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Urban pluvial flood adaptation: Results of a household survey across four German municipalities

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Abstract

In recent years, German cities were heavily impacted by pluvial flooding and related damage is projected to increase due to climate change and urbanisation. It is important to ask how to improve urban pluvial flood risk management. To understand the current state of property level adaptation, a survey was conducted in four municipalities that had recently been impacted by pluvial flooding. A hybrid framework based on the Protection Motivation Theory (PMT) and the Protection Action Decision Model (PADM) was used to investigate drivers of adaptive behaviour through both descriptive and regression analyses. Descriptive statistics revealed that participants tended to instal more low- and medium-cost measures than high-cost measures. Regression analyses showed that coping appraisal increased protection motivation, but that the adaptive behaviour also depends on framing factors, particularly homeownership. We further found that, while threat appraisal solely affects protection motivation and responsibility appraisal affects solely maladaptive thinking, coping appraisal affects both. Our results indicate that PMT is a solid starting point to study adaptive behaviours in the context of pluvial flooding, but we need to go beyond that by, for instance, considering factors of the PADM, such as responsibility, ownership, or respondent age, to fully understand this complex decision-making process.

KEYWORDS

adaptive behaviour, integrated flood risk management, property-level adaptation, urban flooding

1 | INTRODUCTION

In recent years, pluvial flooding has heavily impacted urban areas all over the world, e.g. several cities in Turkey between 2015 and 2020 (Koç et al., 2021), Beijing (China) in 2012 (Liu & Jensen, 2017), Sao Paulo (Brazil) in 2011 (Valverde & dos Santos, 2014), Copenhagen (Denmark) in 2011 (Liu & Jensen, 2017), Hull (UK) in 2007 (Coulthard & Frostick, 2010), and Heywood (UK) in 2004 and 2006 (Douglas et al., 2010). German municipalities have been heavily impacted, too. For instance, the city of Münster was flooded in July 2014, causing insured losses to private households of €75 million (GDV, 2017a). From May to June 2016, several heavy rain events in Germany caused €800 million in insured damages (GDV, 2017a). In 2017, a heavy rain event caused ~€60 million of insured losses in Potsdam and Berlin (GDV, 2017b).

Flooding is a significant global problem, and in the case of river flooding the implementation of adaptive measures was found to significantly reduce property-level flood damage cost-effectively (DEFRA, 2008; Hudson et al., 2014; Kreibich et al., 2011; Lamond et al., 2018; Poussin et al., 2015). Adaptive measures must be implemented by flood-prone residents, thus their adaptive behaviour needs to be well understood. This is important for integrated flood risk management, in which all stakeholders actively and collaboratively manage flood risk Bubeck et al. (2016), (Kuhlicke et al., 2020). This is also relevant because protective infrastructure cannot provide full safety, thus complementary action is required to limit flood impacts.

Therefore, several studies have tested socio-psychological models of adaptive behaviour in the context of fluvial flooding, e.g., Bubeck et al. (2018), Grothmann and Reusswig (2006), and Lindell and Perry (2012). Although many of the adaptive measures studied by these authors are applicable to both fluvial and pluvial flooding, the differences between the two types of flooding may cause the decision-making process underlying adaptive responses to vary. Some key differences between the two flood types are: (a) pluvial flooding can potentially occur anywhere and is not tied to the presence of water bodies; and (b) hazard maps for pluvial flooding are often not available, unlike the widespread availability of (river) flood hazard maps with clear(er) hazard zones. This could result, for instance, in a limited recognition of pluvial flooding as a threat. Taken together, this could induce different cognitive processes leading to different adaptations towards different flood types. Therefore, while the same theoretical frameworks can be used, their applicability and strengths across various hazards can differ. Consequently, a larger evidence base is required, especially given the ongoing arguments about a replication crisis in science (Baker, 2016; Maxwell et al., 2015). Moreover, the results produced by socio-psychological models can depend quite strongly on the local socio-cultural context.

We extend the scientific literature on flood-adaptive behaviour by investigating adaptive behaviour towards pluvial flooding in two stages. First, descriptive analyses were used to indicate the characteristics of respondents' most recent pluvial flood event and the type of adaptive measures respondents implemented or planned to implement to protect themselves, providing a baseline of knowledge not previously considered for these cities. Second, a structural statistical modelling approach was used to test the suitability of a hybrid framework to explain adaptive behaviour. We developed a hybrid framework based on two popular socio-psychological models of adaptive behaviour: The Protection Motivation Theory (PMT) (Rogers, 1975, 1983) and the Protection Action Decision Model (PADM) (Lindell & Perry, 2012). A detailed description of both models can be found in Section 2.3. We extended PMT with important factors derived from PADM. We considered the residents' appraisal of their responsibility and relevant socio-demographic characteristics (e.g., income, ownership, or age), and integrate maladaptive thinking as a core variable potentially inhibiting adaptive behaviour. In addition, we tested the capabilities of our hybrid model more formally with a structural modelling approach, aiming to enable an understanding of the entire decision-making process as a necessary basis for developing ways to promote adaptive behaviour of potentially affected households.

This analysis uses data collected from a harmonised survey deployed in four German municipalities of varying sizes and socio-environmental contexts that were recently hit by heavy rainfall events of different severities. Therefore, the sample composition allows us to obtain more robust and relevant results for Germany as a whole.

Our goal is to identify not only the drivers of pluvial flooding adaptive behaviour, but also how these drivers interact with each other to gain a deeper understanding of the overall decision-making process. We explore the following hypotheses:

> **Hypothesis 1.** Other studies identified coping and threat appraisal as important drivers of adaptive behaviour in the context of fluvial flooding, for example, Bamberg et al. (2017), Bubeck et al. (2018); Grothmann and Reusswig (2006); Poussin et al. (2014); Terpstra and Lindell (2012), and we expect these drivers to also play a central role for pluvial flooding.

> **Hypothesis 2.** Furthermore, we expect that the extensions from PADM, as well as the consideration of all linkages in our extended hybrid model, will provide an additional understanding of what forms an adaptive response. For example, we extend the structural approach by Bamberg et al. (2017) to include maladaptive thinking, which in theory should be negatively related to adaptive outcomes. This provides both a new application and a methodological extension.

