Global Environmental Change 84 (2024) 102778

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Quantifying community resilience to riverine hazards in Bangladesh

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ARTICLE INFO

Keywords:
Resilience measurement
Community
Flooding
Erosion
Bangladesh

ABSTRACT

Every year, 30–70% of Bangladesh is inundated with flood waters, which combined with erosion, affect between 10 and 70 million people annually. Rural riverine communities in Bangladesh have long been identified as some of the poorest populations, most vulnerable to riverine hazards. However, these communities have, for generations, also developed resilience strategies – considered as the combination of absorptive, adaptive, and transformative approaches – to manage significant flooding and erosion. It is not clear whether such existing strategies are sufficient to generate resilience in the face of increasing hazards and growing pressures for land. In this study, we quantify community resilience to flooding and erosion of 35 of the most poverty-stricken and exposed communities in riverine Bangladesh by applying the systematic resilience measurement framework provided by the Flood Resilience Measurement for Communities tool. The low levels of resilience observed in the riverine communities, as well as their continued focus on enhancing absorptive capacities are alarming, especially in the face of growing climate threats and continued population growth. Innovative transformative responses are urgently required in riverine Bangladesh, which align with and complement ongoing community-centred efforts to enhance rural resilience to riverine hazards.

1. Introduction

The highly fertile soils and diverse ecosystem services provided by delta systems have resulted in these landscapes being some of the most densely populated areas on Earth, home to over 500 million people (Darby et al., 2015; Nicholls et al., 2016). Their highly dynamic nature can result in frequent and severe flooding and riverine and coastal erosion, which can lead to the loss of valuable floodplain land, destruction of livelihoods and ecosystem services, exacerbation of poverty, and the displacement of millions of people annually (Adel, 2012; Ahmed, 2008; Murshed et al., 2019; Paszkowski et al., 2021). The sudden force of water associated with flooding can also exacerbate erosion hazards (Haque and Zaman, 1989; Paszkowski et al., 2021). The combined hazards of flooding and erosion are therefore especially interwoven in riverine and estuarine environments, where erosion and flooding often occur concurrently. Although the impacts and responses to these riverine hazards have been acknowledged and qualitatively assessed in different parts of the world (Ahmed et al., 2018; Haque and Zaman, 1989; Rahman et al., 2015; Schmuck-Widmann, 1996), a deeper understanding and quantification of vulnerability and resilience is limited.

Fluvial flooding and riverbank erosion are common in Bangladesh, a deltaic nation renowned for its exposure to natural hazards (Rahman et al., 2015). Over 80 % of Bangladesh consists of floodplains of the Ganges, Brahmaputra and Meghna (GBM) rivers, as well as of several other tributaries and distributaries (Brouwer et al., 2007). Every year, 30–70 % of Bangladesh is inundated with flood waters due to either monsoonal rains, fluvial flooding, tidal flooding or cyclonic storm surges, or a combination of these (Islam et al., 2010; Mirza, 2011; Rahman et al., 2015). Moreover, the dynamic deltaic environment of Bangladesh means that frequent channel migration and erosion and deposition of river islands are continuous background processes, where sometimes channel migrations of up to 400 m in a single season are observed (Paszkowski et al., 2021; Renaud et al., 2013). Given Bangladesh's high population density of 165 million people living on under 150,000 km^2 of land, between 10 and 70 million people are exposed to flooding and riverbank erosion every year (Division, 2018; Paszkowski et al., 2021; Rahman et al., 2015). The high population density on floodplain lands means that migration of river channels and frequent inundation result in valuable cultivable land being lost, and hundreds of thousands of people being displaced annually (Haque and Zaman, 1989). Between 1970 and 2009, for instance, approximately 48 million

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https://doi.org/10.1016/j.gloenvcha.2023.102778
Received 18 May 2022; Received in revised form 30 August 2023; Accepted 17 November 2023
Available online 30 November 2023

Bangladeshi people were internally displaced due to natural hazards, of which 40 million were displaced due to flooding and riverbank erosion alone (Haque et al., 2020; IDMC, 2021).

On *chars* (low-lying ephemeral river islands formed from banks of sediment), for instance, resettlement is a cyclical process. More than 6.5 million people live on river *chars* and cope with regular flooding and riverbank instability (EGIS, 2000; Haque and Zaman, 1989; Islam et al., 2010; Lein, 2009; Monirul Alam et al., 2017). Previous studies have shown that, in these high-risk areas, temporary displacement occurs on average every five years, although some households may experience displacement as much as three times within a single year of severe flooding and erosion (as observed in 1997–98) (Islam et al., 2010; Lein, 2009). Displaced populations typically temporarily resettle on other areas of the same *char,* or on a neighbouring *char,* and then return to their land if and when it re-emerges from the river (Islam et al., 2010; Lein, 2009). This repeated set-back of livelihoods inflicts chronic economic, social and psychological costs on affected populations (Haque and Zaman, 1989), and can exacerbate the process of impoverishment, as the recurring losses may exceed the local recovery capacity, impeding longer-term asset growth (Haque et al., 2020; Lázár et al., 2020; Leichenko and Silva, 2014; Paszkowski et al., submitted; Sarker et al., 2003). Thus, these rural and resource-dependent riverine communities in Bangladesh have been identified as the poorest and most vulnerable populations, disproportionately affected by climatic hazards, particularly flooding and erosion (Baqee, 1998; Hallegatte and Rozenberg, 2017; Lein, 2009; Paszkowski et al., submitted; Rahman et al., 2015; Zaman, 1989).

It is important to note, however, that people have been living in these high-risk areas for generations, due to the extremely fertile lands for agricultural livelihoods, and have also managed to adapt themselves to remain flexible and resilient to everchanging environmental conditions (Lein, 2009; Paprocki, 2019; Paprocki, 2018; Schmuck-Widmann, 1996). Local populations have, for instance, converted from traditional clay, straw and bamboo houses to tin sheds, as these are easier to dismantle and shift in the case of erosion (Lein, 2009), they have adjusted their harvesting technique to leave the crop stems to stabilise soils (Khalequzzaman, 1994), and have reintroduced *bandal* structures, which are locally-sourced bamboo groynes that help to stabilise smaller channels (Nakagawa et al., 2013). However, in the face of unprecedented climatic changes, population growth and associated resource demands, the extent to which such indigenous adaptive behaviours can generate resilience is unclear.

This study explores this notion of resilience further by providing a first quantification of community resilience in terms of both flooding and erosion, as well as a better understanding of how populations at the front lines of hazard impacts live and cope with these riverine shock events. Community resilience is defined as *"the ability of a community to pursue its development and growth objectives, while managing its risks over time in a mutually reinforcing way"* (Keating et al., 2017a). This definition centres on the interplay between development trajectories and disaster risk management; if one undermines the other, resilience is not achieved (Keating et al., 2017b; Laurien et al., 2020). Communities' absorptive, adaptive, and transformative capacities are therefore enablers for attaining resilience (Tanner et al., 2017). The absorptive capacity implies that risks are deemed acceptable (further efforts in risk reduction are not required as they can be absorbed), the adaptive capacity means that risks are considered tolerable (incremental risk-reduction efforts are required for risks to be kept within reasonable limits), and transformative capacity is when risks become intolerable and thus communities decide to discontinue current behaviour to avoid the risk or move location (Brien et al., 2012; Deubelli and Mechler, 2021; Dow et al., 2013; Rahman et al., 2015; Tanner et al., 2017).

Studies have emphasised that in order to address the climate crisis and simultaneously support sustainable development, new and transformative responses and approaches to managing risk are required (Barnes et al., 2020; Deubelli and Mechler, 2021; Schipper et al., 2021). Climate change is increasing the magnitude, intensity and frequency of flooding in Bangladesh, and associated riverbank erosion is projected to increase by 18 % over the next 100 years (Haque et al., 2020). As a result, the Government of Bangladesh together with the International Centre for Climate Change and Development (ICCCAD) is already trying to facilitate mass managed relocation away from high climate-risk areas by preparing more migrant-friendly peripheral towns - that provide diverse employment opportunities, social protection, access to education, affordable housing, health facilities, and utilities, amongst other factors - to shift migration routes away from Dhaka and other large cities towards smaller towns (Khan et al., 2021). These high-risk areas predominantly include riverine and coastal regions around Bangladesh. Thus, better understanding and quantifying both the overall levels of resilience, as well as the transformative capacities to enable such transitions within some of these most critically exposed communities is crucial for the identification of effective longer-term trajectories towards growth.

