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PROGRESS UPDATE

Assessing Community Resilience: Validating a Universally Applicable Flood Resilience Measurement Framework and Tool

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Abstract

Understanding and strengthening community-level resilience to natural hazard-induced disasters is critical for the management of adverse impacts of such events and the growth of community well-being. A key gap in achieving this is limited standardized and validated disaster resilience measurement frameworks that operate at local levels and are universally applicable. The Flood Resilience Measurement for Communities (FRMC) is a foremost tool for community flood resilience assessment. It follows a structured approach to comprehensively assess community flood resilience across five classes of capacities (capitals) to support strategic investment in resilience strengthening initiatives. The FRMC is a further development of an earlier version (the FRMT, the Flood Resilience Measurement Tool). The FRMT has been developed and applied between 2015 and 2017 in 118 flood prone communities across nine countries. It has been validated in terms of content and face validity as well as in terms of reliability. To reduce redundancy and survey effort, the FRMC holds a lesser number of indicators (44 versus 88) and has now been applied in over 320 communities across 20 countries. We examine the validation for the revised resilience construct and the new community applications and present a comprehensive overview of the statistical and user validation process and outcomes in both practical and scientific terms. The results confirm the validity, reliability as well as usefulness of the FRMC framework and tool. Furthermore, our approach and results provide insights for other resilience measurement approaches and their validation efforts. We also present a comprehensive discussion about the dynamic aspects of flood resilience at community level, and the many validation aspects that need to be incorporated both in terms of quantification efforts as well as usability on the ground.

Keywords Community resilience · Floods · Resilience measurement · Standardized tool · Universal · Validation

1 Introduction

Understanding and strengthening community-level resilience to natural hazard-induced disasters (Kelman 2020), such as flooding, is critical for mitigating adverse impacts of disasters and the protection and growth of community well-being (World Bank 2010). A key gap, however, is the limited standardized and validated measurement approaches that can be applied at local levels. The Flood Resilience Measurement for Communities (FRMC), developed by the Zurich Climate Resilience Alliance (formally the Zurich Flood Resilience Alliance), is a structured approach to assess community flood resilience to support strategic investment in resilience strengthening initiatives. The FRMC is the most widely used community-level, standardized disaster resilience measurement approach in the world, having been applied in over 400 communities across the globe (Keating et al. 2025).

This extensive application of a standardized framework has enabled quantitative analysis of the resultant data, together with qualitative analysis of user experience. An important step in rendering an approach and tool credible is to validate it. Apart from the FRMC, the literature reports only limited instances of standardized and validated community (disaster) resilience measurement approaches that are universally applicable. Therefore, reporting on the complex endeavor of exploring validation of a resilience

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measurement framework is an important contribution to the body of scholarship on resilience in general and its measurement in particular.

We refer to validation of the FRMC framework and tool not only in terms of quantitative analysis, that is, statistical testing, but also in terms of its usefulness for users on the ground or "user validation." There are several major challenges that need to be considered when exploring validation of a community disaster resilience measurement approach. For example, there is no agreed-upon definition of community disaster resilience (Norris et al. 2008; Cutter et al. 2010; Alexander 2013). However, it can be said that the field is converging on an agreed conceptualization of community disaster resilience as a multi-dimensional construct, spanning dimensions of social capital and governance aspects, natural and built environments, and human well-being including health and education (Lewis and Kelman 2010; Laurien et al. 2020). In addition, resilience is a latent construct, until tested by a disaster event. This means that it is not until a system (in this case a community) is challenged by a disaster that one can explore whether what is measured in the framework actually made a difference (Keating et al. 2017). Furthermore, validation requires a high number of standardized applications; because community disaster resilience is highly context specific, many measurement frameworks allow for or even depend on extensive local customization. While the benefits of customizability are not to be discounted, they preclude the possibility of robust empirical validation.

In tackling these aforementioned challenges (as well as others), the FRMC approach was developed not only to provide practical, on-the-ground support to community flood resilience programming, but also to support scientific advancement in the fields of resilience measurement and building by allowing for validation-oriented analysis. The approach was designed to generate empirical evidence on how resilience can be measured and strengthened in diverse, real-world contexts. Importantly, the FRMC framework, tool, and application guidance were developed collaboratively between practitioners, academic researchers, and policymakers, in order to ensure practical utility, community impact, and scientific robustness (Keating et al. 2017; Campbell et al. 2019; Keating et al. 2025).

The result of these design objectives around practical utility and enabling validation is a standardized measure of community flood resilience applicable on the global scale. At the same time, the data collection approach is flexible, allowing for local customization. Implementation is undertaken collaboratively with community stakeholders and data are drawn directly from community, ensuring that community voice is central to the process and results. This approach was designed to allow for sufficient local customization while achieving enough consistency to generate comparable, high-quality data across communities (Hochrainer-Stigler et al. 2021). Results are visually explored and represented through a user-friendly interface and web application (Laurien et al. 2020). It should be noted that the FRMC does not replace existing processes nor direct users as to invest in a particular area of resilience; instead, it identifies areas of strength and gaps to support a wider process of intervention design (Keating et al. 2017).

In order to allow for pre- and post-event comparison, that is, to collect data on the latent construct of resilience as well as the revealed resilience when an event occurs, the FRMC is in fact two measures. The FRMC baseline measures the latent construct and fits what is typical for a resilience measurement framework, in that it measures a set of characteristics, capacities, and resources that exist at the community level prior to disaster and are thought to contribute to the community's flood resilience. For example, indicators measuring the existence and quality of safe evacuation plans. When a flood occurs in a community where the FRMC baseline has been taken, the FRMC post-event study is then applied. The post-event study measures the impacts of the disaster as well as the performance of various community systems during and following the event. For example, it assesses how well the early warning system performed when tested by the disaster.

