 2021).

Financial Capital refers to indicators of both public financial capacities, such as the governmental ability to allocate and manage resources for DRR and response, and private financial capacity, such as businesses' and households' ability to sustain operations, recover assets, and maintain income continuity during disruptions. Higher financial capital is positively correlated with enhancements in governance aspects of disaster response and recovery, such as lower property crime and higher external support during and after floods. Higher financial capital is also positively correlated with post-event livelihood outcomes, particularly in reducing risky livelihoods uptake after floods, minimizing the sale of productive assets, and maintaining household income stability.

Taking these three capitals together, we find that communities with higher financial, natural and physical capital are more likely to be able to protect their assets and maintain their livelihoods and income stability after a flood. Interestingly, communities with higher natural capital, but lesser financial capital seem to be more likely to learn from past floods. This is possibly related to the urban-rural nature of the communities, as we observed a negative correlation between learning from floods and community population size. Generally speaking, financial capital is higher in urban areas whereas natural capital is higher in rural areas. Our results suggest that urban communities with higher household income and disaster response budgets have lower levels of mutual assistance and learning from past floods. On the other hand, rural communities with higher natural capital tend to have stronger social connections and better collective learning mechanisms. A weak negative relationship between natural capital and governance outcomes could be related to the lack of large-scale protection infrastructure in rural communities. This finding supports the argument that financial capital is the primary driver of resilience in urban communities whereas social capital is the key driver of resilience in rural communities (Cutter et al. 2016).

Social Capital includes measurement of elements such as community structure, including participation, representation, inclusiveness, local leadership, solidarity, and mutual assistance, as well as external flood response and recovery services, and national and community-level DRM policies and plans. Higher social capital corresponds to enhancements in governance aspects of disaster response and recovery, mainly lower property crime and higher external support during and after floods. External support is higher in smaller communities, likely because even a small amount of external support is significant in smaller communities. A similar positive role of social capital in enhancing the resilience of rural communities to floods has also been observed in other studies, highlighting its potential for improving community flood resilience (Balgah et al. 2019; Hudson et al. 2020; Savari et al. 2024).

Human Capital measurement primarily aims to capture the human aspects of disaster response and recovery, including collective knowledge, skills, and awareness in first aid, WASH, flood safety, evacuation procedures, and overall environmental management and governance. Our study indicates that while education and skills are critical for certain aspects of disaster management, they may not directly translate to immediate post-event recovery benefits. This is supported by the positive correlation between sources of human capital such as first aid knowledge and water and sanitation awareness with most of the post-event outcome indicators. Interestingly, higher human capital scores correlate with poor post-event performance in lifelines outcomes. For example, there is a negative correlation between baseline evacuation, safety and flood exposure knowledge with post-event communication system performance. The lack of a significant positive, or indeed negative relationship between human capital and post-event outcomes is difficult to explain and needs further investigations but similar findings have been observed in other research as well (Balgah et al. 2019). The results suggest that there may be other important determinants not captured by the analysis so far.

Finally, we find events with higher flood return periods to correlate with worse post-event governance performance. Communities with larger populations show lower scores in terms of external support, possibly because support is insufficient for the community's size. Higher flood return periods also increase flood-related fatalities and injuries. In the context of climate change, higher community resilience reduces flood impacts, mainly total fatalities and injuries. However, as climate hazards, measured by flood return periods, increase, the impacts will also increase if resilience does not increase as well. The positive relationship between flood return periods and social norms could potentially indicate that communities exhibit higher levels of mutual support during high-intensity floods and learn from such events.

5. Conclusion

In this paper we empirically assessed how latent community resilience, as measured by the baseline FRMC, influences post-flood outcomes or realized resilience when an event occurs. The analysis focused on 66 communities in seven developing countries where the FRMC baseline measurement had been implemented and had experienced floods in recent years. Our findings reveal that the baseline resilience in most of these communities was quite low, with significant deficiencies across all resilience capitals. When floods struck, the impacts were mostly severe: across our sample approximately 150 lives were lost, 4,000 individuals were injured, and substantial economic losses were incurred. Additionally, the performance of community systems during and after the floods was consistently inadequate across many areas, with the Livelihoods theme being the most adversely affected. For instance, post-flood, many community members lost income stability and were compelled to engage in erosive coping strategies such as taking on hazardous jobs, taking out high-interest loans, interrupting the education of their children, and selling productive assets.

Our analysis indicates a statistically significant relationship between low baseline resilience levels as measured by the FRMC and poor post-flood performance across multiple themes. Specifically, higher natural, physical, and financial capitals were found to be correlated with better post-flood outcomes in relation to assets, livelihoods, life and health, lifelines, and governance. The relationship between social and human capital, and flood damage, was less pronounced in the sample overall. However, we did find that in rural communities, the relationship between pre-disaster social capital and better post-flood outcomes was strongest, while in urban communities better post-flood outcomes were most strongly correlated with financial capital.

In most cases, multiple sources of resilience correlate with a given flood outcome, underscoring the multidimensional nature of disaster resilience (Zaman et al. 2023). Furthermore, we identified certain sources of resilience that were strongly correlated with better flood outcomes across several outcome themes. For example, early warning systems, large-scale flood protection, emergency food supplies, and community safety measures were found to positively correlate with lower impacts across multiple areas. Given their apparent broad benefits, these resilience sources may well be cornerstones of community disaster preparedness and worth prioritizing for strengthening through interventions (Gu et al. 2023).

