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Flood experience and access to insurance contribute to differences in homeowners' post-disaster adaptation in a cross-border region of Western Europe

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The July 2021 floods in Europe stand out as one of the most devastating flood-related disasters to impact the continent in recent years, affecting multiple countries at once. As climate change intensifies, such cross-border disasters are expected to become more frequent. Here we use unique cross-country survey data from flooded homeowners to understand the patterns and limits of how households in different nations respond to shared flood crises. We find evidence of financial, institutional, and psychological limits to household adaptation. Insurance compensation is associated with private adaptation actions shortly after flooding. Households that suffered flood damage are more likely to mitigate future risks to their homes. Yet, this intention encounters limits for extreme flood damage. Once experienced flood damages exceed a threshold of around 60% of the home reconstruction value, homeowners begin to view private adaptation efforts as less effective, prompting a shift toward relocating to safer areas.

Flood damage mitigation measures (FDM) by households have become an important strategy to cope with increasing climate risks[1,2]. FDM includes structural measures before the event to protect homes (e.g., water-resistant materials or elevating electrical systems), emergency measures (e.g., sandbags), flood insurance coverage, or a decision to relocate[3,4]. The widespread impacts of the 2021 floods across several European countries highlight the importance of understanding household's adaptive behaviour and its limits[1], as effective recovery requires not just restoring what was lost but also increasing preparedness for future flood events[5–8]. In this study we utilize unique international survey data to assess the post-disaster adaptive actions and intentions of flooded homeowners in Germany ($n = 225$), Belgium ($n = 222$), and the Netherlands ($n = 272$); three countries with different flood experiences and institutional flood management contexts but having experienced the same flood disaster in July 2021[9–11]. This case study allows for a cross-country comparison of post-disaster recovery and disaster management, which may assist with transboundary cooperation through, for example, early warning systems or flood risk awareness campaigns[12].

An expanding literature has examined household flood adaptation. However, most studies only focus on single countries[13–15], and case studies involving recent flood events are also rare[16]. Two key studies looking at flood adaptation in an international context are Duijndam[17] and Noll et al.[16], investigating migration as an adaptation option and assessing cultural differences as a driver for private adaptation actions, respectively. Our study adds that besides cultural differences, the institutional setting (i.e., the flood management and insurance context) affects household flood preparedness through insurance availability and uptake, and household's perceived adaptation responsibility, which could erode adaptation demand[18,19]. Furthermore, while existing international flood adaptation studies use a more global perspective, we add more understanding of how flood adaptation works in transboundary river catchments, where cultural differences are relatively small but the institutional context regarding flood risk management differs strongly[20].

Flood experience has been identified as an important predictor of the uptake of FDM by households[14,21–23]. On the one hand, experience with floods can increase risk perceptions and demand for adaptation[14,21–23].

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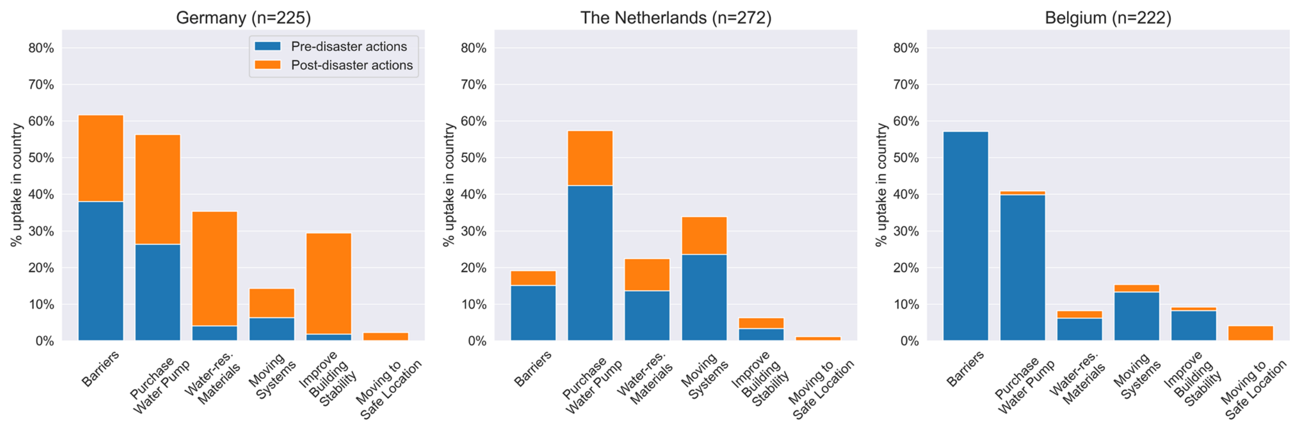

Fig. 1 | Pre- and post-disaster adaptation actions. Percentage relative to the number of responding homeowners in the country. Underlying data available in Supplementary Table 2.

On the other hand, experiences of extreme damage could reveal limits to adaptive behaviour for households, and repeated flood experiences may erode the motivation to adapt[24–26]. Most studies that consider flood experience in their analyses treat flood experience as equal among all affected households, failing to account for the variability in personal flood experiences, such as flood magnitude, personal losses, and emotional impacts[27]. As our study is based on post-disaster survey data, all respondents have direct but different flood experiences from the same event. Due to the steep terrain, the event had a more flash flood character in Germany and Belgium compared to the Netherlands[9,11,28]. Germany experienced the highest flood damage, while the lowest average flood damage was observed in the Netherlands (Supplementary Table 1). Our post-disaster cross-country survey data allows us to identify potential limits to adaptation through heterogeneity in experienced flood damages and insurance schemes.

A large share of the existing literature does not use a consistent theoretical framework to assess the drivers of private adaptation[29]. Hence, we use an adjusted version of the generic framework of the protection motivation theory (PMT)[30,31] for a consistent analysis of private FDM actions in different countries. The PMT framework traditionally defines flood adaptation efforts through threat and coping appraisals[1,21,32,33]. We extend its application by incorporating the severity of the past flood event, already undertaken FDM measures and insurance compensation, while also applying standard PMT in Supplementary Table 4. Threat appraisal in PMT describes respondents' perceived flood risk, which includes expected damage and the probability of flooding[21,32,33]. In this study, we use recent flood damage as a proxy for threat appraisal. Experienced flood damage, defined as the percentage of damage to the home relative to its reconstruction value, serves as an indirect measure of perceived risk, reflecting the household's flood experience severity and its potential influence on future expectations. We measure institutional flood management context through insurance compensation and trust in public protection standards. The three included countries differ in their national flood insurance programmes. In the Netherlands, flood insurance is not possible for 'primary water bodies' and is often ambiguous and uncertain[34]. In Belgium, flood insurance is excluded for new properties in flood-prone areas[35], and in Germany, flood insurance is optional but excluded in high-risk zones[34].