In this study, the resilience of 35 communities across Bangladesh is therefore measured through the lens of absorptive, adaptive, and transformative capacities, by linking national-scale analyses of erosion and flood hazards with systematic community-centric resilience assessments. This mixture of "top-down" physical hazard assessments combined with "bottom-up" insights related to place-based complex adaptive social and environmental systems has been acknowledged as the only way to arrive at a more nuanced understanding of resilience (Horton et al., 2021; Laurien and Keating, 2019; Tanner et al., 2017). Therefore, this study provides a first quantification of community resilience in the context of both flooding and erosion hazards, and although the findings are specific to riverine communities in Bangladesh, the approach taken is widely applicable to other rural communities in the world that face similar challenges.

2. Study area

The study examines riverine communities in the lower reaches of the Ganges and Brahmaputra rivers. 35 riverine communities have been selected (Fig. 1), located within the most poverty-stricken and exposed areas to riverine hazards (Paszkowski et al., submitted). These communities are located along the Teesta river in the north-western part of Bangladesh, the Jamuna river (lower Brahmaputra), the Padma river, and in the south-western Kumar distributary river channel. The 35 communities were selected for community engagement by two local Non-Governmental Organisations (NGOs), Practical Action and Concern, based on socio-economic indicators such as levels of poverty and vulnerability, their representative nature of other riverine communities in the region in terms of flood risk history, and because they have a demand and some level of capacity to benefit from resilience-building measures (Campbell et al., 2019; Laurien and Keating, 2019). These communities, with long historical experiences of riverine hazards, can provide valuable insights on confronting riverine challenges over many generations (Ayeb-Karlsson et al., 2016).

All of the 35 communities are rural, with an average population size of approximately 2,000 people (total population of over 71,000 people). Poverty rates across the communities are high, with an average of 47 % of community members below the national poverty line (less than US $1.90 purchasing power parity per day). The communities are highly resource-dependent, with around 80 % of livelihoods being agricultural (approximately 30 % cultivating their own land and 50 % cultivating other people's land). Table S1 in the Supplementary Information provides further detail on the socio-economic characteristics of the communities.

3. Materials and methods

Riverine hazards are assessed at the national scale. These national-scale hazard assessments are then combined with community-based

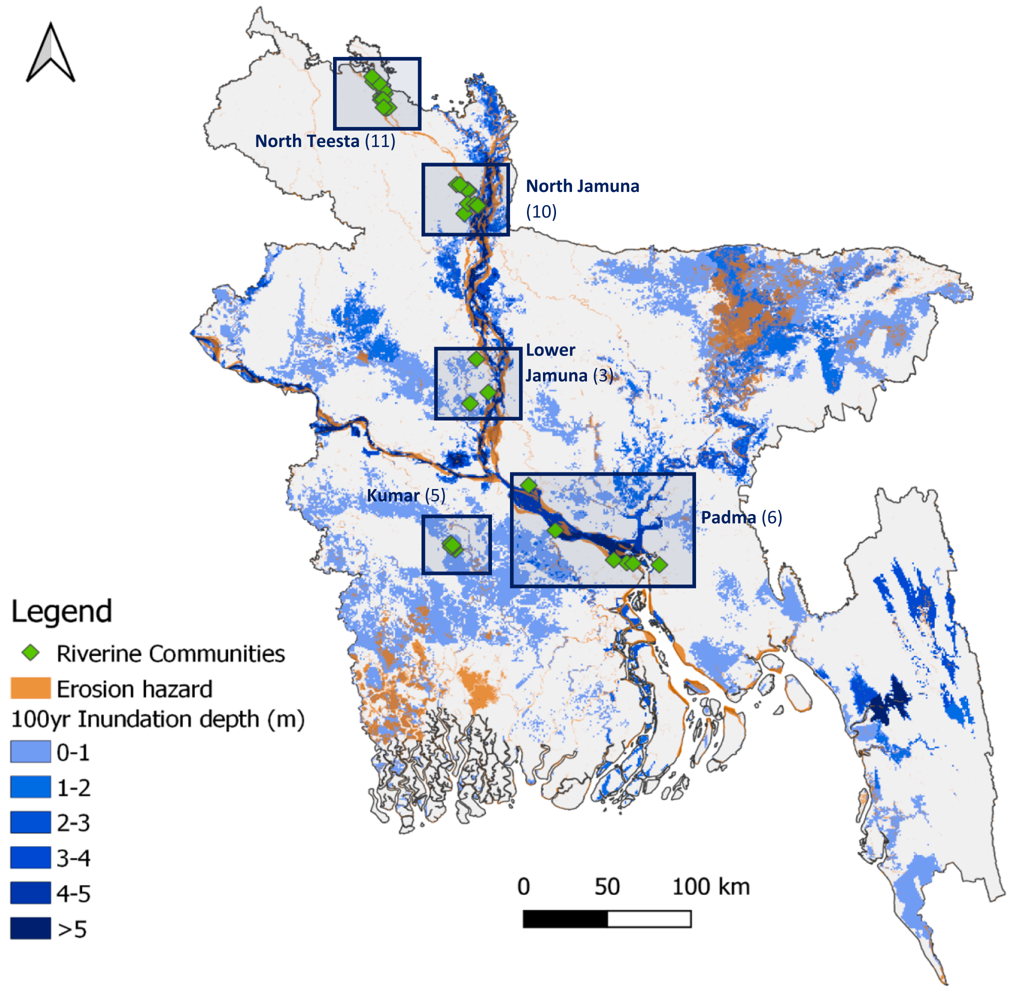

Fig. 1. Map of the 35 riverine communities assessed in this study, including the country-wide spatial distribution of flooding and erosion hazards. Riverine regions in dark blue boxes are discussed throughout the paper, and numbers represent the number of communities within each region. The delineation of flood and erosion hazards is described in more detail in Section 3 below.

resilience data to understand how communities exposed and susceptible to these hazards have been managing the impacts. Thus, this study analyses (i) the spatial distribution of fluvial flood and erosion hazards across Bangladesh; (ii) how communities currently manage their riverine risks; (ii) how resilient communities currently are; and (iii) communities' strategies for managing future riverine risks. The ways in which these factors are measured is illustrated in the schematic of Fig. 2, and the following sections describe the steps in more detail.

3.1. National-scale assessment of riverine hazards

In this study, we are extracting the findings from Paszkowski et al. (submitted), who undertook national-scale spatial assessments of erosion and accretion hazards across Bangladesh using the DeepWaterMap model. The DeepWaterMap model is a satellite-based model developed by Jarriel et al. (2020), which built on previous work by Isikdogan et al., (2017), Isikdogan et al., (2015) and Passalacqua et al. (2013). The model uses a convolutional neural network to distinguish water from land, clouds and shadows within each satellite image, and produces an almost binary representation of channel presence (Jarriel et al., 2020). Thus, it automatically detects river channel changes across a channel network. The resulting DeepWaterMap channel system is then used to map the Channelised Response Variance (CRV), a metric that was developed to track changes in channel morphodynamics over space and time (Jarriel et al., 2020). High positive CRV values illustrate hotspots of increasing channel presence (erosion), whilst high negative CRV values represent key areas that are decreasing in channel presence (accreting land). Here, we extract the areas with high positive CRV values to understand the spatial distribution of erosion across Bangladesh. The erosion hazard map illustrated in Fig. 1 demonstrates the areas that have experienced erosion multiple times over the 35-year period assessed (1987 until 2022).

In order to spatially visualise flood magnitudes and extents, national flood maps of return periods ranging from 5 years to 1000 years were obtained from the GLOFRIS global flood model (Ward et al., 2013), as shown in Fig. 1. The data is openly available and has a resolution of 30 arc seconds (approximately 1 km at the equator). Although this is a coarse resolution, the data was only used for visualisation; flood information for this study is extracted from community-level information (as described in the next section). Spatial analyses of riverine hazards, such as calculating the area exposed to erosion, were undertaken in a Geographic Information System (GIS).

