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Building Back Better: Strengthening Resilience and Supporting Climate Adaptation in the Aftermath of the 2021 Flood in Germany—Insights From a Transdisciplinary Research Project

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ABSTRACT

The 2021 floods in Western Europe caused unprecedented damage, revealing major weaknesses in early warning as well as disaster risk governance. In Germany, the inter- and transdisciplinary KAHR project was established to provide science-based support for climate-adapted reconstruction. This paper analyzes how KAHR operationalized an expanded Building Back Better (BBB) framework through interdisciplinary collaboration and close engagement with authorities and communities. Key contributions include advanced flood risk modeling to guide catchment-scale planning, household-level adaptation, as well as input for the relocation of critical and social infrastructure. Surveys on psychosocial impacts supported the design of mental health services, while new governance structures and planning instruments enabled more effective reconstruction. Our findings show that embedding research into recovery processes can be an effective strategy for translating scientific knowledge into actionable solutions aiming at strengthening climate adaptation during the reconstruction. While the results contribute to international debates on disaster risk reduction and climate change adaptation, they also offer practical insights for implementing BBB in flood risk management under climate change.

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1 | Introduction

The 2021 flood events led to widespread impacts across Western Europe, particularly in Germany, Belgium, the Netherlands, and Luxembourg. It was a record-breaking flood, not just in hydrological terms, but also in its societal impacts (DKKV 2023; Tradowsky et al. 2023). In Germany alone, 190 fatalities occurred, and one person remains missing (Rhein and Kreibich 2025; Thieken, Zenker, and Bubeck 2023; Thieken, Bubeck, et al. 2023). Economic losses were estimated at €30–40 billion (Birkmann et al. 2023), with damage spanning thousands of destroyed buildings and major disruption to critical (transportation, roads, bridges, power, water supply, sewage systems) and social infrastructures (schools, kindergartens) (Burghardt et al. 2025; Madruga de Brito et al. 2025; Schaum et al. 2025; Szymczak et al. 2022). The event exposed serious deficiencies in Germany's early warning systems (Reinert et al. 2025; Thieken, Zenker, and Bubeck 2023; Thieken, Bubeck, et al. 2023) and disaster risk governance (Dittmer et al. 2021). It also resulted in several resignations of leading politicians in the two most affected federal states of Rhineland-Palatinate (RP) and North Rhine-Westphalia (NRW). Parliamentary inquiries were launched to investigate delays in warning dissemination (Heidenreich et al. 2025) and the broader failures of emergency management (Fekete and Sandholz 2021), which were seen as key contributing factors to the immense damage in the affected areas.

Within days after the event, science-led policy papers (Albert et al. 2021; Thieken et al. 2021) and public statements by NGOs, lobbying organizations and interest groups (BUND 2021) called for improvements in the German Disaster Risk Reduction (DRR) and climate change adaptation. Furthermore, in response to the devastation caused by the flood, the then German Federal Ministry of Education and Research (BMBF) established a funding mechanism to support a science-based adaptation-oriented reconstruction process.[1] This initiative led to the establishment of the KAHR project ("Klimaanpassung, Hochwasser und Resilienz" in German), a large-scale, highly interdisciplinary consortium launched just 3.5 months after the flood event. It brought together 13 partners from different disciplines, including hydrologists, hydraulic engineers, spatial planners, and human geographers. It also included practice and policy partners such as the Water Board Eifel-Rur (regional water authority) and the county of Ahrweiler (i.e., the most affected county in Germany), as well as regional research organizations working at the science-policy interface.

This paper provides insights into how KAHR's results shaped reconstruction processes, structured around a Building Back Better (BBB) framework adapted from (Mannakkara and Wilkinson 2014; Mannakkara et al. 2021). Building on this framework, this study examines how inter- und transdisciplinary research can effectively support the transition from post-disaster recovery to climate-adapted reconstruction, using the KAHR project's response to the 2021 German floods as a case study. It analyzes the challenges, innovations, and lessons learned from embedding scientific research directly into ongoing recovery processes to inform both local reconstruction efforts and broader disaster risk reduction (DRR) strategies. Though rooted in the German 2021 context, our findings contribute to broader global debates on DRR and resilience, aligning with the UN's Sendai Framework (UNISDR 2015). Insights into how such science-practice collaborations can support the recovery of heavily flood-affected regions are urgently needed, given the projected increase in frequency and intensity of climate-related disasters (e.g., flood in the Marche region in Italy in 2022 (De Lucia et al. 2024) or the floods in Valencia, Spain, in 2024 (Fekete et al. 2025)).

2 | Building Back Better: The Kahr BBB Framework

Despite increasing research, disaster recovery remains the least studied phase in the disaster risk management (DRM) cycle (Berke et al. 1993; Kuhlicke et al. 2023). Key contributions include research on family recovery (Bolin and Trainer 1978), psycho-social factors supporting the recovery of affected households (Bubeck et al. 2020; Bubeck and Thieken 2018; Lamond et al. 2015; Roy et al. 2016), and the long-term effects on exposed communities (Bates and Peacock 1989; Mitchell 1996a, 1996b). The relevance of social networks and social capital during recovery (Campanella 2006; Delanty 2003; Nakagawa and Shaw 2004) as well as post-disaster housing reconstruction (Bilau and Witt 2016) are also important strands of research. Research also highlights how disaster experience may increase the motivation to adapt (Berghäuser et al. 2023; Kienzler et al. 2015; Köhler and Han 2024; Köhler et al. 2025, 2023; Thieken et al. 2016). Governance studies stress the relevance of participatory bottom-up processes to complement top-down approaches (Imperiale and Vanclay 2020; Kuhlicke et al. 2016; Kuhlicke and Drünkler 2005) as well as the general role of policies (Bryner et al. 2017; Macaskill and Guthrie 2018; May 1985).

Critiques of the concept of recovery and/or reconstruction often argue that it implies a return to a pre-disaster state. However, post-disaster contexts may increase vulnerability, but can also open opportunities for reducing it (Birkmann et al. 2023; Kuhlicke and Drünkler 2004, 2005). Therefore, alternative terms have emerged, including post-disaster adaptive phase (Bates and Peacock 1987), redevelopment (Berke et al. 1993), community renewal (Comerio 2014), urban regeneration (Güzey 2016), and bouncing forward (instead of bouncing back) (Manyena et al. 2011). In this view, recovery should offer a window of opportunity to address the underlying root causes of vulnerabilities (Blaikie et al. 1994; Tobin 1999).

This perspective on recovery as a pathway toward resilience builds upon the concept of BBB that gained prominence following the 2004 Indian Ocean Tsunami (Clinton 2006). It emphasizes non-structural aspects in recovery and reconstruction efforts, such as the role of community and families, as well as general principles like fairness and equity. BBB promotes a forward-looking strategy that integrates DRR, preparedness, and resilience. Since then, BBB is central to numerous guidelines (for an overview see: Mannakkara et al. 2021) and has also been emphasized in several policy documents, including the United Nations' Sendai Framework for DRR 2015–2030, which demands that authorities introduce risk reduction measures in all phases of the disaster cycle, including recovery and reconstruction (UNISDR 2015).

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This paper slightly adapts this framework (i) to reflect the specific challenges of flood risk management (i.e., updating hazard and risk assessment to inform risk reduction strategies); (ii) to highlight important challenges so far neglected (i.e., rapid impact, stakeholder and need assessment); and (iii) to reflect the specific foci of KAHR (i.e., science-policy interface, critical role of social infrastructure) (see Table 1).