The first version of the FRMC framework and tool (called the Flood Resilience Measurement Tool, or FRMT) was developed and applied between 2015 and 2017 in 118 flood prone communities across nine countries. Following extensive user feedback, it evolved into the FRMC Next Gen (Keating et al. 2017; Keating and Hanger-Kopp 2020; Keating et al. 2025). While many of the building blocks of the framework were retained, the number of indicators—called "sources of resilience"—was halved from 88 to 44. In addition, content was edited to improve usability and data quality, and improvements were made in the capacity for exploring data disaggregated by gender, age, and disability status. It is this Next Gen version of the FRMC that has been applied in communities across the globe and is the focus of the analyses reported on here.

This article provides a comprehensive overview of the validation process and outcomes in both practical and scientific terms. It is structured around three main pillars including validity, reliability, and usability aspects. For each pillar a detailed discussion of results found is given that confirms the validity, reliability, as well as usefulness of the FRMC framework and tool. In addition, this novel contribution to resilience knowledge and implementation is designed to provide actionable insights about resilience measurement and strengthening initiatives, and on the dynamic aspects of flood resilience at the community level. In the next section we present the methodology, framework, and tool in some detail. The corresponding results are presented in Sect. 3.

Afterwards, we discuss the results within a broader setting in Sect. 4 and conclude with an outlook to the future in Sect. 5.

2 Validation: Methodology, Framework, and Tool

We start with a discussion of the FRMC framework and associated application tool as well as introduce the data gathered for validation purposes, which are later discussed in greater detail.

2.1 Framework, Tool, and Data Gathered

The FRMC is based on the so-called "5C-4R" framework: it includes 44 indicators called "sources of resilience" that are distributed across and represent critical aspects of five complementary "capitals" (5Cs). The 5Cs follow the five capitals of the Sustainable Livelihoods Framework (DFID 1999), which emphasizes that resilience comprises various dimensions including physical, social, human, financial, and natural aspects that interact over time. Each source is also assigned to one of four resilience properties derived from resilient system-thinking (4R). The sources are selected for the roles they play in helping people on their development path and/or providing capacity to reduce flood risk, prepare for, respond to, and recover from floods.

Users collect and analyze data using the FRMC tool, a practical hybrid software application comprising an online web-based platform for setting up and analyzing the process, and a smartphone- or tablet-based app that can be used offline in the field for data collection. The FRMC includes several data collection methods (household surveys, focus groups, key informant interviews, and secondary source data) and allows for the collection of data on various community perceptions, knowledge, and capacities (Fig. 1, left hand side). Data collection methods and the overall data collection strategy are designed