To gain insights into the recovery and preparation process after flooding, we look into both the flooded homeowner's actions after flooding as well as the intentions for future actions in the two years after the event of July 2021. Included adaptation actions are placing barriers in front of the building, purchasing a water pump, building with water-resistant materials, moving electrical and/or heating systems to higher floors, and improving the building's stability. We use ordinary least squares (OLS) regression techniques to assess the drivers of private adaptation actions and intentions after flooding while controlling for existing adaptation actions on the household level.

We find that access to insurance compensation and prior adaptation actions are positively and significantly associated with post-disaster adaptation actions across Belgium, Germany, and the Netherlands. For post-disaster adaptation intentions, we find that homeowners who have already taken adaptation actions are more likely to intend to take more measures in the future. We also identify a nonlinear effect of recently experienced flood damage on adaptation intentions. When flood damage surpasses around 60% of the home's reconstruction cost, homeowners start to perceive private adaptation measures as less effective, leading them to consider moving to safer locations.

Results

Drivers of post-disaster adaptation actions

Pre- and post-disaster adaptation actions implemented by the sampled flooded homeowners differ strongly between the three countries (Fig. 1 and Supplementary Table 2). For pre-disaster preparedness, it stands out that dry-proofing through barriers is relatively popular in Germany and Belgium. Placing barriers is considered an emergency measure that is triggered by early warnings[3]. This may explain the higher uptake of these measures. However, the performance of warnings differed strongly during the floods in July 2021[10]. Lower costs of uptake may also be a driver of adaptation uptake[16,36,37], as the low-cost measures of placing barriers and purchasing a water pump are relatively popular across all countries. Higher-effort structural FDM measures, such as building with water-resistant materials, moving electrical and/or heating systems to higher floors, and improving building stability, are especially popular in the Netherlands.

For post-disaster adaptation actions, there is also a shift towards the implementation of more wet-proofing measures across all three countries, which may be explained by recent flood experience[23]. Improving building stability and moving to a safer location is the least popular action across the surveyed countries, potentially because these actions take more effort compared to other FDM measures. The cross-country differences in post-disaster actions shown in Fig. 1 cannot only be attributed to differences in protection motivation, but also to the timing of the survey. The German survey was distributed 17–18 months after flooding (compared to 6–8 months for the Netherlands and 8–22 months for Belgium). German respondents had more time to implement FDM measures, while also experiencing higher flood damages, which can also indicate why more post-disaster actions have been taken in Germany. It stands out that very few post-disaster adaptation actions have been taken in Belgium, although the data collection started around roughly the same time as the Dutch survey and ended around the same time as the German survey. The regression analysis in Table 1 corrects for differences in survey timing.

Table 1 | Drivers of post-disaster adaptation actions

Variables	(1) Model 1	(2) Model 2	(3) Model 3	(4) Model 4
# Measures in place before flooding	0.012**	0.012**	0.012**	0.012**
	(0.006)	(0.006)	(0.006)	(0.006)
Damage ratio		−0.039	−0.060	−0.059
		(0.054)	(0.054)	(0.054)
(Damage ratio)^2		0.040	0.057	0.056
		(0.049)	(0.050)	(0.050)
Flood experience before 2021 (Y/N)		−0.001	0.000	0.000
		(0.011)	(0.011)	(0.011)
Insurance compensation (Y/N)	0.023**		0.025**	0.025**
	(0.012)		(0.012)	(0.012)
Socioeconomic indicator				0.001
				(0.002)
Months since the July 2021 flood	−0.001	−0.000	−0.001	−0.001
	(0.000)	(0.000)	(0.001)	(0.001)
Germany	0.064***	0.054***	0.063***	0.064***
	(0.015)	(0.014)	(0.015)	(0.015)
Belgium	−0.039***	−0.037***	−0.037***	−0.036***
	(0.009)	(0.009)	(0.009)	(0.009)
Constant	0.026*	0.044***	0.031**	0.023
	(0.012)	(0.013)	(0.015)	(0.027)
Observations	719	719	719	719
R-squared	0.105	0.100	0.107	0.107

Results based on OLS regression analyses with adaptation ratio as the dependent variable.
Robust standard errors in parentheses.
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

We present the coefficients of the drivers of post-disaster adaptation actions across countries using an OLS regression analysis in Table 1. The dependent variable is the adaptation ratio, the fraction of actions taken after flooding related to the total FDM actions that were still available for the respondent ("Methodology" section). To account for potential non-linearities in the impacts of experienced flood damage on adaptation behaviour, we include both the damage ratio and its squared term in the analysis. The damage ratio describes the amount of flood damage compared to the rebuilding value of the home (see also "Methodology" section). Our analysis does not reveal significant relationships between recent flood damage experience (damage ratio and its squared term) and post-disaster adaptation actions, potentially caused by a focus on rebuilding rather than adapting shortly after flooding[38].

We do observe that both the number of measures already in place before flooding and flood insurance coverage are significantly positively associated with adaptation actions after flooding across all models. The positive coefficient for adaptation measures prior to the event may suggest the existence of a subgroup of homeowners who are consistently proactive and motivated to take adaptive actions[39]. In contrast, another subgroup may be less inclined toward adaptation[37]. A potential explanation is that households that adapt more extensively may also face objectively higher risk levels, which increases both the perceived need and actual benefits of repeated adaptation[40]. Another possibility is that a subset of homeowners is particularly interested in adaptation and seeks to minimise flood risk as much as possible[32]. There is mixed evidence in the literature on the impact of undergone actions on adaptation behaviour. While some studies report limited or negative effects of undergone adaptation on adaptation behaviour[16,23], positive effects are also found[23]. The behaviour identified in our study could potentially be attributed to the fact that our surveys were distributed after a disaster, capturing motivations influenced by recent flood experiences. Unlike surveys conducted in isolation from flood events, a post-disaster survey context may capture respondents acting based on an elevated sense of urgency, leading to a subset of proactive homeowners who view adaptation as a continuous resilience-building process.

We also identify a significant positive coefficient of expected or received insurance compensation. Homeowners who received (or expected to receive) damage compensation were more likely to engage in post-disaster actions compared to homeowners who had not received (or were not expecting) any compensation. Receiving insurance compensation likely provides homeowners with the immediate financial means necessary to start reconstruction. Additionally, the insurer could demand adaptation before coverage is provided in the high-risk zone in Germany (i.e., 1/10-year flood zone)[34]. These findings suggest the absence of moral hazard, where households are less proactive in protecting their homes because they expect damage compensation[41]. In contrast, we find an indication of advantageous selection, as insurance is considered complementary to adaptation on the building level, which also further promotes adaptive behaviour after disasters[42].