3.2. Community-scale resilience data

To assess community-level resilience, the Flood Resilience Measurement for Communities (FRMC) data was used (Flood Resilience Alliance, 2019). The FRMC tool was developed by the Zurich Flood Resilience Alliance – a collaboration between researchers, international humanitarian and development NGOs, and risk engineers – with the aim

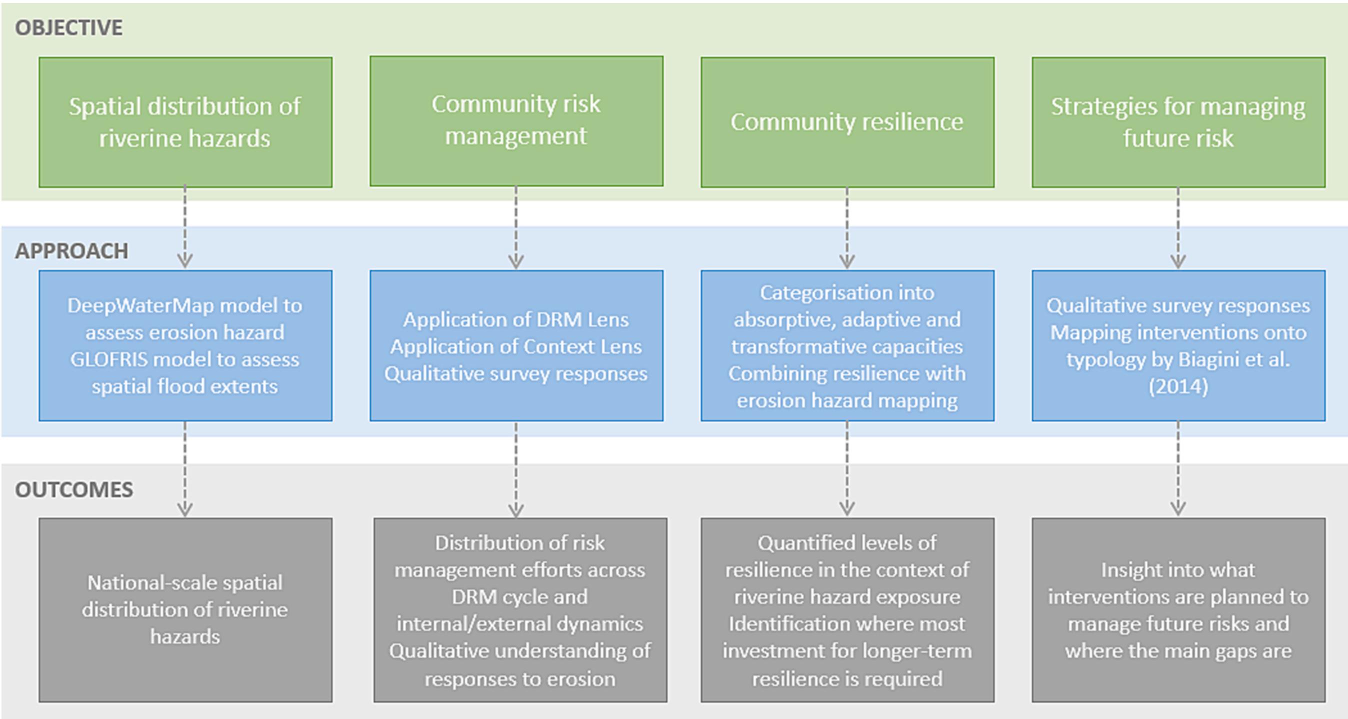

Fig. 2. Approach of measuring community resilience using national-scale hazard assessments and community-based resilience information.

of generating a holistic and integrated understanding of community flood risk resilience, shifting from an emphasis on post-event recovery towards pre-event resilience (Flood Resilience Alliance, 2019; Laurien and Keating, 2019). The FRMC tool was developed and applied to Bangladesh in 2019 by the Zurich Flood Resilience Alliance, the dataset of which was made available for this study.

The first phase of the FRMC framework comprised 88 discrete "sources of resilience", which were subsequently narrowed down to 44 sources of resilience in the second phase of the framework (Fig. 3). These sources of resilience are a set of indicators, that include aspects such as

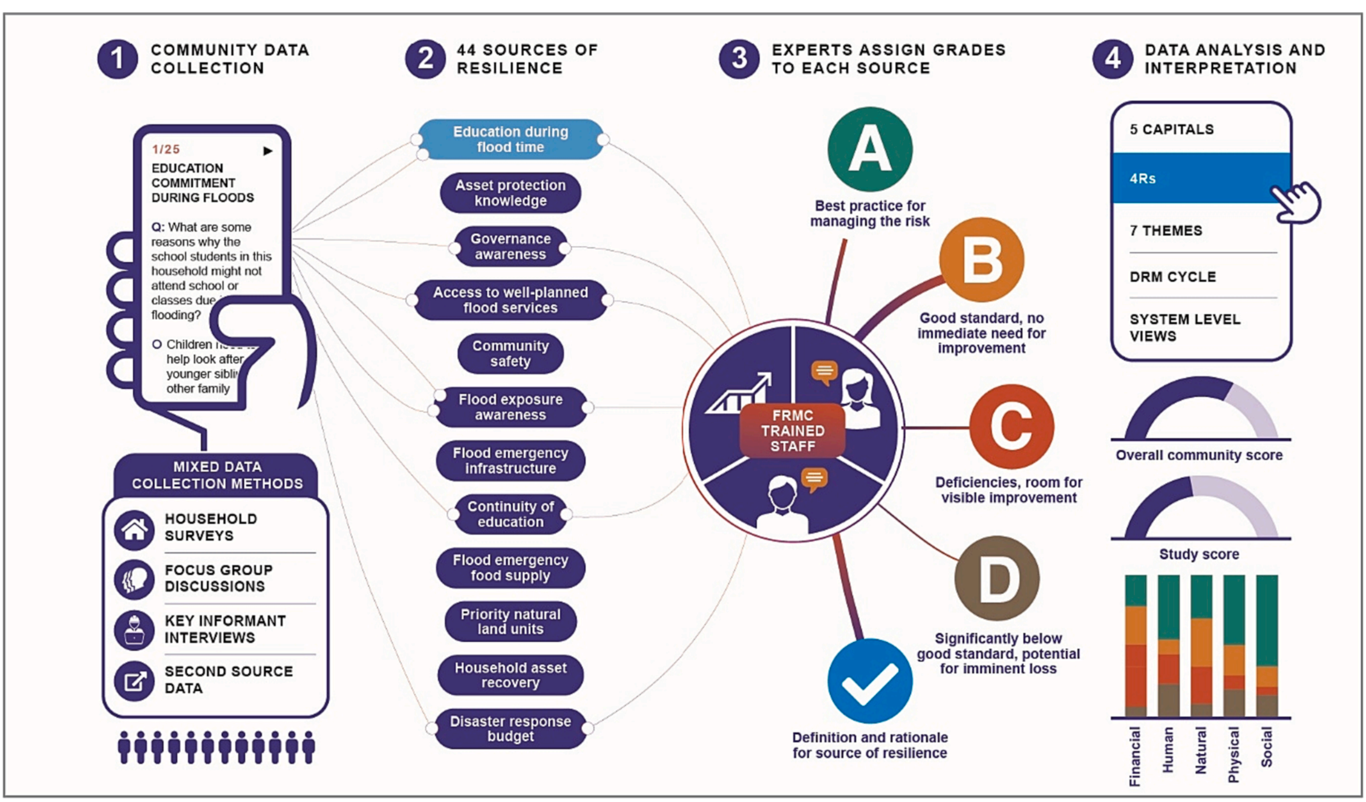

Fig. 3. The Flood Resilience Measurement for Communities (FRMC) approach (Laurien et al., 2020).

education, assets, and livelihoods, amongst others, and when combined, form a quantification of overall resilience. The indicators are measured during normal (non-flood) and post-flood times, and the information underpinning the measurement of each source is collected via household surveys, community group discussions, focus group discussions, key informant interviews, and existing secondary data sources (Flood Resilience Alliance, 2019; Laurien et al., 2020; Laurien and Keating, 2019). Such qualitative approaches allow a unique and dynamic view of how shock events have affected community members, how they have managed the immediate consequences, how they have tried to recover, and which barriers were hindering full recovery (Ayeb-Karlsson et al., 2016; Hochrainer-Stigler et al., 2021; Hochrainer-Stigler et al., 2020).