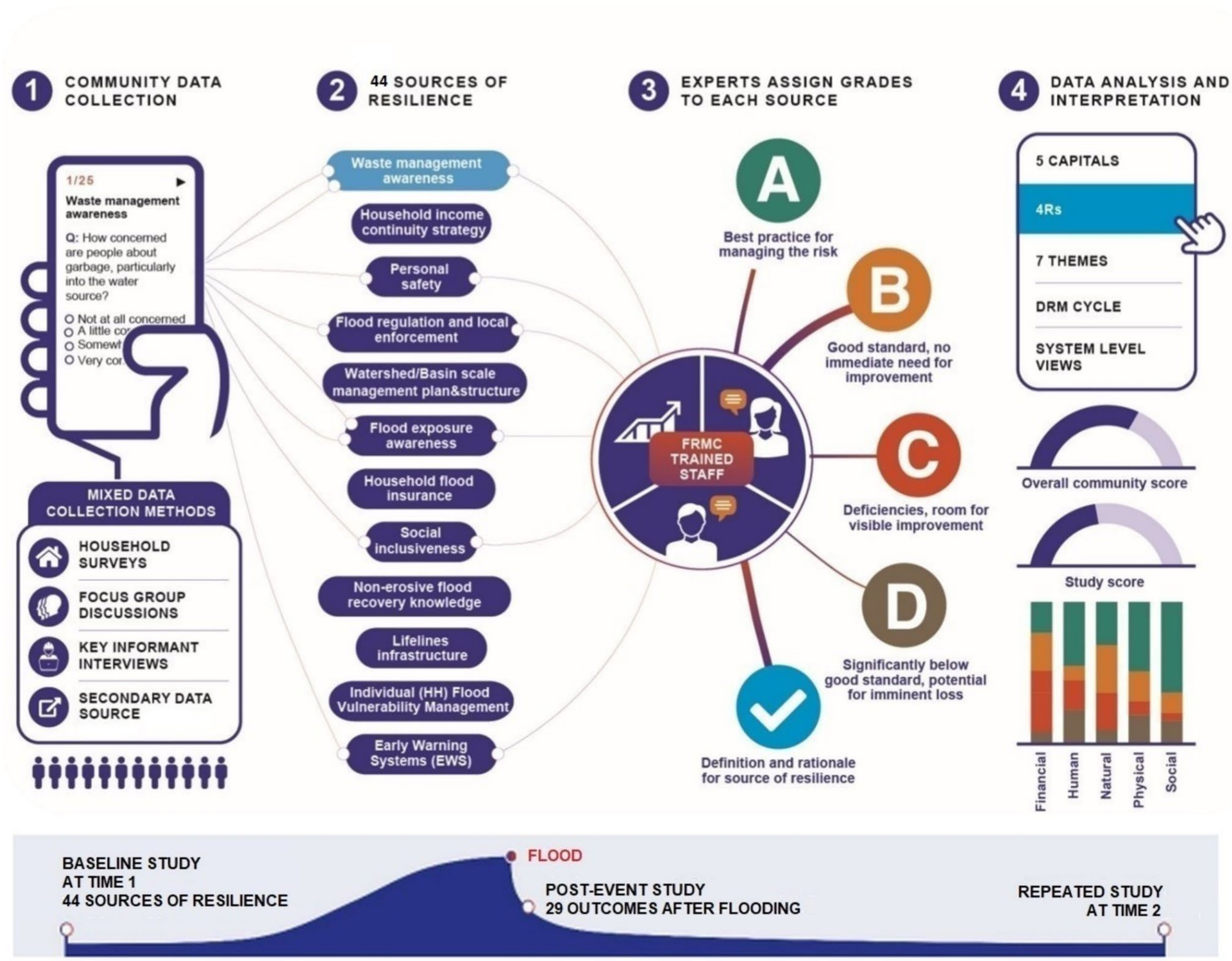

Fig. 1 Flood Resilience Measurement for Communities (FRMC) data implementation process *Source* Based on Laurien et al. (2020)

at the local level in response to local context. Use of data collection software technologies are supported by online or in-person user-training and guidance resources, which help ensure systematic and consistent data collection and framework use.

After data are collected on the app, they are uploaded to the web application. A grading team—typically composed of the FRMC implementing team, community members, and often local government representatives—compare collected data to pre-determined grading rubrics to grade each of the 44 sources of resilience on an A–D scale (A being best practice, D being poor) (Fig. 1, middle). For aggregation, A–D grades correspond to number scores as follows: D = 0, C = 33, B = 66, A = 100. The number scores of corresponding sources of resilience for each capital are then averaged to get an aggregate score for each capital; for example, if all sources of resilience in a capital group were graded "A," the community would score 100 for that capital group. Graded results can be explored according to different "lenses" including the 5Cs, 4Rs, seven themes (relating to sectors such as health and education), five steps of the disaster risk management (DRM) phases, and system or context level (community level or enabling environment) (Fig. 1, right hand side). The online platform includes data analysis features that facilitate exploration of interconnections between results and preparation of reports that can be shared with community stakeholders (Fig. 1, right hand side).

As Fig. 1 (bottom) indicates, in addition to the baseline resilience assessment there are further studies with their respective data: the post-event study that is undertaken after a flood event, and the endline study that is a re-application of the baseline study conducted 1–4 years after baseline. Finally, data on interventions applied after the baseline studies are also collected and used in our analysis. Together, these parts make up a cohesive, empirical analysis of community flood resilience over time. When data from applications of the FRMC and interventions across the globe are brought together, one has an unprecedented dataset with which to explore questions of validation.

Regarding data gathered, the FRMC Next Gen dataset of baseline resilience assessments encompasses over 320 communities across 20 countries, representing a total estimated community population of approximately 1.07 million people. Data were collected from 19,911 households and focus groups, key informants, and secondary data sources, and grades were assigned to each of the sources of resilience. In total, the baseline dataset includes 2,562,689 data points that were used to grade 14,300 sources of resilience. The endline resilience assessments were completed in more than 290 of the original 325 communities across 19 countries, with responses from 16,946 households and with an estimated population of 0.7 million people. These resulted in 2,224,409 data points and 12,892 graded sources.

Post-event assessment (Fig. 1, bottom) was applied in 66 communities across seven countries that had experienced flooding sometime after the baseline but before the endline. Post-event study data take the form of qualitative insights from focus group discussions, key informants, and secondary sources. This represented a population of 157,900 people and yielded 48,575 data points from 1,716 graded indicators. Finally, interventions assessment was applied in 270 communities in 20 countries where interventions were implemented following the baseline. This comprises 123,720 households and a total community population of 576,954 people.

2.2 Validity, Reliability, and Usefulness

In regard to the FRMC, we developed the following working definition of validation: validation of the FRMC means to discern evidence that the sources of resilience contribute to improved resilience outcomes in case of a flood event and are reliably measured in a standardized way, and to synthesize feedback from users on the practicality or usability of the approach. Following this definition, the FRMC validation process is structured around three key pillars:

- Validity is about whether the sources of resilience actually measure community flood resilience. We used multiple lines of evidence to explore face validity, content validity, external validity, and construct validity.
- Reliability is about how the FRMC tool and process constitute a standardized measurement approach. In other words, that the same is being measured across communities, grading teams, and time.
- Usability is the user-friendliness and practicality of the FRMC approach, including the framework, tool, and processes.