When controlling for differences in survey timing, the results in Table 1 indicate that there are structural differences between countries that have not been explained by the other independent variables. Country fixed effects were added to the regression to control for such unexplained structural cross-country differences. Compared to the Netherlands, a significantly higher number of adaptation actions has been taken in Germany. Homeowners in Belgium have taken significantly fewer adaptation actions compared to the other two countries. A potential explanation for this lower uptake in Belgium is that some regions that were not classified as flood-prone in any flood scenario unexpectedly experienced severe flooding, and residents do not expect to be flooded again[28]. This perception is strengthened by local media[43,44] who, without supporting evidence, attributed the flood event to human error with dam management[45,46]. The most common reason Belgian respondents gave for not taking adaptive measures was that they did not expect another flood event in the future. One-third of the Belgian respondents who did not implement any measures indicated that they did not anticipate a future flood (Supplementary Table 3).

Drivers of post-disaster adaptation intentions

Compared to Fig. 1, Fig. 2 includes post-disaster adaptation intentions alongside pre- and post-disaster adaptation actions. Belgium is excluded from Fig. 2, as adaptation intentions were not covered in the Belgian survey. Summing post-disaster actions and intentions provides a more comprehensive understanding of the recovery process for homeowners in Germany and the Netherlands up to two years after flooding. This shows that overall, homeowners in Germany prefer dry-proofing actions such as placing barriers and improving the building stability compared to their Dutch equivalents. Moving heating and/or electrical systems is more popular in the Netherlands compared to Germany, reflecting a stronger focus on wet-proofing measures. Other FDM measures show similar uptake across both countries.

Table 2 shows the outcomes of a linear regression analysis with the intention ratio as the dependent variable to further assess the drivers of these differences. The intention ratio is defined as the proportion of adaptive actions intended after flooding relative to the number of FDM actions still available to the respondent ("Methodology" section).

The *R*-squared of the models is relatively low, which is expected due to the complexity of human decision-making in post-disaster settings. Adaptation intentions and actions are shaped by psychological, social, and contextual factors that are challenging to capture fully in survey data. Comparable studies on flood adaptation behaviour also report on relatively low *R*-squared values[18,19,22]. Even with harmonised variables and country fixed effects, unobserved differences across national contexts and personal circumstances introduce variability, naturally limiting the model's

Fig. 2 | Pre-disaster adaptation actions and post-disaster adaptation actions, and intentions. Percentage relative to the number of responding homeowners in the country. Underlying data available in Supplementary Table 2.

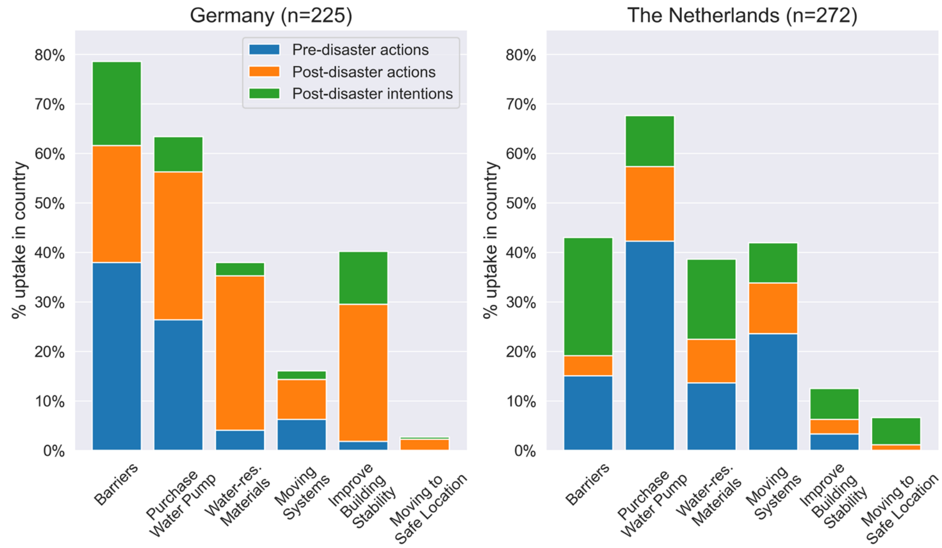

Table 2 | Drivers of post-disaster adaptation intentions

Variables	(1) Model 1	(2) Model 2	(3) Model 3	(4) Model 4	(5) Model 5
# Measures in place after flooding	0.022*	0.027**	0.027**	0.028**	0.027**
	(0.012)	(0.012)	(0.012)	(0.012)	(0.012)
Damage ratio		0.271**	0.263*	0.254*	0.283**
		(0.132)	(0.136)	(0.135)	(0.134)
(Damage ratio)^2		−0.235*	−0.228*	−0.222*	−0.246**
		(0.120)	(0.122)	(0.122)	(0.121)
Flood experience before 2021 (Y/N)		−0.008	−0.008	−0.009	−0.010
		(0.026)	(0.026)	(0.026)	(0.026)
Insurance compensation (Y/N)	0.019		0.007	0.009	0.010
	(0.022)		(0.023)	(0.023)	(0.023)
Socioeconomic indicator				−0.011*	−0.011*
				(0.006)	(0.006)
Adaptation responsibility					0.021**
					(0.010)
Months since the July 2021 flood	−0.002	−0.004	−0.003	−0.003	−0.006
	(0.049)	(0.049)	(0.049)	(0.049)	(0.049)
Germany	−0.030	−0.026	−0.030	−0.041	−0.061
	(0.478)	(0.479)	(0.478)	(0.476)	(0.472)
Constant	0.147	0.135	0.127	0.223	0.197
	(0.345)	(0.347)	(0.345)	(0.341)	(0.339)
Observations	489	489	489	489	489
R-squared	0.026	0.036	0.036	0.043	0.051

Results based on OLS regression analyses with intention ratio as the dependent variable.
Robust standard errors in parentheses.
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

explanatory power. Rather than aiming for high predictive accuracy, the goal of this study is to uncover broader patterns in adaptation behaviour.

Controlling for survey timing reveals no significant differences in adaptation intention between Germany and the Netherlands. Again, the number of undergone adaptation actions is significantly positively associated with adaptation intentions in all models. Unlike short-term post-disaster actions, flood insurance coverage plays a smaller role in influencing post-disaster adaptation intentions. Homeowners who received or expected to receive insurance compensation do not indicate greater intentions compared to those without any insurance payouts, which again suggests the absence of moral hazard[41].