For each pillar (see Figure 1), we identify a set of challenges encountered and addressed during the project, which are discussed in depth in Section 4.

3 | Case-Study Region and Methods

In mid-July 2021, high precipitation led to flash flooding in western Germany and neighboring countries (Junghänel et al. 2021; Schäfer et al. 2021). The Ahr Valley, a rural area in RP was most severely affected, followed by the towns of Stolberg and Eschweiler at the Inde and Vicht rivers in NRW (Lehmkuhl et al. 2022) (Map 1). Those two catchments are the focus areas of the KAHR project, with additional research conducted in the Erft and Wupper catchments. Table 2 provides relevant information on both focus areas as well as the 2021 flood event.

The framework presented in this paper is the outcome of an iterative process and aimed at providing a synthesis framework that would link the results of the consortium to the international scientific debate on BBB as well as to well-established policy frameworks. Therefore, we used a series of workshops internal to the project consortium to map research topics of different partners on the BBB framework by Mannakkara et al. 2021 and adapted the established framework to the specific expertise and research contexts of the KAHR project. Figure 1 is an outcome of this process.

4 | Insights and Impacts of the Kahr Project

Key insights and impacts of the project are organized along the KAHR BBB framework (Figure 1). Each section represents one of the four pillars and starts with the key challenges we addressed, followed by our key activities, and how we supported BBB activities in the affected region.

4.1 | Rapid Assessments: Impacts, Stakeholders and Needs

A rapid risk assessment is a crucial first step under the time pressure following a disaster. It can provide a first overview of damage, relevant stakeholders, and recovery needs. This early evidence base can support timely and informed decisions that balance urgent recovery needs with opportunities for building back better.

4.1.1 | Rapid Impact Assessment

A primary challenge immediately following the 2021 flood event was to comprehensively assess the extent of impacts. Reconnaissance field trips to document damages and gather perishable data started already in August 2021, including the collection of flood marks, bathymetry and sediment samples (Lemnitzer et al. 2022; Wüthrich et al. 2025). Afterward, we applied remote sensing data-based analyses (Samprogna Mohor, Koch, et al. 2025) and natural language processing (NLP) tools (i.e., computer-based tools that allow for the analysis of large text corpora) (de Brito et al. 2020, 2024; Sodoge et al. 2023). While remote sensing data, a 3D-mesh from aerial survey, was instrumental in quickly evaluating direct and tangible damage at the building level (Samprogna Mohor, Koch, et al. 2025; Samprogna Mohor, Sieg, et al. 2025), NLP tools provided rapid insights into the indirect and intangible effects as reported in newspapers, including mental health impacts (Madruga de Brito et al. 2025). Besides that, an in-depth analysis of the death causes in NRW (Thieken, Zenker, and Bubeck 2023; Thieken, Bubeck, et al. 2023) and in RP (Rhein and Kreibich 2025) was conducted.

Results showed that aerial surveys and NLP can reasonably quickly gather extensive data across large geographical domains, providing a much-needed rapid assessment of flood impacts on buildings (Samprogna Mohor, Koch, et al. 2025; Samprogna Mohor, Sieg, et al. 2025).

The detailed analysis of fatalities revealed that around 49% of the flood victims in NRW and 75% in RP died in locations outside designated flood hazard zones for an extreme flood event (HQextrem) (Thieken, Zenker, and Bubeck 2023; Thieken, Bubeck, et al. 2023), emphasizing both the magnitude of the event and the limitations of clearly delineating flood hazard zones.

To clarify the scope of the analysis, we relied on flood zones defined for extreme flood scenarios, which, unlike 100-year flood zones, are not generally associated with construction bans. Post-flood updates to 100-year flood zones led to selective rebuilding restrictions, and while some households, companies, and municipalities had measures or evacuation plans for extreme scenarios, these often failed to account for residual risk, contributing, in some cases, to a false sense of safety. The analysis furthermore highlighted the importance of individual vulnerability factors, particularly age, as elderly people were overrepresented among the flood fatalities. Finally, it revealed that a significant number of people died due to ill-informed or risk-taking behavior, often underestimating the force of the event and/or their own capabilities, such as driving a car into flood water. The findings were presented to a parliamentary inquiry in NRW, which was established after the event, and made publicly accessible (Thieken et al. 2022).

4.1.2 | Rapid Stakeholder and Need Assessment

A second major challenge was to rapidly identify relevant stakeholders and their recovery and reconstruction related needs to shape an outcome-oriented co-creation approach within KAHR. We mapped relevant regional stakeholders (i.e., those with significant influence over the reconstruction or those heavily affected by the flood (Zingraff-Hamed et al. 2020)). We mapped relevant stakeholders based on partners' expertise and

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TABLE 1 | Comparison of the original BBB framework by (Mannakkara and Wilkinson 2014; Mannakkara et al. 2021) with the adapted version of the KAHR framework (changes are highlighted in bold).

Original BBB framework by (Mannakkara and Wilkinson 2014; Mannakkara et al. 2021)	**Adapted framework by KAHR**
Not included as a key element of BBB.	**Rapid impact, stakeholder and need assessment** Was added to highlight the project's responsiveness. Since the window for influencing reconstruction is short, timely data and input on impacts and stakeholders' needs are essential to avoid rebuilding vulnerabilities instead of reducing them.
Risk reduction Focus on improving structural design of built environment and hazard-based land-use to reduce future risks.	**Risk assessment** and risk reduction We identified risk assessment as a key challenge in post-disaster recovery. The scale of the 2021 flood prompted a critical review of existing hazard assessments and flood maps, requiring updated design values, extreme scenarios, and climate change considerations to guide climate-adapted reconstruction. Risk reduction was defined more specifically and includes **different groups of measures** that is, technical retention, local redirection of flood flow, and river restoration, property level adaptation, risk-based land-use planning as well as relocation of critical (social) infrastructure.
Community recovery Focus on socio-psychological support to ensure effective social and economic recovery and to restore livelihoods and entrepreneurship, and economy	Community recovery Similar focus as in the original framework, that is focus on psycho-social support. In addition, we highlight the critical role of **Social Infrastructures** during recovery. Economic aspects were not the focus of KAHR, but were touched upon in a survey among affected companies (Guntu et al. 2025).
Implementation to support BBB Includes the means by which BBB is implemented in affected areas, with a focus on legislative and regulatory measures and stakeholder interaction.	**Governance** implementation to support BBB Similar focus as in the original, that is newly established legislative, regulatory as well as organizational measures. We added the relevance of **science-policy interaction** to highligh the role of science in reconstruction.

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FIGURE 1 | Components of Building Back Better (BBB) after the July 2021 flood in Germany. Adapted and extended from Mannakkara et al. (2021).

a review of policy documents. Next, we assessed stakeholder needs through consultations, participation in public meetings and workshops, and analysis of policy and administrative reports. This rapid assessment revealed the diversity of stakeholders and their divergent needs. For instance, affected households required practical guidance for property-level adaptation, while planning authorities needed recommendations on how to realize risk-based planning principle during the reconstruction process. To address this, we bundled and prioritized needs and defined specific "products", that is practical outputs to manage stakeholder expectations to the project (Droste-Franke et al. 2026). This included information products (e.g., flyers/leaflets, website, brochures), products aiming at enhancing capacities and skills (e.g., education concepts, topical workshop for practitioners, regional networks), scientific services (e.g., model and assessment results, consulting, databases) as well as events (e.g., science-policy dialogues, scientific conferences).

