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ORIGINAL ARTICLE

Property-level adaptation to pluvial flooding: An analysis of individual behaviour and risk communication material

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Abstract

Integrated risk management requires all stakeholders to work together proactively. Residents of floodplains can participate by implementing property-level adaptive measures. Risk communication materials can motivate those households to do so. Research on these materials is limited. Therefore, we systematically assessed freely available German risk communication materials in terms of their recommendations and how their content aligns with behavioural theories. We compare these results with data from surveyed households affected by urban flooding ($N = 1{,}352$) on their attitudes towards flood adaptation and the adaptation measures implemented.

209 risk communication materials were reviewed. Adaptation options (mostly evasion or resistance strategies) were communicated in 93%, the hazard itself in 78%, the local hazard situation in 48%, and responsibilities in risk management in 54% of the risk communication materials. These aspects were rarely broken down for the reader by, for example, presenting the damage that can be expected or by presenting measures with the expected costs or their response efficacy. However, these details commonly increase the adaptive behaviour of residents according to commonly used behavioural theories.

Survey data indicated that households feel able (82%) and responsible (41%) for implementing adaptive measures. However, many households indicated that measures are not effective (41%), too expensive (34%), and that there are not enough support programs (87%). We recommend that future risk communication materials focus more on communicating the efficacy and costs of adaptive measures and highlight funding opportunities. Our mixed method approach highlighted mismatches in information needed and provided.

Keywords Risk communication materials · Pluvial flooding · Adaptive behaviour · Household survey

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1 Introduction

Extreme rainfall (e.g. cloudbursts or heavy rainfall) is one of the hazards that will require an increasing level of adaptation as it is likely to become more frequent and intense in Central Europe due to climate change (Müller et al. 2019; Mann et al. 2018; Rosenzweig et al. 2018; Caldas-Alvarez et al. 2022, IPCC 2023). Extreme rainfall can cause pluvial flooding if rainfall intensities exceed the infiltration capacities of the soil and surface runoff exceeds the capacity of the sewer system, causing localized flooding, particularly in urban areas (Rubinato et al. 2019; Rosenzweig et al. 2018). Pluvial floods can be differentiated from fluvial floods by (a) being independent of a water body overflowing, which makes it more challenging to identify risk areas and to produce hazard maps, and (b) flood heights being on average higher for fluvial floods than for pluvial floods (Thieken et al. 2022; Dillenardt et al. 2022). However, while the hydrological traits of pluvial and fluvial flooding differ, they may be similar regarding adaptive measures and human behaviour. For example, fluvial flood adaptive measures also aid with pluvial floods (e.g., water and pressure-resistant windows and doors) and are driven by similar behavioural drivers (Dillenardt et al. 2022).

In Germany, pluvial flood events have caused high losses in recent years. From May to June 2016, several severe weather events in Germany caused ~ €800 million in insured losses (GDV 2017a; MunichRE 2017) and a total loss of €2.6 billion (MunichRE 2017). The city of Münster was heavily affected in July 2014, causing insured damage of ~ €240 (GDV 2018), and in 2017, a heavy rain event caused ~ €60 million in property damage in Potsdam and Berlin (GDV 2017b). The increasing threat from pluvial flooding has also become apparent in many other places around the globe, including several cities in Turkey (Koç et al. 2021), the City of Hull in Britain (Coulthard and Frostick 2010), Beijing in China (Liu and Jensen 2017) or Sao Paulo in Brazil (Valverde and dos Santos 2014) among others. Cities are particularly prone to pluvial flooding because urbanization is accompanied by increased paved surfaces, which reduces retention capacity and promotes surface runoff (Timm 2019). In addition, urbanization increases the number and density of people and assets in urban areas (Elmqvist et al. 2013) and thus increases potential flood damage. High losses caused by pluvial flooding in urban areas may hint at the insufficient adaptation of urban areas to pluvial flooding.

(Pluvial) flood risk is composed of the hazard (e.g. rainfall amount or water depth), exposure (e.g. assets in flood-prone areas) and vulnerability (e.g. susceptibility of exposed items to be damaged by flooding) (Kron 2005). The exposure and vulnerability elements can be reduced via property-level adaptive measures. Property-level adaptive measures can be assigned to six main groups (Fig. 1). Such adaptive measures can reduce flood damage at the property level cost-effectively (DEFRA 2008; Hudson et al. 2014; Kreibich et al. 2011; Lamond et al. 2018; Poussin et al. 2015). Risk transfer does not directly lower risk but aids in fostering a rapid recovery process after a damaging event.

Risk communication is a standard approach of public administrations to motivate households to protect themselves by employing adaptive measures. For risk communication to be successful, the cognitive processes behind adaptive behaviour must be well understood to stimulate adaptive behaviours (sometimes also called protective behaviour; in this paper, we will use adaptive behaviour consistently) (Kuruppu and Liverman 2011; Lindell and Perry 2004; Höppner et al. 2010; van Valkengoed and Steg 2019; Bechtoldt et al. 2021). There are various behavioural frameworks used to explain adaptive behaviour. Figure 2 shows the Protection Motivation Theory (PMT), a commonly employed framework developed and revised by Rogers (1975), (Maddux and Rogers

