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Learning from the past to inform flood risk management: Analysis of public survey data in Belgium on flood early warning and response during the July 2021 flood

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Abstract. In July 2021 an intense rainfall event resulted in severe flooding in Belgium as well as neighbouring countries. The Walloon Region of Belgium was severely affected with 39 fatalities reported; in the aftermath, the warning system was criticised. In this paper we assess the flood forecasting, warning and response system in the Walloon Region of Belgium for the July 2021 flood event. The analysis is based on an online survey of affected residents (n = 550) and investigates the reception of official warnings, the interpretation and trust in those warnings, and subsequent response behaviour. We find that among the respondents in the Walloon Region 33% reported not having received any warning, and 56% did not know how to respond effectively. We analyse the most important influencing factors across the warning chain using the Protective Action Decision Model as a theoretical framework and test influencing factors using logistic and linear regression models. We find that those who were most severely affected at the household level were less likely to receive an official warning. Additionally, flood experience, the level of perceived surprise at the household level, and perceived flood severity significantly influenced whether individuals knew how to respond to the upcoming flood. Despite the flood's huge magnitude, those who took damage-reducing actions were more likely to report an actual reduction in flood damage. This analysis highlights the need to improve Belgium's flood warning system by ensuring timely issuance of clear warnings and underscores the benefits of enhanced flood risk awareness for damage reduction.

1 Introduction and background

In mid-July 2021 an extreme flood event affected communities in Belgium, Germany, Luxemburg and the Netherlands and highlighted the severity of rapid onset flood events in the region (Dietze et al. 2022; Szönyi et al. 2022). In particular, the Walloon Region in Belgium was severely affected with 39 fatalities recorded and extensive damage to people, homes and infrastructure (Dewals et al. 2021; Journée et al. 2023; Lietaer et al. 2024; Rodríguez Castro et al. 2025a). The most affected areas in the Walloon Region were within several tributaries of the Meuse including the Vesdre (catchment area: 700 km²), Amblève (1100 km²), and the Ourthe (1850 km²) (Dewals et al. 2021). In the Vesdre catchment alone, 20 homes completely

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collapsed in the municipality of Pepinster, and after the flood 10 000 residents of the town of Verviers were evacuated due to building damage (Szönyi et al. 2022; Reinert et al. 2023).

Rainfall warnings were issued by the Belgian Royal Meteorological Institute (RMI) and flood warnings were issued by Service Public Wallonie (SPW) and other responsible agencies of the Walloon Region public service (Zeimetz et al. 2021; RMI 2024; Parlement Wallon 2022a). In line with the EU Floods Directive (2007/60/EC), flood hazard maps exist for Belgium and are publicly available (Mustafa et al. 2018; SPW 2024). Despite these measures many were surprised by the severity and spatial extent of flooding and the fatality level was unexpectedly high (Deffet 2022; Rodríguez Castro et al. 2025a). Therefore, the performance of the flood warning and response system requires a closer investigation.

1.1 Flood forecasting, early warning, and response behaviour

The timely delivery of accurate and actionable information using Flood Forecasting, Warning, and Response Systems (FFWRS) enables authorities and the public to reduce loss of life and damage caused by flooding (Parker and Priest 2012; Cools et al. 2016; Jonkman et al. 2024). Modern FFWRS use meteorological, hydrological, and hydraulic models, enhanced by information technology for detection and warning transmission, and while limitations remain they have become increasingly accurate in recent decades (Parker and Priest 2012; Golnaraghi 2012). For rapid onset floods, warnings based on forecasts are especially important, though particularly challenging with high uncertainty. The flood processes are fast with less than 6 hours rising time being typical and there is a higher chance that people are surprised as compared to fluvial floods (Najafi et al. 2024; Marchi et al. 2010). The effectiveness of FFWRS, however, depends not only on technical accuracy of models and systems but also on the content, format and dissemination channel of warnings and their level of accessibility, clarity, and credibility (Cools et al. 2016; Kreibich et al. 2017; Kreibich et al. 2021; Kuller et al. 2021). Increasingly, research highlights that flood experience, individual perception, and other demographic factors also play a role in influencing protective behaviour before, during, and after flood events (Thieken et al. 2023a; Köhler et al. 2023; Morss et al. 2016).

While detection and forecasting of floods involves mostly natural science and engineering disciplines, warning and response components of FFWRS require expertise from behavioural, sociological, and organizational disciplines (Parker et al. 2009). To better understand the behavioural components of flood warning and response the Protective Action Decision Model (PADM) provides a theoretical foundation for understanding how individuals process and respond to information across the warning chain (Lindell and Perry 2012). The PADM model presented by Lindell and Perry (2012) can be conceptualized in three groups of steps to explain decision making on protective behaviour including (1) inputs, pre-decision processes, and perceptions (2) decision making, and (3) behavioural response. We expand on these steps by separating pre-decision process and perceptions as well as adding the effect of the behavioural response and additional influencing variables as presented in Fig.1. Within the figure, the target variables for each model used in this paper are identified by number.

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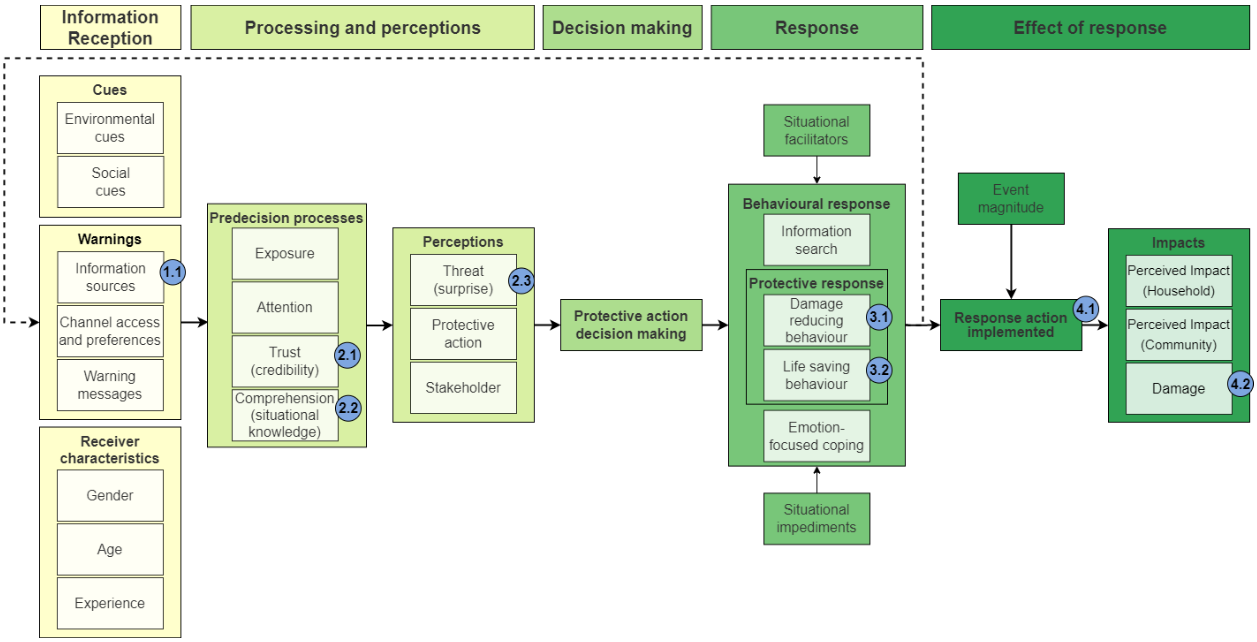

Figure 1. Behavioural steps related to decision making and influencing factors shown as an expanded version of the Protective Action Decision Model (PADM based on Lindell and Perry 2012); Blue numbering indicates the target variables for regression models in this paper

In the expanded version of this behaviour model we categorize each stage from (1) Information reception, to (2) Information processing and perceptions, (3) Decision making, (4) Response, and (5) Effect of response. We group the relevant aspects of information reception as cues, warnings, and receiver characteristics and add details such as what is included in receiver characteristics (gender, age, experience). We treat trust and credibility as part of the pre-decision processes, distinguish between damage reducing behaviour and life-saving behaviour for protective response, and consider the effect of this behaviour in an emergency context. These added variables are aspects that can be quantified by empirical survey data and are relevant to the implementation and benefit of protective behaviour.

The PADM has been effectively used by other studies to explain protective behaviour both for the implementation of damage reducing measures as well as life-saving behaviour in emergency response contexts for floods and other natural hazards (Dillenardt et al. 2022; Li et al. 2024; Zhang et al. 2024; Rufat et al. 2025). The explicit inclusion of hazard cues and warnings makes PADM especially suitable for analysing decision making in relation to response behaviour including ex-ante and ex-post actions (Kuhlicke et al. 2020). In addition, PADM has been found to be effective for explaining how social vulnerability influences risk perception and adaptive behaviour (Rufat et al. 2025). The study by Rufat et al. (2025) showed empirically for the study area of Paris that PADM works better than other more simple models to explain the variability in risk perception and adaptive behaviour by incorporating aspects of social vulnerability through demographic factors, social cues, and perceptions. To better understand what makes flood warnings effective and identify the key factors that influence the response behaviour of people affected during a flood, using PADM as an analysis framework seems to be a promising approach.