4.2 | Community Recovery

Focusing on community recovery helps to ensure that rebuilding efforts strengthen not only physical structures but also psychological, cultural and social aspects (Otto et al. 2025). Assessing and monitoring negative mental health outcomes and for example symptoms of Post-Traumatic-Stress-Disorder (PTSD) provides critical insight into the hidden, long-term impacts of disasters and helps tailor mental health and support services to affected populations. Evaluating the role of social infrastructure (i.e., schools, community centers, and care facilities) reveals how these spaces can foster inclusion during recovery.

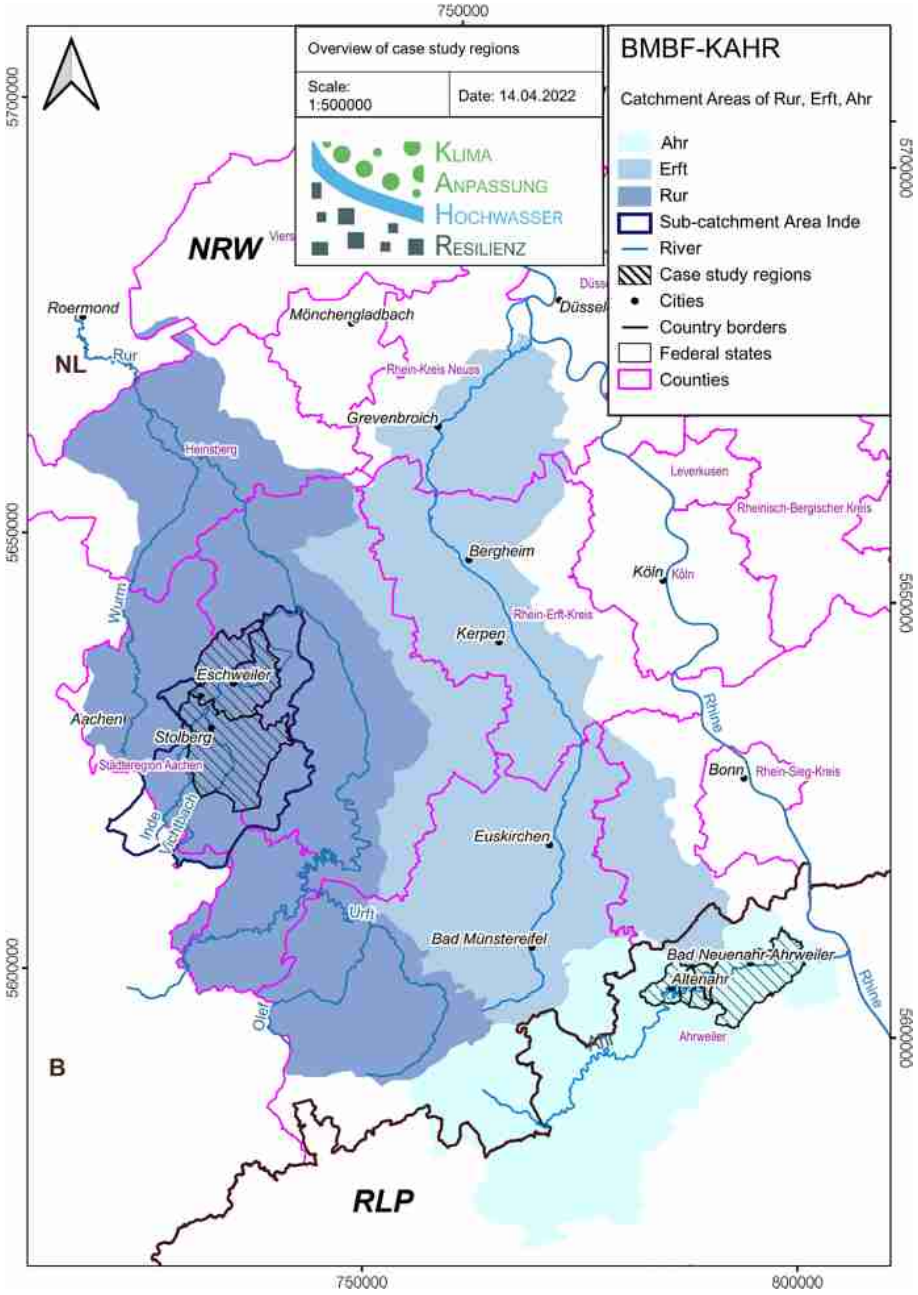
4.2.1 | Assessment of Psycho-Social Stress and Symptoms of PTSD

Shortly after the flood event, increasing demand for psychosocial support led to the establishment of a trauma help center in the Ahr Valley to address the psychological impacts of the event.[2] However, specific information on the extent to which the event impacted the mental health of those affected, which could also serve as a basis for planning community demands on recovery, was missing.

Approximately 1 year after the event, a household survey ($N = 516$, Survey 1) was conducted to assess indications of PTSD in the county of Ahrweiler, RP (Zenker et al. 2024). The German version of a short epidemiological screening scale for PTSD was employed (Siegrist and Maercker 2010). It was found that 28% of the respondents showed indications of suffering from PTSD, which is considerably higher than what would be expected in a representative population survey (Zenker et al. 2024). Slightly reduced values were observed in Survey 3, which was carried out 1.5 years after the flood in Ahrweiler (24%) and in heavily impacted regions of NRW (23%) (Zenker et al. 2026). There was also evidence of psychological distress, reduced well-being, and impaired functioning (Sairam, Buch, et al. 2025; Sairam, Sánchez, et al. 2025; Zenker et al. 2026). For both surveys, regression analyses highlighted that people who were (physically) injured during the flood were at high risk of developing PTSD symptoms. Results show that physical and mental health have to be thought of and treated together. One recommendation is that when people visit a physician to have their physical injuries examined, they should simultaneously be offered psychosocial support and have their mental health monitored. Further, stressors like having lost a family member or friend during the event, the perception of being negatively impacted by another flood event in the future, and socio-demographic variables like gender were identified to be relevant but did not show a consistent pattern among the surveys.

Findings demonstrate the necessity for long-term psychological assistance and integrated health care concepts to support community recovery. Findings were shared and discussed, among others, with the county of Ahrweiler and those providing psychological assistance in the affected regions.

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MAP 1 | Overview of case study regions. *Source:* (Otto et al. 2025).

Stakeholders from different medical and psychological departments and care organizations were interested in the results and used the PTSD data to justify resource demands from regional/state authorities.

4.2.2 | Assessment of the Role of Social Infrastructure to Support Effective Recovery

The 2021 flood event not only destroyed private and public buildings, but also interrupted established social networks and infrastructures. We therefore decided early in the project to assess the role of social infrastructure during the recovery and rebuilding phase. Following Klinenberg (2018), we interpret social infrastructure as the array of physical settings and institutions that has an influence on how and where people connect. They cover places where people gather, such as libraries, sports venues, schools, community centers, and religious sites. Although each serves different functions (for instance, schools focus on education and libraries provide access to information), they nonetheless offer built-in opportunities for social interaction, relationship-building, and community cohesion. We conducted 54 semi-structured interviews (see Table 3; Interviews 1 and Interviews 3) in the affected regions (Fuchs 2025; Fuchs et al. 2025; Fuchs and Michalski 2026; Otto et al. 2025; Reckhaus et al. 2026). We analyzed how social infrastructures were affected during the flood event and how they contributed to the recovery of affected communities.