2 | DATA AND METHODS

2.1 | Surveying four German municipalities

A household survey was conducted in the German cities of Berlin, Potsdam, Remscheid, and Leegebruch between July 2019 and June 2020, covering three federal states (see Table 1). These cities were selected based on their different geographic settings (e.g., Leegebruch is located

TABLE 1 Demographic information of participants derived from the survey "Starkregen im Fokus" conducted in four German municipalities between June 2019 and August 2020. Data on age and gender are compared with census data from 2011, but it should be noted that these only differentiate genders into female and male

	Berlin	Potsdam	Remscheid	Leegebruch	Total
Information about the four municipalities					
Federal state	Berlin	Brandenburg	North Rhine-Westphalia	Brandenburg	—
Total area of the city (km^2)	893	189	75	6	—
Residents	3.3 million (DeStatis, 2020)	160,000 (DeStatis, 2020)	110,000 (DeStatis, 2020)	6800	—
Recent heavy rain events	2017, 2018, 2019	2017, 2018, 2019	2018	2017	—
Demographic information about the survey participants					
Number of participants	115	119	64	96	394
Participants [%]	29.2	30.2	16.2	24.4	100
Age [years]	49	49	57	56	53
Age Census2011 [years][a]	50	49	52	52	51 (DL)
Gender (male/female/diverse) [%]	48/50/3	55/41/4	57/41/2	40/59/1	50/48/2
Gender (m/f/d) [%] Census2011	(49/51/–)	(47/53/–)	(48/52/–)	(49/51/–)	(48/52/–)
Homeowners [%] per subsample	34	60	68	90	61

[a]Since all participants were older than 21, we excluded data of respondents younger than 20 from the 2011 census before comparing the datasets.

in a low-lying area, while Remscheid's topography can be described as hilly) and socio-economic contexts (e.g. Leegebruch is a very small town, Potsdam a medium-sized city, and Berlin a big city). Furthermore, all four municipalities were recently affected by heavy rainfall. Information on their size, the number of residents, and the occurrence of recent heavy rainfall events can be found in Table 1. Since the survey aimed to study the impact of heavy rainfall events, only affected households were surveyed. To identify the areas affected by pluvial floods within the four municipalities, media reports, fire brigade notifications, and social media activity were used.

The survey was conducted in three waves. For the first wave (July–September 2019), a professional survey company contacted a random sample of 500 households each in Potsdam, Remscheid, and Leegebruch within the identified affected areas, for a total of 1500 contacted households. The survey company delivered printed questionnaires solely to households located on the ground floor of buildings. After a few weeks, reminders were sent out and households were contacted by phone. In the second wave (September–November 2019), flyers were distributed within the affected areas in Potsdam and Leegebruch. In Remscheid, flyers were sent with the local newspapers. People could participate online via a link or QR code. During the third wave (March–June 2020), the online questionnaire was advertised on posters in affected areas of Berlin. It was also advertised using online platforms for neighbourhood networking. During the second and third waves, people had the option of sharing the survey within their personal networks. During the first wave, the response rate was 11.46%. Since respondents could participate online in the other two waves and the survey was widely advertised and shared by individuals and online forums, we cannot say how many people we reached and therefore cannot give a concrete response rate. However, the survey design allows us to exclude the possibility that respondents participated twice in the survey or were ineligible, meaning they had not been affected by pluvial flooding. Altogether, 394 household responses were gathered.

The demographic information of people surveyed in the four municipalities and the official census data are depicted in Table 1. Overall, the survey respondents have a median age of 53 years and are thus 2 years older than the average German. The participants displayed a split of 50% male, 48% female, and 2% non-binary. This is a slightly higher proportion of male participants compared to the 2011 census (48% male, 52% female)˙ With respect to age and gender, our sample is considered sufficiently representative of the underlying population.

2.2 | Adaptive behaviour in the context of pluvial flooding

Figure 1 indicates the adaptive behaviours studied. These measures can all be considered adaptive measures, as an overall category, that must be implemented before a flood to reduce damage, and can be divided into low, medium, and high-cost measures (Rözer et al., 2016). Furthermore, they can be categorised as risk transfer, protective, and mitigative measures. Protective and mitigative measures aim to limit potential flood damage by preventing water entry (protective) or limiting negative impacts (mitigative). Risk transfer is a complementary measure that helps the insured recover faster even if not directly reducing the potential flood damage.

2.3 | Identifying drivers of adaptive behaviour

To explain flood-prone residents' adaptive behaviour, two psychological models are increasingly mentioned: PMT (Rogers, 1975, 1983), which is more frequently used, and the (2) PADM (Lindell & Perry, 2012).

PMT is a socio-psychology model of the drivers of adaptive behaviour (Bubeck et al., 2018; Grothmann & Reusswig, 2006; Poussin et al., 2014) and has been used to investigate and understand why people adapt to flooding. It assumes that an adaptive response is the outcome of multiple processes: the decision-maker assesses the threat (threat appraisal), then considers the options for coping with the threat (coping appraisal). Once the threat and coping appraisals have reached a sufficient threshold, a sufficient adaptive motivation is assumed to occur, leading to actual adaptive behaviours. Otherwise, it leads to a non-adaptive motivation and emotional coping via maladaptive thinking (e.g., denial or fatalism). Whether a protection motivation leads to an adaptive behaviour further depends on actual barriers that may hinder the step from motivation to action (Grothmann & Reusswig, 2006).

PADM (Lindell & Perry, 2012) creates a broader context around the drivers considered by PMT by including not only the pre-decision process, but how it depends on the resources available to an individual. Furthermore, the appraisal section, while named differently in PMT, is functionally similar but supplemented by the perceived stakeholder responsibility. Applying the more complex PADM to flood-adaptive behaviour provides valuable insights into such decision-making processes. However, the higher model complexity places greater demands on an input dataset.

To take advantage of both models, we employed a hybrid framework. Our hybrid model considers threat and coping appraisal as described by Grothmann and Reusswig (2006), responsibility appraisal as described by Lindell and Perry (2012), and maladaptive thinking as described by Grothmann and Reusswig (2006). In our hybrid model, maladaptive thinking and protection motivation form the basis for adaptive behaviour. Whether a person undertakes adaptive behaviour ultimately depends on actual barriers (Grothmann & Reusswig, 2006) and the person's socioeconomic context (Lindell & Perry, 2012), which we describe as framing factors (Figure 2). By adding the most novel extensions from PADM to PMT, we can make the best use of our database to understand the decision process in more detail than would have been possible with PMT alone.