In order to investigate the validity of the FRMC, we employed two main methodological approaches: (1) a structured empirical approach using quantitative data inputted into the FRMC, involving statistical reliability and validity tests, to identify which sources of resilience contribute most to resilient outcomes; and (2) a user validation process using qualitative feedback data, to synthesize the collective expertise of FRMC practitioners, understand the FRMC's practical utility, and enable users to provide input into the framework and the tool evolution. To be more precise, **validity** is looked at through:

- Face validity. For the FRMC to be valid, it must align with resilience practitioners' and communities' understanding of what constitutes community flood resilience, so-called "face validity." This is important for two key reasons: first, community flood resilience practitioners

and communities themselves are experts on community flood resilience since they work directly on and experience floods. Practitioner and community endorsement and uptake of the FRMC framework contributes substantially to face validity. Second, for the FRMC tool to be useful for users, it should make sense to them. Data to undertake this analysis were gathered via various qualitative methods. This includes conducting qualitative interviews to understand practitioner perspectives and practitioner-reported community perspectives on flood resilience and the FRMC; interpretation of user feedback provided during peer workshops; analysis of comments inserted into the FRMC tool; and drawing on the "source relevant" and "grading confidence" tick-boxes filled out by users when grading a source.
- Content validity. This refers to the validity of the content in the framework and was based on an extensive literature review, expert design input from practitioners, disaster risk experts, and risk engineers, and an extensive peer review process. It is important to note that content validity, which looks at the underlying theoretical underpinnings of the FRMC framework, is also an important aspect of overall validity.
- External validity. For the FRMC to be a valid measure of community flood resilience, it must be applicable across various different types of communities—this is called external validity. Establishing external validity is based partially on face validity and partially on statistical analysis exploring the impact of community characteristics (such as location, community type, poverty level, sociodemographic statistics, and so on) on FRMC outcomes.
- Construct validity. The validity of the FRMC construct was investigated empirically via statistical validity tests between the sources of resilience and theoretical framework.

Reliability is important for demonstrating that the FRMC is plausible and comprehensive as a standardized measure of resilience. To empirically explore the reliability associated with the process of collecting and grading the sources, we used the following statistical tests to explore:

- Inter-rater reliability, which refers to the consistent use of raw data to assign grades across grading teams.
- Test-retest reliability, which refers to the consistency of the use of raw data to assign grades across time.
- Internal consistency reliability, which refers to the consistency of the sources of resilience between communities in one framework (that is, 5Cs or 4Rs).

Usability dimensions are largely based on qualitative methods that were applied with users, in conjunction with data collection exploring questions of face validity and content validity. Semistructured qualitative interviews conducted at key points throughout the process, content analysis of Alliance reporting, and peer review processes are being used to document and assess the usability of the FRMC framework, tool, and process. Exploring usability includes answering questions about, among others: ease of use of the FRMC; required resources for effective implementation; impact on staff capacity development; integration of FRMC with other project processes and tools; input of the FRMC into intervention design; advocacy-related outcomes; and outcomes of post-flood studies. This also includes deep-dives into specific communities to analyze the complex interrelationships between resilience dimensions as well as possible intervention sets and outcomes. One example is presented in the results section.

3 Results

As indicated, we want to provide a comprehensive picture of the main processes involved and results found in our multi-pronged FRMC validation evaluation, rather than provide details of the various validation analyses. We first present validation analyses related to the framework and tool, then move on to the equally important user validity analyses.

3.1 Validation of the Flood Resilience Measurement for Communities (FRMC) Framework and Tool

Starting with validity dimensions, the content validity of the FRMC framework was established based on an extensive literature review, expert design input from practitioners, disaster risk experts, and risk engineers, and an extensive peer review process (see Keating et al. 2017). As described above, the 5C-4R framework is built on widely accepted concepts and frameworks in disaster risk management and development programming (Campbell et al. 2019). The sources of resilience were designed on the basis of the 5C-4R model with input from risk and resilience experts and community practitioners. The post-event outcome variables were developed from models with similar operationalizations.

Regarding face validity, we found that practitioners have a high degree of agreement with the framing and content of the FRMC. Alliance practitioners confirmed that, in their expert opinion, all 44 of the sources of resilience included in the FRMC are indeed important for strengthening community flood resilience. Additionally, practitioners did not identify any major gaps in the sources of resilience, that is, sources that they believed were missing. Practitioners overwhelmingly stated that the various lenses used in the FRMC framework—in particular the five capitals and disaster risk management phases—were particularly useful for informing programming. Practitioners using the FRMC reported widespread acceptance and engagement by the communities they are working with, which further supports the finding that the FRMC makes sense to people on the ground (Keating et al. 2025).

Both the FRMC's external validity and construct validity are supported by evidence from analysis using clustering techniques and principal component analysis (PCA). A detailed statistical analysis can be found in Chapagain et al. (2024a). Chapagain et al. (2024a) especially showed that the FRMC is able (in terms of explaining variation in the capitals through clustering agglomeration) to measure community flood resilience across different types of communities, that is, in communities that fall into statistical clusters. For the FRMC capitals, a single-component PCA explains around 31–45% of the total variance in the set of sources; this is a remarkable result as the sources have to explain the quite complex, latent capital construct. It is reassuring that if a Kaiser criterion (eigenvalue > 1) is applied, we found 2–3 sub-components within each capital that represent different dimensions of it, altogether explaining 55–67% of the original variance—again an acceptable level for such a complex construct like community flood resilience across multiple dimensions (capitals). Moreover, resilience capital grades strongly correlate with communities' socioeconomic characteristics, including poverty, female education levels, and income from remittances, which further strengthens the claim for construct validity. Furthermore, the PCA guided the grouping of the post-event outcome variables into six themes, collectively explaining 71% of the total variance in post-event assessments (see Chapagain et al. 2025). These findings show a good agreement with the underlying framework, supporting both external validity and construct validity of the framework and tool.