We find that social infrastructures have been significantly impacted by the flood in multiple ways, that is, material damage to buildings, impact on personnel or clients. Although strongly

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TABLE 2 | Overview of the two focus areas as well as the 2021 flood event.

Inde/Vicht River	Ahr River
Location: The Inde river, with its largest tributary, the Vicht river, is a gravel-dominated lowland river in western Germany, near the City of Aachen, and a main tributary of the Rur river. Catchment size: 374.23 km^2 (≈15.9% of the Rur basin). Hydrology: Mean annual discharge: 2.8 m^3/s; Highest flood before 2021: 89.5 m^3/s (September 28, 2007). (main) Tributaries: Vicht and Wehebach. Reservoirs: Wehebach Reservoir (constructed between 1977–1981); Dreilägerbach Reservoir (constructed between 1909–1912); both provide drinking water supply Anthropogenic influence: History of coal and metal ore mining (iron, lead, zinc); development of processing industries; long-term pollution of river systems, still evident today. River modifications: Lower Inde and tributaries are partly straightened and canalized (20th century).	Location: The Ahr river is a left tributary of the Rhine, running southwest–northeast through the Ahr Valley. It is characterized as silicate-rich low mountain range river with fine to coarse material content. Catchment size: The Ahr is ~86 km long and has a catchment area of ~900 km^2. Hydrology: Mean annual discharge: 6.75 m^3/s; Highest flood before 2021: 236.0 m^3/s (June 2, 2016); (main) Tributaries: largest tributary is the Trierbach. Reservoirs: none Anthropogenic influence: Since the mid-19th century: settlements and transport expansion led to river narrowing, bank fixation, and channel straightening. Since the 1990s: river restoration efforts, for example, dismantling of weirs and artificial barriers. Today, the Ahr Valley is popular for its vineyards and serves as a local recreation area and touristic destination.
Event period: July 13–15, 2021. Conditions: Rainfall fell on already saturated soils. Rainfall intensity: 100 mm across large areas; 150 mm in 24 h at several locations. Rarity: Event return period ≈400 years (Tradowsky et al. 2023); Roetgen station: 223 mm in 72 h corresponds to > 1000-year return period Impacts: Severe destruction in Eschweiler and Stolberg, with the upper Inde and Vicht most affected.	Event period: July 13–15, 2021. Conditions: Rainfall fell on already saturated soils. Rainfall intensity: 66.2 mm in 24 h at Bad Neuenahr-Ahrweiler Rarity: Event return period between ≈500 and 8000 years (Merz et al. 2026). Flooded area (based on satellite images): ~200 ha along the Ahr. Population: ~56,000 residents in the valley; ~42,000 affected Casualties: 135 dead, 1 missing. Impacts: > 3000 of 4200 building along the river damaged; significant damage to infrastructure and supply networks (Szymczak et al. 2022; Burghardt et al. 2025). Municipal damage reports are compiled in local action plans.

Note: https://www.hochwasser.rlp.de/flussgebiet/ahr/altenahr#pegelkennwerte; https://www.hochwasser.rlp.de/flussgebiet/ahr/altenahr#pegelkennwerte; https://www.proplanta.de/wetter-statistik/bad-neuenahr-ahrweiler-rheinland-pfalz_niederschlag_wetterstatistiken_03490_yymm202107.html#google_vignette.

affected, all social infrastructures in our sample continued to perform their caring tasks and substantially supported coping processes after the 2021 event. As shown by Aldrich (2011, 2012, 2023), Metaxa-Kakavouli et al. (2018), and Klinenberg (2018) in other research settings, also after the 2021 flood event many of the social infrastructures became important hubs in the coping and recovery process, including SI that already existed before the flood but also social infrastructures that emerged as response to the flood (Drabek 1987; Fuchs 2025).

Social infrastructures supported the recovery and reconstruction by providing counseling for accessing reconstruction funds, establishing information points on rebuilding and future risk protection, and reducing mobility and language barriers through shuttles and outreach services. They acted as intermediaries between local administrations and affected residents by distributing donations, sharing knowledge, and fostering social capital. In addition, local associations emerged that focused on social aspects of disaster recovery and implemented projects such as temporary housing with tiny homes. Social infrastructures played a particularly relevant role in highly vulnerable neighborhoods, not only by maintaining care functions, but also by supporting more equitable access to recovery resources and contributing to collective resilience capacities in the aftermath of the disaster (Fuchs 2025; Fuchs and Michalski 2026).

With our research, we supported water management authorities seeking to improve risk communication and participation processes during the reconstruction process by using social infrastructures as intermediaries to overcome communication barriers and support inclusive outreach, particularly toward hard-to-reach populations.

4.3 | Improving Risk Assessment and Supporting Risk Reduction

Updating and strengthening risk assessment and risk reduction is a central dimension of BBB, as reconstruction should go beyond that status quo ex ante and ideally be grounded in an improved understanding of risk. Therefore, updating hazard assessments and flood maps is particularly important as changing flood dynamics and climate conditions result in outdated hazard and risk information. Expanding the perspective to the catchment scale is necessary to ensure that risk reduction

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TABLE 3 | Social science methods applied in the project.

Method	Description
Survey 1	An online survey advertised by mail was conducted in the county of Ahrweiler 1 year after the event ($N = 516$); the sample was created by randomly selecting every third household that had applied for immediate disaster aid in the county. Topics included: effects of the flood, risk perception, mental health and potential influencing factors, social vulnerabilities, the status of reconstruction and opinions on flood risk management (Truedinger et al. 2023; Zenker et al. 2024)
Survey 2	A survey among visitors to the Flood Competence Center's (HKC) information mobile on risk perception, information needs, and precautionary behavior was conducted ($N = 773$).
Survey 3	An online survey advertised by mail was conducted in the county of Ahrweiler 18 months after the event ($N = 277$); the sample was created by randomly selecting every third household that had applied for immediate disaster aid in the county, but avoiding overlap to survey 1. Topics included: flood impacts, mental health and potential influencing factors, warning, emergency response and evacuation, status of recovery, compensation payments, insurance, adaptation and opinions on property-level flood risk adaptation (Dillenardt and Thieken 2025; Sairam, Buch, et al. 2025; Sairam, Sánchez, et al. 2025). The same questionnaire was used in an online survey in NRW ($N = 332$), advertised by Meta/Facebook.
Interviews 1	Semi-structured interviews with stakeholders in social infrastructure (i.e., Care facilities, Culture, Sport, Churches, Neighborhood associations) in both regions were conducted ($N = 21$), with an emphasis on Bad Neuenahr-Ahrweiler (RP) as well as Stolberg, and Eschweiler (NRW), in 2022 (D. Otto et al. 2025).
Interviews 2	Semi-structured interviews with administrative staff from the most affected municipalities and counties in both regions, as well as representatives from water boards, civil society, and conservation groups ($N = 26$), were conducted with a thematic focus on governance challenges and changes.
Interviews 3	Informal and semi-structured interviews that explored community-based recovery and the role of social infrastructures ($N = 28$) in NRW, with a focus on the City of Hagen (Fuchs 2025; Fuchs and Michalski 2026).

measures account for upstream–downstream interdependencies and to avoid fragmented local solutions. In addition, promoting property-level adaptation supports households in actively reducing their exposure and damage potential.