Each of the 44 indicators of resilience is then graded from A (best practice for managing the risk) to D (significantly below good standard, potential for imminent loss) by FRMC-trained NGO staff. These trained assessors compare the data collected in the field to specific grade definitions, which were both designed to be universally applicable and reduce subjectivity as far as possible (Laurien and Keating, 2019). This approach is based on the wealth of experience of Zurich Insurance (a central player of the Zurich Flood Resilience Alliance) in working with Technical Risk Grading Standards (Laurien and Keating, 2019). Grading both the qualitative and quantitative data on the same ordinal scale sets this approach apart from previous efforts to measure resilience, which often used different scales for different dimensions (e.g., percentages, monetary values, etc.) (Hochrainer-Stigler et al., 2021; Hochrainer-Stigler et al., 2020). In addition to the sources of resilience, a set of community context parameters were also collected through further household surveys and community expert consultations (Campbell et al., 2019; Laurien and Keating, 2019). This additional qualitative information focuses on past flood and erosion experiences and key socio-economic and demographic characteristics that could influence a community's resilience (Campbell et al., 2019).

The 44 ordinal scaled sources (A-D) are then translated to a numeric scale by defining the grades as A = 100 %, B = 67–99 %, C = 33–66 %, and D = 0–32 %. This generates a numerical score for each source of resilience for every community, which can then be used to derive other statistical parameters, such as an overall total resilience score per community by taking the average across all sources. This approach has been used before (Hochrainer-Stigler et al., 2020; Laurien and Keating, 2019) and has shown to be a valid approximation of a continuous scale when working with ordinal data (Backhaus et al., 2016). Such quantitative information is crucial as it enables tracking of progress in a standardised way, creates evidence on which characteristics contribute most to community resilience, and identifies where most investment through community-led projects is required (Hochrainer-Stigler et al., 2021; Laurien and Keating, 2019). All results from the different data collection methods are immediately aggregated from the household to the community level for the protection of households' information. Inevitably, detail is lost through this aggregation process, but the information captured remains highly relevant for studies at the community scale. Finally, although resilience is a dynamic and everchanging concept, which is not captured by this static quantification of community resilience (from 2019), the Zurich Flood Resilience Alliance are repeating these measurements on an approximate 3-year basis, enabling changes in resilience to be monitored and analysed over time.

To facilitate the interpretation of the results across the communities, each of the 44 sources is tagged according to several lenses (Laurien and Keating, 2019). The five capitals lens (5Cs), for instance, assesses the human, social, physical, financial and natural capital of each community, which entails greater richness of information on community resilience than any single metric, such as average income (Flood Resilience Alliance, 2019). The other lenses are the 4Rs (redundancy, rapidity, resourcefulness and robustness), context (community-level versus enabling environment), and the Disaster Risk Management (DRM) cycle (preparedness, response, recovery, corrective risk reduction and prospective risk reduction) (Keating et al., 2017b). For the purpose of this study, the 44 sources of resilience are also categorised into absorptive, adaptive and transformative capacities. Although some sources are important for more than one capacity (e.g., household asset recovery or business continuity), the distinct categorisation involved assessing the survey questions defining each source to understand whether the main aim was to recover from existing shocks, adjust to changing conditions, or plan for uncertain future conditions. For the full list of the 44 indicators of resilience and their tagged classifications, see Table S2 in the Supplementary Information, as well as the Zurich Flood Resilience Alliance report (Alliance, 2020) for more detail.

3.3. Evaluation of strategies for managing current and future riverine risks

In order to assess how communities currently manage their riverine risks, we apply the DRM analytical lens to the FRMC data. The DRM cycle is a well-known and widely utilised concept in disaster research and practice, and links objectives to avoid, lessen or cope with risks with activities and measures for prevention, preparedness, recovery, and reconstruction (Keating et al., 2017b; UNISDR, 2009). By applying this lens, community risk management efforts can be analysed across the different stages of the DRM cycle, namely preparedness, response, recovery, corrective risk reduction, and prospective risk reduction. In this framework, corrective risk reduction corresponds to activities that seek to correct or reduce risks where they are already present, whilst prospective risk reduction activities avoid the development of new or increased disaster risks (Keating et al., 2017b). The Context lens is also applied, in order to understand which DRM activities are happening within the communities versus at the external enabling environment level. In addition, qualitative information from survey findings is also assessed to explore how community members respond to erosion risks and understand whether alternative risk management measures are being applied.

To extract the plans for managing future riverine risks, an additional questionnaire was undertaken by the local NGOs, Practical Action and Concern, exploring the types of interventions that are currently planned and being implemented across the communities, which sources of resilience these interventions contribute to, whether there is potential for the interventions to be scaled up, and whether there are any co-benefits. These interventions are then mapped onto the typology of interventions developed by Biagini et al. (2014), to identify where the key gaps in the types of management approaches are.

3.4. Measuring overall community resilience

The overall level of resilience of each community can be measured by categorising the 44 sources of resilience into absorptive, adaptive, and transformative capacities, and combining the performance of the resilience indicators across these three capacities (see Table S2 in the Supplementary Information for the indicators included in each of the three capacities). The overall level of community resilience is then integrated with the erosion hazard mapping to identify which communities are most vulnerable to the inevitable threats of riverbank erosion, and where most investment for longer-term resilience is required.

In addition, the ways in which communities plan and organise themselves have shown to play fundamental roles in contributing to adaptive and transformative actions. Thus, we extract the key indicators that contribute to community planning and organisation, based on expert judgement amongst core FRMC members, to assess their overall performance. The indicators that make up the planning category are business continuity, household income continuity strategy, early warning systems, integrated flood management planning, and national forecasting policies and plans, whilst the community organisation category entails indicators such as a community disaster fund, community disaster risk management planning, community structures for mutual assistance, community representative bodies, local leadership, and inter-community flood coordination (see Table S3 in Supplementary Information for the full composition of these two categories).

4. Results

4.1. Physical risks: Flooding and erosion in communities

Fluvial flooding and riverbank erosion are the two key hazards experienced across the 35 communities assessed in riverine Bangladesh. Fig. 1, created using the national-scale modelling of erosion and flooding, illustrates the spatial extents of flood and erosion hazards across Bangladesh, as well as the location of the 35 selected communities with respect to these hazards. The erosion hazard mapping results show that 10,800 km^2 of land in Bangladesh has been experiencing erosion over the last 35 years. As evident, the fluvially-active zones along the Ganges, Jamuna, and Padma rivers experience the greatest flood inundation depths and erosion rates, with the Jamuna fluvial corridor being particularly exposed to these two hazards.

All of the 35 communities experience significant flooding at least once per year, with the majority of communities experiencing 40–60 % inundation of their communities each year. Of these 35 communities, 26 are also exposed to erosion, with 19 communities located in lands that erode frequently and/or severely, such as river *chars*. An additional seven communities are situated immediately adjacent to such highly erosive lands. The most extreme riverbank erosion is observed along the Jamuna river, as well as the northern Teesta River.

The impacts of flooding and erosion hazards on communities are significant. In the majority of communities, villagers are affected by losses in agricultural crops and assets, as well as substantial income disruptions. In many communities, these disruptions can generate a crisis of livestock fodder and force many farmers to sell their livestock, stalling their longer-term socio-economic development. Moreover, flood events damage roads, prevent children from continuing schooling, and disrupt water and waste infrastructure services, which worsen the spread of diseases. In many of the studied riverine communities, people become unemployed during flood events and leave their communities to work and recover from their losses. The duration of these impacts can be prolonged in some areas that are protected by embankments; although these embankments provide higher ground for refuge during flood events, they can also cause a drainage congestion problem when breached or overtopped. In many of these communities, villagers have stated that flood water takes a long time to recede due to the embankments, extending the damage and disruptions caused by flood events.

Flood-induced erosion has also been recognised by community members as a common and destructive hazard that drives poverty in their villages; erosion causes the loss of homes, cultivable lands, household assets and more. As a result of erosion, many households get displaced and have to take shelter in other places. Given the highly resource-dependent livelihoods of villagers in these communities, it is evident that both flooding and erosion have devastating impacts on local lives and create significant setbacks in their socio-economic development.