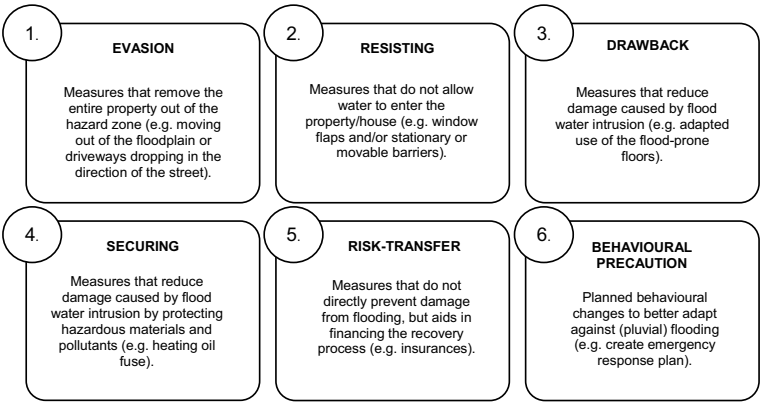

Fig. 1 The six main groups of adaptive measures based on the wider literature

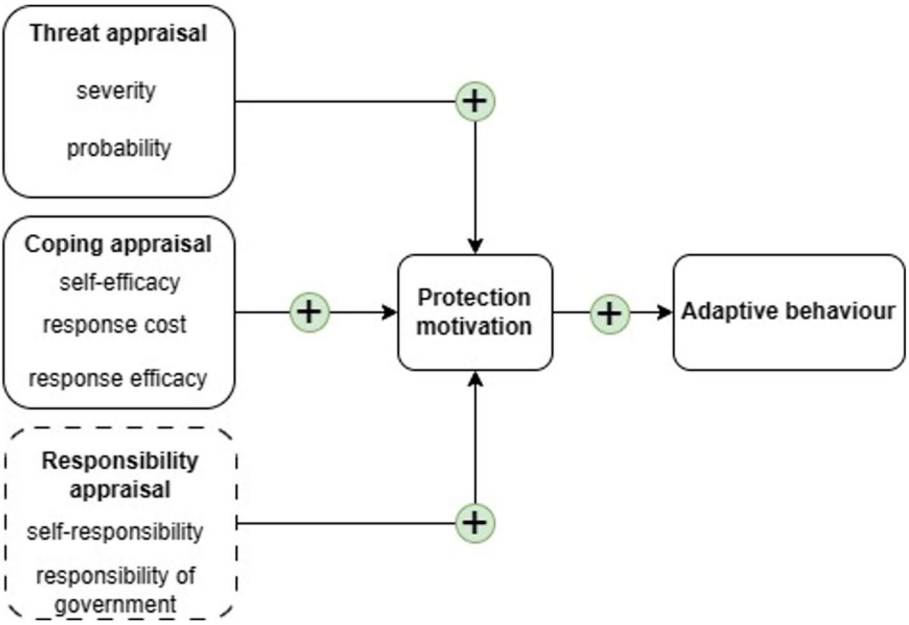

Fig. 2 Simplified structure of the Protection Motivation Theory (PMT) with the additional aspect "Responsibility appraisal" from the Protection Action Decision Model (PADM) ("dashed box"); plus signs indicate a positive relation, i.e. a high value of one goes along with a high value of the other

1983) and widely used within flood risk research (Bamberg et al. 2017; Bubeck and Thieken 2018; Grothmann and Reusswig 2006; Dillenardt et al. 2022*)*. PMT assumes that adaptive behaviour results from a high protection motivation, which is produced through threat and coping appraisals.

Threat appraisal consists of the perceived flood occurrence probability and the perceived flood severity. Threat appraisal will positively affect protection motivation at first, as a threat must be acknowledged to promote action. When communicating a

pluvial risk, the recipients of communication materials should be made aware of the general risk, i.e. global risk, and the risk at their specific location, i.e. local risk (Netzel et al. 2021).

Once a threat has been acknowledged, coping appraisal is then assessed to determine the response employed. According to PMT, coping appraisal is divided into three subaspects considering their perceptions of self-efficacy (to what extent one can implement the measure), response efficacy (how effective a measure is perceived to reduce damage), and response costs. (Perceived) response costs, in this sense, do not only refer to (perceived) financial costs but also include how burdensome this implementation is being perceived (Bubeck et al. 2013). Coping appraisal is positively linked to protection motivation. If a person perceives a measure as effective, implementable, and with a low implementation burden, one is likely to implement it. Self-efficacy and response efficacy are often critical determinants for adaptive behaviour across different studies and hazards (van Valkengoed and Steg 2019).

An offshoot of the PMT is the Protection Action Decision Model (PADM) of Lindell and Perry (2012). PADM has shown that it is helpful to add the aspect of responsibility appraisal, e.g., to what extent people feel responsible for protecting themselves and their property. Responsibility appraisal can be divided into an individual's perception of their responsibility and that of the government. Self-responsibility is an essential part of integrated flood risk management (Kuhlicke et al. 2020) and, as such, has translated into legal obligations in Germany, such as those defined in the Federal Water Act (WHG (Wasserhaushaltsgesetz), 2009 § 5 Abs. 2).

The presented behavioural models offer an avenue for designing risk communication material to increase threat, coping, and responsibility appraisal to spark a suitable adaptive response. There are various ways in which risk communication materials can be provided. There can be active risk communication campaigns whereby an actor proactively provides information to those potentially affected (i.e., directly mailing property owners/residents information) or passive risk communication campaigns where risk communication materials are provided to a recipient to inform them about their risk (i.e., placed on a website as a leaflet PDF). A wide range of communication tools exists, such as workshops, 3D visualization, flood risk maps, websites and flyers. Previous research has evaluated their performance (Hagemeier-Klose and Wagner 2009; Heidenreich et al. 2020; Kuser Olsen et al. 2018; Höppner et al. 2010). Höppner et al. (2010) have prepared a review of communication practices in the context of hazards, including flooding, at regional, national and international levels but have not evaluated their content in detail and a structured manner. Therefore, it is still unclear to what extent risk communication materials in grey literature are available to households and whether those materials consider scientific findings of behavioural research and thus motivate adaptive behaviour against pluvial flooding.

We aim to fill these gaps by conducting a review of the passive risk communication material freely available on the internet, focusing on those produced for residents of Germany. Once this review has been conducted, we contrast our findings with insights from surveys of pluvial flood-affected households to add further nuances to what we uncover. In doing so, we address the following research questions:

(R1) What adaptive measures are communicated in open-access risk communication materials on pluvial flooding in Germany?
(R2) To what extent are findings from behavioural research considered in the identified risk communication materials?

(R3) Residents implemented what adaptive measures, and what are their attitudes toward adaptive measures?
(R4) What can we learn from R1 to R3 to improve risk communication materials on pluvial flooding?

To answer those questions, we reviewed risk communication materials that are freely available online following the PRISMA reporting framework (Liberati et al. 2009). We used descriptive analysis to analyse data from surveys of flood-affected residents.

2 Data and methods

2.1 Collecting, extracting, and analyzing suitable risk communication materials

An internet search was conducted to investigate which risk communication materials German citizens would likely find if they searched by themselves. Therefore, we used a set of thematic search terms, such as "heavy rain/cloudburst" and "precaution", combined with terms reflecting the federal states (e.g., names of the federal states) who are essential actors in risk communication Tables 1. This resulted in a total of 96 search terms, see Appendix 1 Table 3.