4.3.1 | Updating Hazard Assessments and Maps

The 2021 flood disaster led to a critical re-examination of existing hazard assessments and flood hazard maps (Vorogushyn et al. 2022). The official HQextrem flood map (i.e., the extreme flood scenario to be mapped according to the EU Flood Directive) for the Ahr Valley, for instance, showed substantially smaller flooded areas than the 2021 flood event (Apel et al. 2022; Vorogushyn et al. 2022, 2025). Therefore, a reconsideration of flood design values, the development of plausible extreme scenarios, and potential future changes in flood characteristics due to climate change were needed to support a forward-looking and climate-adapted reconstruction process in the regions.

We implemented a flood risk model chain for the Ahr, Erft and Rur catchments that comprehensively describes the processes involved during extreme events leading to severe impacts. The model chain consists of a hydrological model, a 2D hydrodynamic model, and a damage model. It generates plausible flood events for current and future climate scenarios, and estimates flood probabilities and associated peak flows, inundation areas, and damages (Apel et al. 2022; Najafi et al. 2024; Vorogushyn et al. 2022, 2025). To estimate flood probabilities for current and future climates, the model chain was driven by rainfall and temperature fields produced by a stochastic weather generator (Nguyen et al. 2024). This weather generator provided spatially correlated daily data at 5 km resolution, which was then disaggregated to hourly values (Guan et al. 2023). By conditioning the weather generator on output from GCMs (General Circulation Models), namely large-scale pressure and temperature, which are typically more accurately simulated by GCMs than precipitation, it accounts for climatic changes. In that way, several thousand years of past and future weather were generated and used as input into the model chain. The resulting streamflow time series were then analyzed by extreme value statistics to obtain flood probabilities. The estimated 100- and 1000-year flood peaks in the Ahr Valley are consistent with an alternative method, which extends the flood frequency analysis of systematic streamflow observations by integrating five historical floods dating back to 1804 (Vorogushyn et al. 2022). The fact that two different methods and datasets (observed climate data, weather generator and flood model chain; observed streamflow and historical events) provided similar estimates of extreme flood peaks enhances the credibility of our estimations.

The model chain was also used to generate easily understandable extreme scenarios, known as downward counterfactuals. Based on the idea that the storm track of July 2021 could have followed a slightly different path, we shifted the observed rainfall fields in space and simulated the resulting flooding. These shifts lead to floods that are significantly higher than the already catastrophic event in 2021. A plausible shift of rainfall by 15–25 km to the east increases peak discharges in the Ahr Valley at the mainstream by around 30% and at tributaries by up to 150%, with significantly larger flooding areas and water depths (Vorogushyn et al. 2025). Communicating extreme scenarios and probabilistic risks to the public is often challenging. Using

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slightly altered versions of real events proved to be an effective approach for helping people grasp the possibility and consequences of unprecedented but plausible flood events.

We communicated our model results to different regional agencies: new flood design values and flood scenarios to the most severely affected county of Ahrweiler, time series for current and future climate to the Environmental Office of RP and Water Boards in NRW (i.e., Erftverband, Wupperverband) to be used as input to their own (validated) hydrological models for estimating flood design values or training an AI-based forecasting model. The KAHR model approach is used in a follow-up project to estimate extreme rainfall under different climate scenarios for a 5 km grid across NRW. These datasets are intended to serve as official data for water resources management in NRW when planning future water infrastructure. Our hydrodynamic simulations provided water levels, flow velocities, and inundation areas for the 2021 flood, which were shared with various project partners for comparison with other hydraulic models, damage analysis, evaluation of morphological processes, and assessment of the risk to human life. In some cases, our models have been used to answer specific questions; an example is the flood stress test for the dams in the Rur catchment together with the Water Board Eifel-Rur.

4.3.2 | Comprehensive Assessment of Risk Reduction Measures at the Catchment Scale

Already some weeks after the flood, authorities planned comprehensive DRR measures at the catchment scale to prepare for future flood events, both in the Ahr catchment in RP and the Inde catchment in NRW. Within just a few months after the 2021 flood, the Water Board Eifel-Rur (WVER) in NRW established a "master plan" that identified more than 200 measures to increase flood resilience in the Inde and Vicht catchments (Kaleß et al. 2022). We supported this process by testing the effectiveness of proposed measures and their combinations using multiple modeling approaches to prioritize the most effective measures and assess the potential level of protection.

As the Inde and Vicht catchments transition from upland to lowland areas, a plethora of different measures were initially proposed by a panel of experts organized by the local water board WVER. The dynamically evolving, publicly accessible plan contains 63 sub-projects with around 200 individual proposed measures, including flood retention basins, flood protection walls, floating debris retention, and river restoration (WVER 2022). The effectiveness and potential capacity of three groups of measures (i.e., technical retention, local redirecting of flood discharge, and river restoration) were evaluated utilizing hydrodynamic 2D modeling. We concluded that adaptation is possible and extreme flood events require technical retention in the upland area of the Inde and Vicht catchments for a supra-regional effect, while local flow redirection is effective in wide floodplain areas in downstream reaches.

In the mostly narrow Ahr Valley with limited floodplains, flood protection structures such as dikes and flood protection walls are only feasible to a small extent. Flood protection must therefore be implemented upstream through technical and natural retention measures. In a preliminary study, Wolf et al. (2024) estimated the theoretical potential for natural retention in the Ahr valley by catchment-wide substantial land-use improvements (reduced urban densification, conservation farming, afforestation of shrublands and healthy and dense forests). However, the analysis revealed that the risk reduction potential was too low compared to the volume of the July 2021 flood. The order of magnitude of all changes would provide about 10% of the needed retention volume (Wolf et al. 2024). Thus, to prepare for such extreme events in settings like the Ahr Valley, technical retention measures are unavoidable and are ideally complemented with natural measures to address the range of flood events possible and cope with both water extremes—droughts and floods.

Although following different approaches, the KAHR project provided local decision-makers with scientific input and facilitated the communication of results to other stakeholders. In NRW, the analysis was conducted in close cooperation with the responsible water authorities and directly informed the development of the master plan at Inde and Vicht (Steudtner et al. 2026). In RP, the results were passed on to the Ahrweiler County. In both catchments, our results helped prioritize the most effective group of measures, leading to follow-up projects for implementation. While our analyses highlight the relevance of building larger retention basins further upstream to reduce the risk further downstream, they also quantify the effect of different groups of measures within the boundaries of different upland to lowland geomorphological settings.

4.3.3 | Migration and Property Level Adaptation

The 2021 flood impacted thousands of properties and hit a population that was to a large extent not aware of being exposed to the risk of flooding (Truedinger et al. 2023). Based on standardized surveys, we provided insights on migration movements in the aftermath of the flood as well as on household-level adaptation.