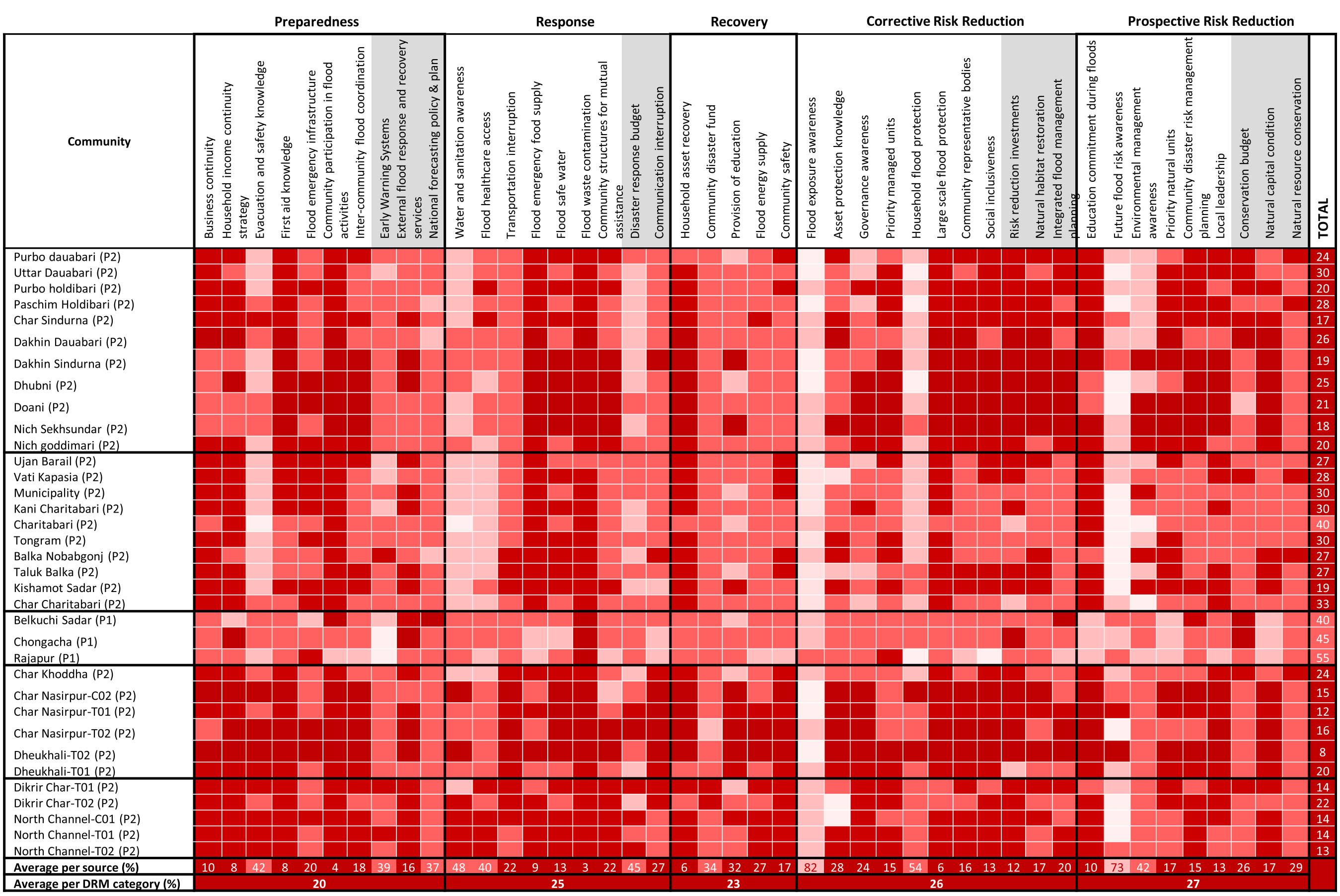

Fig. 4. Heatmap of disaster risk management for riverine communities in Bangladesh. The 44 sources of resilience are classified into the DRM categories, shown along the top of the heatmap. Colours indicate performance, in line with FRMC grading, where dark red is the lowest grade (D), whilst white is the highest grade (A). Sources along the top in grey are external enabling environment indicators, whilst white are at the community-level. The numbers represent the average resilience scores per indicator, per DRM category, and per community, where numbers between 0 and 32 = grade D, 33–66 = grade C, 67–99 = grade B, and 100 = grade A, on average.

4.2. Community risk management

In order to assess how communities currently manage their riverine risks, we apply the DRM and the Context analytical lenses to the FRMC data. By applying these lenses, the distribution of risk management efforts across the different stages of the DRM cycle can be identified, as well as which measures are occurring within versus outside of the communities (Fig. 4).

The heatmap in Fig. 4 illustrates that risk management measures are relatively evenly spread across the DRM cycle. The weakest point in the DRM cycle, when averaged across all communities, is the first step of preparing for the hazard. Although early warning systems and evacuation knowledge are relatively strong across communities, community participation in flood-related activities, first aid knowledge, and household income continuity strategies are particularly poor. This can have further ramifications, as these factors are fundamental for an orderly transition to response, recovery and reconstruction. In fact, the poor household income continuity strategies may be one of the key reasons why so many community members struggle to recover from asset losses (see the "Household asset recovery" indicator in the "Recovery" section of the heatmap of Fig. 4). Perhaps surprisingly, prospective risk reduction measures are strongest across all communities, predominantly driven by the two indicators of awareness (future flood risk awareness and environmental management awareness). It is important to note, however, that although prospective risk reduction activities are strongest, they are still rated a grade D overall ('significantly below good standard, potential for imminent loss').

When focusing on flood protection, the key management measures at the household level according to the questionnaires are flood barriers or sand bags, raising of homesteads, building a wall around homesteads, locally diverting flood water, or moving homes. The combined performance level of these measures for each community is indicated in the heatmap in Fig. 4, under the indicator of "Household flood protection", within the corrective risk reduction DRM category. As evident, household-level flood protection is perceived to be performing relatively well, with an overall of 54 % across all the communities, equating to a high Grade C. However, when looking at larger-scale management measures, under the "Large scale flood protection" indicator, the measures often implemented are riverbank stabilisation, river levees and embankments, sandbags and other mobile protection measures for the entire community, river dredging, and floodplain zoning. The performance of these measures, as perceived by the communities themselves, received an overall performance score of 6 %, one of the lowest across all indicators, and the lowest within the corrective risk reduction category. This implies that such larger-scale flood risk management measures are either entirely absent, significantly inadequate in protecting the communities from flooding and erosion, or have been perceived as a maladaptation, where current risks to flooding and erosion have increased since the implementation of these measures, such as suggested by some villagers regarding the embankments (according to the qualitative responses from the questionnaires).

Finally, multiple other studies have shown that temporary or permanent migration away from high-risk areas is also often either a voluntary or involuntary response to riverine hazards, as well as other stressors (Ayeb-Karlsson et al., 2016; Bernzen et al., 2019; Haque and Zaman, 1989; Haque et al., 2020). In the 35 communities assessed in this study, 32 % of community members, on average, leave their community for more than one month per year, with some communities experiencing temporary out-migration of between 60 % and 75 %. Furthermore, 'relocating the house' was also the most frequent suggestion from community members within Belkuchi Sadar and Rajapur – both in the Lower Jamuna area – for preventing future flood and erosion events from reaching houses and assets within the community. In Char Nasirpur-T02 and Dheukhali-T02 (Padma River area), community members highlighted that "people become jobless during floods and they need to migrate to have a job/earning and women become unsafe", which was also felt in Dikrir Char-T01 (Kumar River in the south-west of Bangladesh), where community members highlighted that during times of flooding people migrate out for making a living and "small holder farmers need to sell their cattle for the crisis of fodder" (see more detail for all communities in Table S1 of the Supplementary Information). Erosion has also been raised by multiple community members as a key driver of temporary migration, and members in the Municipality community in the Northern Jamuna region also highlighted that erosion victims have permanently migrated to this community from elsewhere. These examples highlight that such changes in location or livelihood are occurring due to capacity thresholds being surpassed (e.g., homes eroded into the river, unemployment due to flooding, crop no longer productive, land severely damaged by flooding and erosion, etc.). Therefore, although some temporary and permanent migration is already taking place, it does not seem to be voluntary and planned.