Regarding reliability, inter-rater reliability was tested using big-data analysis to examine if different FRMC users undertaking the grading step give consistent grades when presented with the same raw data. To test this kind of reliability, we compared the collected raw data and corresponding grades of the sources of resilience across the baseline study sample. Due to the very different scales used across the sources (for example, nominal, ordinal, and continuous), we applied boosted regression tree approaches, following similar analysis in the first phase (Hochrainer-Stigler et al. 2021). Overall, we found that grades are more consistent between graders when the source requires less subjective judgment. The overall inter-rater reliability was at acceptable levels, particularly considering that the design of the FRMC assumes that the grading of the sources of resilience based on raw data necessarily requires deliberation by local experts.

Internal consistency was measured using the classic Cronbach's Alpha metric (Nardo et al. 2005). We found that the internal consistency of the 44 sources used to measure the 5Cs in the FRMC baseline and endline assessments fall within the commonly accepted threshold of 0.7 (see Table 1). This confirms that the sources of resilience within each capital are closely related and can be aggregated to measure the latent capital. Finally, a test-retest reliability method was applied to compare the internal consistency of the grading process for baseline and endline studies, again using Cronbach's Alpha method.

3.2 Realized Resilience and Interventions

Taking the above validation dimensions together, we conclude that the FRMC is assessing resilience in a valid and reliable manner. The next element of the validation analysis therefore relates to the post-event outcomes and interventions, to explore which baseline resilience sources, or groups of sources, are most important for resilience when it is realized during and after a disaster, and which intervention types best support it (Fig. 1, bottom). As described above, when a community where the FRMC baseline has been measured experiences a flood disaster, FRMC users conduct a post-event assessment to understand what actually happened—specifically, how the community's underlying resilience played out during the disaster. Unlike the resilience sources, which focus on the characteristics that make a community more resilient, this assessment looks at 29 post-flood outcome variables. These variables measure both the direct and indirect impacts of the flood event, as well as how different community systems performed during and after the event. Among these variables, three are classified as "hazard trait" variables, which assess the size and type of the flood. This helps to ensure that researchers account for the severity of the event when analyzing its effects. The remaining 26 variables cover a broad range of community aspects, including assets, livelihoods, life and health, lifelines, governance, and social norms.

The post-event analysis examined how a community's underlying resilience—measured by the baseline FRMC—affects post-flood outcomes. The findings, detailed in Chapagain et al. (2025), confirm that communities with higher

Table 1 Results of internal consistency tests using Cronbach's Alpha for the five capitals, baseline, and endline assessments

No.	Capital	No. of Sources	Classic Cronbach's Alpha coefficient	
			Baseline	Endline
1	Financial	7	0.79	0.86
2	Human	9	0.71	0.66
3	Natural	5	0.72	0.73
4	Physical	12	0.84	0.82
5	Social	11	0.85	0.85

baseline resilience tend to experience significantly lower flood impacts, controlling for the severity of the triggering hazard. Specifically, communities with strong natural, physical, and financial capital generally perform better across most post-flood measures, while social capital plays a key role in governance-related outcomes. Moreover, resilience is found to be the result of complex interactions between multiple factors. For example, investments in risk reduction, early warning systems, large-scale flood protection, emergency food supplies, community safety measures, and coordination between communities all contribute to better outcomes. Since these resilience-building efforts have widespread benefits in reducing flood damage, they should be considered key priorities for strengthening community disaster resilience. Overall, the post-event analysis results further support the validity of the FRMC framework of measuring resilience.

Next, different intervention types were analyzed. Using the FRMC to inform interventions is a resource intensive two-stage process of analyzing results and planning interventions. First, FRMC user teams conduct an internal analysis to understand the results and determine the most effective ways to share them with the community and other stakeholders. Second, a participatory process engages the community and relevant stakeholders in sharing and discussing the results to collaboratively develop an action plan. The FRMC serves as a decision-support tool, identifying critical flood resilience needs and opportunities within the community. It is important to note that the FRMC does not generate specific interventions. Instead, it highlights key areas requiring further exploration and community-led decision making. It especially promotes a systems-thinking approach, encouraging an analysis of interconnections between different factors and avoiding an isolated view of individual resilience sources and their relative strengths and weaknesses.

We identified a clear lack of data or empirical investigations of community flood resilience interventions that looked across multiple communities in diverse contexts. Therefore, we utilized the interventions data collected in the Alliance to generate evidence of intervention types, themes, distribution, and determining factors. Furthermore, we developed a classification scheme as much needed in addition to the existing conceptual approaches currently dominating the debate, including seven different intervention types. As in the case with the post-event analysis, we also related interventions to the baseline data. In this way, our empirical analysis should make also an important contribution to the conceptual literature. For example, we find that interventions in the same category can be very different in regard to their functionality for enhancing resilience for different capitals. This calls for caution regarding which interventions and possible broad-based implementation perspectives ought to be prioritized in different contexts. While our analysis focuses on current intervention implementation, it is equally important for contributing to thinking around climate change adaptation options that will ultimately build on these current interventions. It is therefore necessary to bring these short- and long-term intervention horizons together, along with consideration of transformational potential, for a deliberate, effective, and seamless transition of strategies for reducing climate related risks from today into the future.

3.3 Usefulness and Deep-Dives

We now go into more detail about the usability dimension of the FRMC validation process. As discussed above, usefulness and usability on the ground are critical. Here we also include some country program scale deep-dives in order to demonstrate usability and the wealth of community resilience insight possible with the FRMC.