The 2021 substantially impacted the habitability (Sterly et al. 2025) of the affected area led to both short-term and long-term migration. Almost 42% of Survey 1 respondents (see Table 3) stated they needed to leave their homes for at least a few weeks or months after the 2021 flood (Truedinger et al. 2023). Approximately 1 year after the flood, around 27% of households surveyed were still not living in the same house or apartment as before the flood ($n = 512$). Around 13% were still living in temporary accommodation, while around 14% moved permanently to a new location. Outmigration is particularly high within the designated floodplain, at 50%. The stated reasons for migration include respondents living in rented apartments, which makes it relatively easy to move (43.5%; $n = 124$), a perceived reduction in quality of life at the location at risk (40.3%), an increased threat appraisal (27.4%), or the reconstruction and/or refurbishment process being too complex/expensive. Reported reasons for staying include strong place attachment (56%), risk denial (50.5%) as well as a lack of personal resources and capacities, including a reported lack of vitality (19.6%) and finances (17.1%) ($n = 414$, multiple answers possible).

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To help improving risk reduction at the property level among households staying in the floodplain, KAHR supported the uptake of property level adaptation by implementing a demand driven information campaign. The Flood Competence Center e.V. (HKC) provided substantial and cost-free information in the affected regions. They organized a team of experts that visited affected communities repeatedly in the aftermath of the flood event. They used a so-called "Info Mobil", a bus that was equipped with concrete measures and examples on how to improve property level adaptation. The Survey 2 (cf. Table 3) conducted among people consulting the bus ($N = 773$) identified a number of key information needs (Meyer et al. 2026). The highest need was documented with respect of "dry flood proofing" (i.e., preventing the water to penetrate the building). Interested people were often lacking basic knowledge on potential measures and, therefore, needed an overview of all potential measures at the building level. Often, this group of people was not directly affected by the flood but became aware of flood risk through the 2021 event and are therefore motivated to take adaptive actions. A similarly large group was interested in receiving more information on specific measures, often as a result of direct flood experience, which made them aware of weak points in their buildings. The survey shows further that about 27% had already implemented property level adaptation and 38% planned to do so in the future, indicating a substantial change of adaptive behavior in the aftermath of the flood event. Similar numbers were found by Dillenardt and Thieken (2025). They revealed that flood adaptation and communication should address the dominating flood type. For example, fast onset floods tend to result in lower perceived response efficacy of property-level adaptation. Due to high financial impacts, affected people tend to invest more in emergency devices and flood insurance in comparison to people affected by slow-onset fluvial (e.g., at larger rivers like the Danube or Elbe) or urban pluvial flooding. However, they also perceive costs of property-level adaptation as lower (Dillenardt and Thieken 2025).

4.4 | Effective Recovery and Risk Governance

Effective recovery and risk governance are fundamental to initiating and sustaining BBB outcomes. Establishing mechanisms for exchange at the science–policy–society interface ensures that reconstruction decisions are informed by scientific evidence. Assessing and fostering governance innovations helps identify institutional arrangements that enhance coordination among diverse societal actors and support effective recovery and BBB. Furthermore, adapting existing legislation to enable risk-based planning embeds BBB principles into long-term policy frameworks, ensuring that reconstruction efforts lead to long-lasting improvements in the affected regions.

4.4.1 | Assessing Risk Governance Innovation to Build Back Better

To support effective recovery and initiate a more flood-adapted reconstruction process, risk governance innovation was established in the aftermath of the 2021 flood. In our understanding risk governance includes "the various ways in which many actors, individuals, and institutions, public and private, deal with risks surrounded by uncertainty, complexity, and/or ambiguity" (van Asselt and Renn 2011). Risk governance innovations thus refer to substantially modified institutional arrangements, actor constellation, process, or instrument through which societal actors manage risks. Our analysis is based on Interviews 2 (see Table 3), complemented by document analysis.

As a response to the enormous physical damage caused by the flood 2021 events, a crucial legislation by the German government was the federal act for establishing a special fund "Reconstruction Aid 2021" (Aufbh 2021) that provided the basis for the establishment of two funding mechanisms: an emergency aid package and a special flood relief fund. The first mechanism, the emergency aid package (Soforthilfe) totaling €800 million, was implemented through a federal-state agreement and aimed at mitigating acute damage and addressing urgent humanitarian needs of affected households, businesses, agricultural producers, and municipalities. Its design emphasized speed and administrative simplicity to enable swift disbursement of funds for repair and replacement rather than strategic reconstruction (BMI/BMF 2022). The second mechanism, the special flood relief fund for reconstruction aid (Aufbh 2021), aimed at supporting the most affected to provide medium- and long-term financial support for reconstruction activities. Allocations were determined according to rapid damage assessments, with €12.3 billion designated for NRW and €15 billion for RP (with the majority allocated to the county of Ahrweiler). Based on this federal legal framework and corresponding administrative agreements, both states issued detailed administrative regulations and funding guidelines in September 2021 that defined four categories of eligible recipients: (1) enterprises; (2) private individuals; (3) agriculture and forestry; and (4) municipalities or other public infrastructure providers (LR RP 2021; MHKBG NRW 2021).

The special flood relief fund also considered principle of BBB. When applying for the fund, households needed to implement risk reduction measures on the property level to avoid or reduce future losses (see Art. 7.6 of the North Rhine-Westphalian Funding Directive[3] and Art. 8.6, 8.7 of the Rhineland-Palestinian directive[4]). However, during the early implementation phases of the special flood relief fund, the priority was rather on reconstructing to the status before the flood event, largely due to existing building codes and local development plans rather than incentivizing structural improvements or flood adapted land-use changes (Birkmann et al. 2023). Interviews revealed that the application for the funds was perceived as rather complex and there was high uncertainty among property owners which adaptation measures were covered by the fund and which were not (Reckhaus and Kuhlicke 2025). In addition, both uninsured households and businesses who relied on the governmental disaster fund recovered slower and were more dissatisfied with the compensation process than those who were insured, this was revealed by Survey 3 and a survey among flood-affected companies (Guntu et al. 2025; Thieken et al. 2026).

Our findings indicate that reconstruction efforts placed major strains on local municipal and county administrations, which

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were already operating with limited resources. In many instances, the floods directly damaged government buildings and affected staff. Reconstruction plans typically encompassed 100 of individual projects, in some cases amounting to twice the municipality's annual administrative budget. As a result, local administrations faced a dramatic increase in workload—they had to prepare funding applications and plan, coordinate, and implement reconstruction activities while also keeping up with their regular duties. Hiring additional personnel was difficult due to ongoing shortages of skilled workers. These factors significantly overstretched local administrative capacities, reducing their ability to cope with the increasing demands of reconstruction.

Therefore, new organizational structures were established in the aftermath of the flood to coordinate the reconstruction process more effectively. The city of Bad Neuenahr-Ahrweiler in RP was the first to establish a reconstruction organization ("Aufbau- und Entwicklungsgesellschaft") as a 100% city-owned subsidiary. This newly created organization enabled the outsourcing of tasks and the recruitment of personnel without interfering with the city's ongoing administrative work. It draws up plans for reconstruction projects and implements them once they have been approved by the city's political bodies, which means decisions are still taken by the local council (Gemeinderat). Similar organizational structures were created by a coalition of small towns in the Ahr Valley (Zukunft Mittelahr Aör) and in NRW (Wiederaufbau Stolberg), with the aim of building the institutional capacity to plan and implement reconstruction projects.

Several factors made the establishment of these new organizations an effective innovation in reconstruction processes (Stein et al. 2026). Among them, they reduced the pressure on local administrations while hiring highly skilled and motivated staff (e.g., 55 employees in Bad Neuenahr-Ahrweiler). The flood relief fund, established by the German government, stipulated that up to 25% of a reconstruction project could be used for project management, meaning these organizations are self-financing.