The search engine 'Google' was used on two consecutive days (30 June 2021 and 1 July 2021). Beforehand, the browser cache was cleared, and cookies were deleted; no Google account was used to improve the reproducibility of the results. For each combination of search terms, the first ten results were transferred to a list, resulting in 1080 entries (Fig. 3). These items were reviewed as suggested by the PRISMA framework for literature reviews (Liberati et al. 2009); see Fig. 3.

From the 1080 identified records, duplicates were excluded. The remaining 581 records were then screened for relevance. Materials were excluded if they had no thematic connection to flooding and adaptive measures or were fee-based. Some duplicates not recognized in the first step were identified during the screening and deleted. One hundred twenty-six records were excluded but included hyperlinks to further information material. This further information material has been included in the list if they could not be assigned to any of the exclusion criteria mentioned above. Seven records were relevant and linked to other materials. This procedure led to a final list of two hundred and nine relevant informational materials (Fig. 3). To examine the structure of risk communication materials, the title, authors, type of material, number of pages, target group, year of publication, the federal state in which it was published, and the flood types were recorded (Table 1). In the next step, it was analyzed whether adaptive measures of the six main classes (i.e., Evasion, Resisting, Drawback, Securing, Risk-Transfer and Behavioural Precaution) were presented (see Appendix 3 for a detailed description).

To investigate whether the risk communication materials contain factors that promote adaptive behaviour, we also coded the document's alignment with the critical elements of the PMT and PADM behavioural theories. An intercoder reliability (ICR) test was conducted to ensure the reproducibility of the coding used for analyzing risk communication materials. In three waves, the coding guideline was applied independently by three testers to ten randomly selected materials, to a total of 30 randomly selected materials, which corresponds to approximately 14% of the total data set. After each round, ambiguities and discrepancies in the coding were discussed. When necessary, the definitions of each aspect

Table 1 Summary of characteristics of risk communication materials

Item	Description	Codes
Title	The title of the information material (IM)	open text entry
Published by	All parties or authors who contributed to the publication	open text entry
Type	We distinguish flyer (print layout, maximum two pages), brochure (print layout with 2–47 pages), checklist (a structured topic-related list of information), book and e-book (print layout with at least 48 pages), website (no print layout, specific web address), presentation (a lecture in the form of slides), video (an information video)	Flyer, brochure, checklist, book, video, website
Pages	Number of pages of the IM. Not applicable for videos and web pages	open text entry
Target group	The target group to be addressed by the IM	Homeowners, tenants/renters, planners & architects, municipalities, others (multiple selection possible)
Year	The year in which the IM was published	open text entry
Federal state	If the information was prepared for or in collaboration with a state, that was included in this category	All 16 federal states of Germany (multiple selection possible)
Flood type	The flood type, which is the subject of the IM	Pluvial, fluvial, coastal, general, other (multiple selection possible)

were rephrased in the coding guideline. Ultimately, all testers independently agreed on at least 80% of their analyses per aspect and risk communication materials. An IRC of 80% was considered a good level of agreement, as this provides a sufficient balance between room for different interpretations and consistency of the analysis and is within the standard of 80% agreement on 95% of the code, as suggested by (O'Connor and Joffe 2020).

2.2 Surveying flood-affected residents

To contrast the contents of risk communication materials with empirical findings on what measures have been implemented by residents or how they think about private adaptation, survey data was analysed. The data was collected after damaging pluvial flood events in German cities by the University of Potsdam and partners; several studies using these individual data sets have already been published (Dillenardt et al. 2022; Spekkers et al. 2017; Berghäuser et al. 2021). For this study, we merged data from four comprehensive data sets that were based on a common survey design for households affected by pluvial flooding as described by Thieken et al. (2017), see Table 2. Sampling was based on lists of flooded streets and postcodes in cities impacted by pluvial flooding. These were collected using computer-aided telephone interviews (CATI) in Münster and Greven in 2015 (Spekkers et al. 2017) and acros 67 municipalities in southern and western Germany in 2017 (Thieken et al. 2022); In the cities of Berlin, Potsdam, Remscheid and Leegebruch, CATI were accompanied by computer-aided web interviews (CAWI), and paper/pencil surveys in 2019 and 2020 as described by Dillenardt et al. (2022), see Table 2.

Altogether 1,352 responses have been collected and analysed. All surveys contained questions on which adaptive measures were implemented by residents before and after each damaging event (compare Appendix 2 Table 4, "Items in the surveys"). Not all adaptive measures were asked in all surveys due to the development of the questionnaires necessary to adapt them to different survey contexts, see Appendix 3. In addition, the respondents' attitudes on items capturing threat, coping and responsibility appraisals were queried (compare Appendix 2 Table 5, "PMT aspects"). We analysed the data using the statistical software package SPSS 27.

3 Results

3.1 Who published what risk communication materials and how well do the surveyed households feel informed?

The number of risk communication materials availablein germany on the internet on pluvial flooding has jumped since 2014, reaching a maximum in 2017. Whether this increase is primarily due to damaging pluvial floods, e.g., in 2014 and 2016, is unclear (Fig. 4). Homeowners are the most frequently addressed target group (21%), followed by municipalities (17%), tenants (11%) and architects and planners (2%), while the remaining 51% did not have a specifically targeted group. Most risk communication materials come from the federal states of North Rhine-Westphalia (NRW) and Rhineland-Palatinate (RP). In this context, it should be noted that Germany, as well as Belgium and Luxembourg, were hit by intense rain on July 13 and 14, 2021, leading to severe flooding, especially in the German

Table 2 Description of the surveys employed; CAWI: computer-assisted web interview, CATI: computer-aided telephone interviews

No	Place of flood and survey	Responses used	Flood event	Survey period	Methods	Publications
1	Münster, Greven	510	July 2014	20 Oct 2015 – 26 Nov 2015	CATI	(Spekkers et al. 2017)
2	67 municipalities in South and West Germany	448	May–June 2016	28 March 2017 – 28 April 2017	CATI	(Laudan et al. 2020; Thieken et al. 2022)
3	Potsdam, Remscheid, Leegebruch	279	2017, 2018, 2019	9. July – 9 Sept. 2019	Paper/ pencil, CATI	(Dillenardt et al. 2022)
4	Berlin	115	2017, 2018, 2019	27 March – 31 May 2020	CAWI	(Berghäuser et al. 2021; Dillenardt et al. 2022)