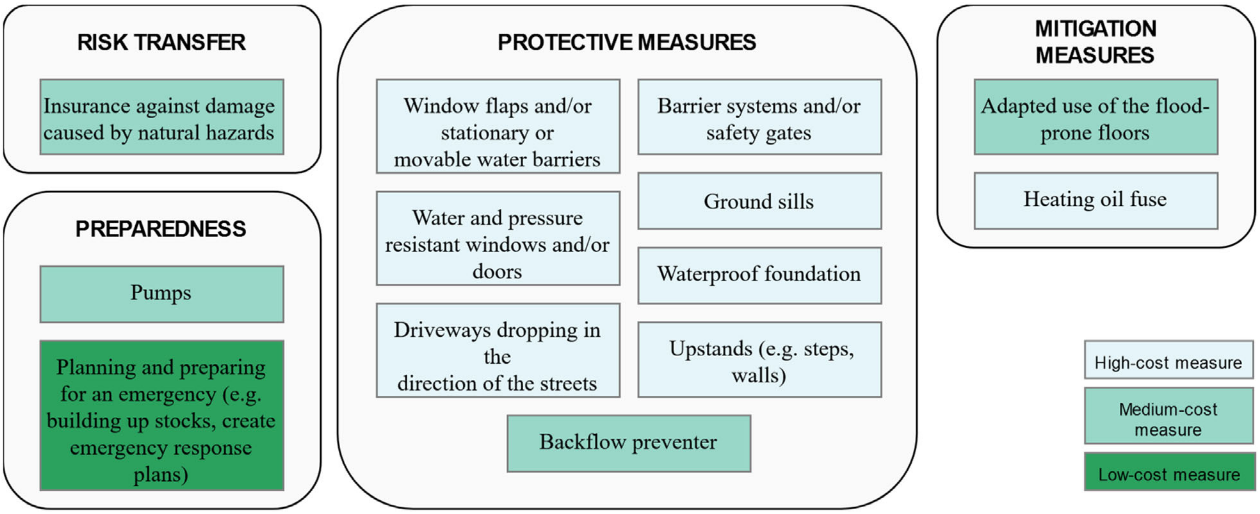

FIGURE 1 Adaptive behaviours focusing on precautionary measures asked in the survey, categorised into low-, medium- and high-cost measures (colours) and mitigation, protection, preparedness, and risk transfer (boxes)

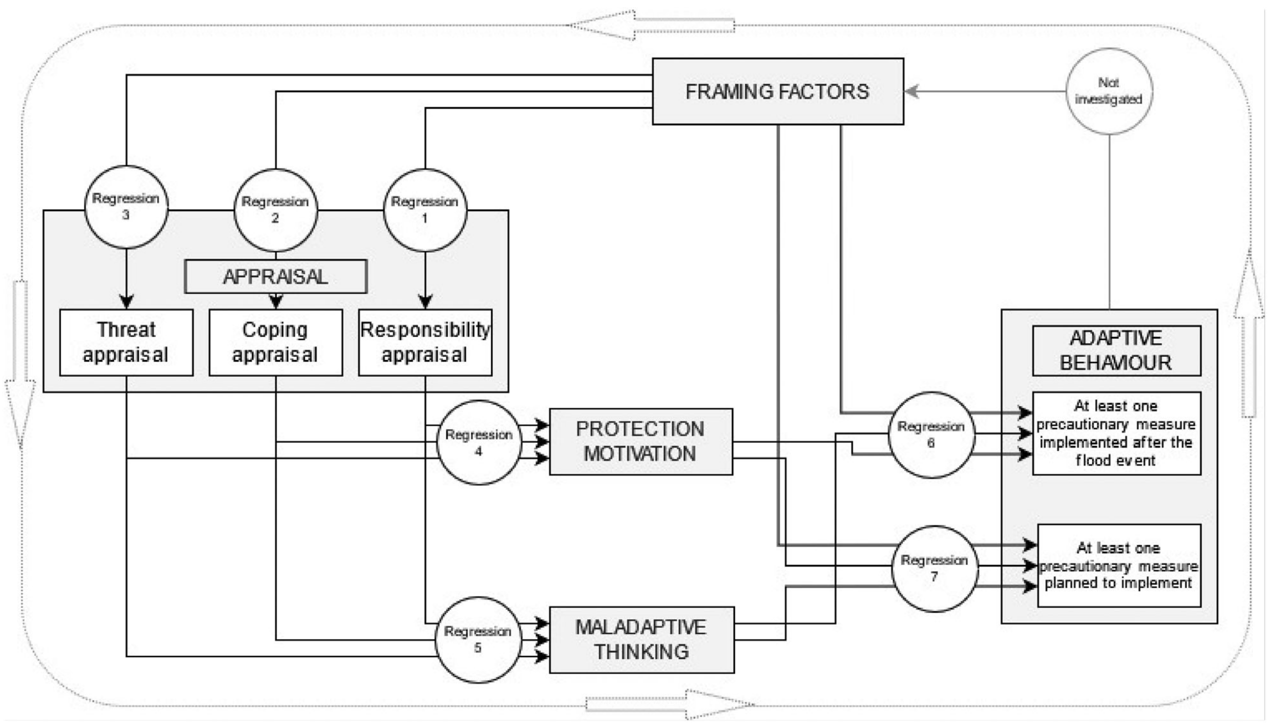

FIGURE 2 Hybrid model based on (Grothmann & Reusswig, 2006) and (Lindell & Perry, 2012). Linkages within the hybrid model are investigated by the use of 7 regression models (Regression 1–7); lines are used to illustrate a regression with its explanatory variables (origin of the lines) and the dependent variable of the respective regression (end-points of lines)

In the present analysis, we assume that these processes do not run sequentially, but simultaneously. That is, a person does not first assess the risk, then the coping options, and then develops either protection motivation or maladaptive thinking, but rather all these processes run side by side once the risk has been identified. Thus, we consider the possibility that a person may, for example, implement measures (show an adaptive response) and at the same time also display maladaptive thinking. In our application to flooding, a maladaptive outcome or behaviour would mean the person takes no adaptive action. In contrast, maladaptive thinking describes an emotional coping response to the threat. This is because rather than being proactive and dealing with the threat, the person employs emotional coping mechanisms, which reduces the probability of taking adaptive actions. Therefore, both protective motivation and maladaptive thinking can appear simultaneously and influence whether or not maladaptive outcomes occur.

2.4 | Operationalising the survey data for the descriptive and regression-based analysis of precautionary adaptive behaviour

Figure 2 displays the schematic of the hybrid model, while also indicating the steps of the regression analyses. There is no direct starting point within the process described in Figure 2. Table 2 presents all the questionnaire items used to build the hybrid model. Threat appraisal is described by the item “perceived probability of a future damaging event”. Coping appraisal is captured by the items “perceived response efficacy”, “perceived response costs”, and “perceived self-efficacy”. Responsibility appraisal is described by two items: “perceived self-responsibility” and “perceived responsibility of the government”. Since coping appraisal and responsibility appraisal are captured by several items, these were aggregated to produce one index for each factor by taking the average value of the single items once the items' scales were converted to use the same direction. This reduced the complexity of the model in a way that fit with the underlying theoretical framework, as is appropriate in a structural statistical modelling approach. For instance, PMT states that coping appraisal is composed of three sub-units, each of which we queried with a single-item question. Therefore, the theoretical aggregation gained primacy.