3.3.1 Usability and Usefulness

In-depth qualitative feedback from FRMC users—the only people qualified to report on the usability and usefulness of the FRMC on the ground—overall finds strong results on this dimension of validation. We first discuss the usability of the FRMC framework and tool itself, followed by a discussion on the contribution of the FRMC process to capacity development. It should be noted that prior to starting the FRMC process, users must complete training; the accessibility and usefulness of this "pre-work" step is critical to the overall smooth use of the approach. Overall, FRMC users found that the online training provided to them is comprehensive and were positive about the experience, particularly the step-by-step explanations and examples. Some did find elements of the online training long or technical, particularly for those with less strong English skills. However, support from more experienced colleagues within the Alliance enabled user teams to effectively plan for and implement the FRMC.

The study setup—one of the first steps in the FRMC process—was found to be a straightforward process for most users. A collaborative approach that involves working with local authorities and stakeholders can be a time-consuming but necessary step for socializing the project and collecting data. Data collection was reported to be achievable, with many users appreciating the deep community and stakeholder engagement enabled by the FRMC data collection process. The graphic tools for the display and analysis of results were reported as a major benefit of using the FRMC. Overall, many users referred to the strength and innovation of the FRMC's holistic approach on a conceptual and/or practical level. They also highlighted the strength of the participatory and collaborative methods for collecting, using, and validating the data and results. Another key strength is having a rich source of data to support program development and advocacy. The technical language and complexity of the concepts and process are the most challenging part. This can be a steep learning curve for some users. People also find it to be a time-consuming and resource-intensive process, although this is balanced with benefits and not to the extent that would make it unusable.

An important result that emerged from this and previous FRMC research is the positive impact on users learning and capacity regarding resilience thinking. The FRMC helps to operationalize the concept of resilience in a holistic way, and to link with diverse expertise and stakeholders. The participatory approach used throughout the entire FRMC process is empowering compared to other approaches. The systems-based framework was designed to foster new and innovative ways to think about flooding; evidence from users indicates that using the FRMC helps expand thinking about what it means to build flood resilience and what kind of actions to take to make that a reality. Further, the data generated through the process are being utilized to deliver concrete resilience actions and support local advocacy.

3.3.2 Deep-Dives

A qualitative analysis of FRMC data collected in Malawi demonstrates the potential of community cluster deep-dives, including gaining a holistic understanding of the mechanisms of resilience building in one particular area of the country. The research revealed tight couplings between capitals, connected through numerous mechanisms (see Fig. 2). Findings underline that social capital plays a central role in connecting and leveraging other capitals, particularly in facilitating financial access, knowledge sharing, and community organization. In addition to the importance of social capital, findings underscore the key roles of financial and human capitals, particularly in relation to local knowledge and leadership. The findings emphasize the importance of integrated approaches that strengthen inter-capital interactions, particularly those leveraging social networks, to enhance community resilience to floods in Malawi and other flood-prone regions.

This deep-dive analysis indicates that there are various complex mechanisms involved within context-specific