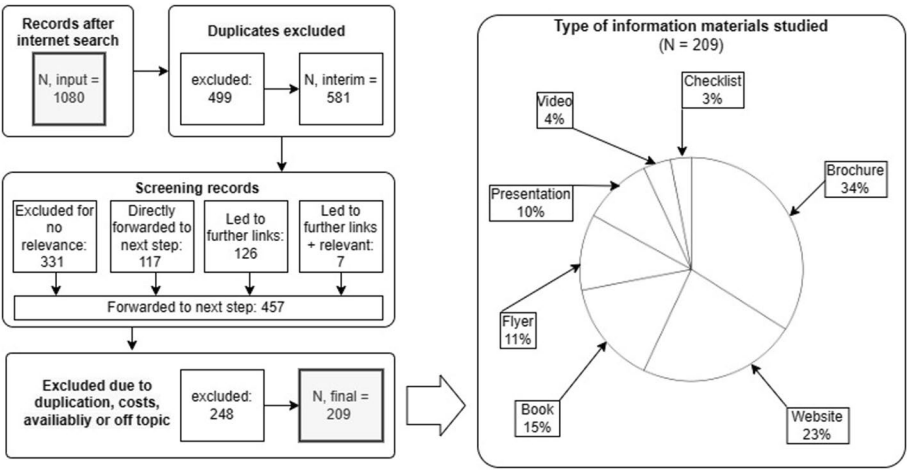

Fig. 3 (left) Scheme of how the results of the internet search were refined using the PRISMA-framework, (right) Type of materials included in the detailed content analysis

federal states of North Rhine-Westphalia and Rhineland Palatinate (Schäfer et al. 2021). Since our analysis was conducted before this event, the results presented here are not influenced by this event.

If the number of risk communication materials is normalized to the number of inhabitants, Bremen published the most risk communication materials. Many risk communication materials were produced by or in cooperation with the German Association of Insurers (GDV) or the Federal Office of Civil Protection and Disaster Assistance of Germany (BBK). Departments or ministries within the federal states were involved in 40% of the risk communication materials analyzed. 23% of the risk communication materials were produced directly with cities, municipalities, or water infrastructure operators (mostly public companies). The surveyed respondents do not feel that there is too little risk communication materials in general (63% of households surveyed ($n = 1162$)), but rather feel that they are not well informed by their municipality specifically (18% of households surveyed ($n = 1257$)).

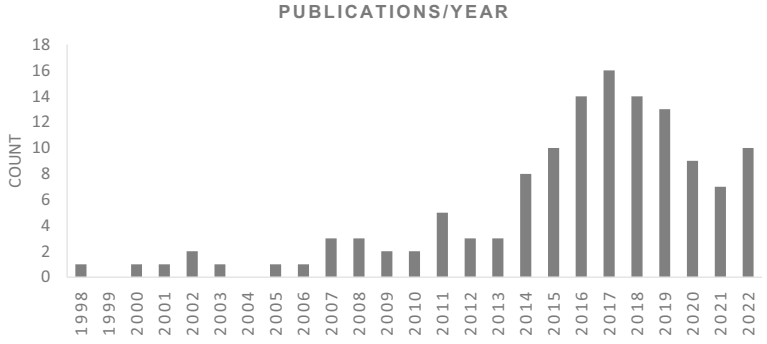

Fig. 4 Number of information material on pluvial flooding containing a year of publication ($n = 130$) (y-axis) per year (x-axis), materials without a year of publication ($n = 79$) were excluded

3.2 Which measures were communicated vs. which measures were implemented?

Figure 5 shows the ranking of the adaptive measure categories based on how often a surveyed respondent or risk communication materials mentioned at least one measure from a given category. Not all adaptive measures were asked in all surveys (Appendix 3) since the questionnaires have been developed over time and were adapted to different survey and event contexts. The six main groups (Fig. 1) were represented by at least one measure in all three surveys. Additionally, we create two categories of adaptive action from the survey respondents. We created a category recording if the respondent had implemented at least one of the measures for a given adaptive measure category before a flood. The second category records if the respondent had implemented at least one of the measures for a given adaptive measure category after a flood. We discuss the risk communication materials and the measures implemented by households regarding their ranking to focus more clearly on the most common suggestions and actions undertaken.

Evasion measures, such as moving out of the hazard zone or driveways dropping in the direction of the street, were mentioned second most often in risk communication materials. Before and after the event, these measures were least frequently implemented by those surveyed. Resisting measures were mentioned most frequently in the risk communication materials and were frequently implemented by survey participants before (second most frequently implemented measure) and after the event (third most frequently implemented measure). Drawback measures were most frequently implemented before and after the event but were communicated relatively little in risk communication materials (fourth most frequent). Securing measures were not only communicated least frequently but also rarely implemented by the residents (fourth most frequently implemented after the event and fifth most frequently implemented before the event). Risk transfer measures were the fourth most frequently presented in the risk communication materials and the fourth most frequently implemented by households before the event. After the event, it was the third most frequently added measure. Behavioural precaution measures were rarely communicated in the risk communication materials (second most). Residents rarely implemented them before an event, but they were implemented rather frequently by affected residents after the event.

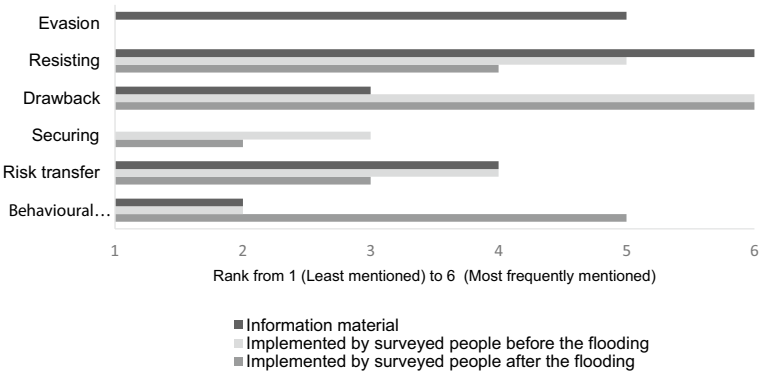

Fig. 5 Comparison of the results from the analysis of the IM and the results from the surveys regarding which groups of measures were mentioned least frequently (1) or most frequently (6); a detailed overview of the measures investigated can be found in Fig. 1 and Appendix 3