These three drivers affect (1) protection motivation, that is, how motivated people are stated to be to take any action to protect their home, and (2) maladaptive thinking, calculated as the mean average response to the following three items: (a) delayed adaptation, (b) denial (of the threat), and (c) fatalistic thinking. Both protection motivation and maladaptive thinking form the desire to (not) carry out adaptive behaviour. We measure adaptive behaviour by whether an individual intends to or has taken at least one precautionary measure (see Figure 1). The number of measures employed was not counted, as different households could not apply all proposed measures and therefore it would be inappropriate to describe one household as more active than another based on the absolute number of measures.

Framing factors are considered to influence whether a person can perform adaptive behaviour. These factors are: (1) household income, (2) respondent age, (3) being informed about adaptive behaviours, (4) measures taken before the last event, (5) homeownership, (6) gender, and (7) Leegebruch as a dummy variable. Respondents were asked to assign their household income to one of six categories. We used the median household income in Germany of € 3,726 (see Table 2) as a threshold to divide respondents' income into the two classes of “below the median household income” and “above the median income”. We were thus able to simplify income to a single variable rather than five. It also provided a simple indicator of the relative resources available to a household. To classify respondents' age, we chose the retirement age of 65 as a threshold because it is reasonable to assume that the population below this threshold has other financial and time resources. Above this threshold, the likelihood of health problems increases, too. While this threshold may not perfectly capture all individual cases, it provides a threshold that can be easily integrated into the definitions currently used in government policy and corporations. Being informed about precautions captures whether individuals have sought information about adaptive behaviour on their own and/or believe they have been adequately informed by their community. Measures in place before the event capture adaptive measures taken before the last flood event. A binary code of 0 (no measures) and 1 (one or more measures) is used to capture this theme. Binary codes are further used to distinguish homeowners from participants who do not own the house/apartment in which they live, the gender of participants, and the dummy variable Leegebruch to distinguish small towns from larger cities (see Table 2). With reference to how we classify gender, it should be noted that the “non-binary” gender is not individually considered because the subsample would be too small.

The elements of the model are justified by the underlying theories and known influencing factors, for example, Bubeck et al. (2012); Bubeck et al. (2018), and Grothmann and Reusswig (2006).

TABLE 2 Overview of items used from the household survey, their classification in the hybrid model (see Figure 2) and their value range used

Classification	Question/Item (which the degree of [dis-]agreement was asked)	Value range
Threat Appraisal ([future] probability)	"How likely do you think it is that your apartment or house will be hit by another heavy rain event?"	1 (very unlikely) to 6 (very likely)
Coping Appraisal (response-efficacy)	"Private precautionary measures can reduce flood damage."	1 (I disagree) to 6 (I fully agree)
Coping Appraisal (perceived response cost)	"Private precautionary measures are too expensive."	1 (I fully agree) to 6 (I disagree)
Coping Appraisal (perceived self-efficacy)	"Personally, I do not feel able to implement any of the aforementioned measures."	1 (I fully agree) to 6 (I disagree)
Responsibility Appraisal (perceived self-responsibility)	"Each individual has a duty to prevent damage caused by heavy rain."	1 (I disagree) to 6 (I fully agree)
Responsibility Appraisal (perceived responsibility of the government)	"Heavy rain prevention is the task of public institutions and not the task of private individuals."	1 (I fully agree) to 6 (I disagree)
Protection Motivation	"Personally, I will do everything I can to protect the house I live in from damage from heavy rain."	1 (I disagree) to 6 (I fully agree)
Maladaptive Thinking (denial)	"I try as little as possible to think about a future heavy rain event."	1 (I disagree) to 6 (I fully agree)
Maladaptive Thinking (fatalism)	"Nothing can be done about heavy rain and the damage it causes."	1 (I disagree) to 6 (I fully agree)
Maladaptive Thinking (postponement)	"I think precautionary measures against heavy rain make sense. But as long as it does not seem urgently necessary to me, I will postpone their implementation."	1 (I disagree) to 6 (I fully agree)
Adaptive Behaviour Planned	At least one measure of Figure 1 planned, *excluding planning and preparing for an emergency*; (Yes = 1, No = 0)	Value: 0,1
Adaptive Behaviour After	At least one measure of Figure 1 installed after, excluding *planning and preparing for an emergency*; (Yes = 1, No = 0)	Value: 0,1
Framing Factors (Being informed about precautionary measures)	Person looked for information OR feels (very) well informed by the municipality (Yes = 1, No = 0)	Value: 0,1
Framing Factor *(Perceived sufficiency of available financial aid)*	"There are enough tax breaks and subsidy programs to finance private precautionary measures."	1 (I disagree) to 6 (I fully agree)
Framing Factor (Income)	"What is roughly your monthly net household income in Euros?" (1 = >3726 EUR; 0 = <3726 EUR) (DeStatis, 2020)	Value: 0,1
Framing Factor (Ownership)	"Do you rent or own the house or apartment?" (Owner = 1; tenant = 0)	Value: 0,1
Framing Factor (Measures Before)	At least one measure of Figure 1 installed before the event. (Yes = 1; No = 0)	Value: 0,1
Framing Factor (Age)	"How old are you?" (takes value 1 if age is equal to or larger than 65 years and 0 otherwise)	Value: 0,1
Framing Factor (Gender)	Which gender do you feel to belong to? (0 = male or non-binary; 1 = female)	Value: 0,1
Framing Factor (Leegebruch)	Dummy-variable for the municipality Leegebruch (Berlin, Potsdam or Remscheid = 0; Leegebruch = 1)	Value: 0,1

Descriptive analyses are used to explore the intensity of the events within the four municipalities. Frequency statistics provide insights into the adaptive behaviour implemented. Adaptive behaviour is explored using seven linear regression models (see Figure 2) and SPSS 27. This approach and the selection of variables is guided by a structural statistical modelling approach, which means that the variable selection and operationalisation are driven by the underlying theory (see Figure 2). Linkages between the framing factors (explanatory variables in regressions 1–3) and threat appraisal (dependent variable in regression 1), coping appraisal (dependent variable in regression 2), and responsibility appraisal (dependent variable in regression 3) were investigated first. Regression 4 studies the linkage between protection motivation (dependent variable) and threat, coping and responsibility appraisals (explanatory variables). Regression 5 studies the linkage between maladaptive thinking (dependent variable) and threat, coping and responsibility appraisals (explanatory variables). In regressions 6 and 7, we connect adaptive behaviour (explanatory variable) with the framing factors (explanatory variables), maladaptive thinking (independent variable), and protection motivation (independent variable). We define two types of adaptive behaviour. The first is employing or implementing at least one additional adaptive measure after the most recent flood. The second is displaying a stated intention to employ one at least one more adaptive measure in the future. Both regression models 6 and 7 refer to the adaptive behaviours presented in Figure 1, excluding "planning and preparing for an emergency", since including that item did not result in a systematic difference regarding the results. Therefore, to make our analysis as homogeneous as possible, we excluded this measure from the regression analysis.