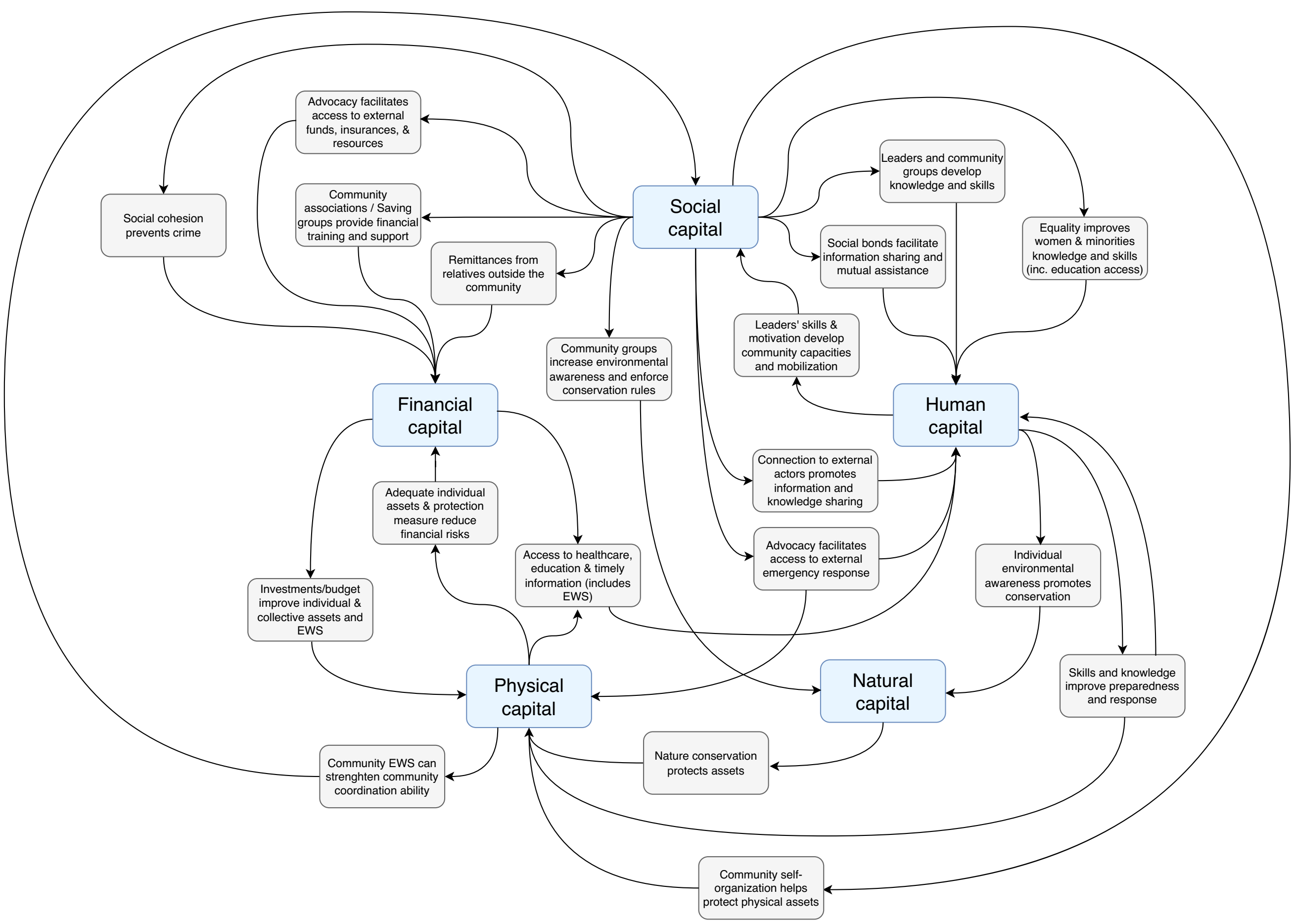

Fig. 2 Mechanisms (grey boxes) connecting capitals (blue boxes) for communities in Malawi. Arrow heads indicate the direction of impact. Mechanisms were identified through qualitative analysis of FRMC data. *EWS* Early warning system

resilience, and that the standardized measurement approach of the FRMC has the potential to reveal highly context-specific insights. Both standardized as well as locally specific approaches can then provide complementary, meaningful ways forward for enhancing resilience based on a multiple line of evidence approach.

Another deep-dive relates to the exploration of health outcomes in the FRMC data. This study of health outcomes is highly relevant as floods pose both immediate and long-term risks to human health. These include fatalities, injuries, and delayed mortality due to various factors, such as a weakened healthcare system and water contamination (Du et al. 2010; Paterson et al. 2018; Chapagain et al. 2024b). As before, the analysis utilized the data from the 66 communities where the post-event study was applied and used a quasi-experimental research design to control for demographic and economic confounders. Empirical findings indicate that while community resilience levels are not statistically linked to reductions in flood-related mortality, certain forms of capital—specifically social and human capital—do contribute significantly to lowering the number of injuries. This suggests that while resilience capacity, as measured, may not be sufficient to prevent fatalities during extreme flood events, it does play a role in mitigating non-lethal harm. The lack of significant associations with mortality could point to threshold effects, where only very high levels of capital accumulation yield life-saving benefits, or to measurement limitations in capturing the nuances of community resilience. These findings highlight the importance of complementing resilience-building efforts to achieve meaningful reductions in flood-related deaths. The Malawi and health dimensions deep-dives indicate the wealth of information enabling exploration of both relevant resilience dimensions as well as mechanisms that can be analyzed from both top-down and bottom-up approaches to indicate in a comprehensive manner the underlying complexities as well as dynamics needed for an understanding of resilience.

4 Discussion

The validation results presented have focused on the FRMC tool and framework, building on the first version of the approach (FRMT, applied in phase 1 of the Alliance), where a variety of similar validation activities were performed (see Keating et al. 2017; Campbell et al. 2019; Hochrainer-Stigler et al. 2020; Laurien et al. 2020; Keating et al. 2025). Apart from decreasing the set of sources of resilience from 88 to 44, a further key difference between the phase 1 FRMT and phase 2 FRMC was that many more post-event studies were carried out, as well as the additional data collection and subsequent analysis of interventions. The driving force behind the changes made between phase 1 and phase 2 was to improve the usefulness for communities, practitioners, and other decision makers. Indeed, based on our validation definition, the indicators measured in the framework should reflect users' and communities' perspectives of what constitutes community flood resilience. In doing so, the sources of resilience should be able to explain the different impacts of flood disasters; learnings from phase 1 were used to improve the user validity of the framework in phase 2. The benefits are not only in regard to the statistical analysis of which sources of resilience are especially relevant but also relate to detailed data that were gathered on outcome indicators that include health aspects as well as details of each community and its trajectories (of resilience) over time (see the application to Bangladesh by Paszkowski et al. 2024).

When taken together, the three pillars of our validation process—validity, reliability, and usefulness—form a self-reinforcing system of checks and balances for the FRMC. That is, for example, having strong theoretical underpinnings and clearly defined grading guidelines (content validity) ensures that different graders grade the same raw data reliably (inter-rater reliability). On the other hand, having good usability also ensures that the FRMC aligns with practitioners' expectations and needs (face validity). Taking the three pillars together, the final results, as discussed here, indicate that the FRMC framework and tool is assessing resilience in a valid and reliable manner. In addition, previous resilience research has emphasized the role of individual dimensions or capitals in building resilience, but the interplay between capitals remains poorly understood (Aldrich 2017; Gaisie et al. 2021). The deep dives should contribute to filling this gap by empirically identifying mechanisms driving community resilience to floods and by demonstrating the interconnections between capitals.

Our results challenge the conventional emphasis on physical capital, or the built environment, being the cornerstone of flood resilience (Aldrich and Meyer 2015). While flood protection infrastructure is critical, results underline that human, social, and financial capitals—and the interplay between them—are key foundations of community resilience to floods. The interconnections between capitals also suggest that integrated resilience strategies are warranted, and that stronger capitals (for example, social and human) could be leveraged strategically to reinforce other capitals (Laurien et al. 2020).