4.3. Community resilience

According to the data collected across the 35 communities in Bangladesh, the overall resilience of communities to riverine hazards is low, averaging at 25 % (Grade D), although there is some variability, as shown in the final column of the heatmap in Fig. 4. When considering the five regions, the overall levels of resilience are greatest in the lower Jamuna River region (48 % – Grade C), followed by the northern Jamuna communities averaging at 30 %, the northern Teesta communities (22 %), and the two southern areas of the Kumar and Padma river communities averaging at 18 % and 16 %, respectively. The final column in Fig. 4 shows that the northern Jamuna communities have the greatest range in overall levels of resilience (range of 21 %), whilst the Kumar riverine communities' low resilience levels are all within 9 % of one another. Within the northern Jamuna region, Kishamot Sadar stands out as having a particularly low level of resilience, which appears to be driven mainly by a low provision of education, poor community structures for mutual assistance, and poor community disaster risk management planning. On the contrary, Charitabari has higher levels of resilience than other communities in this region, predominantly due to particularly strong evacuation and safety knowledge, water and sanitation knowledge, and risk reduction investments.

Fig. 5 illustrates the absorptive, adaptive, and transformative capacities for each of the riverine regions, which when combined, make up their overall levels of resilience. It is evident that the majority of current actions and efforts are contributing to communities' absorptive capacity, focusing on dealing with and recovering from riverine hazards, with much less attention paid to adapting to changing conditions or planning on how to manage future risks.

Previous studies have highlighted that the ways in which communities plan and organise themselves play fundamental roles in cross-cutting both adaptive and transformative actions, predominantly because the bonds between people and their environment shape processes of social influence and determine whether and how people access information, resources and support (Barnes et al., 2020; Marshall et al., 2012). Thus, in order to further explore why adaptive and transformative actions are less advanced, community organisation and planning strategies are assessed in more detail (Fig. 6) (see Table S3 in Supplementary Information for details on the indicators used for these categories). When averaged across all communities, levels of planning are graded at 23 %. In the lower Jamuna region, however, planning indicators average at 51 %; in this region, therefore, the planning space acts as an enabler for longer-term resilience, but in other areas of riverine Bangladesh, the low levels of planning act as a critical barrier. Similarly, community organisation (i.e., community management and governance) seems to be significantly below good standard, with an average of 17 %. The community organisation indicators are higher for the lower Jamuna region again, but concerningly low for all other regions. Along the Padma and Kumar rivers, for instance, both planning and community organisation are exceptionally low, with community

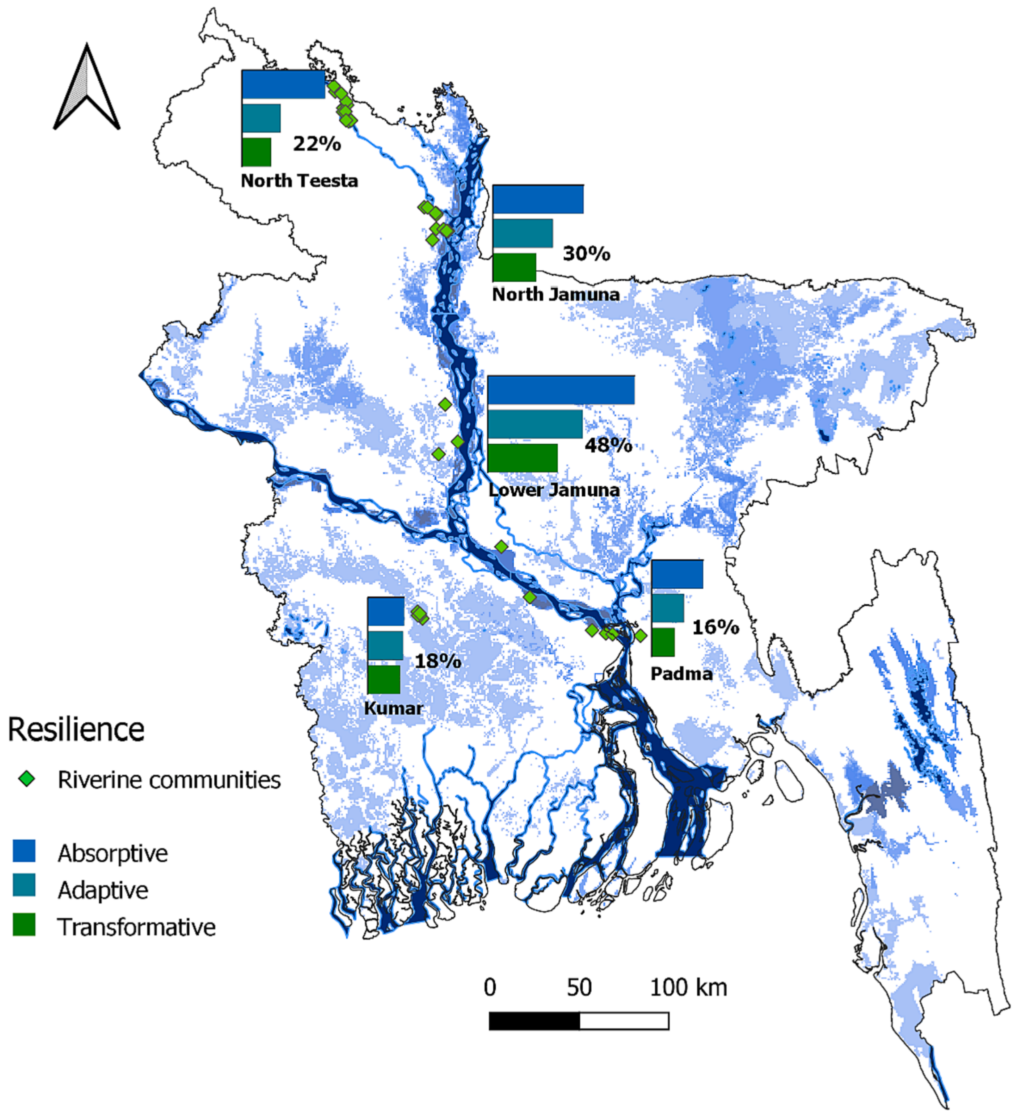

Fig. 5. Map of the overall absorptive, adaptive, and transformative capacities of riverine communities in Bangladesh with percentages showing the overall levels of resilience for each riverine region.

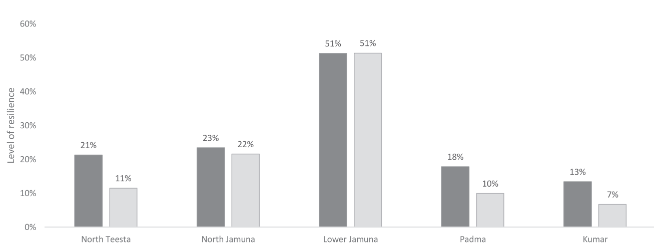

Fig. 6. Resilience levels across planning and community organisation indicators in riverine Bangladesh.

organisation averaging at 10 % and 7 %, respectively. In these regions, as well as in the northern Teesta region, more action is required that focuses on improving community plans and organisation for longer-term resilience.

Finally, as the assessment of community risk management measures has presented, erosion of floodplain lands seems to lead to a limit in adaptation, where options are not available to avoid the risks through adaptive action (IPCC, 2022); i.e., when rivers consume floodplain lands, there is very little that inhabitants can do other than temporarily or permanently move away. This has been evident in the community-level data, and the previous sections have shown that communities tend to respond to riverbank erosion through temporary or permanent migration. In order to gain a better understanding of where relocation is most likely already occurring and will continue to occur in the future, the 19 communities living on highly erosive lands, identified using the erosion modelling results in Section 4.1, are assessed in more detail and shown in Fig. 7. The matrix in Fig. 7 critically illustrates that there are seven communities within the red zone, spread across the northern Teesta, the northern Jamuna, and the Padma rivers. The seven communities along the riverbanks and on *chars* of these vast river systems experience frequent and severe erosion and have low levels of overall resilience. It is in these areas, therefore, that the greatest need for fostering resilience – predominantly in the form of transformative capacity – to erosion arises.