3 | RESULTS AND DISCUSSION

3.1 | Results of the descriptive analyses

Figure 3 shows the median inundation depths and durations in the four surveyed areas based on the survey data as reported by the respondents. The impacts in Berlin, Remscheid, and Potsdam are comparable regarding inundation depths, while the event in Leegebruch stands out with higher inundation levels for cellars. The median flood duration was similar in Potsdam and Remscheid, with an average of 7 hours. Berlin's median duration was 24 hours. Leegebruch stands out with a four-times higher median duration of 4 days (Figure 3). This is plausible, since Leegebruch is located within a topographical depression with a high groundwater level potentially leading to longer periods of inundation (GDV, 2018).

Moreover, according to the survey data, Potsdam households had taken the most adaptive measures before the event (average of 2.8 measures per household). Households in Leegebruch had taken an average of 2.5 measures (Figure 3), while Remscheid and Berlin showed the lowest number of adaptive measures, with an average of 1.6 per household. High-cost measures (see Figure 1) were the scarcest measures implemented in all four municipalities. On the contrary, the purchase of insurance against flood damage was the most common measure in Potsdam and Remscheid and the second-most frequent measure in Leegebruch. In Berlin, insurance uptake was the fourth-most common measure, while backflow preventers were the most frequent (data not shown).

According to the survey data, households in Potsdam, Remscheid, and Berlin installed on average fewer measures per household after the event compared to those in Leegebruch, who implemented 1.2 measures per household on average (Figure 3). In all four municipalities, pumps were the most or second-most frequently implemented measure. The most common measure planned by households was planning and preparing for an emergency. Buying insurance against natural hazards was the second-most frequent measure in Berlin and Leegebruch, while this was waterproof foundations in Potsdam and Remscheid (data not shown).

3.2 | Discussion of affected households' adaptive response

Section 3.1 revealed how affected households have acted or are planning to act to protect themselves, their property, and/or others from the impacts of heavy rain events. Not only the extent but also the type of newly implemented measures changed after the event. For instance, before the event, most measures implemented were to keep water out of the house (protective measures, Figure 1), while after the flood relatively more measures were newly implemented to deal with water in the house (mitigative and/or preparedness measures, Figure 1). This could be because after a flood it is easier to imagine water in the house, and/or it could be a sign that the adaptive measures in place did not provide sufficient protection. However, the fact that further measures were implemented and planned directly after the event shows that the lack of some measures' effectiveness does not diminish the implementation of alternative measures. In addition to further preparedness measures, high-cost adaptive measures are also implemented after the event. This may be a sign that people with flood experience are willing to invest more in additional measures. An

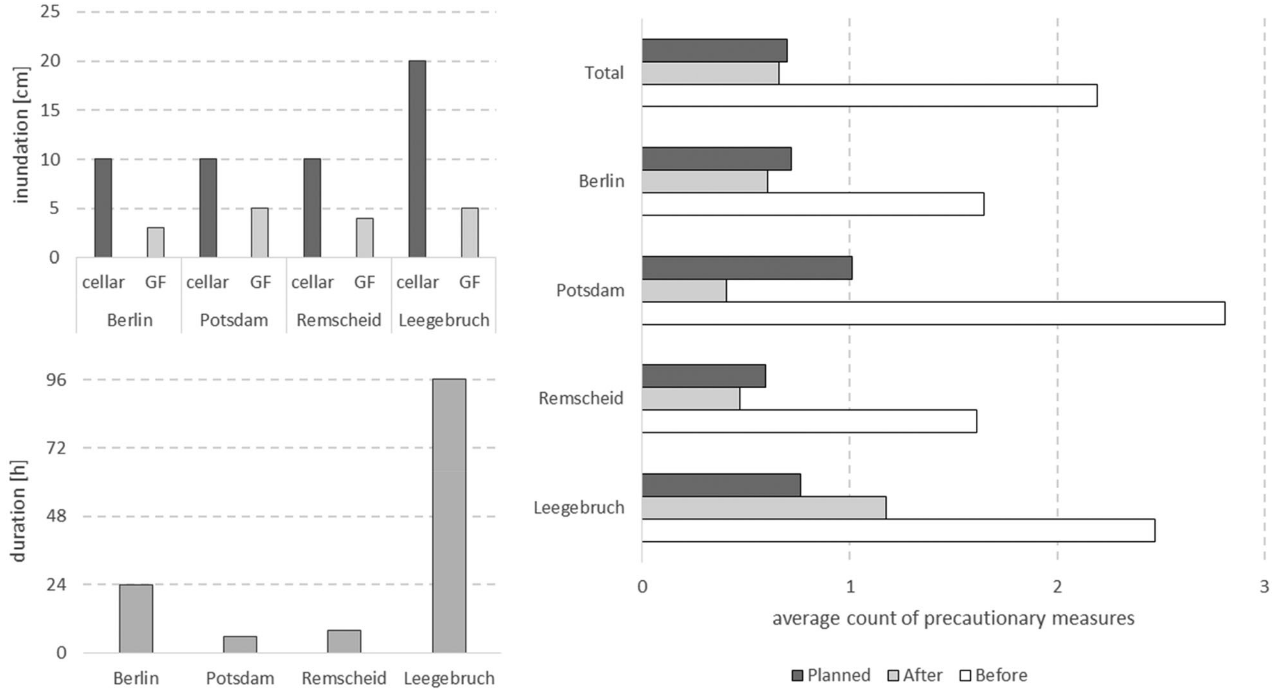

FIGURE 3 Median flood inundation levels (upper left panel), h = hour, GF = ground floor; flood inundation duration (lower left panel); and in the right hand panel the count of precautionary measures implemented before (before, white bars), precautionary measures implemented after (after, grey bars) and precautionary measures planned to be implemented (planned, dark grey bars) in the four municipalities

increase in implementation of high-cost measures after flooding events was also found by Rözer et al. (2016) in the context of pluvial flooding and by Bubeck et al. (2020) in the context of fluvial flooding.