3.3 Risk communication material and behavioural drivers

3.3.1 Communication vs. perception of threat

In terms of behavioural insights, the risk communication materials were examined to determine how the concept of threat appraisal was employed (e.g., providing occurrence probabilities indications of potential severity) and whether the hazard was presented at a large scale (e.g., for the whole of Germany), or on a local level (e.g., neighbourhood level). While 78% of the materials communicated the hazard at a global level, i.e. without local context, only 43% of the risk communication materials communicated the hazard at the local level, i.e. with a local context (Fig. 6). It should be noted that a risk communication material can communicate a hazard on a larger scale and on a local level. Such a risk communication material was then counted in both categories. The threat was mentioned at the local and global levels twice as often in general terms as it was broken down into (future) probability and severity (Fig. 6). Flood maps are one way of presenting a hazard, the expected damage and the probability of occurrence at a local level. Within the analysed risk communication materials, flood and or/risk maps specifically for pluvial flooding were shown in approx. 15% of all risk communication materials analysed. The survey data reveal that only 32% ($n = 1267$) of residents recently affected by pluvial flooding believe it is likely or very likely that they could be hit again. Approx. 25% ($n = 1237$) of respondents said they considered the consequences of a future event to be bad or very bad for them.

3.3.2 Communication vs. perception of coping opportunities

To trigger coping appraisal in potentially affected households, flood adaptive measures can be presented in risk communication materials. In the material analyzed, measures are

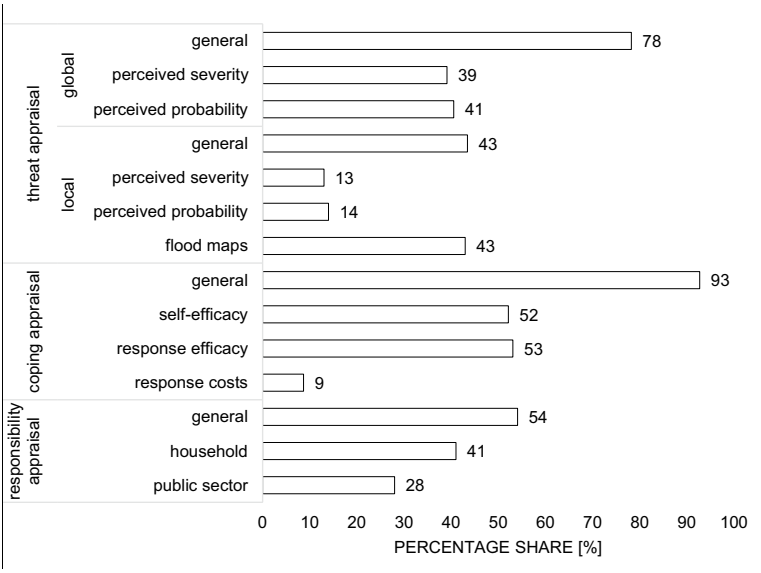

Fig. 6 Results of the analysis of the risk communication materials ($n = 209$) regarding the key components of behaviour models

mentioned in 93% of risk communication materials. However, this does not mean that all of them described the measures in more detail, what hints to unused potential of risk communication: To trigger an adaptive behavior, one could additionaly describe the response efficacy of a measure and/or show the reader how to implement a measure (to enhance self-efficacy). In addition, implementation costs could be presented so that the reader can select a measure that fits their own budget (in terms of money or effort) and needs. In 52% of the materials, at least for one measure, more details are given on how this measure can be implemented in practice what can promote self-efficacy. Response efficacy is addressed in 53% of the materials, by describing how at least one of the measures reduces flood damage. Much less frequently (9%), the costs of at least one measure are mentioned.

The survey data reveals that most respondents (82%, $n = 1206$) see themselves in a position to implement a measure, hence have a high self-efficacy. However, response efficacity is much lower, as only 59% ($n = 1255$) of respondents believe that adaptive measures sufficiently reduce flood damage. In terms of cost, 34% ($n = 1171$) of the residents surveyed believe that adaptive measures are too expensive while just 13% ($n = 905$) of respondents believe that there are sufficient financial support programms.

3.3.3 Communication vs. perception of (self-) responsibilities

Responsibility was communicated in about half of risk communication materials, and thus, less often than the threat or coping options (Fig. 6). In 41% of risk communication materials, the self-responsibility of potentially impacted residents was highlighted. The responsibility of public authorities was outlined in 28%. The survey data show that 33% ($n = 1234$) believe that provision against (pluvial) flooding is the responsibility of public agencies. 64% (n = 1244) of the respondents believe everyone must make their provisions. Both questions were not asked exclusively. Respondents could thus see the responsibility both with the public sector and themselves.

4 Discussion

4.1 Who published what materials

Previous research has shown that "being informed" is linked to households being more likely to adapt to pluvial flooding (Dillenardt et al. 2022; Netzel et al. 2021). While most surveyed households felt that there was generally enough informational material available, at the same time, they did not feel well informed by their municipalities. This perception is consistent with our review findings, where we found relatively few risk communication materials from or in cooperation with municipalities. Hence, municipalities can and should increasingly approach their citizens with information campaigns after an event as those seeking more local information. This is particularly important because many structural measures can be effectively implemented after an event and during reconstruction (Kreibich et al. 2005). Our results show that government ministries, the GDV, and the BBK are very active in producing risk communication materials and thus already have much experience producing those, which may be lacking for smaller municipalities. Therefore, associations and institutions such as GDV and BBK in Germany can help municipalities

prepare local risk communication materials for citizens if they have more expertise in this area than they do.

Of the federal states studied, Bremen produced the most materials per person. This may be due to Bremen's coastal location. Due to this location, Bremen can be impacted by storm surges, fluvial flooding, and pluvial flooding (Scholz et al. 2012). Hence, the experience of multiple floods may triggers municipalities to invest more in informing their citizens. This is supported by a survey among city administrations that revealed that the development of pluvial flood hazard maps is facilitated by past (and anticipated) damaging events, putting some pressure on the administration to address this policy field (Huber et al. 2022). Thus, there is a need to inform municipalities more about the increasing risk of pluvial flooding in urban areas so that more local information campaigns can be initiated.