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1.2 Warning in Belgium for the flood of 2021

Fundamental principles of early warning and response systems are expressed by the World Meteorological Organization (WMO) in a four-pillar framework for end to end, people-centred Multi-Hazard Early Warning Systems (MHEWS) which includes floods among many other hazards (WMO 2018, 2023): “Disaster risk knowledge” (Pillar 1), “Detection, observation, monitoring, analysis, and forecasting” (Pillar 2), “Warning dissemination and communication” (Pillar 3), and “Preparedness and response capabilities” (Pillar 4). Momentum towards achieving early warning for all is also reflected in the Sendai Framework for Disaster Risk Reduction (SFDRR) which explicitly includes the goal of increasing the availability and access to MHEWS and disaster risk information by 2030 (UNDRR 2015). Belgium signed the SFDRR when the framework was adopted in 2015, and recently reaffirmed this commitment during the midterm review along with other EU member states (UNDRR 2023; EU 2023).

Here we describe the FFWRS for the Walloon Region of Belgium as it functioned prior to and during the flood of July 2021 within WMO’s four pillars. Since 2021 some technical and governance aspects of FFWRS in the Walloon Region have changed; these are discussed in Section 3. Pillar 1 includes knowledge of possible flood hazards in given locations as well as exposure, vulnerabilities, and capacities to respond which is part of preparedness planning. The EU Floods Directive (2007/60/EC) has required to have flood hazard and risk maps available for regions with significant flood risk by December 2013. Consequently, maps have been created for rivers in Belgium and are made available to the public through a web portal hosted by the principal administrative body of the Walloon Region (EU 2007; SPW 2024). The maps include four hazard zones from high, to intermediate, low, and very low (Mustafa et al. 2018; Rodríguez Castro et al. 2025a). During the flood of 2021 most inundation areas in floodplains matched the available hazard maps well. However, several areas outside the designated flood areas were flooded in the July 2021 event. This discrepancy can principally be attributed to the event being considerably more extreme than the scenarios considered in the preparation of the official flood hazard maps (Dewals et al. 2021; Rodríguez Castro et al. 2025a).

Detection, observation, monitoring, analysis and forecasting (Pillar 2) for floods require the use of meteorological and hydrological services and the governance to support these functions. Flood forecasting requires rainfall information, rainfall-runoff models, and the transformation of surface runoff to water levels for particular watercourses. In Belgium, rainfall forecasts and warnings are managed at a national level. The rainfall forecast is generated by the Royal Meteorological Institute (RMI) who issues rainfall warnings on four levels from green, yellow, orange, to red through their website (www.meteo.be) and an app. Green level indicates “no significant problems are expected due to rain” and the more severe red level indicates “widespread impacts due to rainfall are already affecting the province and we expect more heavy rainfall to exacerbate the problems” (RMI 2024). In 2021 there were also pre-defined lead times for these warning levels. A yellow warning can be issued 48 hours before the expected event, an orange warning 24 hours before, and a red warning 12 hours before, which made it difficult during the flood event of 2021 to flexibly issue warnings as the situation progressed rapidly at times (Lietaer et al. 2024). There was a parliamentary inquiry on the 2021 floods, which addressed these forecasts and warnings for rainfall and

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river flooding and the timeline is documented in parliamentary proceedings (Parlement Wallon 2022a, 2022b). On July 12, 2021 RMI issued a yellow alert for the Walloon Region with 80 to 130 mm of rain expected in the coming 48 hours and up to 150 mm in some very localized areas. On this day RMI also activated their reserve personnel. On July 13, RMI issued an orange alert for the provinces of Liège, Namur, and Luxembourg. On the morning of July 14, RMI issued a red alert for the province of Liège. It was reported that these rainfall warnings were not well understood by all users in terms of what the expected impacts could be (Lietaer et al. 2024; Parlement Wallon 2022a).

The detection, monitoring, and forecasting for river flooding in the Walloon Region in 2021 was the responsibility of the Directorate of Hydrologic Management (Direction de la Gestion hydrologique [DGH]) within the SPW Mobility and Infrastructure division (SPW-MI). There are two distinct hydrometric station networks "Wacondah" which covers navigable waterways and "Aqualim" for first order non-navigable waterways with watersheds over 50 km^2 (SPW 2025). The DGH is responsible for maintaining "Wacondah" and the Directorate of Non-navigable waterways (Direction des Cours d'eau non navigables (DCENN) within another department of SPW is responsible for maintaining the "Aqualim" hydrometric network and general flood risk management for first order non-navigable waterways such as the Vesdre (SPW 2023). For flood forecasting, the DGH used a mathematical model "HYDROMAX" to calculate expected flows at the outlet of basins within the "Wacondah" network based on precipitation and streamflow observations (Zeimetz et al. 2021). The lead time for providing this forecast depends on the catchment size but no forecasts were made for the smaller tributaries within the "Aqualim" network in July 2021 and there were no inundation forecasts produced or used operationally (Busker et al. 2025; Zeimetz et al. 2021). Some of the smaller tributaries in the "Aqualim" network are the most affected watersheds during the 2021 flood including the Vesdre, Amblève, and Lesse as shown in Fig.2.

Flood warning dissemination and communication (Pillar 3) requires organization and decision-making processes to be in place and be operational. In 2021, within the Walloon Region, the responsibility for disseminating flood warnings was shared between the Regional Crisis Centre of Wallonia (Centre Régional de Crise de Wallonie or CRC-W) at the region level, the provinces, and local authorities (Lietaer et al. 2024). The established procedure was that CRC-W received rainfall warnings from RMI and river flood warnings from the DGH. The DGH was responsible for triggering the pre-warning and flood warning phases and disseminating them to CRC-W as stipulated in a cooperation agreement between SPW-MI and SPW-CRC (Zeimetz et al. 2021). If the RMI rainfall alert was yellow or higher, then the DGH was activated to estimate the impacts to water courses. For river flooding, the three warning levels are Green (Normal), Yellow (Pre-Alert), and Red (Alert) (SPW 2025).

The main warning channel for communicating flood warnings to the general public is the BE-Alert system which has been in place in Belgium since 2017. Currently 89% of Belgian municipalities are registered, however this number was lower during the flood of 2021 (CCN 2025, 2022; Parlement Wallon 2021). The BE-Alert system is a service that warns people who have registered to be warned in a particular location or are located in a warning area at the time of an event. The warnings can be received via SMS, phone call, or e-mail and they can be issued by the Minister of the Interior, a provincial governor, or municipal mayor (CCN 2025). The warning levels for particular rivers are also shown on an interactive map on the

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"hydrometrie" website (hydrometrie.wallonie.be) (SPW 2025). Flood warnings are typically also shared on municipal or provincial websites as well as through media outlets and social media.

During the July 2021 flood in the Walloon Region, while warnings were issued, the communication was at times unclear. According to the parliamentary proceedings, the SPW began internal coordination and communication with RMI regarding rainfall forecasts on July 12, 2021 (Parlement Wallon 2022a, 2022b). On July 13, CRC-W began to issue high vigilance pre-alert messages to multiple municipalities as local forecasts showed that rivers such as Vesdre, Ourthe, and Amblève were likely to experience flooding. At 6:00 on July 14, the flood alert phase was officially activated and BE-Alert flood notifications were issued. At 9:27, RMI issued the red alert level for the entire province of Liège and throughout the day the capacity of the dams was closely monitored. While the Vesdre valley was under a flood warning, a message was issued to the town of Verviers stating that they would not be affected by dam releases, then later in the evening of July 14 at 20:26 a message was sent notifying the public to exercise extreme caution due to the flood situation (Parlement Wallon 2022a). Some evacuation orders were issued by regional and provincial authorities, while other evacuations were carried out based on the decision of municipal officials. The flood peaks along the Vesdre river occurred during the night and early morning from July 14 to 15 with model-based peak timing ranging from 1:00 for Eupen to 5:00 for Verviers and 7:00 for Chaudfontaine (Rodríguez Castro et al. 2025a). On July 15, the federal phase of emergency was activated by the Interior Ministry and recovery after the flood began. In July 2021, the channels used for warning local authorities were not consistent. Indeed, some municipalities reported that they first became aware of the severe flood situation through an alert issued by the CRC-W via the BE-Alert system on the morning of July 14, while others became aware of the situation when they were contacted about evacuations by the provincial agent responsible for emergency planning ('l'agent provincial compétent en matière de planification d'urgence (PLANU)') also on the morning of July 14 from around 6:00 (Parlement Wallon 2022a).