Our findings highlight the critical importance of investing in community resilience to reduce flood impacts; for comparable events, communities with higher initial resilience, as measured using the FRMC, suffered fewer impacts and damages. This provides empirical support for the validity of the FRMC measurement framework and emphasizes the need for further research to unravel the complex interactions between different sources of resilience and their effects on flood outcomes on different scales (Matsukawa et al. 2024). As climate change continues to intensify flood risks, understanding and enhancing community resilience will be increasingly vital for sustainable development and disaster risk reduction.

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Table 1: Regression results for baseline capital grades on post event outcome themes.

	Assets		**Governance**		**Life and Health**		**Lifelines**		**Livelihoods**		**Social Norms**	
Predictors	*Estimates*	*p*	*Estimates*	*p*	*Estimates*	*p*	*Estimates*	*p*	*Estimates*	*p*	*Estimates*	*p*
(Intercept)	-3.89	0.521	32.39	**<0.001**	13.02	**0.001**	28.36	**<0.001**	-22.19	**<0.001**	29.63	**<0.001**
Financial Capital	0.40	**0.048**	0.71	**<0.001**					0.43	**0.016**	-0.50	**0.003**
Physical Capital	0.83	**0.001**			0.47	**<0.001**	1.23	**<0.001**	0.58	**0.012**		
Natural Capital	0.29	0.077	-0.33	0.09	0.66	**<0.001**	0.39	**0.016**	0.74	**<0.001**	0.66	**<0.001**
Social Capital			0.41	**0.04**								
Human Capital							-0.72	**<0.001**	0.22	0.148		
Flood Return Period	0.51	0.062	-0.74	**0.003**							1.40	**<0.001**
Population					-0.00	0.132			-0.00	0.126		
Observations		66		66		66		66		66		66
R^2		0.592		0.421		0.736		0.409		0.79		0.47
AIC		574.325		565.29		505.037		575.823		556.765		567.399

Table 2: Regression results for capitals on fatalities in events.

	Total Fatality		**Total Injury**	
Predictors	*Estimates*	*p*	*Estimates*	*p*
(Intercept)	4.91	**<0.001**	113.04	**<0.001**
Physical Capital	-0.09	**0.039**		
Social Capital	-0.06	0.058	-1.53	**0.017**
Natural Capital			-1.23	**0.048**
Flood Return Period	0.19	**<0.001**	2.90	**<0.001**
Observations		66		66
R^2		0.413		0.461
AIC		341.049		725.714

Supplementary D:

Table D1: *Regression results. Post event themes grade as dependent variables and baseline and baseline capitals (5Cs) as explanatory variable. [full models]*

	Assets		**Governance**		**Life and Health**		**Lifelines**		**Livelihoods**		**Social Norms**	
Predictors	*Estimates*	*p*	*Estimates*	*p*	*Estimates*	*p*	*Estimates*	*p*	*Estimates*	*p*	*Estimates*	*p*
(Intercept)	-3.05	0.721	31	**<0.001**	15.95	**0.002**	31.35	**<0.001**	-21.03	**0.004**	33.59	**<0.001**
Financial Capital	0.42	**0.047**	0.57	**0.003**	0.11	0.391	0.08	0.725	0.40	**0.028**	-0.6	**0.003**
Physical Capital	0.91	**0.001**	0.32	0.212	0.39	**0.021**	1.21	**<0.001**	0.55	**0.024**	0.05	0.862
Natural Capital	0.30	0.15	-0.32	0.092	0.59	**<0.001**	0.38	0.076	0.66	**<0.001**	0.61	**0.003**
Social Capital	0.11	0.673	0.27	0.242	0.15	0.33	-0.09	0.726	0.19	0.386	0.09	0.708
Human Capital	-0.19	0.319	0.05	0.80	-0.09	0.459	-0.68	**0.001**	0.17	0.314	0.01	0.967
Flood Return Period	0.50	0.077	-0.66	**0.012**	-0.13	0.429	0.06	0.845	0.04	0.887	1.36	**<0.001**
Population	0.00	0.446	0.00	0.215	0.00	0.213	0.00	0.261	0.00	0.151	0.00	0.236
Observations		66		66		66		66		66		66
R^2		0.602		0.453		0.746		0.427		0.793		0.485
AIC		578.618		567.548		510.482		581.743		559.804		573.485

Table D2: *Regression results. Flood impacts (total fatality and total injury) as dependent variables and community resilience (baseline themes), hazard scale (flood return period) and exposure (population) as explanatory variable. [full models]*

	Total Fatality		**Total Injury**	
Predictors	*Estimates*	*p*	*Estimates*	*p*
(Intercept)	4.76	**0.001**	129.34	<**0.001**
Financial Capital	-0.02	0.501	0.45	0.509
Human Capital	-0.03	0.295	-0.48	0.436
Natural Capital	0.03	0.431	-1.27	0.058
Physical Capital	-0.06	0.202	-0.31	0.734
Social Capital	-0.05	0.25	-1.22	0.128
Population	0.00	0.303	0.00	0.997
Flood Return Period	0.19	<**0.001**	2.61	**0.004**
Observations		66		66
R^2		0.443		0.472
AIC		345.611		732.271

Declaration of interests

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.