4.2 Which measures were communicated vs. which measures were implemented?

Evasion measures are costly and challenging to implement into existing building structures. These measures are frequently communicated in risk communication materials but are rarely implemented by the surveyed households. This is potentially because their coping appraisal is too low since many surveyed households think that measures are too expensive and insufficient financial support programs exist. Measures of the resisting group were implemented more frequently by households in general, but especially before the event. This may be because this strategy includes measures that can be implemented in an existing structure and consist of both cost-intensive and low-cost measures. This hints at residents being more willing to implement lower-cost measures and measures that can be implemented in the existing building structure if they adapt to pluvial flooding, as Rözer et al. (2016) found. Another important reason may be that implementing backflow preventers, assigned to the resisting group of measures, is often a prerequisite for access to flood insurance in Germany (Osberghaus and Philippi 2016).

Drawback and securing measures reduce the vulnerability of exposed assets. They include measures that are both costly and difficult to implement in existing building structures (e.g. heating oil fuse or installation of electrical cables above the potential flooding height), as well as low-cost measures that are implementable with less effort (adapted use of exposed floors and elevated storage of hazardous substance) (FEMA 2015, BMWSB (Bundesministerium für Wohnen 2022). There is no need to focus more on drawback measures in risk communication materials, as they were implemented frequently, although relatively rarely communicated. However, a focus should be put on the communication of securing measures, as they were rarely communicated in risk communication materials and rarely implemented by households. This group of measures is crucial since contamination of floodwater, e.g. heating oil, significantly increases the expected damage (Kron 2008, Thieken et al. 2005; Thieken et al. 2022), not only to the building from which heating oil has leaked, but also in its surroundings, which not uncommonly requires demolition of the affected buildings (Kammerbauer and Wamsler 2018). Securing measures include measures that are easy to implement and, in fluvial flooding (Kreibich et al. 2011), oil tank protection pays off with one (fluvial) flood event. Hence, the measures may be rarely implemented because information campaigns have not adequately addressed the risk of contamination and ways to prevent it.

Measures for risk transfer and behavioural precaution do not include any structural measures. Risk transfer does not directly reduce risk but primarily aids in promoting a faster recovery post-flood (Thieken et al. 2006). However, there may be indirect,

risk-reducing effects if insurance conditions require the implantation of adaptive measures (as mentioned above regarding backflow values). In either case, Thieken et al. (2006) found that insured households adapt better to flooding than uninsured households. In the context of fluvial flooding, it was shown that those insured were more satisfied with the damage compensation after experiencing a damage event (Thieken et al. 2006), which helped affected households better recover from the damage. The survey shows that less than half of the respondents had taken out an insurance policy against flood damage at the time of the survey. Since insurance was communicated only fourth most frequently in the risk communication materials, it may be worthwhile to focus more on this in future information campaigns.

Measures of behavioural precaution like searching for flood-related information, participating in neighbourhood networks, and preparing for future events are urgently needed for recovery. This is because those measures help people redevelop a sense of control, which mental health researchers have argued is part of a recovery process (Hudson 2023). Particularly after a loss event, they were implemented by those affected. This indicates that people are increasingly willing to adapt their behaviour after an event and, if necessary, to look for information about their risk situation. Two insights can be derived from this for developing risk communication strategies. First, it confirms that those affected must be informed about their risk and adaptive options, especially after an event. Secondly, however, it must be noted that a behaviour change must be constantly maintained to achieve a long-term effect.

4.3 Risk communication material and behavioural drivers

4.3.1 Communication vs. perception of threat

Making potentially affected people aware of their risks and coping options is one of the core ideas of PMT since it is a fear appeals strategy (Rogers 1975). Most of the respondents have a low perceived severity (68% of households surveyed) and a low perceived (future) probability (75% of households surveyed), leading to an overall low threat appraisal. However, those households had been flooded before being surveyed and thus are located in a potential flood zone. The fact that their flood experience did not result in a high appraisal of threat might be partly due to the perception that the flood event they experienced was significant (Wachinger et al. 2013). However, it may also be because households are not sufficiently informed about their hazard situation. It can be concluded that even after an event, municipalities cannot assume that the appraisal of threat is high among affected households and that those must be informed about flood hazards. From behavioural science, we know that in order to alert households to the threat, it is helpful to communicate both the severity and the probability of occurrence (Bubeck et al. 2012, Dillenardt et al. 2022, Grothmann and Reusswig 2006, Rogers 1975, Maddux and Rogers 1983). Therefore, future risk communication materials should be better aligned with behavioural science findings in this regard.

Additionally, presenting a pluvial flood threat on a general rather than a local level may result in potentially affected residents being generally aware of the threat of future pluvial flooding but unaware of their local and personal threat. The enhanced development of flood maps could provide the opportunity to convey localized information and be a great communication tool if understood correctly. The latter is essential since communicating an event's probability and magnitude can be challenging. Using return periods to communicate the

probability of occurrence can lead to a "flood is due" effect (Grounds et al. 2017). This effect describes that lay people tend to misinterpret the probability of occurrence communicated via return periods. There are ways to overcome this issue, e.g. by (additional) communication of the likelihood in any given year (Grounds et al. 2017; Kellens et al. 2012). In any case, it is essential to ensure that communication via a map is well-designed and that sufficient explanations accompany the map to avoid misunderstandings.

4.3.2 Communication vs. perception of coping opportunities

A high coping appraisal has been identified as a clear and robust positive driver of adaptive behaviour in the context of pluvial and fluvial flooding (Dillenardt et al. 2022; Grothmann and Reusswig 2006). Hence, it is positive that almost all materials at least generally refer to adaptive measures and, therefore, trigger somehow the coping appraisal of households. However, coping appraisal could have been triggered more specifically by presenting measures of response efficacy and response costs, which has been done to a much lesser extent. This can not be due to medium used not providing enough space since flyers and checklists, whose nature is to briefly and compactly highlight a topic, together comprise only 14% of the risk communication materials examined. Segmenting coping appraisal into self-efficacy, response efficacy, and response cost offers the possibility of systematically promoting coping appraisal. It can be assumed that households will not implement a measure if it is considered unfeasible, ineffective or far too expensive. Hence, barriers to implementation are reduced by ideally addressing all three aspects of coping appraisal.

While over 80% of respondents feel able to implement at least one measure, attitudes toward the measures themselves could be better. Many respondents feel that measures are not effective and are too expensive. This emphasizes again the need to address response efficacy and response costs better. While response efficacy is considered in about half of the materials, the implementation costs were communicated in just 9%. Hence, there needs to be more information on the specific costs of adaptive measures. Although this is understandable because the cost of implementing a measure depends on many individual factors, e.g., the specific building structure and its location, it is essential to at least provide readers with further sources or an approximate range of costs.