In contrast to post-disaster actions, recently experienced flood damage is linked to post-disaster intentions, as both the building damage ratio and its squared term are significantly associated with adaptation intentions. The different role of recent flood damage for actions and intentions can potentially be explained by differences in perceived risk. Shortly after flooding, rebuilding may be prioritised, while intentions may be driven by more long-term planning. This could also be an explanation for the observed parabolic relationship between experienced flood damage and adaptation intentions (Table 2 & Supplementary Fig. 1). Initially, homeowners are more likely to intend to take additional adaptation measures with increasing experienced flood damage during the July 2021 floods. At lower damages, flood damage experience is associated with stronger adaptation intentions. However, when determining the top of the parabola in Supplementary Fig. 1, we find that adaptation intentions decrease with flood damage beyond a threshold of around 60% of relative damage.

A potential explanation for the decline of FDM intentions beyond the damage threshold of around 60% is that households may perceive measures as no longer meaningful because flood damage was too high to cope with. These findings are in line with existing literature[36], where it was found that respondents affected by severe flash flooding perceived adaptation actions as less effective compared to households affected by less severe flood events. Households experiencing severe flood events may be more inclined to relocate, as they are more likely to perceive the flood risk as too high to continue adapting and may choose to move to safer locations[23]. A total of 3.9% of the group that experienced flood damage above the threshold of 60% moved to a safer location, compared to only 0.9% in the group below the threshold. A *t*-test ($t(550) = -2.43$) and a Wilcoxon-Rank Sum test ($z = -1.9$) confirm that households experiencing flood damage above the 60% threshold are significantly more likely to relocate than those with lower levels of damage.

Respondents were also asked to what extent they personally felt responsible for reducing flood damage in their homes. Table 2 shows that respondents who had a higher sense of adaptation responsibility also intended to undertake more FDM actions. Potential explanations for this can be that respondents with a higher trust in public protection programmes feel less inclined to take actions in the future to reduce flood damage in their homes[1,18,19].

In line with the empirical literature, we also apply a more classical approach of PMT using perceived likelihood of a future flood event for threat appraisal, cost appraisal, response efficacy, and self-efficacy as coping appraisal in Supplementary Table 4. We observe that the coefficient of the number of measures in place after flooding and the socioeconomic indicator remain constant compared to the baseline models in Table 2. Looking at new variables, it stands out that the respondent's perceived likelihood of the event is positively and significantly associated with adaptation intentions. Homeowners who expect a flood event to be very likely in the future are more inclined to take further adaptation measures compared to homeowners who do not believe such a flood event to happen again soon. Additionally, we find a positive and significant coefficient for *response efficacy*, which indicates that the perceived effectiveness of adaptation measures contributes to a higher uptake of these measures. We do not identify significant coefficients for self-efficacy (i.e., the respondent's confidence in their ability to implement adaptation measures) and cost appraisal (i.e., the perceived burden or financial costs of adaptation measures).

Discussion and conclusion

With increasing climate risks, it is essential to gain an understanding of household adaptation behaviour and the limits to these adaptation options[24,47,48]. We find evidence of financial, institutional, and psychological barriers to adaptation on the building level. The majority of research on private adaptation behaviour focuses on single-country contexts, with limited case studies taking a transboundary perspective to identify shared patterns or key differences[16]. To address this research gap, we analysed unique post-disaster survey data from 719 homeowners in Germany, Belgium, and the Netherlands. These countries had been affected by the same flood event in 2021, which allows us to assess differences and patterns in post-disaster adaptive behaviour across borders and identify barriers to adaptation. Using fixed effects, we find that after flooding, Belgian homeowners have taken significantly fewer adaptation actions compared to their Dutch counterparts, while German homeowners show the highest level of adaptation uptake after flooding. For post-disaster adaptation intentions, we find no significant differences between Germany and the Netherlands. We also identify patterns that are consistent across countries.

Across all countries, we found that flood insurance coverage is associated with post-disaster adaptation actions, which suggests the absence of moral hazard. Government and insurance compensation provide financial resources for homeowners to rebuild shortly after flooding, also creating financial capacity to improve preparedness with their own financial means[47,49,50]. Access to insurance compensation varies significantly between countries. In the Netherlands, flood insurance compensation is often ambiguous and uncertain[34]. In Belgium, flooding is covered under fire insurance, but only if the property was built at least eighteen months before the area was designated as a flood hazard zone[35]. In Germany, flooding coverage is optional under homeowners' insurance, but homes in high-risk zones are usually excluded[10,51]. Hence, a part of our sample in Germany did not have access to insurance compensation. We observe varying levels of insurance uptake across the countries (Supplementary Table 1). Additionally, insurance compensation typically only covers rebuilding structures to their pre-flood condition[51], rather than rebuilding in a more resilient way. 'Building Back Better' policies that promote greater insurance uptake and ensure clear, straightforward compensation for flood damage – including (partial) coverage for resilient rebuilding - could support both post-disaster recovery and future flood preparedness[49,52].

Next, we identified institutional barriers to adaptation, as policies around flood insurance and public flood protection programmes shape household adaptation behaviour. We identified a group inherently more willing to take flood adaptation measures in their homes, as more implemented measures before flooding are associated with a higher willingness to implement future FDM measures. However, we also found that some German and Dutch homeowners take less personal responsibility for reducing flood damage in their homes[23,53]. Strong reliance on public protection programmes may reduce the urgency for households to take proactive measures at the building level, especially in the Netherlands[18,19,36], even though these actions are crucial in reducing flood damage when dykes fail[3].

The final barrier to adaptation that has been found is psychological, as we find that recent flood experiences and perceived likelihood of a future flood event affect adaptation behaviour. A comparison of post-disaster adaptation across countries revealed that relatively few adaptive actions after flooding have been taken in Belgium. A movement in the Belgian media attributed the flood event to a human error in dam management without supporting evidence[43–46]. As a result, a large share of Belgian respondents indicated that they did not expect a flood event to happen again in the future, indicating that they have a low threat appraisal. This also highlights the important role of news outlets and attribution studies in shaping household flood perceptions and adaptation behaviour after flooding[8,54,55]. Miscommunication or misinformation in the aftermath of disasters can undermine public trust in flood risk management and reduce motivation for private FDM measures[56]. Addressing this challenge requires transparent communication strategies and the promotion of scientific attribution studies. Strengthening collaboration between scientists, policymakers, and media could further support informed post-disaster decision-making.

A nonlinear relationship between experienced flood damage and the intention of households to take adaptation measures in their homes was identified (Table 2 & Supplementary Fig. 1). At damage levels up to 60% of the total building value, adaptive intentions become stronger with higher flood damage. However, beyond this threshold, adaptive intentions are reduced with an increased likelihood of migration to safer areas, regardless of insurance uptake. This suggests that households are willing to adapt to a certain level and that increasing flood risks can also be a driver of migration[4,17,51,52]. Severe flood experiences may surpass a psychological threshold, where private adaptation actions are perceived as insufficient[36], prompting homeowners to relocate instead of further adapting their current homes. This may even be amplified, as our survey could not reach all homeowners who moved away after flooding. For households with moderate experience of flood damage, however, adaptation intentions remain more consistent, emphasising incremental measures to reduce future flood risks.