3.3 | Results of the regression analyses

This section contains the results of the structural modelling approach. In the following, numbers in brackets are coefficient estimates taken from Tables 3 to 6.[1] Regression 1 tackles the impacts of the framing factors on threat appraisal. Ownership (0.90), age (−0.91), and pre-flood measures (0.75) show high and significant values (Table 3). Age has the highest value, although the value of ownership is only negligibly lower. Ownership and measures implemented before the flood are positively related to threat appraisal, while age is negatively related, meaning that people below the official retirement age showed a higher threat appraisal. Regression 2 investigates the relation between coping appraisal and the framing factors. The variables of ownership (0.36) and perceived sufficiency of available financial aid (−0.17) show a significant positive relation (Table 3). Ownership shows the strongest linkage to coping appraisal. Regression 3 reveals the impact of the framing factors on responsibility appraisal. Two framing factors have significant positive values: ownership (0.36) and perceived sufficiency of available financial aid (0.17) (Table 3). Of those, ownership has the higher value and increases the responsibility perceived by participants within our dataset.

Regression 4 links protection motivation (dependent variable) and threat, coping, and responsibility appraisals (explanatory variables). Coping appraisal has a positive significant relation (0.26) and threat appraisal a negative significant relation (−0.12) to protection motivation, while we found no significant link between responsibility appraisal and protection motivation (Table 4). Regression 5 investigates the impact of responsibility, threat, and coping appraisals on maladaptive thinking. While all explanatory variables show a negative relation, solely the values of coping appraisal (−0.20) and responsibility appraisal (−0.10) are significant (Table 5).

Regression 6 investigates the linkage between the measures implemented after the event (MIA) and the independent variables of framing factors, protection motivation, and maladaptive thinking. The variable of measures implemented before the flood (−0.15) has a significant negative linkage to MIA, while the dummy variable Leegebruch has a positive significant relation to MIA (0.25) (Table 6). Regression **7** presents the connection between the measures planned to be implemented

(MP) and framing factors, protection motivation, and maladaptive thinking. Protection motivation (0.05), next to being informed about precautionary measures (0.04), ownership (0.26), and age (−0.15), have significant linkages to MP (Table 6). Age is the only significant variable negatively related to MP, while all other significant linkages are positive.

Figure 4 summarises all significant connections revealed by the regressions introduced above. Figure 4 solely considers adaptive behaviour described by at least one MP, since we found that regression 7 produces stronger results than regression 6. This was as expected, due to the time points between which the variables were measures and actions taken. Notable is that ownership and perceived sufficiency of available financial aid are important positive drivers in the decision process investigated here, while age acts as an important negative driver. While threat appraisal solely affects protection motivation, and responsibility appraisal affects solely maladaptive thinking, coping appraisal affects both. A direct link between maladaptive thinking and adaptive behaviour was not found.

3.4 | Discussion of the decision-making process behind adaptive responses

Section 2.3 explained that a decision process precedes an adaptive response. Our hybrid model breaks this process down into different steps. Analysing these steps allows us to better understand households' adaptive behaviour (see Figure 4). Although there is no direct starting point within this continual process, we discuss the results beginning with the influence of framing factors on threat, responsibility, and coping appraisals and then move clockwise (see Figure 4) to describe the circular process leading to the adaptive response to create a deeper understanding of the decision-making process as a whole for planned/intended measures.

Significant linkages between the framing factors and appraisals of coping, threat, and responsibility (see Figure 4) will be discussed from left to right. "Measures implemented before the event" can hint at previously experienced flooding, however, which was not addressed in the survey. Nevertheless, the negative linkage to threat appraisal could indicate an influence of previous flood experience on how threats are assessed. The significant

TABLE 4 Results of the linear regression model 4 (see Figure 2), dependent variable is protection motivation

Explanatory variables	Protection motivation
Threat appraisal	−0.12**
	(0.05)
Responsibility appraisal	0.09
	(0.07)
Coping appraisal	0.26***
	(0.08)
Constant	3.54***
	(0.44)
Observations	343
R^2	0.09

Note: Standard errors in parentheses.
***$p < 0.01$; **$p < 0.05$; *$p < 0.1$.

TABLE 3 Results of the linear regression models 1–3 (see Figure 2), dependent variables are (1) TA = threat appraisal, (2) RA = responsibility appraisal, (3) CA = coping appraisal

Explanatory variables	TA (Regression 1)	CA (Regression 2)	RA (Regression 3)
Perceived sufficiency of available financial aid	−0.08 (0.09)	0.17*** (0.06)	0.29*** (0.06)
Being informed about precautionary measures	−0.35 (0.39)	−0.08 (0.22)	0.33 (0.28)
Income	−0.09 (0.25)	0.25 (0.16)	0.34 (0.17)
Ownership	0.90*** (0.28)	0.36** (0.16)	0.35** (0.17)
Measures implemented before the event	0.75** (0.29)	0.36 (0.19)	0.08 (0.21)
Age	−0.91*** (0.29)	−0.11 (0.18)	0.08 (0.21)
Gender	−0.09 (0.11)	−0.09 (0.07)	0.04 (0.08)
Leegebruch	−0.34 (0.31)	−0.16 (0.19)	−0.09 (0.22)
Constant	3.62 (0.51)	3.32*** (0.33)	2.68 (0.37)
Observations	208	212	212
R^2	0.13	0.11	0.13

Note: Standard errors in parentheses.
***$p < 0.01$; **$p < 0.05$; *$p < 0.1$.

TABLE 5 Results of the linear regression model 5 in which the dependent variable is maladaptive thinking

Explanatory variables	Maladaptive thinking
Threat appraisal	−0.02
	(0.03)
Responsibility appraisal	−0.10*
	(0.05)
Coping appraisal	−0.20***
	(0.06)
Constant	4.34***
	(0.26)
Observations	347
R^2	0.08

Note: Standard errors in parentheses.
***$p < 0.01$; **$p < 0.05$;
*$p < 0.1$.

TABLE 6 Results of the linear regression models 6 and 7 (see Figure 2); dependent variables are "measures implemented after the event" (MIA; regression 6) and "planned measures" (MP; regression 7)

Explanatory variables	Measures implemented after the event (MIA) (Regression 6)	Planned measures (MP) (Regression 7)
Protection motivation	0.03	0.05**
	(0.02)	(0.02)
Maladaptive thinking	−0.00	−0.03
	(0.03)	(0.028)
Perceived sufficiency of available financial aid	−0.03	−0.04
	(0.02)	(0.02)
Being informed about precautionary measures	0.13 (0.11)	0.04* (0.11)
Income	0.07	−0.06
	(0.07)	(0.06)
Ownership	0.08	0.26***
	(0.06)	(0.06)
Measures implemented	−0.15**	−0.03
Before the event	(0.08)	(0.08)
Gender	−0.03 (0.03)	0.02 (0.03)
Age	0.07	−0.15**
	(0.08)	(0.07)
Leegebruch	0.25***	−0.04
	(0.08)	(0.08)
Observations	209	209
R^2	0.13	0.16

Note: Standard errors in parentheses.
***$p < 0.01$; **$p < 0.05$; *$p < 0.1$.

positive linkage between "perceived sufficiency of available financial aid" and both coping and responsibility appraisal allows two interpretations: (a) the presence of financial aid stimulates a sense of responsibility and encourages people to take more opportunities to protect themselves, and/or (b) a person who has a high sense of responsibility and is aware of options to cope is likely to have already looked for information about financial aid and thus have a higher awareness of its availability. Both interpretations indicate that financial aid support adaptive behaviour by enhancing responsibility and/or coping appraisal. However, among the framing factors investigated, "ownership" works as the strongest and a positive driver, similar to what was found for fluvial flooding by Grothmann and Reusswig (2006).