Innovation in governance also required new catchment-wide structures beyond single municipalities to enable comprehensive flood risk management. The flood events underscored the necessity of inter-municipal cooperation to develop an effective flood risk management strategy at the catchment scale. The establishment of such catchment-wide governance arrangements is time-consuming and demanding, as it requires formalizing the cooperation between municipalities and determining how the costs and benefits are shared between them and has not been fully implemented so far.

4.4.2 | Adapting Existing Legislation to Support Risk-Based BBB

The reconstruction process provided an opportunity to test the implementation of so-called Federal Spatial Flood Protection Plan ("Bundesraumordnungsplan Hochwasserschutz", BRPH), which came into force in September 2021 (BMI 2021). Its goal is to reduce overall flood risk, especially in areas with settlements and transport infrastructure, and to limit potential damage. This is mainly done by improving spatial planning procedures and strengthening cooperation with water management authorities. The BRPH emphasizes spatial planning tools and legal requirements that support water management measures and enable risk-oriented planning (Hartz et al. 2019). Key elements include nationwide harmonized planning standards (protection of downstream areas, uniform flood-risk definitions), a risk-based approach that considers different safety and protection needs, and regulations for critical infrastructure to better protect facilities of national or European importance.

In many respects, the BRPH thus initiates a paradigm shift and a reorientation of flood prevention in spatial planning, as decisions on flood risk mitigation have previously been made based on flood hazard only, but not the flood risk, as the exposure and vulnerability components were usually not considered (Prenger-Berninghoff 2017). Thus, one of the central aspects of the BRPH is the introduction of the principle of risk-based planning into German spatial planning (Greiving et al. 2023). This means that in spatially significant infrastructure and settlement development, the flood risks (and not simply the flood hazard) must be examined. In addition to the probability of occurrence of a flood event and its spatial and temporal extent, this also concerns the water depth and flow velocity. Furthermore, the different sensitivities and desired levels of protection of types of land use are to be considered for the examination of flood risks (BMI 2021).

However, the new legal requirement still lacks broad implementation at regional and local levels and good practice examples hardly exist so far. Therefore, the participating regions in the KAHR project (mainly the county of Ahrweiler in RP and the county of Euskirchen in NRW) served as test cases for showing that the BRPH can be successfully implemented in regional and municipal planning. This was carried out in two main elements.

We developed and tested the framework in a simulation game using the city of Erftstadt in NRW as a case study (Greiving et al. 2023). The test simulated a land-use plan approval process for a flood-prone area in Erftstadt-Liblar. Following the "gaming simulation" approach, a formal hearing with 70 participants was carried out in January 2023 to prepare the municipality for an upcoming planning decision. During the simulation, the flood hazard zone plan and a risk-based flood-proof land-use plan were presented and discussed. Participants evaluated the hazard zone plan as a suitable tool for integrating flood-risk reduction into planning and agreed that a risk-based approach can be implemented within the current Federal Building Code (BauGB). The simulation also highlighted innovative elements such as differentiating protection needs for various infrastructures. The hazard zone concept and results were subsequently used by the state planning authority to amend NRW's state development plan (Principle 7.4.8), which now explicitly refers to the BRPH.

As a second element, municipalities presented specific planning cases at a participatory consultation meeting focused on strengthening risk assessment and resilience (Greiving et al. 2025). The event, held with the Aachen city region in May 2024, involved 46 participants from municipalities, consultancy firms, and regional water authorities. Municipalities could apply for

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support on flood-risk issues in ongoing land-use plan approval processes. The evaluation reviewed plan documents, including maps and environmental reports, assessing their compliance with planning standards, their alignment with the Federal Spatial Flood Protection Plan, and the quality of evidence used to analyze flood risks. The consultation consisted of three sessions in which planning departments presented their cases, discussed data uncertainties, and addressed legal aspects of proposed mitigation measures. Typical planning scenarios such as rezoning, building conversions or extensions, and new developments were covered. The meeting confirmed that the greatest challenge lies in dealing with existing built-up areas and underlined how challenging it is to use the reconstruction phase for implementing the principle of BBB.

4.4.3 | Establishing Mechanisms for Effective Exchange at the Science-Policy-Society Interface

To effectively bridge science and practice in the aftermath of the 2021 flood disaster, a set of targeted products was developed to make outputs generated by KAHR easily accessible and to strengthen coordination and dialogue in the affected regions (Droste-Franke et al. 2025).

A central means for ensuring effective coordination and enabling a sustained dialogue was the establishment of regional project office hubs in RP and NRW. Their main functions are to maintain regular communication with political and administrative actors, to collect and systematize regional needs, and to ensure a coherent, transparent information flow. They supported researchers with their regional expertise and facilitated the transfer of scientific findings into practice through events, guidelines, and direct advice (Droste-Franke et al. 2026). KAHR also initiated a regional emergency management network, accompanied by training programs, to transfer experience from the 2021 flood to future generations of emergency managers and thereby strengthen regional resilience (Jüpner et al. 2026).

Beyond that, the KAHR consortium decided early in the project to publish a policy paper, the "10 Recommendations for supporting climate and flood resilient reconstruction" (Birkmann et al. 2025). The recommendations reflected first insights of the research, published 12 months after the flood and were hence based on preliminary findings. The recommendations resulted in high media attention, state parliament hearings, and were also discussed in regional workshops. Various stakeholders have repeatedly cited key recommendations to highlight the advantages of reconstruction strategies that go beyond simply restoring the status quo (Birkmann et al. 2025). A notable case is the relocation of the Levana School for students with disabilities (Truedinger et al. 2025). Drawing on the KAHR recommendations, consortium members developed more targeted guidance advising against rebuilding the school at its original, flood-prone site. Instead, they recommended relocating it to a safer area to better protect this highly vulnerable group. This recommendation also provided the basis for securing funding for the move through the public compensation fund, as endorsed by the responsible authority. Currently, a new location for rebuilding the school is being searched for.

5 | Discussion

The KAHR project aimed at scientifically supporting a flood adapted reconstruction process and by doing so to contribute to implementing the idea of BBB. The conceptual grounding of the project in the expanded BBB framework by Mannakkara et al. (2021), adapted through the addition of a fourth pillar on stakeholders' needs assessment and early impact assessment. This reflects the dual ambition of the project: to provide outputs of scientific assessments, and to co-design practices for recovery and reconstruction. In this sense, recovery is not merely a return to the status quo, but a phase characterized by significant challenges but also opportunities, either for deepening vulnerabilities or transforming conditions toward greater resilience (Blaikie et al. 1994; Tobin 1999; Manyena et al. 2011). KAHR pursued the latter by identifying opportunities to improve risk governance, risk management, and community preparedness.

At the core of KAHR was the idea that scientific research responds to on-the-ground issues; it aimed at addressing the needs of different groups of stakeholders and creating societal impacts.