Flood preparedness and response planning (Pillar 4) in Belgium are the responsibility of multiple agencies at the federal, provincial, and municipal levels. The CRC-W and national crises centre are involved with preparedness and response planning as well (Lietaer et al. 2024). The EU Floods Directive also stipulated that member countries should have flood preparedness and response plans developed by 2015 as part of their flood risk management plans, which have to be updated and reported on in 6-year cycles by all member states (EU 2007). Flood preparedness and response plans had been prepared by the relevant agencies but during the flood of July 2021 there were issues with coordination and limited available time for response as warning information was received by most on the morning of July 14 and the flood peaked that night. For Verviers, for example, the authorities had around 16 hours between being aware of a severe situation and the flood peak. In addition, due to the severity of the event, the capacities of authorities were exceeded in some areas, and due to flooded roads there were significant access issues (Parlement Wallon 2022a; Lietaer et al. 2024). In the aftermath of the event, high costs were incurred for clean-up, repair, and reconstruction with a focus on the most affected municipalities, which are mostly within the Vesdre River catchment as shown in Fig. 2. While emergency plans were in place at the municipal authority level prior to 2021, few had plans that specifically targeted flooding and even fewer practiced these (Thiry and Fallon, 2021).

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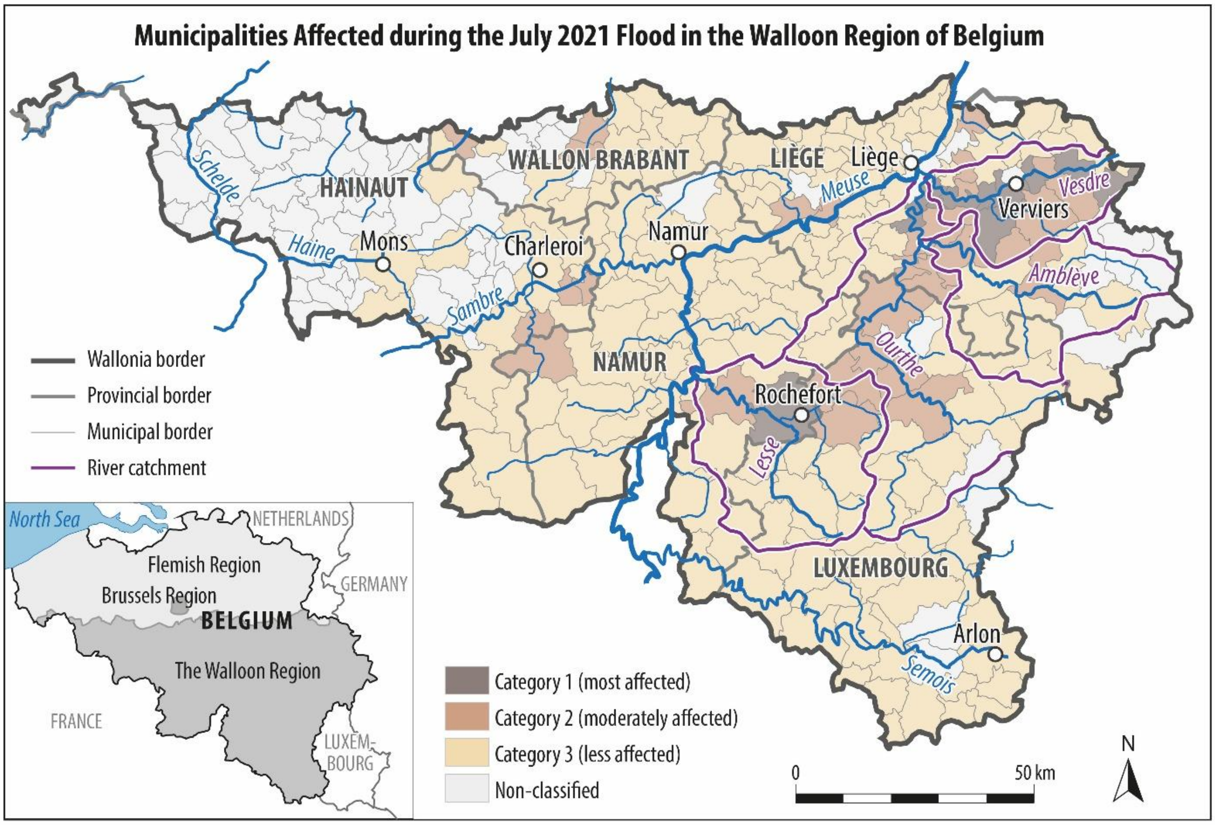

Figure 2. Municipalities in the Walloon Region affected by the 2021 flood according to government classification (Category data from (SPW 2021), Hydrographic data from (SPW 2025))

1.3 Focus of this article

While extensive plans were in place, the impacts of the July 2021 flood were severe for many people in the Walloon Region and the FFWRS was criticised. This is reflected in the commissioning of expert reports and the parliamentary inquiry to better understand what went wrong and how systems could be improved. To better understand the role of the Belgian FFWRS for the population affected in July 2021, this paper mainly focusses on pillars 3 and 4 (warning and response) of the WMO MHEWS framework, while also discussing implications for pillars 1 and 2 (risk knowledge and detection). For an early warning system to be effective, warning messages need to be received by users with a sufficient lead time allowing them to take protective action (called response in Fig. 1). In addition, it is important that people are well prepared and have the capacity to respond (WMO 2018). Kreibich et al. (2021) showed that it is not only important that people receive a flood warning but that they also know what to do. We analyse the decision making processes by using PADM as a theoretical framework from Lindell and Perry (2012). To better understand which variables influence people receiving a warning message, finding the warning credible, having situational knowledge of protective behaviour (knowing what to do) and responding effectively we pose the following research questions:

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RQ1: How many people received a warning before they were in danger in July 2021 and what factors influence this process?

RQ2: How did people interpret the flood warnings and what factors influence people finding the warnings credible, their situational knowledge on protective behaviour, and their level of surprise?

RQ3: How did people respond to the warnings and what factors influence people taking any response action and finding those actions effective?

RQ4: How severe was the damage experienced and what factors influence damage and damage reduction?

We aim to learn from the past by first gaining a baseline understanding of the FFWRS performance in the Walloon Region during the July 2021 flood and then develop further insights through the statistical analysis of influencing factors.

2 Data and methods

2.1 Survey procedure

To evaluate the warnings and response of people during the July 2021 flood event in the Walloon Region, an online survey was conducted. The survey was available to the public from June 9 to September 9, 2023 with a total of 550 valid survey responses. The French language questionnaire included 23 questions that covered the warning reception and channels, contents of the warning message, previously experienced floods, perceived impacts at the community and household levels, response measures undertaken, damage and socio-demographics. English and French versions of the full questionnaire are available in the Supplement (S1) of this paper. A similar online questionnaire on flood early warning had been distributed in Germany as described by Thieken et al. (2023a). The online survey for Belgium was advertised using spatially targeted Facebook advertisements in the Walloon Region through the Facebook Ad Center service hosted by Meta. A Facebook page was created for this purpose and in addition to the open answers in the survey, the comments on the page related to the warning and response situation were documented.

2.2 Sample description

To assess the representativeness of our sample we compare our survey's demographics with that of the January 2024 Belgian statistical office (Statbel) official population data (Statbel 2024). As shown in Table 1, women are slightly overrepresented in the survey sample as compared to the general population by 4.8%. Further certain age groups are overrepresented, namely 41–60-year-olds, while over 80-year-olds are underrepresented (Table 1). Generally, the survey represents a broad range of population age groups. Still, the slight biases are a limitation that have to be considered when interpreting the results.

Other studies show that Facebook and other social media were widely used in the Walloon Region during and following the flood event to share information and co-ordinate volunteer support (Ginzarly et al., 2025). Studies on the demographics of Facebook users indicate that women tend to be overrepresented and older groups tend to be underrepresented among users and

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so these differences in the sample can most likely be attributed to the survey being distributed through Facebook (Filipe N. Ribeiro et al. 2020; Gil-Clavel and Zagheni 2019). (Ginzarly et al. 2025)Click or tap here to enter text.

Table 1. Socio-demographic characteristics of the survey sample in comparison to the general population of the Walloon Region as per Statbel on January 1, 2024 (Statbel 2024).

Demographic categories	Number of respondents (n)	% of survey data	% population in Wallonia on January 1st 2024 (over 16)	Difference
Gender				
Female	283	55.8%	51.0%	4.8%
Male	224	44.2%	49.0%	-4.8%
Subtotal	507			
Other	1			
Missing	42			
Total	550			
Age				
16-20 years	4	0.8%	2.6%	-1.8%
21-40 years	127	24.1%	21.6%	2.5%
41-60 years	240	45.5%	31.0%	14.5%
61-80 years	148	28.1%	30.2%	-2.1%
>80 years	9	1.7%	14.7%	-13.0%
Subtotal	527			
Missing	23			
Total	550			

2.3 Data processing

To prepare the survey data, several indicators were computed and some variables had cases that needed to be reclassified based on information reported in open answers. A Warning Source Indicator (WSI) was used, which takes into account how official the source of the warning received was. Respondents reported if they received a warning from local authorities, national news, or personal contacts for example, and the indicator is computed on a scale of 0 to 4, with 4 being the most official (see Thieken et al. 2005a for more details). Further, a Warning Information Indicator (WII) assessed the content that was included in the warning. This could be information about how to protect oneself, timing of rainfall, or evacuation information for example and the indicator is also computed on a scale of 0 to 4, with 4 being information on life saving and damage reducing actions (for more details, see Heidenreich et al. 2025; Thieken et al. 2005a; Thieken et al. 2023a). The full list of warning sources included in each indicator value is available in the Supplement (S3).