Furthermore, our research complements previous research on social capital that demonstrated its role as a determinant of community resilience (Kerr 2018; Aldrich et al. 2020; Aldrich and Meyer 2022), but nonetheless also underlined that social capital was not sufficient on its own and could even have negative impacts. For example, strong in-group cohesion (bonding capital) was found to sometimes lead to the marginalization of out-groups and exacerbate inequalities between groups (Kerr 2018; MacGillivray 2018; Aldrich and Meyer 2022). Our findings demonstrate the important role of bridging and linking capitals—that is, the links between groups and with external stakeholders—to steer political decisions and mobilize external resources, underlining that community resilience emerges from multi-level interactions (MacGillivray 2018).

In addition, using the interventions data we were also able to identify seven key categories of resilience-building interventions implemented in Alliance communities: Infrastructure and Physical Improvements; Community Engagement and Knowledge Building; Community Flood Resilience Planning; Community Brigades; Nature-Based Solutions; Asset Protection and Diversification; and Early Warning Systems. Together they create a useful framework for understanding the various strategies aimed at enhancing community flood resilience and provide valuable empirical evidence that complements existing conceptual frameworks. Importantly, they show that even interventions within the same category can differ significantly in how they function and their specific impacts on resilience capitals. This, again, highlights the need to move beyond broad classifications to adopt a more detailed, context-oriented approach in designing and evaluating interventions. The Zurich Flood Resilience Alliance's two-stage process for analyzing outcomes and planning actions emphasizes that effective resilience building calls for an in-depth understanding of the impacts of interventions and a community-driven approach to planning.

The FRMC's systems-thinking perspective, which captures resilience holistically and values the connections between resilience factors, aligns well with our observation that interventions often have complex effects, impacting multiple capitals and capacities at once. This categorization framework and the accompanying empirical data provide a meaningful foundation for evaluating intervention effectiveness and guiding future strategies for climate change adaptation. Acknowledging the diverse roles within intervention categories is useful for connecting present practices with the need for innovative adaptation solutions moving forward. For example, when considering the role of the FRMC framework and tool to inform policy and practice regarding health outcomes, our findings align with existing research emphasizing how disruptions in social networks and support systems can lead to serious health consequences for disaster victims (Van Landingham et al. 2022). The role of financial capital in post-flood mortality reduction further underscores the importance of economic stability in long-term disaster resilience. Investing in financial and social capital may therefore serve as critical interventions to mitigate health risks in flood-affected communities. However, other dimensions also play important roles (see Chapagain et al. 2025).

Concluding our discussion, studies have demonstrated, and our research supports, that disaster resilience varies significantly depending on the context. The FRMC approach provides a standardized method for empirically assessing community flood resilience in diverse contexts across the globe. It also establishes a taxonomy for categorizing communities based on their similarities and differences in absolute and distributional resilience levels, as well as socioeconomic factors (Chapagain et al. 2024a). Each community taxonomy identified based on FRMC profiles possesses distinct strengths and gaps, clearly distinguishing them from each other. This supports identifying, selecting, and prioritizing resilience strategies and interventions tailored to the specific resilience profiles of different community types. Hence, the FRMC serves as a useful decision-support tool for both community programs and policy making as well.

5 Conclusion

When the Zurich Flood Resilience Alliance began in 2013, the community disaster resilience measurement field was far less advanced than it is today. The last decade has seen significant progress and increasing academic and practitioner consensus around what community disaster resilience is, as well as useful and conceptually robust approaches to measurement. Yet validation of resilience metrics remains a significant challenge for the field. The results presented here along the multiple validation dimensions of the FRMC is—to our best knowledge—one of the most advanced resilience measurement validation endeavors currently being undertaken, supporting a universally applicable and standardized approach. The results and discussion demonstrate considerable evidence for the validity, reliability, and usefulness of the FRMC for measuring community flood resilience. Both quantitative and qualitative analyses of this unprecedented dataset extend the field of community disaster resilience measurement and strengthening.

Looking ahead, a significant next step for the FRMC and similar tools lies in the integration of emerging climate change projections and scenario analysis. As climate shifts, floods may become more prevalent and patterns more unpredictable, communities may face compound hazards or sequential disasters (for example, floods followed by heatwaves, or cascading infrastructure failures). The evidence for the conceptual robustness of the FRMC, together with strong user feedback around usability and usefulness, made the case for the Alliance to invest in extending the approach to include other rapid-onset hazards. Following an in-depth peer review process and framework redesign, the FRMC has evolved into the CRMC—the Climate Resilience Measurement for Communities. Like in the progression from FRMT to FRMC, insights from analyses together with lessons from experience were used to inform the redesign of the sources of resilience. The CRMC was first designed to measure community resilience to flood and/or heatwave. Later, what is now the Zurich Climate Resilience Alliance partnered with researchers in Australia to design the wildfire hazard. In the future, more hazards are planned to be added.

The inclusion of advanced modeling techniques alongside community-based insights contributes to more dynamic resilience assessment, which illustrates not only how well communities cope with current risks but also how they might adapt to uncertain, evolving future risk landscapes. Such expansion can deepen the scientific rigor of resilience measurement and offer even more actionable guidance for practitioners. This ongoing evolution provides opportunities for further evidence generation and user-based validation of what community disaster resilience is and how to measure it.

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