Regarding risk assessment and risk reduction (including early warning), the project had and will very likely have an impact on the policy level. Through advanced modeling activities, the KAHR project supported catchment-scale planning and the prioritization of flood risk measures. Models were developed in close cooperation with responsible authorities, and model outputs were fed directly into master plans (NRW and RP) developed in the aftermath of the 2021 flood to support an effective DRR strategy across the entire affected region. However, the varying time lines of different processes in disaster reconstruction represent a challenge. The master plan for the Inde and Vicht catchment (NRW), for instance, was specified very early in the reconstruction process, partly to demonstrate to the public that restoring a safe environment was a top priority of the responsible authorities. However, the completion of the risk assessments actually required for such measures, particularly when aiming at a sound scientific basis, took considerably longer. There was hence a noticeable mismatch between the time required to implement and validate region-specific models and the urgent demand for rapid results on the ground. This means that potential impacts of the KAHR project are unfolding gradually with time. A follow-up project in NRW investigating extreme precipitation in future climate only commenced in early 2025. Similarly, NRW is preparing to launch a project aimed at developing new guidelines and procedures for estimating flood design values for dams; however, this initiative has yet to commence. Although this transfer into practice is inherently slow, understanding and preparing for such temporal mismatches is crucial for transdisciplinary projects that support BBB.

At the individual household level, the project also had impact and supported risk reduction. Through the Info Mobil campaign, the project translated technical knowledge on property-level adaptation into information accessible to and actionable for interested homeowners. However, research findings also indicate the struggles and difficult decisions households face during recovery and reconstruction. A substantial number of surveyed

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households moved out of the floodplain in the aftermath of the flood, at least temporarily (Truedinger et al. 2023). Research on sensitive SI, such as the Levana School (Truedinger et al. 2025), has highlighted the challenges of rebuilding in the same location. Scientific input from KAHR influenced decisions at both municipal and state levels, including the relocation of infrastructure to safer areas and the allocation of reconstruction funds. Moreover, the transition toward the establishment of catchment-wide governance structures reflects a critical shift in addressing the systemic nature of flood risk. The application of the Federal Spatial Flood Protection Plan (*Bundesraumordnungsplan Hochwasserschutz, BRPH*), which introduces risk-based spatial planning principles at the federal level for the first time in Germany, marks a significant step forward. By organizing gaming simulations, the project demonstrated that risk-based approaches are feasible within the existing legal framework—an important insight for the practical implementation and scaling of BBB principles.

However, KAHR's contributions are best understood as pilot or demonstration projects that illustrate how a more resilient, future-oriented recovery could be achieved. They show how vulnerability to future flood events might be reduced, at the levels of individuals, critical infrastructures, or entire catchments. Yet, the KAHR activities took place in a risk-governance context that sought to restore the pre-disaster status quo. This becomes especially clear in the case of the well-funded Reconstruction Fund, which does enable flood-adapted restoration of buildings, infrastructure, and waterways, but neither prioritizes nor requires it. As a result, potential future damages were reduced to some extent, yet without a systematic or strategic alignment with the principles of BBB.

KAHR also supported community recovery. While there was general awareness of the enormous psychosocial strain the flood and its aftermath would place on affected populations, empirical evidence on the extent of these socio-psychological impacts was lacking. Through surveys conducted among the affected population, data was provided on the widespread prevalence of PTSD symptoms. This research informed the planning of mental health services. Our work on the role of SIs highlighted their critical importance for inclusive recovery processes. Nevertheless, community recovery, and the "invisible" aspects of reconstruction (Gunning and Rizzi 2022), remain the most neglected components of the rebuilding agenda. The federal reconstruction fund primarily focused on physical reconstruction and economic compensation, with few explicit requirements or dedicated mechanisms to strengthen social cohesion or support long-term psychosocial care. As a result, efforts to restore community life depend heavily on local governments, voluntary organizations, and NGOs, many of which are overstretched. This decentralized and unevenly resourced approach has led to substantial regional variation, making social recovery highly contingent on local capacity rather than part of a systematic, strategic mandate.

Researchers closely followed how organizational-institutional approaches were adapted to reflect the particular challenges that come along with the reconstruction process and the need to develop more comprehensive DRR strategies. The creation of new institutions, such as the "Aufbau- und Entwicklungsgesellschaft" (Reconstruction and Development Agency) in Bad Neuenahr-Ahrweiler and similar entities elsewhere, illustrates how municipalities outsourced reconstruction tasks to specialized subsidiaries. This approach alleviated administrative bottlenecks and enabled focused, expert-led reconstruction management, an important institutional innovation for BBB. These entities are financially sustained through flood relief funds and remain politically accountable, ensuring efficient and transparent reconstruction governance. Yet, the municipal actors themselves had to make decisions under extreme conditions. The municipalities were under additional pressure due to the flood consequences, amid an already tense financial and personnel situation. They had to decide for themselves which organizational and institutional structures would enable effective and future-oriented reconstruction. There was no overarching strategy to guide them in this process.

However, the relevance of transdisciplinary projects like KAHR goes beyond the implementation of exemplary demonstration projects; they can also support the reframing of established concepts. Very early in the project, the concept of "reconstruction" itself became a topic of debate, initially understood at the policy level as primarily a matter of damage compensation. In contrast, the KAHR project advocated for a forward-looking approach by emphasizing that reconstruction should go beyond restoring the status quo and instead aim for structural improvements and higher standards of flood protection to also support climate change adaptation. This perspective aimed to ensure that the substantial financial resources allocated to rebuilding would help make affected regions better prepared for future flood events. While the focus on rapid rebuilding is understandable in the aftermath of an extreme event, it often hinders progress toward BBB. Quick reconstruction tends to reinforce existing structures, be they social, technical, organizational, and infrastructural that require more time to be adapted for greater resilience. One of the main challenges for BBB is finding a balance: on the one hand, providing clear signals to local stakeholders and publics that repair work is underway and forward-looking, while on the other hand creating space for more deliberate, resilient rebuilding.

While the KAHR project can be considered a successful initiative, its limited three-year span posed inherent limitations. Bringing together a diverse group of partners and delivering actionable results within a short time frame was highly ambitious. Ideally, a more sustainable model would involve the establishment of a pre-existing network of scientific institutions that are familiar with each other's expertise, methods, and modes of communication, as well as with the needs and practices of decision-makers and the region affected. Such a network could be mobilized rapidly in case of a disaster, offering affected regions immediate access to relevant expertise, data, and models. To function effectively, this network would require ongoing baseline funding for coordination and relationship-building, supplemented by event-specific funding for targeted activities. Crucially, time and sustained investment would be needed to develop mutual trust, shared standards, and operational readiness. Establishing such a structure could significantly enhance the responsiveness and effectiveness of science-based disaster support in the future.

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6 | Conclusion

This paper aims to demonstrate how scientific approaches can contribute to building back better in the context of flood risk management as well as climate change adaptation. The KAHR project aimed at providing specific examples that show how a science-based interdisciplinary approach can support building back better in the context of flood risk management across multiple scales, from property-level adaptation to catchment-wide planning. By coupling modeling approaches and data-driven social science research with participatory outreach and stakeholder engagement, the project aimed to translate knowledge into actionable solutions for both authorities and affected communities. This illustrates how vulnerability to future flood events could be reduced at the levels of individuals, critical infrastructure, and entire catchments. However, these activities were embedded in a risk governance context oriented toward restoring the pre-disaster status quo, as reflected in the Reconstruction Fund, which enables but neither prioritizes nor mandates climate-adapted reconstruction.

Author Contributions

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Related WIREs Articles

Defining "water resilience": Debates, concepts, approaches, and gaps.

Paradoxes of financial schemes for resilient flood recovery of households.

Endnotes

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