For response actions, a Behaviour Action Indicator (BAI) was created in two versions based on the reported actions including damage reducing measures (BAI1) and life saving measures (BAI2). Damage reducing measures include securing

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documents and valuables, putting furniture up to a higher elevation, or erecting water barriers. Life saving measures include going to a safe place (evacuation), turning off electricity and or gas in the house, or getting help. The indicator is computed on a scale from 0 to 3, with 3 being the most protective action. While damage reducing measures have the highest ranking in BAI1, life saving measures received the highest rank in BAI2.

For some variables, including flood source, warning source, and protective behaviour, cases needed to be reclassified due to additional relevant information being included in open answers. Many people identified dam releases as a potential flood pathway, since the Vesdre River watershed contains both the Gileppe and Eupen dams. A new option for flood pathway labelled "operation of dams" was therefore added. For warning source, some people described not being warned or being warned by others; these answers were assigned to the existing items. For protective behaviour, some respondents mentioned damage reducing behaviour, vertical evacuation in their house, or no action in their open answers, these cases were assigned to either evacuation actions or no action. The indicators and re-classified variables described here were then used in logistic and linear regression models.

2.4 **Statistical** methods

We use an explanatory model approach where we test components of an expanded version of PADM using logistic and linear regression models. The regression models are set up with target (outcome) variables structured in order of PADM processes for decision making. Explanatory (predictor) variables are selected based on the structure of the PADM model with the additional inclusion of the types of protective response behaviour and impacts of the event. All regression models are set up to identify what variables influence decision making during a flood event to gain insights on protective action and not to make predictions in an operational setting. All statistical analyses were conducted using IBM SPSS, Version 29.

To answer RQ1 we present descriptive statistics on warning reception, source of warnings, and timing of warning. Receiving an official warning (WSI = 3 or 4) is especially important and we look at the factors that are related the receipt of an official warning issued by the authorities. We use a binary logistic regression model since the target variable is binary and the explanatory variables are categorical (Field 2017). Note that we consider the scales for data where respondents selected an answer from 1 to 6 to be equidistant. The explanatory variables examined for this first regression model include age, gender, household size, flood experience, flood water level, municipal affectedness, perceived household impact, perceived community impact. All variables are derived from the survey data except for the surprise variable which comes from previous research on surprise and flood hazard areas in the Wallon Region and is measured at the postal code level (Rodríguez Castro et al. 2025a) and municipal affectedness which comes from a post flood government ranking, i.e. the three categories depicted in Fig. 2 (SPW, 2021).

To answer RQ2 we use descriptive statistics on perceived warning credibility and the assessed severity (magnitude) of the anticipated flood event. To understand what variables influence respondents finding the warning credible and situational knowledge, we use single level multiple linear regression models as for each model we have one target variable (dependent variable) and several explanatory variables (independent variables) (Field 2017).

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To answer RQ3 on response actions we use descriptive statistics and linear regression models with response behaviour as target variable. We use two different regression models to test the differences between life-saving actions and damage reducing actions. To answer RQ4 on damage and damage reduction we use descriptive statistics and linear regression models with the effectiveness of damage reducing measures and damage level as the outcome variables. In total we use one binary logistic regression model and six linear regression models. A full list of the explanatory variables included in these models with descriptions can be found in the Supplement (S3) and the results of the models are presented and discussed in Section 3.

To identify significant explanatory variables, we use *p*-values of 0.1 as a threshold. We consider *p*-values of 0.1 or less as slightly statistically significant, *p*-values of 0.01 or less being statistically significant and *p* values of 0.001 or less to be statistically very significant. While a significance level of 0.05 is common in many natural science disciplines, a significance level of 0.1 is often used in economics, behavioural science especially for exploratory studies, which are comparable to this paper (Field 2017; Holmes et al. 2023) For all variables in the models we checked multi-collinearity using the variance inflation factor (VIF) and found the values to be below 3 which is considered acceptable and not requiring correction (Field 2017).

3 Results and discussion

3.1 Warning reception

In this section we first present the descriptive statistics and regression model results to explain warning reception (RQ1) and then discuss the implications. Warning reception is based on Question 4 (ex-ante): How did you find out that the risk of flooding was becoming acute for you? In the sample (n = 541) it was found that 32.9% of respondents did not receive any warning. This number is a bit higher than the rate of around 22% found by Rodriguez et al. (2025b) based on an in-person survey (n = 385) focusing solely on the Vesdre valley. Among those who had been warned (n = 360), 42.5% were warned by official sources.

The government in the Walloon Region classified municipalities after the event into three groups, most affected (1), very affected (2), and less affected (3), as shown in Fig. 2. Among the respondents that reported their postal code (n = 531) the majority were located within the most affected municipalities (67.5%) and among this group 33.7% were not warned. Among the moderately affected and less affected municipalities 22.0% and 34.5% were not warned respectively, and in other municipalities 39.0% were not warned.

The results of a binary logistic regression model with receiving an official warning as the outcome variable (Table 2) show that perceived impact at a household level has a statistically significant negative effect, meaning that respondents whose household was highly affected are less likely to have received an official warning. Based on the government classification, we see that the rate of not being warned is slightly higher in the most affected municipalities compared to the moderately affected ones. However, in the model results, no significant effect is shown for the perceived impact at the community level. Similarly, no significant effect is shown for age, household size, flood experience prior to 2021 or flood water level (Table 2). Furthermore, in our sample of respondents who were warned and reported a warning time (n = 219) most were warned on

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Wednesday July 14th 2021 (56.6%) which also corresponds with the official reports (see Section 1.2 and (Parlement Wallon 2022a). Since the flood levels peaked in the evening of July 14th for the most affected watersheds in Belgium, most people had less than a day of lead time.

Table 2. Results of a logistic regression (Model 1.1) explaining the receipt of an official warning (n=479)

Explanatory variable	Odds ratio	Unstandardized B	Standard Error	p	95% conf. interval	
Age	0.994	-0.005	0.008	0.501	0.979	1.010
Gender	0.944	-0.057	0.045	0.206	0.865	1.032
Household size	1.028	0.028	0.078	0.718	0.883	1.197
Flood Experience (prior to 2021)	0.953	-0.048	0.103	0.641	0.778	1.167
Flood Water Level	0.945	-0.059	0.099	0.552	0.776	1.145
Municipality Level Affectedness	1.012	-0.004	0.163	0.979	0.724	1.370
Perceived Impact (Household)	0.757	-0.276	0.105	0.008	0.618	0.931
Perceived Impact (Community)	1.029	0.029	0.108	0.788	0.833	1.273
Surprise Effect (Postal Code)	0.972	-0.029	0.075	0.701	0.839	1.125
_Constant	2.373	0.832	0.702	0.236		

Pseudo R^2 (Nagelkerke) = 0.056

The logistic regression model results show that many severely affected people were among those who did not receive timely warnings. This applies to the household level but not larger scales at the community or post code level. Some areas closer to the river were highly affected while others at high elevations away from the river were not. The extreme nature of the event appears more important than demographic factors or other variables in determining whether people received an official warning or not. Producing timely and accurate warnings for flash floods faces unique challenges, including uncertainty in location and intensity of rainfall, particularity for small catchments (Braud et al. 2018; Marchi et al. 2010).

The fact that the households that were severely affected were less likely to receive an official warning is concerning, as those are the people who most needed to be warned. Based on post event reports, there are several factors that can explain why the warnings did not reach people in time. In Belgium in July 2021, only the navigable waterways were integrated into the hydrological forecasting system Hydromax and for this reason the expected water levels for some of the most affected

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watersheds were not clear until the flood situation was already becoming severe (Zeimetz et al. 2021; Wallonie 2025). The BE-Alert warning system was used by some municipalities but not all, due to either the information being uncertain or affected municipalities not being registered as, prior to the July 2021 flood, 80% of Walloon Region municipalities were registered. The provincial crisis centre did use BE-Alert to warn the public about blocked roads with advice to stay home on July 15 (Zeimetz et al. 2021). In addition, many people were severely flooded in areas where no flood was expected due to differences between officially mapped flood hazard zones and the extent of this extreme flood (Rodríguez Castro et al. 2025a). However, this variable at the postal code level, which was included as "surprise effect" in the first model (Table 2), does not explain much, nor does the perceived impact at the community level. Instead, we see the household level being most important.