The analyses further revealed how protection motivation and maladaptive thinking are influenced by the appraisal of threat, coping, and responsibility. Threat appraisal is negatively related to protection motivation, that is, a person who perceives a pluvial flooding threat as highly likely is less motivated. In contrast, coping appraisal has a positive connection with protection motivation, that is, individuals seeing themselves as capable of coping with a threat increases their motivation to adapt. Hence, people will likely take no adaptive measures if their threat appraisal is high and their coping appraisal low. This finding for pluvial floods is similar to those for fluvial floods, for example, Grothmann and Reusswig (2006). In addition, the results indicate that responsibility appraisal may not be a direct driver of protection motivation.

Of the variables investigated, coping appraisal has the highest impact on maladaptive thinking. This strong effect indicates its importance within the decision-making process, which is consistent with regression 4. The significant and negative link between responsibility appraisal and maladaptive thinking indicates that participants who feel more responsible report less maladaptive thinking.

While the previous relationships indirectly shape the adaptive response, regression 7 involves actual adaptation and examines the influence of the framing factors, protection motivation, and maladaptive thinking on the MP. The positive linkage between MP and protection motivation is

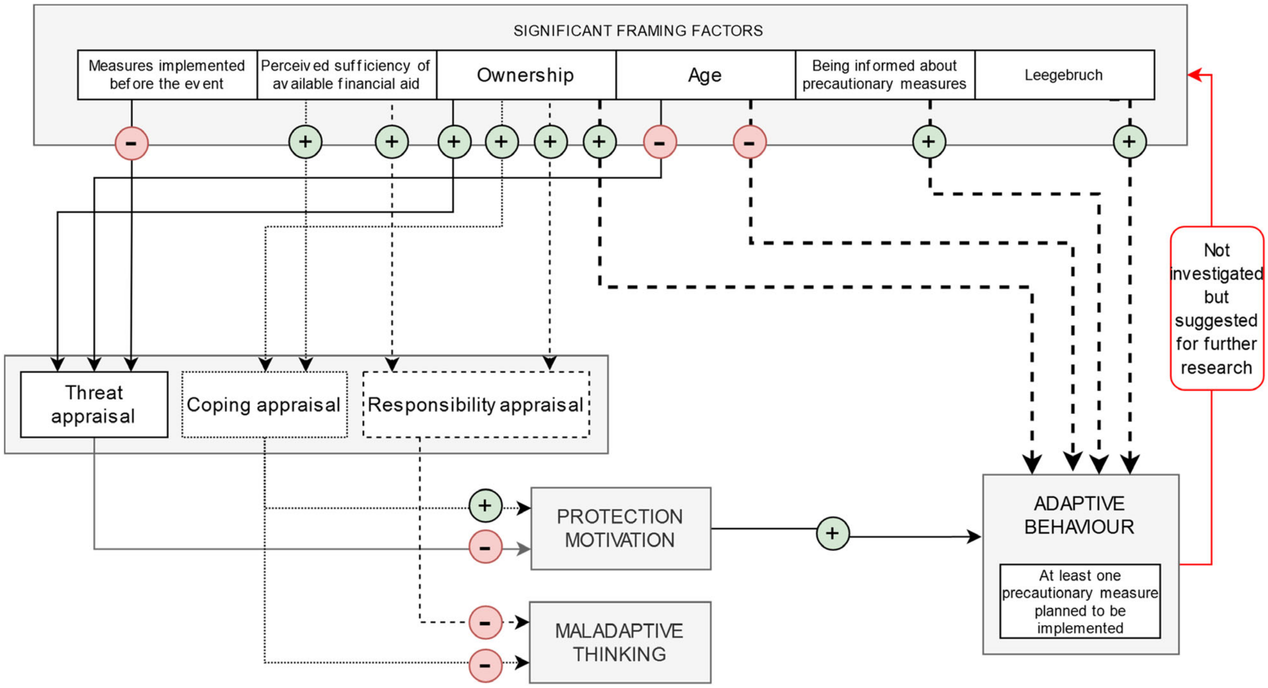

FIGURE 4 Overview of significant results revealed based on regressions 1–7 regarding adaptive behaviour intentions; different line styles are used to illustrate the relevant regression stage (see Section 3); "+" means a significant positive regression coefficient and therefore an enhancing linkage, "−" means a significant negative regression coefficient and therefore an attenuating linkage. In contrast to Figure 2, only significant relationships are shown here with arrows

in line with our hybrid model's structure and expected findings (i.e., people who are more motivated wish to do more). The framing factors of ownership and age have the highest values and therefore the highest impact among the variables investigated. This finding could be expected, since both variables already impact threat, coping, and responsibility appraisal (see regressions 1 to 3, Table 3). In the hybrid model, we suggest that protection motivation is a positive driver of adaptive response. Hence, if protection motivation is high, the (planned) adaptive response increases. In fact, the positive linkage between MP and protection motivation confirms the model. While we find being informed about adaptive behaviours is useful, Attems et al. (2020) suggest that such communication efforts have to be well tailored to the context. Since we have already identified "perceived sufficiency of available financial aid" as a positive driver of coping appraisal and responsibility appraisal, it would be useful to integrate information about financial aid into such communication efforts. Furthermore, it has been shown that framing factors have a stronger influence on the adaptive response than protection motivation and maladaptive thinking. This highlights how important these factors are in moving from motivation to action, which is in line with findings of Grothmann and Reusswig (2006).