4.4. *Regional strategies for future risk management*

In response to the identified low levels of resilience, interventions for managing current and future flood and erosion risks within and across communities are being put in place. Fig. 8 illustrates the key measures being implemented to manage future riverine risks, categorised using

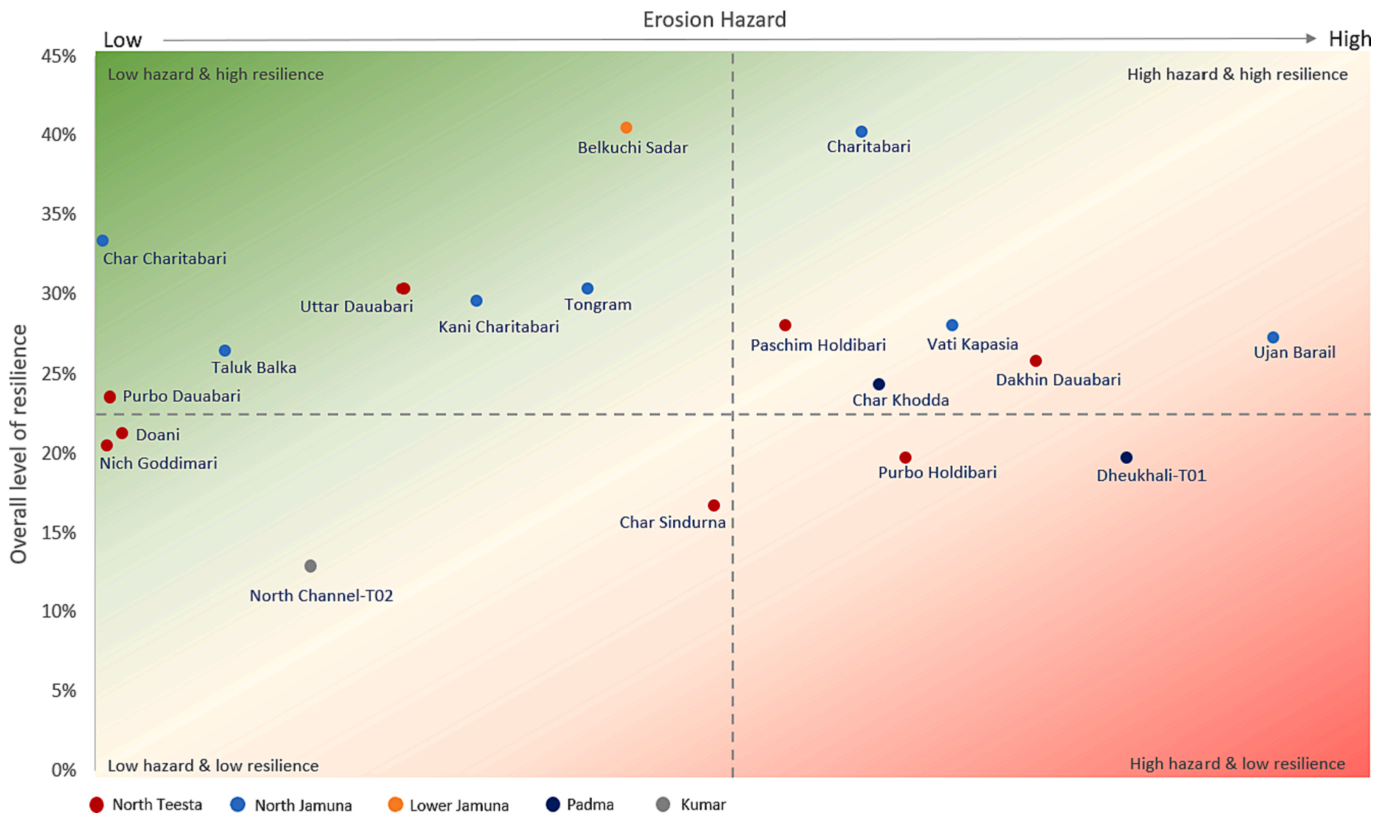

Fig. 7. Matrix plot of erosion hazard against the overall level of community resilience for the 19 communities most exposed to riverbank and charland erosion. Green area in the top-left corner shows communities that have relatively lower exposure to erosion hazards and higher levels of resilience, and the red area in the bottom-right corner shows communities that have higher erosion hazard exposure and lower levels of overall resilience.

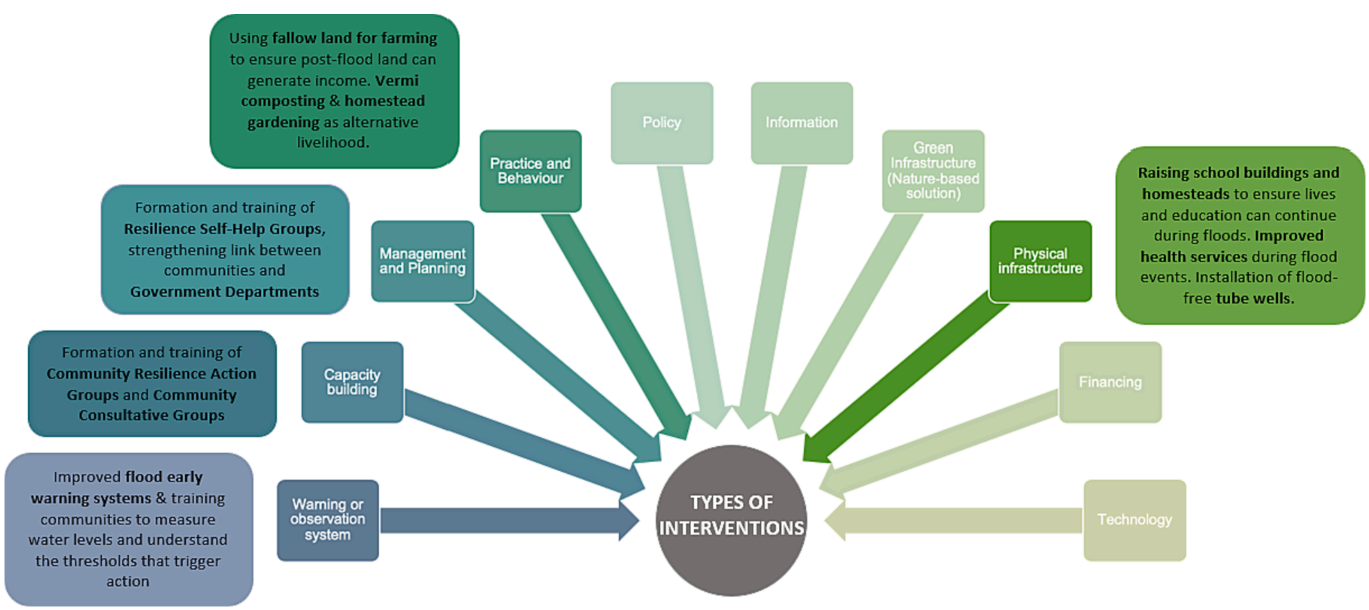

Fig. 8. Community interventions currently being applied across the 35 communities, classified according to the intervention typology developed by Biagini et al., (2014).

the intervention typology developed by Biagini et al. (2014). Alongside physical infrastructure improvements, better early warning systems, and practice and behaviour management, communities are also implementing multiple different planning and organisational committees to build capacity and enhance longer-term resilience.

Amongst these, is the formation of Community Resilience Action Groups (CRAGs), which are community-representative groups that are trained in topics such as resilience, leadership, communication, and gender equality. The aim of these groups is to build capacity to lead and take ownership of their own community resilience. Community members identified the need for these groups themselves, and the members within each CRAG are nominated by the represented community, with a requirement of at least 40 % female CRAG members, as well as one leading female role. The CRAGs are also in close collaboration with wider Union Disaster Management Committees, enabling the communities to be more embedded within the governance structure, providing them with greater decision-making power. In addition to CRAGs, communities have also created Resilience Self-Help Groups (RSHGs), which are groups of approximately 25 (self-selected) most vulnerable people in each community. The aim of these groups is to mutually support the most vulnerable in the preparation of Household Resilience Plans that focus on livelihoods and continuity of income and savings to improve longer-term flood coping capacity. Finally, the community and Government Departments Joint Planning aims to strengthen the linkages between communities and service providers, engaging the CRAGs at Upazila level (sub-district) with the Upazila Government Departments (health, livestock, agriculture, and education) to prepare joint action plans. These joint action plans primarily focus on more timely recovery from flood losses.