Even if households view the efficiency of measures positively, the financial burden of implementing them can be a deterrent. Support programs that financially encourage the implementation of adaptive measures increase their affordability and the motivation of citizens to engage with these measures (Brockhoff et al. 2019). The need for financial support programs is evident among the surveyed households, where almost 90% see a need for support programs. This perception of households affected by pluvial flooding aligns with how reconstruction processes can be better managed in the sense of resilient flood recovery, also termed "build back better". This requires integrating and implementing adaptive measures, contrasts with rapid reconstruction and requires long-term support that provides time to plan and implement adaptive measures in private households (Slavíková et al. 2020). Programs that financially support the implementation of adaptive measures as part of a reconstruction process are rare, but such programs could be critical not only to enhance resilience but also to eliminate the criticism that government financial reconstruction assistance merely passes on the financial loss of households to taxpayers, allowing floodplains residents to remain unadapted (Slavíková et al. 2020).

4.3.3 Communication vs. perception of (self-) responsibilities

In the context of integrated flood risk management, in which all stakeholders jointly manage flood risk, potentially affected households also bear part of this responsibility, particularly for the protection of their property (WHG (Wasserhaushaltsgesetz), 2009 § 5 Abs. 2). Studies have shown that households do not yet recognize this responsibility even in flood risk areas (Bamberg et al. 2017).

However, among the households surveyed, most respondents (two-thirds) showed a relatively high sense of (self) responsibility. In contrast, a smaller proportion of respondents (one-third) saw the responsibility instead of the public administration. This may be due to the lower severity of pluvial flooding, which will be considered in the next section. Anyways, in none of the surveys were these questions asked on a mutually exclusive scale, and as such, both seeing responsibility with public authorities and one's responsibility can exist simultaneously. The extent to which the respondents correctly assess their responsibility and what personal responsibility should be assigned to private households cannot be clarified based on the data evaluated. However, responsibilities play a role in the decision-making process towards a protective response (Dillenardt et al. 2022; Lindell and Perry 2012; Maidl and Buchecker 2015). Naming them clearly can increase the effectiveness of flood management (Thistlethwaite 2017). Therefore, responsibilities should be communicated to advance pluvial flood management.

4.3.4 Transferability of results

When discussing transferability, a distinction must be made between the methodology used, results and conclusions. Internationally transferable is the assignment of various adaptive measures to the super-groups used. However, it must be noted that the way insurance works is country-specific, as conditions differ (Hudson et al. 2019; Tesselaar et al. 2022). Whether and how information materials from other countries are based on PMT and PADM cannot be concluded from our results. Moreover, the attitudes of the surveyed households cannot be transferred to other countries.

The methodology applied is based on the behavioural models PMT and PADM. The relationships between threat appraisal, coping appraisal and protection motivation assumed by the PMT have been applied by the international scientific community to data from different countries in order to understand adaptive behaviour better (Bamberg et al. 2017; Grothmann and Reusswig 2006; Bubeck et al. 2013; Spekkers et al. 2017). Noll et al. (2022) compared the effects of PMT factors in the U.S., the Netherlands, Indonesia, and China. They found that, in essence, the positive effect of Threat and Coping Appraisal on protection motivation existed in all four countries. Internationally recognized frameworks such as the PADM and the Sendai Framework suggest that responsibilities need to be communicated and discussed (Lukasiewicz et al. 2017, Maly and Suppasri 2020, Wolff 2021, Lindell and Perry 2012). Therefore, the methodology presented here, based on PMT and PADM for the structured analysis of communication materials and survey data, can be applied to other countries.

5 Conclusion – Take home messages for future information campaings

We looked at how risk communication materials on pluvial flooding are structured and whether they meet the needs of affected households using commonly accepted behaviour models as a framework. For this purpose, we systematically reviewed risk communication materials accessible on the Internet and analysed survey data from households affected by heavy rainfall. To compare the presented adaptive measures, we assigned them to six main groups. To investigate the extent to which the risk communication materials studied can promote adaptive behaviour, we examined whether the aspects of behavioural theories, namely threat, coping, and responsibility appraisal, were communicated. Five conclusions can be drawn:

I. Information campaigns should be stronger aligned to findings from behavioural science. We recommend that future risk communication materials are closer aligned with behavioural theories to better stimulate adaptive behaviour. While coping appraisal was almost always communicated, however not in much detail, threat and responsibility appraisal were presented less frequently.
II. It is purposeful to communicate (local) threat, coping options and responsibilities by presenting their respective sub-aspects such as self and response efficacy or response costs.
III. There should also be a greater supply of informational materials with direct local ties for those that have recently been flooded. Materials have yet to be developed specifically for or in cooperation with municipalities. However, this is one way of making materials more target-group-oriented. Such campaigns are necessary since many citizens surveyed did not feel sufficiently informed by their municipality and have a low appraisal of the threat, although they have been flooded recently. Hence, it can be helpful to inform those affected about adaptation options, especially after a damaging event. Including local-specific information would result in a higher target group orientation. Flood maps are helpful for this purpose, but they must be explained comprehensively.
IV. Measures that can be integrated into existing building structures are often implemented, except for measures that prevent contamination. The fact that measures to reduce potential contamination were not frequently implemented before or after a flood event suggests that these measures should be a stronger focus of information campaigns in the future, at least in areas where there is still a high penetration of oil heating systems.
V. There seems to be a lack of government support programs. The survey data revealed a need for support programs to help affected households adapt. In the reviewed risk communication materials, funding opportunities were not found. Additional support programs should be launched, integrated into post-disaster reconstruction processes, and highlighted in risk communication materials.