To address improvements which could lead to better warnings, recommendations have been made, including in the parliamentary inquiry report. Since 2021, several changes have already been implemented to improve FFWRS in Belgium. Governance changes have been implemented and the functions of the CRC-W are now under the Centre for Coordination of Risks and Transmission of Expertise (Centre de Coordination des Risques et de la Transmission d'Expertise ([CORTEX]). Its responsibilities now extend to the full disaster risk management cycle (Wallonie 2025). A Flood Expertise Unit (la Cellule d'expertise crues [CELEX]) has been formed and CORTEX convenes this group in the case of an orange or red flood alert to review the available information in an effort to provide improved coordination (CORTEX 2025). It was suggested in the parliamentary reports that it would be helpful to integrate the Aqualim network into Hydromax, take into account the data shared by the European Flood Awareness System (EFAS), and improve the accuracy of meteorological forecasting (Parlement Wallon 2022a). Given that current thresholds are based on expert judgement, it was recommended that the terminology and thresholds for pre-warnings and warnings be clearly stated to improve timely communication of extreme flood warnings (Parlement Wallon 2022a; Busker et al. 2025). In addition, mainstreaming the use of the BE-Alert system among municipalities is also recommended and already more municipalities are registered with the system (Parlement Wallon 2022a; CCN 2025). While the main warning channels for BE-Alert messages are SMS, e-mail, and phone calls, an additional channel has been added. Since 2022, BE-Alert messages can be displayed on digital street information boards and there are plans to have them accessible through apps and the GPS screen on cars (CCN 2025). Since 2022, in addition to BE-Alert warning messages, flood risk information is communicated on the website Hydrométrie Wallonie (hydrometrie.wallonie.be), with spatial information and indications of warning levels from green to red (SPW, 2025). Earlier messages, from official warning sources, that reach as much of the public as possible would help to close the warning gap for future floods in the Walloon Region.

In the other countries affected in July 2021, many people were also not warned before the flood situation became severe. In the most affected watershed in the Netherlands, the Geul, about 75% of people were not warned in time and the group of people who experienced flooding at their house show the highest proportion of people not warned (Endendijk et al., 2023). Similar to Belgium, in the two most affected federal states of Germany, also around a third of people were not warned (Thieken et al., 2023a; Heidenreich et al., 2025). While there are similarities between the warning situation for the July 2021 flood in Belgium and Germany, a notable difference is that men reported much higher levels of being officially warned in Germany than women, with an increased odds ratio of almost 67% (Thieken et al., 2023a). This suggests that women need to be better targeted with warning communications. In the Belgian data, gender is not a significant variable (Table 2), suggesting that gender does not play a significant role for warning reception in the Walloon Region of Belgium. The target group for this survey are people in the areas of the Walloon Region affected by the July 2021 flood, which includes people outside the floodplains. However, the socio-economic characteristics of populations inside and outside the floodplains in the province of Liège have been shown to differ, with generally higher levels of socioeconomic vulnerability within the floodplains (Poussard et al. 2021). This difference in socioeconomic level could also explain higher levels of not being warned for directly affected households.

3.2 Interpretation of flood warnings

To address our second research question (RQ2) on the interpretation of warning messages, we examine to what extent people trusted and understood the warnings as well as their situational knowledge on protective behaviour. Our results show that many people were surprised by the severity of the flood event and many also did not know what to do.

Trust and credibility of warnings

Trust in the warnings is captured by the question on credibility of the warning (ex-ante) (Q7: How credible did you think the warnings were?). The results on warning credibility (n = 346) are mixed, with 25.1% reporting that they found the warnings very credible and 31.5% reporting that they found the warnings to be not very credible. For this reason, we look further into factors that influence finding the warnings highly credible using a linear regression model (Table 3). The results show that gender is a slightly significant explanatory variable with a negative effect meaning that women are more likely to find the warnings credible. No other explanatory variables in the model were found to be statistically significant, including flood experience or the source and content of the warnings. When age is added to this model, it is not a statistically significant explanatory variable, either. This suggests that, in this, case neither the warnings themselves, nor the experience of people influenced finding the warnings credible.

Table 3. Results of a linear regression (Model 2.1) with credibility as an outcome variable (n=294)

Explanatory variable	Coefficient (Unstandardized B)	Standard Error	*p*	95% conf. interval	
Gender	-0.064	0.032	0.047	-0.127	-0.001
Flood Experience	-0.110	0.081	0.175	-0.269	0.049
Warning Source Indicator (WSI)	0.025	0.045	0.584	-0.064	0.114
Warning Information Indicator (WII)	-0.015	0.024	0.521	-0.062	0.032
_Constant	3.444	0.185	0.000	3.079	3.809

R^2 = 0.012, Adjusted R^2 = 0.008

With just one statistically significant explanatory variable, credibility is difficult to explain based on the available data. To better understand this aspect, additional questions could be added to future surveys. For example, people tend to find warnings credible when they get information and cues from multiple sources including official warnings and information from social contacts (Mayhorn and McLaughlin 2014). Aspects like the strength of social networks could be captured in a survey using the Oslo social support scale (OSSS-3) which is constructed using three questions on social contacts (Kocalevent et al. 2018). In future research, such variables should be considered.

While there was very little time to warn people there was also a lot of confusion as the severity of the flood was not clear to many authorities (Parlement Wallon, 2022a). Confusion from inconsistent information has been shown to lead to people seeking more details but less likely to act, suggesting clear warnings are important for response behaviour (Weyrich et al., 2019). Previous research (Zakaria and Mustaffa 2014; Bostrom et al. 2022) indicates that warning source and the content of the warning influence warning credibility, which is however not supported by our data. However, there is still much debate regarding the causal link between trust, credibility, and risk (Siegrist 2021).

Situational knowledge on protective behaviour

For a FFWRS to be effective it is important that people not only receive a warning and trust it but that the warning contains appropriate recommendations for action and people know how to respond (Kreibich et al. 2021)(Kreibich et al. 2021; Weyrich et al. 2019). Situational knowledge on protective behaviour was captured in the questionnaire by the ex-ante question (Q9: Did you know how you can protect yourself and your household from flooding before the risk of flooding became acute for you?). In our sample (n = 538), more than half of the respondents (56%) reported that they did not know how they could protect themselves and their household. We investigated what factors influence this reported situational knowledge using a regression model, and the analysis revealed that the information contained in the warning as well as flood experience are statistically significant with positive effects (Table 4). Respondents who received a warning with more detailed information and those with flood experience were both more likely to know what to do. Perceived surprise and perceived impact at the household level are both statistically significant with negative effects, suggesting that people who were surprised by the flood magnitude and those who were more affected at the household level were less likely to report a good situational knowledge.

Table 4. Results of a linear regression (Model 2.2) with situational knowledge on protective behaviour (knowing what to do) as an outcome variable (n = 462)

Explanatory variable	**Coefficient (Unstandardized B)**	**Standard Error**	***p***	**95% conf. interval**	
Age	-0.004	0.005	0.469	-0.014	0.006
Gender	-0.003	0.034	0.924	-0.069	0.063
Warning Source Indicator (WSI)	0.038	0.064	0.555	-0.088	0.163

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Warning Information Indicator (WII)	0.122	0.065	0.063	-0.007	0.250
Flood Experience (prior to 2021)	0.178	0.066	0.007	0.048	0.308
Perceived Surprise of Severity (Household)	-0.366	0.100	0.000	-0.563	-0.170
Perceived Impact (Household)	-0.113	0.057	0.048	-0.225	-0.001
_Constant	4.799	0.632	0.000	3.557	6.042

R^2 = 0.101, Adjusted R^2 =0.087

Warning information and flood experience were expected to positively influence situational knowledge as other studies have similarly found that both the inclusion of recommendations on protective action in warning messages and flood experience have a positive effect on people understanding the message and having situational knowledge (Sutton et al. 2021; Bubeck et al. 2012; Köhler et al. 2023). Information on what to do for a specific flood should be included in official warning messages and general information on appropriate response actions should be provided through public communications materials (WMO 2018, 2023; Morss et al. 2016). People may also know what to do due to experience from previous flood events, emergency preparedness programs, or other sources of information on flood response (Kreibich et al. 2021; Köhler et al. 2023).

The Walloon Region does have experience with floods. There were several moderate floods prior to 2021 that people affected in July 2021 may also have experienced. However, the most notable event in recent decades is the flood of September 1998 (Chakraborty et al. 2025; SPW 2017). Although the 1998 flood was more than 25 years ago, people who previously experienced this flood mentioned in the open answers that they remembered how high the water was in their building and how they responded. These people also mentioned that they knew to put their valuables at a higher elevation and evacuate vertically or to another location. These open answer responses suggest that flood experience can positively influence situational knowledge on protective behaviour.