In general, we found similar patterns of adaptive behaviour towards pluvial flooding to what previous research suggested for other flood types, for example, Bamberg et al. (2017), Bubeck et al. (2012), and Grothmann and Reusswig (2006). We found significant influences of threat and coping appraisal on protection motivation. Additionally, the extension of our hybrid model delivers additional insights: we identified ownership and measures taken before the event as drivers of adaptive behaviour and found income to not be an influencing factor. We also found that responsibility appraisal may not play a central role in the decision-making process. However, although the role of responsibility appraisal was minor in the whole decision-making process, our results indicate that the perception of responsibility influences maladaptive thinking. Moreover, we attempted to link maladaptive thinking to these outcomes, but failed to establish a significant linkage. This may be due to implementing the adaptive response with a binary variable within the model. If a continuous variable would be used instead, the influence of maladaptive thinking on the adaptive response might be better highlighted. However, maladaptation is a route of PMT, it is potentially less important by itself than for promoting a higher self-perceived coping capacity to implement adaptive measures. Therefore, communication strategies should clearly address and communicate avenues for improving coping capacity. This outcome can be particularly relevant with respect to the findings of Snel et al.

(2020), who revealed that despite the movement towards greater responsibility by households (Kuhlicke et al., 2020), not all households are aware of this movement and thus a new topic of communication may be required.

3.5 | Advantages and disadvantages of our approach and entry points for future research

Grothmann and Reusswig (2006) find that when using PMT in the context of flooding, additional adaptations and extensions are needed. Based on our results, we highly recommend the inclusion of framing factors. The installation of adaptive measures before the event was found to impact threat appraisal. This reveals the importance of the feedback loop described by (Bubeck et al., 2012), which describes the dynamic of people's reactions and perceptions. Future iterations of the model can develop this linkage by creating a circular model, as suggested by Lindell and Perry (2012). Therefore, we suggest including the impact of adaptive behaviour on the framing factors (Figure 4). A greater focus on (currently limited) longitudinal data collection would be needed to validate this understanding of adaptive behaviour (Hudson et al., 2020).

Although the potential impact of maladaptive thinking on adaptive behaviour has been pointed out in other studies, for example, Bubeck et al. (2013) and Grothmann and Reusswig (2006), we did not find a direct impact on adaptive behaviour with the current operationalisation. By investigating each linkage within the hybrid model separately (Figure 2), we could still indicate that maladaptive thinking decreases with increasing coping and responsibility appraisal, and is not linked to adaptive behaviour in this application. However, it may be worthwhile to learn more about maladaptive thinking and similar inhibiting factors in future research by asking why participants did or did not carry out adaptive behaviour in general or specific measures in particular.

This leads to a deeper consideration of what the framing factors are for adaptive behaviour as a direction for future research. For instance, the intensity or severity of the last damaging flood event will most likely affect adaptive responses but has not yet been considered. One reason for this is that the survey covers different heavy rainfall events. Describing their intensity in a comparable way would require several indicators that, in addition to the inundation in the respective areas, also consider the flood duration or further variables. Such an investigation could not be performed here due to the limited number of cases, which limits the number of framing factors. Furthermore, due to our sample size, we did not subdivide measures or consider an index that weights different measures. In the context of pluvial flooding, it may also be crucial to consider emergency measures and how these are combined with precautionary measures. Additionally, future research could focus on what drives the intensity of adaptive behaviour, such as by combining information about how many precautionary and emergency measures and/or which subgroups of measures have been implemented.

To improve studies like the one presented here, the survey design could be adapted. By surveying cities with different geographic characteristics and offering different media for both application and participation, we tried to reach as broad a range of participants as possible. Nevertheless, our survey was targeted exclusively to affected households. Especially if future studies aim to examine the influence of flood experience, surveys should also target households with no previous flood experience. This could inter alia help to identify what initially triggers an engagement with heavy rainfall prevention (e.g., an event experienced or educational campaign), or how the previous implementation of precautionary measures will influence future adaptive behaviour this is to better understand the impulse to adapt. Additionally, we recommend a larger sample so that influences such as gender, income, age, or the intensity of the last event can be considered in more detail by splitting the sample up or including more variables. In addition, a larger sample might reduce noise in the data and therefore better clarify the connection between maladaptive thinking and adaptive response.

To tackle whether and how the specific urban environment impacts its residents' adaptive behaviour in the case of pluvial flooding, linkages between social, socioeconomic, structural, and governmental factors and the size of the cities would have to be investigated. For instance, topography varies as does the quality of the drainage system. This can influence how the flooding occurs and how long it lasts. This also has consequences for the measures people take. In our survey design, we accounted for some differences such as age and ownership, but due to the survey design city-wide structural characteristics could not be accounted for explicitly. As a first approach, we therefore used the dummy variable "Leegebruch" to distinguish the small town from the bigger cities, which is significantly linked to adaptive behaviour. However, it is difficult to disentangle what distinguishes the behaviour of the Leegebruch residents more: the fact that it was the smallest city or the fact that it had the biggest flood impact. Therefore, future studies need to be more purposefully designed to include or account for the different relevant scales of action both within and across cities and communities. Finally, to allow a comparison between cities with different sizes, a larger sample is needed.

Based on the knowledge gathered in this study about the drivers of adaptive behaviour in the context of pluvial flooding, and possibly considering the opportunities for further development presented in this section, it will be necessary to develop ways to approach households in a way that encourages their adaptive behaviour; one potential direction could be workshops, as explored by Heidenreich et al. (2020) and Terpstra et al. (2009).

4 | CONCLUSION

The aim of this study was to understand why households affected by pluvial flooding do or do not protect themselves. Therefore, we used a hybrid model combining PMT and PADM for survey data from nearly 400 households from four German municipalities.

By comparing the implementation of adaptive behaviours across those municipalities using descriptive analyses, we found that high-cost measures are implemented less often compared to medium- and low-cost measures.

As stated in Hypothesis 1, we found threat and coping appraisals to be drivers of adaptive behaviour, also in the case of pluvial flooding. Regarding Hypothesis 2, we can state that the hybrid model with its extensions and our approach examining all linkages among its individual factors are suitable to investigate protection motivation and adaptive behaviour and understand these processes in the context of pluvial flooding. The study revealed that framing factors, particularly ownership, significantly influence threat, coping, and responsibility appraisals and interact with adaptive behaviour. Together, they form an interface between the response to a past event and the appraisal of and adaptation to future events. The appraisal of coping options stands out as significantly affecting both protection motivation and maladaptive thinking more than the appraisals of threat and responsibility.

With regard to promoting future theory-driven approaches to investigate adaptive behaviour in the context of flooding, we can state that the PMT creates a basis for such investigations but does not consider all aspects relevant for pluvial flooding. The above-presented understanding of the entire decision-making process forms the basis from which to further develop theoretical frameworks and enhance households' adaptive behaviour, and should therefore be considered in further investigations.

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ENDNOTE

[1] The constant term (or intercept parameter) is part of the linear relationship estimated by the regression model(s) to correctly estimate the line of best fit. However, it is rarely of interest (Wooldridge, 2012).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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