Our findings carry implications for flood risk management and policy. Policies must not only encourage private adaptation but also critically assess the financial, institutional, and psychological barriers to adaptation. Policies can address these limits, but a critical analysis of whether some regions will remain viable for housing with increasing flood risks has to be undertaken[57]. Policies that enable information sharing on flood risk and adaptation options in flood-prone areas help overcome psychological and financial barriers to adaptation, enabling preparedness for future flood events.

Methodology

Data collection

We use a harmonised dataset from three independently distributed questionnaires in Germany, Belgium, and the Netherlands. All survey data was collected in the area that had been flooded during the 2021 summer floods, and all respondents gave consent for participation in the study. The survey questions were asked in the local language and later translated into English. The survey questions for all the included variables in the three surveys can be found in Supplementary Table 5. In this study, we only consider households that also experienced flood waters in their homes, as we want to assess how different homeowners respond to different flood experiences across countries. This means that tenants are excluded from the sample, which results in 222 eligible respondents in Belgium, 225 in Germany, and 272 in the Netherlands. Supplementary Table 6 shows the demographic composition of the sample, which confirms a balanced sample across the three included countries. The building characteristics differ slightly across countries, with, on average, older, smaller, and less valuable homes in Belgium compared to Germany and the Netherlands.

The Belgian data was collected through structured field surveys over the period of March 2022 and May 2023. A few weeks before data collection, sampled households were notified about the survey through posters in the area and letters providing options for scheduling an appointment with the interviewers. The Dutch data was collected through an online questionnaire six to eight months after flooding. Households located within the flooded area received a letter with an invitation to fill out the online survey. Data from Germany was collected in the states of Rhineland-Palatinate and North Rhine-Westphalia through online questionnaires, seventeen to eighteen months after flooding. In Rhineland-Palatinate, every third household that had applied for immediate disaster aid was invited by a personal letter from the district administration to participate in an online survey. In North Rhine-Westphalia, households in the affected area were sampled through advertisements on (social) media.

Belgian survey data was collected through structured face-to-face surveys, while data from Germany and the Netherlands was collected through an online survey. Online surveys allow for reaching a large group of respondents in a larger region, while also ensuring the anonymity of the respondents. However, it is possible that a selection bias is a concern; those who responded may have stronger feelings about the flood event. This may skew the data toward more extreme experiences of flooding. This selection bias is inherent in most post-disaster survey data collection efforts. However, the variation in impacts between and within countries helps mitigate this effect. The use of a structured survey ensured consistent and closed survey answers, while the regression analyses account for remaining differences through country fixed effects.

The original surveys had response rates of 14.9% in the Netherlands, 7% in Rhineland-Palatinate, and 38.2% in Belgium. Because of the sampling strategy, it was not possible to determine an exact response rate in North Rhine-Westphalia. The higher response rate in Belgium can be attributed to the smaller sample size and the use of in-person appointments. We only included a sub-sample of homeowners who were directly affected by the flooding. Although the different surveys have been collected with different goals and scopes, there was a meeting among the different research groups from the three countries before the data collection started to share past experiences and questionnaires to facilitate future data harmonisation. Hence, the surveys have a large share of variables in common, with largely similar question formats (Supplementary Table 5). The three different datasets were merged, and the harmonised dataset consists of these common variables. Adjustments were made to ensure that all variables are consistent in format and comparable across the datasets (see "Dependent variables" and "Independent variables" sections).

Dependent variables

To gain more insights into post-disaster recovery and preparedness, we study both adaptation actions directly after flooding (i.e., between flooding and answering the survey) and adaptation intentions at the time of the survey (i.e., between answering the survey and two years after flooding). Not all measures were asked in all three surveys. To ensure a consistent comparison of adaptation actions between countries, we only included FDM measures that were common in all the surveys. This resulted in five considered adaptation actions: placing water barriers, purchasing a water pump, building with water-resistant materials, moving heating and/or electrical systems to higher floors, and improving the building's stability. In line with other studies on adaptation behaviour and intentions[16,23,58], the respondents could indicate whether they have taken or intend to take these adaptation measures through the following answer options:

1. I took the measure before the flood
2. I took the measure after the flood
3. I am planning to take this measure
4. I am not planning to take this measure
5. Not possible/not applicable

Option 2 is used for post-disaster actions, the actions taken between the flood event and answering the survey. Option 3 is used to measure post-disaster adaptation intentions. The third option was not included in the Belgian survey, which means adaptation intentions can only be studied for Germany and the Netherlands. It is often shown that there is an intention-action gap regarding private adaptation actions[1,37]. Therefore, we define adaptation intentions as respondents indicating they plan to implement any FDM measures up to two years after experiencing flooding. This timeframe is long enough for individuals to make informed decisions and to wait for their insurance compensation, while it is also short enough to maintain a sense of urgency and relevance.

A standard approach to analyse adaptation actions or intentions with PMT is through the use of a binary outcome variable that has the value 1 if the variable is taken or intended and 0 otherwise[1,21]. However, this approach does not account for potential already undertaken FDM measures, as respondents cannot have the intention to implement a measure they have already implemented[16]. Hence, we use the ratio of the number of taken or intended measures and the measures still left to implement as the dependent variable[16]:

$$\textit{Adaptation ratio} = \frac{\textit{Measures taken after flooding}}{\textit{Total possible measures} - \textit{measures already taken before flooding}} \quad (1)$$

$$\textit{Intention ratio} = \frac{\textit{Intended measures}}{\textit{Total possible measures} - \textit{measures in place at the time of the survey}} \quad (2)$$

Using both the adaptation and intention ratio as dependent variables also allows for a full assessment of post-disaster recovery and preparation. Both the actions taken before flooding and after flooding are therefore also included in the intention ratio variable.

Existing literature sometimes differentiates between low- and high-effort adaptation measures[16,17], as adaptation decisions may vary depending on the type of action. However, our study only includes five common adaptation measures, which results in small groups for each measure. This leads to missing observations and a biased sample, as homeowners who have already completed all measures in a given category have no further actions to undertake or intend to take. Grouping these measures would therefore exclude a group of relatively highly adapted homeowners. For this reason, we chose to analyse all FDM measures together rather than dividing them into subgroups.