Threat perception and surprise

Understanding of the severity of the upcoming flood (ex-ante) and surprise regarding the severity of the flood that occurred (ex-post) was captured by two questions (Q8: Based on the warnings, how did you assess the severity of the anticipated event? and Q14: How surprising did you find the strength of the event in your immediate vicinity?). In the sample, only 20.9% of the people who were warned in the Walloon Region (n = 350) expected a severe event (rating 5 or 6 on a 6 point scale). For the perceived level of surprise (n = 545), the vast majority (92.7%) of all respondents were surprised by the intensity of the event ex-post. As shown in Table 5, the regression model with perceived surprise of the threat as an outcome variable shows a small effect of gender with men being more surprised than women. We also see that those with flood experience and situational knowledge on protective behaviour were less surprised. Finally, those who experienced higher water levels and were more directly affected were more surprised by the severity of the event. The variables on the warning system (WSI and WII), both do not show significant influence.

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Table 5. Results of a linear regression (Model 2.3) with perceived surprise as outcome variable (n=438)

Explanatory variable	Coefficient (Unstandardized B)	Standard Error	p	95% conf. interval	
Age	0.002	0.002	0.469	-0.003	0.006
Gender	0.032*	0.016	0.043	0.001	0.062
Flood Experience	-0.064*	0.031	0.037	-0.124	-0.004
Warning Source Indicator (WSI)	-0.043	0.030	0.150	-0.103	0.016
Warning Information Indicator (WII)	0.004	0.031	0.889	-0.056	0.065
Situational knowledge	-0.093***	0.021	0.000	-0.135	-0.051
Water level	0.129***	0.025	0.000	0.080	0.178

R^2 = 0.151, Adjusted R^2 = 0.137

The high levels of ex-post surprise are due not only to the rapid evolution and uncertain nature of the flood event, but also to limitations in flood mapping for extreme events and the operation of dams. In the Walloon Region, the available flood hazard maps display flood levels of scenarios from very low to high hazard (Mustafa et al. 2018; Rodríguez Castro et al. 2025a). During the July 2021 flood, some of the inundated areas matched the maps but there were notable exceptions, including the municipality of Verviers. The town centre of Verviers was flooded up to 2 m between July 14 to 15, 2021, while this area was not within any mapped flood hazard areas (Dewals et al. 2021). This was a surprise for citizens but also for local authorities.

The operation of dams is an issue of particular concern for the Vesdre River where the operation of the Gileppe and Eupen dams played a role in the flood event, as mentioned in the open answers of the survey, Facebook comments related to the survey, and expert reports (Parlement Wallon 2022a; Zeimetz et al. 2021). This is reflected in the survey data as 22% of people mention that their perceived cause of flooding can be attributed to “dike or dam failure or releases”. However, while this played a role, the independent review found that the operation of dams did not contribute to an increased severity of flooding and that the flood would overall have been worse without them (Zeimetz et al. 2021). The review indicates that the dam’s operating rules and the speed of the flood would not have allowed for sufficient pre-releases to reduce the flood severity. Even with the dams, floodplains within the Vesdre watershed start to flood with discharge levels corresponding to a 25 year return period (Zeimetz et al. 2021). Regardless, dam releases influenced the timing of peak flows, and the parliamentary inquiry recommended better use of forecasts and sub-catchment modelling to improve understanding of the impacts of specific dam discharge levels (Parlement Wallon 2022a). As there is a need to better integrate downstream flood safety into dam operations, a new legal framework for large dams in the Walloon Region has been passed (Dierickx et al. 2025; Parlement Wallon 2024).

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Updated flood modelling and mapping with extreme flood scenarios, updated hydrology, and dam operations can help to improve flood risk awareness and reduce surprise for future events.

3.3 Response behaviour

To reduce flood impacts it is important that people not only know what to do, but also that they actually implement measures suitable to protect themselves and their property. In the questionnaire we ask people what action they took (Q10: When you became aware of the risk of flooding, what did you do?). Addressing our third research question (RQ3) on how people responded to the warnings and what factors influenced their decision to take protective action and find those actions effective, we find that most people (72.5% out of n = 550) engaged in either damage reducing or life-saving behaviour. A smaller proportion (15.8%) sought additional information or made preparations, while only 11.6% took no action. As described in Section 2.3 we use an indicator for response behaviour with two versions (BAI1 and BAI2) in a linear regression model. With BAI1 (damage reducing behaviour ranked highest) as the target variable, flood experience is statistically significant meaning that those who have experienced floods in the past are more likely to take damage reducing actions (Table 6). This is quite different for the model with BAI2 (life-saving behaviour) where flood experience is not statistically significant (Table 7). With both model versions, age is a statistically significant explanatory variable with a negative effect, suggesting that older people are less likely to engage in protective behaviour. Expected or anticipated flood magnitude is statistically significant for the BAI2 model. In both models the perceived impact at the household level and community levels are significant. These results suggest those who expected a more severe event were more likely to take a life-saving response and those who were more affected were more likely to take some kind of protective response. However, situational knowledge on protective behaviour is not found to be statistically significant in either model, nor are warning indicator variables (WSI and WII).

Table 6. Results of a linear regression (Model 3.1) with response action (BAI1) as an outcome variable where damage reducing behaviour is ranked highest (n = 275)

Explanatory variable	Coefficient (Unstandardized B)	Standard Error	*p*	95% conf. interval	
Age	-0.011	0.004	0.011	-0.020	-0.004
Gender	-0.027	0.027	0.312	-0.080	0.023
Household Size	-0.003	0.043	0.940	-0.049	0.109
Flood Experience	0.177	0.054	0.001	0.039	0.246
Warning Source Indicator (WSI)	-0.044	0.054	0.412	-0.042	0.082
Warning Information Indicator (WII)	-0.004	0.047	0.939	-0.016	0.047
Credibility	0.026	0.036	0.475	-0.055	0.081
Expected Flood Severity	0.067	0.043	0.117	-0.019	0.138
Situational Knowledge	0.000	0.038	0.993	-0.075	0.067
Perceived Impact (Household)	0.096	0.047	0.041	0.007	0.190

Perceived Impact (Community)	0.109	0.053	0.042	0.006	0.213
_Constant	1.387	0.395	0.001	0.514	1.963

R^2 = 0.115, Adjusted R^2 =0.099

Table 7. Results of a linear regression (Model 3.2) with response action (BAI2) as an outcome variable where life-saving response is ranked highest (n = 275)

Explanatory variable	Coefficient (Unstandardized B)	Standard Error	*p*	95% conf. interval	
Age	-0.011	0.004	0.005	-0.020	-0.003
Gender	-0.022	0.026	0.340	-0.076	0.026
Household size	0.005	0.042	0.561	-0.055	0.102
Flood Experience (prior to 2021)	0.071	0.054	0.322	-0.051	0.155
Warning Source Indicator (WSI)	-0.099	0.053	0.539	-0.042	0.081
Warning Information Indicator (WII)	0.072	0.047	0.676	-0.025	0.038
Credibility	0.019	0.036	0.791	-0.058	0.077
Expected Severity	0.062	0.042	0.078	-0.008	0.148
Situational Knowledge	-0.033	0.037	0.350	-0.104	0.037
Perceived Impact (Household)	0.136	0.046	0.001	0.061	0.243
Perceived Impact (Community)	0.093	0.052	0.070	-0.008	0.198
_Constant	1.500	0.389	0.001	0.555	1.996

R^2 = 0.152, Adjusted R^2 = 0.136

Knowing how to take action to protect oneself and trust in the effectiveness of those actions are key motivators to taking action when faced with a natural hazard threat (Sutton et al. 2021). As represented in PADM, however, we know that there many factors which influence the protective response of people (Lindell and Perry 2012) Older people being less likely to engage in protective behaviour, particularly evacuation, can be due to mobility issues, lack of resources, and lack of motivation (Cong et al. 2021; Dostal 2015). It should be noted that the oldest age groups are underrepresented in our sample with the 61–80-year-old group by 2.1% and the over 80-year-old group by 13.0% (see Table 1). However, among the fatalities the majority are over 65 years old and it was frequently reported that elderly people had difficulty responding to warnings and evacuating from the flooded areas (Deffet 2022). This was similar in Germany, where elderly people (>60 years) were found to be particularly at risk during the 2021 event and accounted for two thirds of the flood deaths in North Rhine-Westphalia (Thieken et al. 2023b)(Thieken et al. 2023b) and for three quarters in Rhineland-Palatinate (Rhein & Kreibich 2025). While elderly people are often more physically vulnerable, a study in the United States found that they tend to be better prepared in certain aspects among the under 75 age group (Cong et al., 2021). These findings point to the need to explicitly address elderly people in risk communication and evacuation plans.