The different community committees act as crucial advances in improving community organisation and planning, but they primarily continue to focus on enhancing communities' absorptive capacities by ensuring that communities can better prepare for, cope, and recover from flood and erosion impacts. In addition, the physical infrastructure plans of raising school buildings, improving health services, and constructing flood-free tube wells, as well as embedding alternative livelihoods, such as the use of fallow land for farming, will advance communities' absorptive and adaptive capacities. It is evident that overall, although all of these planned activities will strengthen community resilience in riverine Bangladesh, more action is needed on advancing transformative capacities to generate longer-term resilience in the face of uncertain future conditions.

5. Discussion

The riverine communities assessed in this study have previously been classified as very poor, struggling rural communities with significant risk (Laurien et al., 2020), and thus represent some of the most extreme cases of community exposure and vulnerability to riverine hazards in Bangladesh. Their high levels of poverty make them particularly vulnerable to riverine hazards, but their vulnerability simultaneously also drives further poverty (Adnan et al., 2020; Alcántara-Ayala, 2002; Brouwer et al., 2007; Hallegatte and Rozenberg, 2017; Leichenko and Silva, 2014; Paszkowski et al., submitted; Winsemius et al., 2018). In the studied communities, both flooding and erosion have dramatic impacts on the longer-term socio-economic development of rural livelihoods. Erosion, in particular, has been identified by community members as a main driver of furthering poverty. Unlike flooding, the choice of staying and coping with the consequences of the hazard is not feasible with erosion; if a household's land is eroded by a river, options are not available to avoid the intolerable risks through incremental adaptive actions (Haque and Zaman, 1989; IPCC, 2022; Penning-Rowsell et al., 2013; Rahman et al., 2015). Erosion therefore acts as a hard limit to absorptive and adaptive responses; communities are driven to undertake transformative approaches by temporarily or permanently relocating away from hazards. However, the overall transformative capacity of communities, as identified in Fig. 5, remains relatively low, indicating that these responses are currently largely of forced and reactive, rather than of deliberate and anticipatory nature.

Multiple previous studies (Barnes et al., 2020; Chung Tiam Fook, 2017; Laurien and Keating, 2019; Marshall et al., 2012) have highlighted that transformative processes are intrinsically linked with the levels of community organisation and cooperative longer-term planning. However, in the majority of communities, particularly along the Kumar river and on the *chars* of the Teesta and Padma rivers, very low levels of community organisation and planning were observed. Some of the strategies currently being put in place to improve resilience into the future, particularly the communities' initiation of the CRAGs, RSHGs, and improved and more formal planning with Government Departments, are already improving the overall coordination and active decision-making of communities. Nevertheless, the majority of these committees and measures are aimed at further enhancing communities' absorptive capacity, and not enough emphasis is placed on strengthening their adaptive and transformative capacities. This is particularly alarming in the seven communities identified within the north Teesta, north Jamuna and the Padma rivers (Fig. 7) that have low levels of resilience and are located on highly erosive lands. In these areas, as well as in many other areas in riverine Bangladesh (Paszkowski et al., submitted), relocation is likely to be inevitable. In order to avoid further unplanned, catastrophe-driven migration, the transformational capacity of these communities needs to be urgently strengthened.

The communities assessed within this study entail some of the most exposed populations to riverine hazards in Bangladesh, and some of these communities have shown to be able to build some level of resilience. In the Lower Jamuna region, for instance, high levels of flood and erosion awareness have led to strong community cohesion and organisation, better long-term planning, and greater political and scientific interest from external governing bodies. Studies have also shown that place-based identity and occupation can hinder transformational capacity, and possessing strong creativity and innovation are critical to advance transitions (Marshall et al., 2014; Marshall et al., 2012). Although these aspects are not explicitly captured in the FRMC framework, which should be assessed in more detail in future research in these communities, it is evident from other indicators and the ongoing community organisational groups (e.g., CRAGs) that there is a strong sense of learning and joint creation of solutions. There is a lot that can be learnt from these communities, particularly in the Lower Jamuna region, and upscaled to other rural riverine areas facing similar hazards. Governmental departments and NGOs must continue to support these community initiatives in riverine Bangladesh, as the cross-generational indigenous knowledge along the riverbanks and on *chars* of Bangladesh's rivers is absolutely critical for longer-term resilience to flood and erosion hazards (Islam et al., 2010).

This is particularly true in the face of uncertain future conditions. Climate change is expected to increase the frequency and magnitude of hydrological extremes, exacerbate saline intrusion, result in more widespread erosion, and generate more severe and frequent cyclones with greater storm surges (Darby et al., 2015; Haque et al., 2020; Whitehead et al., 2018). At the same time, the population in Bangladesh is expected to continue to grow, and reach 200 million people by 2050 (Van Huijstee et al., 2018; World Population Review, 2021). The resilience of exposed Bangladeshi populations will be put to the test. This study has shown the level of resilience for 35 communities at one moment in time, but continued research by the Zurich Flood Resilience Alliance will reveal changes and fluctuations of resilience over time, and will continue to guide decision-making in Bangladesh into the future. The resilience of today's and tomorrow's populations will require a strong combination of new and transformative management solutions with traditional knowledge and understanding from people living on the deltaic floodplains.

6. Conclusion

Rural riverine communities, living along riverbanks and on river islands, have been identified as some of the poorest and most vulnerable populations, disproportionately affected by climatic and riverine hazards. However, humans have inhabited floodplains for centuries, and have developed resilience strategies to cope with these hazards, particularly in fertile deltaic environments. In this study, we measured the overall community-level resilience to interwoven fluvial flooding and erosion hazards, taking rural riverine Bangladesh as a case study. This enabled a deeper understanding of vulnerability, be assessing how populations at the front lines of hazard impacts live and cope with these shock events. Community resilience has been quantified by linking national-scale assessments of erosion and flood hazards with systematic community-centric resilience measurement; as far as we know, it is the first time that community resilience in the context of both flooding and erosion hazards has been measured anywhere in the world. Although this study has focused on a selection of rural riverine communities in Bangladesh, the approach can be applied across the world. The erosion modelling is based fully on remotely sensed imagery, and FRMC data has been collected for the most vulnerable communities in more than 16 countries across five continents. Thus, this approach can be useful for assessing resilience to riverine hazards in at least those 16 countries, but also more widely. The unified way of quantifying and monitoring progress of community resilience provided in this study supports bottom-up resilience-based decision making, as it enables the identification of where most investment in community-led projects is required.

The low levels of resilience observed in rural communities in Bangladesh are alarming, particularly in the face of growing climate threats and unprecedented population densities and resource demands. New and transformative responses and approaches to enhancing resilience are urgently required, which will not only rely on strengthened planning and implementation supported by external actors, but also on the internal social processes and organisation within exposed communities. These transformative approaches must be aligned with and complement ongoing community-centred efforts focused on recovering from and adapting to riverine hazards.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgements

We acknowledge the financial support from the Z Zurich Foundation and the immense work by all partners of the Zurich Flood Resilience Alliance in collecting the FRMC data. We are especially grateful for all contributions from the two NGO partners in Bangladesh. This research paper was funded in-part by the engineering and consultancy practice Buro Happold, and is an output from the REACH programme funded by UK Aid from the UK Foreign, Commonwealth and Development Office (FCDO) for the benefit of developing countries (Programme Code 201880). However, the views expressed and information contained in it are not necessarily those of or endorsed by the Zurich Flood resilience Alliance, the Z Zurich Foundation, Buro Happold or FCDO, which accept no responsibility for such views or information or for any reliance placed on them.

Part of the research was developed in the Young Scientists Summer Program at the International Institute for Applied Systems Analysis (IIASA), Laxenburg (Austria), with financial support from the German National Member Organisation.

The authors would like to thank Edoardo Borgomeo and Lisa Schipper for feedback on a draft of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2023.102778.

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