Independent variables

We analyse post-disaster adaptation actions and intentions using elements of the PMT framework. The PMT framework consists of a threat appraisal and a coping appraisal[1,21,32]. The threat appraisal indicates the homeowner's perceived threat of the flood, which is included in this study with a proxy through experienced flood damage during the July 2021 floods and experience with flooding prior to this event. Flood damage experience is operationalised as the *damage ratio*, a common practice in flood modelling studies to relate flood damage to the reconstruction value[59,60]. Working with building damage ratios normalises damage across properties and promotes comparability. Reconstruction values are based on the approach by Huizinga et al.[61], which differentiates between different countries and building sizes. Reconstruction values are corrected for 2021 price levels[62]. This resulted in a reconstruction value of €1699/m^2 footprint area in Germany, €1740/m^2 in Belgium, and €1826/m^2 in the Netherlands. Germany was characterised by the highest average and variation in damages, while the lowest average flood damage is observed in the Netherlands (Supplementary Table 1). The descriptive statistics for all independent variables for each country are included in Supplementary Table 1.

Coping appraisal describes the homeowner's perceived capability to implement adaptation measures in their home. We partly follow the coping appraisal variable through the inclusion of undergone adaptation measures, which allows for an understanding of where homeowners started before the disaster, providing context to the decisions they make afterward[16,23]. Homeowners who have already undertaken measures may also have experience with implementing FDM measures, affecting their perceptions about future actions[32]. Moreover, we included the flood insurance status in the analysis, as the insurance status reflects the respondent's financial capability to start reconstruction after flooding[41]. This variable is defined as the respondent receiving compensation or expecting to receive compensation from either household contents or home insurance.

We extend upon the PMT framework by including the homeowner's perceived personal adaptation responsibility[63]. This variable asked the respondent to assess their own responsibility for reducing flood damage in their home. A high value indicates that the respondent feels a strong sense of responsibility for reducing flood damage[36]. This variable can only be included in the intention analysis, as these values are unknown for the Belgian respondents. Additionally, this question was asked differently in the Dutch and German surveys, where a five-point scale was used in the Netherlands and a six-point scale in Germany. To ensure comparability, the middle two categories in the German survey were merged into one to create a five-point scale as well (the same has been done for the coping appraisal variables included in the additional analysis in Supplementary Table 4: self-efficacy, response efficacy, and cost appraisal). Generally, the German respondents indicated a higher sense of responsibility for reducing flood damage compared to the Dutch respondents (Supplementary Table 1).

The sensitivity analysis in Supplementary Table 4 has been performed using a more classic version of PMT. For threat appraisal, the respondent's perceived likelihood of the event is considered, while coping appraisal is represented by the variables *response efficacy, self-efficacy*, and *cost appraisal*. The Belgium survey did not ask for these indicators, while half of the respondents in the Dutch survey had been randomly selected to fill in these questions to minimise survey length. This means that the analysis in Supplementary Table 4 is based on a random selection of 50% of the Dutch respondents and all German respondents.

We include the household's socioeconomic status to account for potential barriers to adaptation. The socioeconomic indicator is determined using respondent education, household size, homeownership, and home living area, where higher scores indicate a higher socioeconomic status[64]. As described in the "Data collection" section, the surveys differ in their timing after flooding. To control for these differences, we include the number of months the survey was completed after the July 2021 flood. In the Netherlands, the exact date of the survey completion is unknown, which is addressed by adding the average number of months that the survey was available for completion for this variable.

Data analysis

The drivers of adaptation behaviour and intentions are estimated using ordinary least squares regression analyses. Respondents from all countries are grouped in the same regression analysis to make generalizable statements while also leveraging the variation in independent variables within and across the different countries to better understand how these factors influence behaviour. Linear regression models are used to estimate the adaptation and intention ratio Y_i for flooded homeowner i as a function of explanatory variables X_k:

$$Y_i = \beta_0 + \beta_1 X_{1,i} + \ldots + \beta_k X_{k,i} + a_i + \varepsilon_i \quad (3)$$

A limitation of the separate data collection across countries is that all surveys were distributed at different moments. Respondents who filled in the survey later had more time to implement adaptation actions after flooding, while losing their intention to implement this specific measure. For this reason, we control for differences in survey timing through a variable that describes how long after the flood the survey was answered (*Months after the July 2021 flood*). We control for unexplained country-level heterogeneity by including country fixed effects (α_i). These are included in the form of a binary control variable for each country that accounts for country-specific differences.

The different timing of the surveys could potentially affect the regression outcomes if there is a correlation between the timing of the surveys and another independent variable. The only variable in the regression analysis that may strongly change over time after flooding is the insurance compensation status, as insurance compensation can be less clear shortly after flooding. We performed a sensitivity analysis to identify whether the different timing of the survey affects the analysis (Supplementary Table 7). By interacting the country variables with the insurance compensation variable, we can identify if the role of insurance compensation differs between countries. The sensitivity analysis shows that the role of flood insurance does not significantly differ between countries, which gives an indication that the different timing of the surveys in each country does not affect the results found in Table 1.

The error term is represented by ε_i. Models 1–3 in Table 1 and Models 1–4 in Table 2 gradually add more variables to test for the robustness of the found coefficients, controlling if the model adds new information with a Wald test and Akaike Information Criterion (AIC) test[65]. A Variance Inflation Factor (VIF) analysis shows that multicollinearity does not form a problem for the regression analysis (all VIFs <3). Heteroskedasticity was revealed in the data through a Breusch-Pagan test, for which robust standard errors have been applied[65]. A Ramsey RESET test[66] revealed that the model has no omitted variables. In some instances, the difference between different groups will be tested using both a t-test and a Wilcoxon-rank sum test. In these cases, both the t-scores or z-scores are reported in the text.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data and code that support the findings of this study are not stored in a public repository because they contain privacy-sensitive information regarding respondents' locations, insurance status, and experienced flood losses from three independently collected surveys. Sharing this information publicly would violate the Dutch General Data Protection Regulation (AVG). Anonymised summary data used to produce Figs. 1 and 2 are provided in Supplementary Information 1.

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References

1. Van Valkengoed, A. M. & Steg, L. Meta-analyses of factors motivating climate change adaptation behaviour. *Nat. Clim. Chang.* **9**, 158–163 (2019).
2. Hirabayashi, Y. et al. Global flood risk under climate change. *Nat. Clim. Chang.* **3**, 816–821 (2013).
3. Endendijk, T. et al. Flood vulnerability models and household flood damage mitigation measures: an econometric analysis of survey data. *Water Resour. Res.* **59**, e2022WR034192 (2023).
4. Hoffmann, R., Dimitrova, A., Muttarak, R., Crespo Cuaresma, J. & Peisker, J. A meta-analysis of country-level studies on environmental change and migration. *Nat. Clim. Chang.* **10**, 904–912 (2020).
5. Schill, C. et al. A more dynamic understanding of human behaviour for the Anthropocene. *Nat. Sustain.* **2**, 1075–1082 (2019).
6. Wilson, R. S., Herziger, A., Hamilton, M. & Brooks, J. S. From incremental to transformative adaptation in individual responses to climate-exacerbated hazards. *Nat. Clim. Chang.* **10**, 200–208 (2020).
7. UN [United Nations]. Sendai framework for disaster risk reduction 2015-2030. https://www.preventionweb.net/files/43291_sendaiframeworkfordrren.pdf (2015).
8. Kijewski-Correa, T. Messaging risk to drive coastal adaptation. *Nat. Sustain.***7**, 952–953 (2024).