The finding that flood experience positively influences damage reducing behaviour aligns with previous studies which show a link between flood experience and knowing what to do along with the intention to prepare, but also flood adaptive behaviour including adapted building use (Bubeck et al. 2012; Bubeck et al. 2013; Köhler et al. 2023; Köhler and Han 2024; Li et al. 2024; Osberghaus 2017; van Valkengoed and Steg 2019). In the open answers and testimonies from people in the parliamentary review, some described past floods and mentioned that they knew how high the water could be in their home and what they had done before (Parlement Wallon 2021, 2022b). It is less clear why flood experience does not influence life-saving behaviour in this case. Much of the literature on flood experience and protective behaviour focuses on damage reducing behaviour or longer term adaptation measures (Botzen et al. 2015; Endendijk et al. 2023; Aerts et al. 2024). Studies on life saving behaviour such as evacuation suggest that other factors are important such as receiving a warning, perceived severity, perceived susceptibility, evacuation access, age, household size, education level, and social norms (Soon et al. 2018; Liu et al. 2024). We also find that perceived severity and age are significant variables influencing life-saving behaviour as shown in Table 7. People without flood experience have been found to simply underestimate flood severity or be over reliant on authorities (Siegrist and Gutscher 2008; Terpstra and Lindell 2013; Botzen et al. 2015; Kuller et al. 2021). In addition, prior experience with less severe floods can lead overconfident behaviour in the case of a more severe and life-threatening flood events (Wachinger et al. 2013). As discussed in the section 3.1 many people simply did not expect the event of 2021 to be as severe as it actually was, did not receive a warning, and might not have expected to need to take life saving measures.

While flood experience was not found to influence life saving behaviour, a higher threat appraisal with a higher expected severity does (Table 7). A higher threat appraisal combined has been shown to trigger an adaptive behaviour when combined with high coping appraisal (Kuhlicke et al. 2020; Grothmann and Reusswig 2006). Respondents who not only expected a more severe event but were more affected at the household and community level were also more likely to take life-saving measures. Those who were more affected may also have had a higher threat appraisal through warning information and environmental cues, indicating that response action was necessary. Among respondents, just over half (52.5%) implemented life-saving measures. In the Netherlands during the 2021 flood this was higher with the majority of people who received a flood warning evacuating based on orders or advice to do so (75% of all cases) and many of those who had sufficient time also implemented damage reducing measures (Endendijk et al. 2023). While this evacuation rate is high, it is less than the 90% evacuation rate expected by Dutch authorities for un-embanked areas (Dutch Ministry of Infrastructure and The Environment 2016).

It is surprising that situational knowledge is not found to be significant for protective behaviour or life-saving behaviour. This could simply be that of the people who were warned (n = 361) few respondents reported that they had situational knowledge on protective behaviour (only 15.2%). During the 2021 flood in Germany in the most affected federal states, the level of situational knowledge for North Rhine-Westphalia (NRW; 18.1%) is similarly low and for Rhineland-Palatinate (RLP; 22.9%) it is only slightly higher (Thieken et al. 2023a). Other studies have shown than men tend to be more confident in their abilities to cope with flooding but in the face of a severe event not always effective (Cvetković et al. 2018; Thieken et al. 2023b), however in the Walloon Region data we don't see gender having a significant effect on situational awareness or protective behaviour. One limitation of this study is that respondents are treated as individual decision makers, however, individuals are rarely alone in receiving warning information and making a decision and there are more complex social processes and social norms involved (Drabek 1999; van Valkengoed and Steg 2019; Kuhlicke et al. 2020). (Sutton et al. 2021)Understanding, what factors influence people to take damage reducing and life-saving actions can support more effective emergency planning.

3.4 Damage and damage reduction

Flood warnings should have the potential to mitigate damage by prompting damage reducing behaviour, and our fourth research question (RQ4) examines the level of damage as well as the factors influencing both its severity and the degree of reduction achieved. The results indicate that a large proportion of respondents were severely affected with 73.0% (n = 544) of respondents indicating that they were highly affected at the household level and 68.0% (n = 546) at the community level. Of those who reported a household damage level (n = 463) the majority reported losses in the range of €1000 to €175,000 with a small number of outliers exceeding €175,000. We look into influencing variables as part of our exploratory modelling approach, not to predict damage for any future events, but to better understand the effectiveness of the FFWRS in the Walloon Region for damage reduction during the July 2021 flood.

Effectiveness of damage reducing measures

To assess whether respondents found their damage reducing behaviour effective we posed the question "What do you estimate: How much were you able to reduce damage through your reaction to the event and / or private preventive measures?" (Q13). We use a single level multiple linear regression model to analyse the variables that influence the effectiveness of damage reducing measures as reported by respondents (Table 8). Situational knowledge on protective behaviour is statistically significant in predicting damage reducing actions being effective. We also find that the BAI1 is a statistically significant explanatory variable with a positive effect meaning that those who took a damage reducing action were more likely to report their action to be effective. This is confirmed by the other version of the model (in Supplement section S2) using BAI2 which prioritized life-saving behaviour, in which BAI2 is not significant. Finally, we find that water level is a significant predictor with a negative effect meaning that those who experienced a higher water level at their primary residence were less likely to perceive their damage reducing actions effective. Socio-demographic variables or the two warning indicators were not significant (Table 8).

Table 8. Results of a linear regression (Model 4.1) with perceived effectiveness of damage reducing measures as an outcome variable (n = 265)

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Explanatory variable	**Coefficient (Unstandardized B)**	**Standard Error**	***p***	**95% conf. interval**	
Age	-0.002	0.006	0.739	-0.013	0.009
Gender	-0.033	0.037	0.374	-0.105	0.040
Flood Experience (prior to 2021)	-0.025	0.074	0.741	-0.170	0.121
Warning Source Indicator (WSI)	0.068	0.071	0.338	-0.072	0.209
Warning Information Indicator (WII)	-0.035	0.064	0.588	-0.160	0.091
Expected Severity	0.031	0.057	0.590	-0.081	0.142
Situational Knowledge	0.208	0.050	0.000	0.108	0.307
Behaviour Action Indicator (BAI1)	0.294	0.080	0.000	0.136	0.453
Water Level	-0.227	0.055	0.000	-0.336	-0.118
_Constant	2.035	0.489	0.000	1.073	2.997

R^2 = 0.196, Adjusted R^2 =0.167

In line with findings reported by Kreibich et al. (2021), situational knowledge on protective behaviour is a statistically significant explanatory variable for effective damage reducing actions. Also for the severe event of 2021, it was found in Germany that situational knowledge was a statistically significant explanatory variable for perceived damaged reduction (Thieken et al. 2023a). In addition, we find that BAI1 is a significant predictor with a positive effect meaning that those who took a damage reducing action were more likely to find their action to be effective. This is what we would expect and it is confirmed by the other version of the model (in Supplement section S2) using BAI2 which prioritized life-saving behaviour, in which BAI2 is not significant. This shows that it does make sense to distinguish between the different types of protective behaviour within PADM or other behavioural studies. That higher water levels reduce the effectiveness of damage-mitigation measures is also unsurprising and in line with findings for the 2021-flood in Germany (Thieken et al. 2023a), since individual-level options become increasingly limited as flood severity rises. Overall, we find that those who knew what to do and took some kind of damage reducing action were more likely to perceive their damage reducing actions effective.

Household damage

To understand which variables influence reported damage at the household level we use a linear regression with reported damage level as an outcome variable and the model shows that age and household size are statistically significant with positive effects. Additionally, WSI is statistically significant with a negative effect suggesting that those who were not warned are more likely to have higher household damage. We also find that water level and perceived impact at the household level are statistically significant. This is a useful consistency check showing that those who reported the highest water levels experienced the highest financial damage. In fact, perceived impact at the household level and reported financial damage are highly correlated (0.537, significant at the 0.01 level) as they measure the same thing in different ways. Again, showing

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consistency in the dataset, we also find that impact at the community level is statistically significant suggesting that respondents in the most affected communities are also more likely to report higher damage at their household.

Table 9. Results of a linear regression (Model 4.2) with financial damage level as an outcome variable (n=411)

Explanatory variable	**Coefficient (Unstandardized B)**	**Standard Error**	***p***	**95% conf. interval**	
Age	0.017	0.009	0.050	0.000	0.035
Gender	0.076	0.060	0.202	-0.041	0.194
Household Size	0.232	0.090	0.010	0.056	0.409
Warning Source Indicator (WSI)	-0.212	0.106	0.047	-0.421	-0.003
Warning Information Indicator (WII)	0.097	0.108	0.369	-0.116	0.310
Behaviour Action Indicator (BAI1)	0.035	0.117	0.767	-0.196	0.265
Water Level	0.895	0.119	0.000	0.662	1.129
Perceived Impact (Household)	0.749	0.127	0.000	0.500	0.998
Perceived Impact (Community)	0.322	0.125	0.011	0.075	0.568
_Constant	2.035	0.489	0.000	1.073	2.997

R^2 = 0.511, Adjusted R^2 =0.500

We find that age and household size are significant explanatory variables for household damage, indicating that older people and those with larger households are more likely to have higher damage levels. Elderly people may have a reduced capacity to implement precautionary measures and emergency measures due to physical limitation or other impairments, which is supported by earlier findings in Tables 6 and 7. This finding linking age to higher damage is consistent with another study on damage during the July 2021 flood in the most affected area of the Vesdre River valley (Rodríguez Castro et al. 2025b). Larger households are more likely to have higher assets, however, there are also more people to implement measures. For pluvial floods, larger households were found to have a lower probability of damage (Rözer et al. 2019), however, private precautionary measures are easier to implement for pluvial flooding in comparison to a highly destructive flash flood like the 2021 event. Indeed BAI1, which ranked damage reducing measures the highest, is not a statistically significant explanatory variable meaning that taking protective action is not shown to influence damage in this case. Additionally, that those who were not warned are more likely to have higher damage is consistent with our findings from Model 1.1, which similarly showed that the respondents whose household was highly affected are less likely to have received an official warning. This finding is consistent with the German study (Thieken et al. 2023a) and might be explained by the fact that communication in highly impacted areas might fail early. Overall, Table 8 confirms that water level strongly influences damage, which is a commonly accepted principle in damage modelling (Smith 1994; Thieken et al. 2005b).