Appendix 1

Table 3 Search terms used. Each term from group A was combined with each term from group B, each state represents a separate search term within group B

Search terms group A		Search terms group B	
German search term	translation	German search term	translation
Starkregen	pluvial flood	Deutschland	Germany
Starkregenvorsorge	pluvial flood precaution	Bund	Federal
Starkregen Broschüre	pluvial flood brochure	Bundesländer:	All federal states:
Starkregen Private Vorsorge	pluvial flood private precaution	- Berlin	- Berlin
Starkregen Bauvorsorge	pluvial flood property-level adaption	- Brandenburg	- Brandenburg
Starkregen Eigenvorsorge	pluvial flood individual precaution	- Mecklenburg-Vorpommern	- Mecklenburg-Western Pomerania
		-Schleswig–Holstein	- Schleswig–Holstein
		- Niedersachsen	- Lower Saxony
		- Hamburg	- Hamburg
		- Bremen	- Bremen
		- Thüringen	- Thuringia
		- Sachsen	- Saxony
		- Sachsen-Anhalt	- Saxony-Anhalt
		- Bayern	- Bavaria
		- Saarland	- Saarland
		- Hessen	- Hesse
		- Nordrhein-Westfalen	- North Rhine-Westphalia
		- Baden-Württemberg	- Baden-Wuerttemberg
		- Rheinland-Pfalz	- Rhineland-Palatinate

[a]601 in total, but for this study 153 cases that had been affected by heavy flash floods were excluded

Appendix 2

Table 4 Aspects of the PMT and their definitions as we used them to analyze the IM, as well as the items from the surveys that we assigned to each aspect

PMT aspect	PMT sub-aspect	Definition used for reviewing risk communication material	Items of survey
Threat appraisal (global)	general	According to Netzel et al. (2021), this describes the assessment of the risk in general related to a broad spatial scale, which is not specifically related to one's own neighbourhood. For example, "climate change is increasing the frequency and intensity of heavy rainfall events in Central Europe."	–-
	perceived severity	e.g. "High losses expected in Germany/Europe/world"	–-
	perceived probability	e.g. "Increase in frequency and intensity due to climate change in Germany/Europe/world"	–-
Threat appraisal (personal)	general	According to Netzel et al. (2021), this means the assessment of one's own risk. Therefore, we included information on the community level or below that	–-
	perceived severity	Expected personal damage or damage to the community	"What is your assessment of the negative impact of a potential future flooding event on you personally?"
	perceived (future) probability	Increase in frequency and intensity due to climate change in my municipality. Or probability of occurrence on Heavy Rain Hazard Map	"How likely do you think it is that your apartment or house will be hit by another heavy rain event?"

Table 4 (continued)

PMT aspect	PMT sub-aspect	Definition used for reviewing risk communication material	Items of survey
Coping Appraisal	general	Measures named	–-
	self-efficacy	Describes how to implement the measure AND/OR provides funding options	"Personally, I do not feel able to implement any of the aforementioned measures."
	response-efficacy	It is described how the measure reduces/prevents damage	"Private precautionary measures can reduce flood damage."
	response costs	The costs are named	"Private precautionary measures are too expensive."
PADM aspect	Sub-aspect	Definition used for reviewing IM	Items of survey
Responsibility appraisal	general	Responsibilities are addressed	–-
	personal responsibility	It describes when the potentially affected person/household is responsible for what	"Pluvial flood prevention is the task of public institutions and not the task of private individuals."
	global responsibility	The responsibility of the municipality is described	"Each individual has a duty to prevent damage caused by heavy rain." It is the responsibility of the state to provide for damage that may result from heavy rain events

Appendix 3

Table 5 Summary of the measure, their definitions, and which items from the Suvey were assigned to them

	Description	Item in survey(-s)	Survey(-s) in which the item was asked
Evasion	Measures that remove the entire house out of the risk zone	Upstands (e.g. steps)	Starkregen im Fokus
		Driveways dropping towards the street	Starkregen im Fokus
		Moving to a less threatened area	Survey in Simbach
Resisting	Measures that do not allow the water to enter the house when it is pending on the house	Ground sills	Starkregen im Fokus
		Barrier systems or safety gates	Starkregen im Fokus
		Backflow flap	Starkregen im Fokus; Survey in Simbach; Survey in Münster
		Waterproof or pressure-resistant windows and/or doors	Starkregen im Fokus
		Window flaps or stationary or mobile water stops	Starkregen im Fokus; Survey in Simbach; Survey in Münster
		Waterproofing of the foundation	Starkregen im Fokus
		Improvement of the flood safety of the building, e.g. improved the structural stability	Survey in 67 municipalities in South and West Germany; Survey in Münster
Drawback	Measures that reduce damage caused by water penetration. Measures that reduce damage due to the protection of pollutants are excluded, as these are listed in a separate category "Securing"	Geringwertige Nutzung der hochwassergefährdeten Stockwerke	Starkregen im Fokus; Survey in 67 municipalities in South and West Germany; Survey in Münster
		Low-value use of the floors at risk of flooding	Starkregen im Fokus; Survey in 67 municipalities in South and West Germany; Survey in Münster
		Buying pumps	Starkregen im Fokus; Survey in 67 municipalities in South and West Germany; Survey in Münster
		Relocation of the heating system and / or the electrical utilities to higher floors	Survey in 67 municipalities in South and West Germany; Survey in Münster
		Acquisition of an emergency generator or a power generator	Survey in 67 municipalities in South and West Germany; Survey in Münster
Securing	Measures that reduce damage from floodwater intrusion by protecting hazardous materials and pollutants	Heating oil protection or relocation of the heating system and/or electrical utilities to higher floors	Starkregen im Fokus
		Do not store varnish, paint or gasoline cans in the basement	Survey in 67 municipalities in South and West Germany; Survey in Münster
		Changing the heating system or providing the oil tank with flood protection	Survey in 67 municipalities in South and West Germany; Survey in Münster

Table 5 (continued)

	Description	Item in survey(-s)	Survey(-s) in which the item was asked
Risk transfer	Measures that do not directly prevent damage from flooding but transfer the cost of the damage to someone else	Insurance against flood damage	Starkregen im Fokus; Survey in 67 municipalities in South and West Germany; Survey in Münster
Behaviour precaution	Measures that cannot be implemented because they are changes in behaviours or the acquisition of new behaviours. Here we also include information seeking, as this can be considered a protective behaviour (Maidl and Buchecker 2015)	Preparations for the eventuality of a hazard	Starkregen im Fokus; Survey in 67 municipalities in South and West Germany; Survey in Münster
		Search for information on how affected individuals can protect themselves	Survey in 67 municipalities in South and West Germany; Survey in Münster
		Participation in seminars	Survey in 67 municipalities in South and West Germany; Survey in Münster
		Participation in neighborhood networks	Survey in 67 municipalities in South and West Germany; Survey in Münster

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