9. Endendijk, T. et al. Experience from the 2021 floods in the Netherlands: Household Survey Results on Impacts and Responses. *J. Coast. Riverine Flood Risk* **2**, 9–36 (2023).
10. Thieken, A. H. et al. Performance of the flood warning system in Germany in July 2021–insights from affected residents. *Nat. Hazards Earth Syst. Sci.* **23**, 973–990 (2023).
11. Dietze, M. et al. More than heavy rain turning into fast-flowing water–a landscape perspective on the 2021 Eifel floods. *Nat. Hazards Earth Syst. Sci.* **22**, 1845–1856 (2022).
12. Sahana, M., Dhali, M. K. & Lindley, S. Global disparities in transboundary river research have implications for sustainable management. *Commun. Earth Environ.* **5**, 786 (2024).
13. Kievik, M. & Gutteling, J. M. Yes, we can: motivate Dutch citizens to engage in self-protective behavior with regard to flood risks. *Nat. hazards* **59**, 1475–1490 (2011).
14. Köhler, L. & Han, S. The driving effect of experience: how perceived frequency of floods and feeling of loss of control are linked to household-level adaptation. *Int. J. Disaster Risk Reduct.* **121**, 104745 (2024).
15. Richert, C., Erdlenbruch, K. & Figuières, C. The determinants of households' flood mitigation decisions in France-on the possibility of feedback effects from past investments. *Ecol. Econ.* **131**, 342–352 (2017).
16. Noll, B., Filatova, T. & Need, A. How does private adaptation motivation to climate change vary across cultures? Evidence from a meta-analysis. *Int. J. Disaster Risk Reduct.* **46**, 101615 (2020).
17. Duijndam, S. J. *Floods of Movement: Drivers of Human Migration under Sea-Level Rise and Flood Risk*. PhD Thesis, Research and graduation internal, Vrije Universiteit Amsterdam (2024).
18. Mol, J. M., Botzen, W. J. W., Blasch, J. & de Moel, H. Insights into flood risk misperceptions of homeowners. *Risk Anal.* **40**, 1450–1468 (2020).
19. Hudson, P., Bubeck, P. & Thieken, A. H. A comparison of flood-protective decision-making between German households and businesses. *Mitig. Adapt. Strateg. Glob. Chang.* **27**, 5 (2022).
20. Gersonius, B., Van Buuren, A., Zethof, M., & Kelder, E. Resilient flood risk strategies: Institutional preconditions for implementation. *Ecol. Soc.* **21**, 28–39 (2016).
21. Bamberg, S., Masson, T., Brewitt, K. & Nemetschek, N. Threat, coping and flood prevention–A meta-analysis. *J. Environ. Psychol.* **54**, 116–126 (2017).
22. Demski, C., Capstick, S., Pidgeon, N., Sposato, R. G. & Spence, A. Experience of extreme weather affects climate change mitigation and adaptation responses. *Clim. Chang.* **140**, 149–164 (2017).
23. Duijndam, S. J. et al. A look into our future under climate change? Adaptation and migration intentions following extreme flooding in the Netherlands. *Int. J. Disaster Risk Reduct.* **95**, 103840 (2023).
24. Aerts, J. C. et al. Exploring the limits and gaps of flood adaptation. *Nat. Water* **2**, 719–728 (2024).
25. Köhler, L., Masson, T., Köhler, S. & Kuhlicke, C. Better prepared but less resilient: the paradoxical impact of frequent flood experience on adaptive behavior and resilience. *Nat. Hazards Earth Syst. Sci.* **23**, 2787–2806 (2023).
26. Brunner, M. I. et al. An extremeness threshold determines the regional response of floods to changes in rainfall extremes. *Commun. Earth Environ.* **2**, 173 (2021).
27. Poussin, J. K., Botzen, W. J. W. & Aerts, J. C. Factors of influence on flood damage mitigation behaviour by households. *Environ. Sci. Policy* **40**, 69–77 (2014).
28. Dewals, B., Erpicum, S., Pirotton, M. & Archambeau, P. Extreme floods in Belgium. The July 2021 extreme floods in the Belgian part of the Meuse basin. In *Hydrolink 2021/4. Madrid: International Association for Hydro-Environment Engineering and Research (IAHR)* 104–107 (Hydraulic Engineering Repository, 2021).
29. Kuhlicke, C. et al. Spinning in circles? A systematic review on the role of theory in social vulnerability, resilience and adaptation research. *Glob. Environ. Chang.* **80**, 102672 (2023).
30. Rogers, R. W. A protection motivation theory of fear appeals and attitude change. *J. Psychol.* **91**, 93–114 (1975).
31. Grothmann, T. & Reusswig, F. People at risk of flooding: why some residents take precautionary action while others do not. *Nat. Hazards* **38**, 101–120 (2006).
32. Bubeck, P., Botzen, W. J. W. & Aerts, J. C. A review of risk perceptions and other factors that influence flood mitigation behavior. *Risk Anal.***32**, 1481–1495 (2012).
33. Noll, B., Filatova, T., Need, A. & Taberna, A. Contextualizing cross-national patterns in household climate change adaptation. *Nat. Clim. Chang.* **12**, 30–35 (2022).
34. Seifert, I., Botzen, W. W., Kreibich, H. & Aerts, J. C. Influence of flood risk characteristics on flood insurance demand: a comparison between Germany and the Netherlands. *Nat. Hazards Earth Syst. Sci.* **13**, 1691–1705 (2013).
35. FPS Belgium (n.d.). *Natural disasters - Flooding*. FPS Economy. https://economie.fgov.be/en/themes/financial-services/insurance/fire-and-natural-disaster/other-risks/mandatory-risks/natural-disasters/natural-disasters-flooding.
36. Dillenardt, L. & Thieken, A. H. Individual flood risk adaptation in Germany: exploring the role of different types of flooding. *EGUsphere* **2024**, 1–28 (2024).
37. Bubeck, P., Berghäuser, L., Hudson, P. & Thieken, A. H. Using panel data to understand the dynamics of human behavior in response to flooding. *Risk Anal.* **40**, 2340–2359 (2020).
38. Birkmann, J. et al. Strengthening resilience in reconstruction after extreme events–Insights from flood affected communities in Germany. *Int. J. Disaster Risk Reduct.* **96**, 103965 (2023).
39. Thieken, A. H., Petrow, T., Kreibich, H. & Merz, B. Insurability and mitigation of flood losses in private households in Germany. *Risk Anal.* **26**, 383–395 (2006).
40. Husby, T. G., De Groot, H. L., Hofkes, M. W. & Dröes, M. I. Do floods have permanent effects? Evidence from the Netherlands. *J. Reg. Sci.* **54**, 355–377 (2014).
41. Hudson, P., Botzen, W. J. W., Czajkowski, J. & Kreibich, H. Moral hazard in natural disaster insurance markets: empirical evidence from Germany and the United States. *Land Econ.* **93**, 179–208 (2017).
42. Ooms, V., Endendijk, T., Aerts, J. C., Botzen, W. W., & Robinson, P. J. Assessing the drivers of flood risk reduction actions of businesses. *The Geneva Papers on Risk and Insurance-Issues and Practice*. **50**, 1–30 (2024).
43. Counasse, P. X. Inondations: y a-t-il eu une erreur dans la gestion des barrages? *Le Soir*. [in French] https://www.lesoir.be/387684/article/2021-08-04/inondations-y-t-il-eu-une-erreur-dans-la-gestion-des-barrages (2021).
44. RTL Info. Damien Ernst: une erreur "colossale" au barrage d'Eupen est la cause de la gravité des inondations dans les. *RTL Info*. [in French] https://www.rtl.be/actu/damien-ernst-une-erreur-colossale-au-barrage-deupen-est-la-cause-de-la-gravite/2021-07-19/article/407329 (2021).
45. Tradowsky, J. S. et al. Attribution of the heavy rainfall events leading to severe flooding in Western Europe during July 2021. *Clim. Chang.* **176**, 90 (2023).
46. Journée, M., Goudenhoofdt, E., Vannitsem, S. & Delobbe, L. Quantitative rainfall analysis of the 2021 mid-July flood event in Belgium. *Hydrol. Earth Syst. Sci.* **27**, 3169–3189 (2023).
47. Berrang-Ford, L. et al. A systematic global stocktake of evidence on human adaptation to climate change. *Nat. Clim. Chang.* **11**, 989–1000 (2021).
48. Sauer, I. J. et al. Limited progress in global reduction of vulnerability to flood impacts over the past two decades. *Commun. Earth Environ.* **5**, 239 (2024).
49. de Ruig, L. T. et al. How the USA can benefit from risk-based premiums combined with flood protection. *Nat. Clim. Chang.* **12**, 995–998 (2022).