As expected, those who experienced higher water levels were less likely to find their actions effective for reducing damage as the flood severity was simply too high. Previous studies have shown that mitigating measures can be effective for

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damage reduction, however the results of Model 4.2 reinforce the point that flash floods in particular pose challenges (Jonkman et al. 2024; Marchi et al. 2010). The effectiveness of property level protection measures is more limited for severe floods and we see this is confirmed for the 2021 flood in the Vesdre valley based on another detailed survey on damage for the most severely affected households (Rodríguez Castro et al. 2025a). There is a need for flood risk management strategies to address different types of floods as argued by Dillenardt & Thieken (2024) and also a range of flood severities from less severe more frequent floods to rare extreme events. Managing the risks associated with more extreme floods could improve both warning and response while reducing vulnerability and exposure. This can be achieved through spatial planning, adapted building use and measures like managed retreat from high hazard areas (Montz and Gruntfest 2002). There is an interest and willingness to improve flood management at the local level including improvements to the flood warning and response system, dam operations, and governance (CORTEX 2025; Dierickx et al. 2025; Environment Wallonie 2025). While some improvements have been made since 2021, numerous challenges remain including financial constraints, institutional barriers, and conflicts of interest between stakeholders (Goër Herve and Pot 2024; Ginzarly et al. 2025). While damage reducing actions have some effect, there is a limit to what is possible at the household level, particularly in a short amount of time.

4 Conclusions

The flood experienced in Belgium's Walloon Region in July 2021 reveals that effective flood warning depends on both the technical functioning of forecasting and communication systems as well as the content of messages and the behaviour of people. Our analysis, based on a household survey with 550 respondents, shows that information reception, demographic factors, flood experience, and perceptions influence the response behaviour of people and this influences the impact of floods at the household level. Using an expanded version of PADM as a framework we target outcome variables from warnings and cues to response actions and the effect of that response with eight logistic and linear regression models. With this approach we identify variables that influence protective action decision making and reinforce the case for designing flood early warning systems that explicitly consider human behavioural responses. The target variables and significant explanatory variables identified in this study are summarized in Fig. 3.

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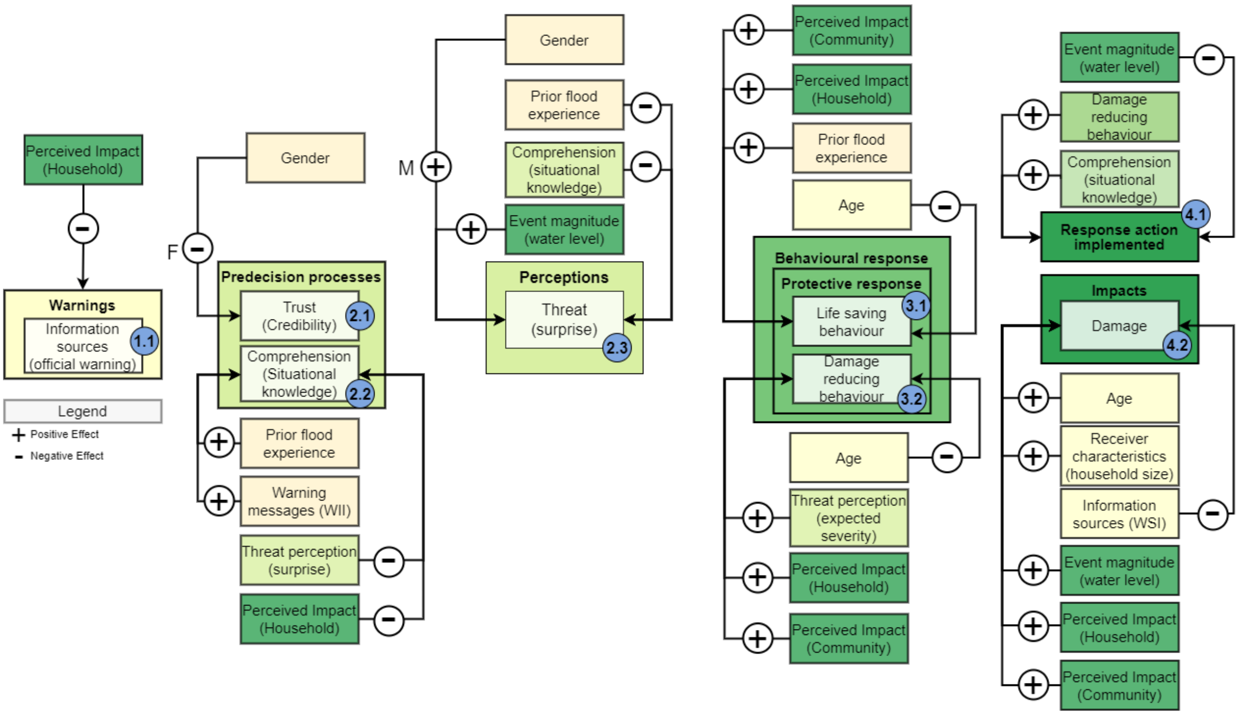

Figure 3: PADM and influencing factors with direction shown

Addressing information reception, we find that one third of respondents received no warning, and the most severely affected people are least likely to be warned. This points to the need for improvement in the early detection and forecasting of floods and transmission of warnings. We know that timely and understandable warnings are important for people responding to floods. Extending the hydrological forecasting system to include the first order non-navigable rivers in the Walloon Region of Belgium and enhance the capabilities for timely flood warnings in these watersheds would probably improve this aspect. Additional warning channels such as sirens and strengthening the reach of existing channels such as BE-Alert would help to reach more people and add redundancy to the warning system. Finally, clear and consistent messages and coordination between organizations responsible for warning and response would help improve trust and credibility, which also play a role. This has already partially been implemented through the creation of CORTEX, having more municipalities use BE-Alert, and other coordination efforts.

Even among those who were warned in July 2021, over half did not know how to respond. This highlights a gap in awareness on protective behaviour and a need for improving the recommendations for action provided. Many of those who were warned also reported being surprised (ex-post) by the severity of the flood that they experienced. Updated flood hazard maps which include more extreme events and increased awareness of potentially flood affected areas would probably help people be less surprised. Explicit use of probabilistic hydrologic forecasts and inundation modelling are tools that could further

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reduce surprise and help people to know better what areas are affected and how severe the event is. Additionally, gender patterns in the Walloon Region for several variables on warning differed from other regions, pointing to the importance of local context. While there are opportunities for cross border learning, with Europe-wide services such as EFAS being a useful tool, local context remains important.

Older adults were consistently found to be more vulnerable as they were less likely to take protective action and more likely to suffer damage. This underscores the need for age-inclusive strategies. While experience with previous floods influenced damage reducing behaviours, it did not motivate life-saving behaviour. This suggests that experience from past, less severe floods only have a limited benefit in helping communities respond to more severe flood events. Prior experience with moderate floods could even make people overconfident or engage in risky behaviour like going into a basement – therefore recommendations for action should be very clear and appropriate for the given expected severity. However, remembering past flood events with memorials or high-water marks remain a useful strategy for public awareness. While severe flood events are more likely with climate change similarly severe events have happened in the past, even if they are beyond living memory. Despite limitations, our results show that the majority of people (72.5%) took some protective action, indicating strong adaptive potential that can be enhanced through better warning design and public engagement.

The case of the Walloon Region in Belgium during the July 2021 flood shows that the response behaviour of people is an important component of FFWRS. To improve the flood management situation an ambitious list of recommendations has been proposed during a parliamentary inquiry process and progress has already been made towards the implementation of several of these measures but challenges remain towards full implementation. As this work progresses, explicitly considering the behaviour of people and characteristics of vulnerable groups will ensure that technical and governance improvements are as effective as possible to reduce damage and improve life safety.

Data availability: The survey data are owned by the authors and can currently be provided upon reasonable request only.

Author contributions: HJM, AH, and AHT developed and conducted the French version of the survey in Belgium with input from BD. DRC provided the surprise effect data from another survey in Belgium. HJM processed and analysed the data with input from all co-authors. HJM prepared the manuscript with input and edits from all co-authors. All co-authors read and agreed upon the final version.

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