50. Lu, S. & Nakhmurina, A. Financial constraints and short-term planning are linked to flood risk adaptation gaps in US cities. *Commun. Earth Environ.* **5**, 43 (2024).
51. Surminski, S. & Thieken, A. H. Promoting flood risk reduction: the role of insurance in Germany and England. *Earth's Future* **5**, 979–1001 (2017).
52. Tesselaar, M., Botzen, W. W., Tiggeloven, T. & Aerts, J. C. Flood insurance is a driver of population growth in European floodplains. *Nat. Commun.* **14**, 7483 (2023).
53. Berghäuser, L., Bubeck, P., Hudson, P. & Thieken, A. H. Identifying and characterising individual flood precautionary behaviour dynamics from panel data. *Int. J. Disaster Risk Reduct.* **94**, 103835 (2023).
54. Aerts, J. C. et al. Integrating human behaviour dynamics into flood disaster risk assessment. *Nat. Clim. Chang.* **8**, 193–199 (2018).
55. Mildenberger, M. et al. Unintended consequences of using maps to communicate sea-level rise. *Nat. Sustain.* **7**, 1018–1026 (2024).
56. Daume, S. Online misinformation during extreme weather emergencies: short-term information hazard or long-term influence on climate change perceptions?. *Environ. Res. Commun.* **6**, 022001 (2024).
57. Reimann, L. et al. Exploring spatial Feedbacks between adaptation policies and internal migration patterns due to sea-level rise. *Nat. Commun.* **14**, 2630 (2023).
58. Kienzler, S., Pech, I., Kreibich, H., Müller, M. & Thieken, A. H. After the extreme flood in 2002: changes in preparedness, response and recovery of flood-affected residents in Germany between 2005 and 2011. *Nat. Hazards Earth Syst. Sci.* **15**, 505–526 (2015).
59. Ward, P. J. et al. A global framework for future costs and benefits of river-flood protection in urban areas. *Nat. Clim. Chang.* **7**, 642–646 (2017).
60. Wing, O. E., Pinter, N., Bates, P. D. & Kousky, C. New insights into US flood vulnerability revealed from flood insurance big data. *Nat. Commun.* **11**, 1444 (2020).
61. Huizinga, J., De Moel, H., & Szewczyk, W. *Global Flood Depth-Damage Functions: Methodology and the Database with Guidelines* (Joint Research Centre, 2017).
62. CPI Inflation Corrector. *Euro Inflation Calculator, 2010-2021*. https://www.in2013dollars.com/Euro-inflation (2024).
63. Dillenardt, L., Hudson, P. & Thieken, A. H. Urban pluvial flood adaptation: results of a household survey across four German municipalities. *J. Flood Risk Manag.* **15**, e12748 (2022).
64. Merz, B., Kreibich, H. & Lall, U. Multi-variate flood damage assessment: a tree-based data-mining approach. *Nat. Hazards Earth Syst. Sci.* **13**, 53–64 (2013).
65. Woolridge, J. M. *Introduction to Econometrics* (Europe, Middle East & Africa Edition) Cengage Learning EMEA, Andover, United Kingdom, 2014).
66. Ramsey, J. B. Tests for specification errors in classical linear least-squares regression analysis. *J. R. Stat. Soc. Ser. B Stat. Methodol.* **31**, 350–371 (1969).

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Author contributions

T.E.: Conceptualisation, Methodology, Formal Analysis, Investigation, Data Curation, Writing – Original Draft. D.R.C.: Investigation, Data Curation, Writing - Review & Editing, Supervision. L.D.: Investigation, Data Curation, Writing - Review & Editing, Supervision. R.K.G.: Investigation, Data Curation, Writing - Review & Editing, Supervision. W.B.: Writing - Review & Editing, Supervision. H.d.M.: Writing - Review & Editing, Supervision. A.T.: Writing - Review & Editing, Supervision. H.K.: Writing - Review & Editing, Supervision. B.D.: Writing - Review & Editing, Supervision. J.A.: Writing - Review & Editing, Supervision.

Competing interests

The authors declare no competing interests.

Additional information

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