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Abstract: The ex-ante evaluation of the effectiveness of Property-level flood risk adaptation (PLFRA) measures proposed remains underdeveloped. Consequently, professionals carrying out vulnerability assessments lack the tools to validate their recommendations of PLFRA measures and costumers should invest in them without estimations of avoided material damage or safety improvements. Furthermore, from an institutional point of view, the evaluation of the effectiveness of PLFRA measures could call into question the validity of programmes designed based on broad principles but applied to specific areas.

This article proposes an innovative, process-based, 3D, building-level model that combines hydraulic and economic modules, as well as a danger index. This tool can successfully evaluate the effectiveness of PLFRA measures in real buildings and, when installation costs are available, enable cost-benefit and efficiency analyses. Additionally, the tool can estimate the dangerousness of a given path to a shelter as well as the time available to reach it.

JEL codes: Q54, C63, C80, D81

Keywords: vulnerability; adaptation; flood damage assessment; modelling; building

1 Introduction

The negative consequences of flooding in Europe are increasing since the beginning of the 20th century, albeit at a slower rate than the general growth (Paprotny et al. 2018). In France, floods are already considered the most significant natural hazard in France in terms of negative consequences, accounting for 53% of insurable damage between 1982 and 2020 according to CCR (2021). Climate change expectations expectations may not be helping in this regard (IPCC 2022).

One of the most important ways in which the consequences of floods can be made bearable is through flood adaptation (IPCC 2022). In France, this has been the subject of a clearly defined public policy since the first flood prevention action programmes (*Programmes d'Actions de Prévention des Inondations*, or PAPI) were launched in 2002 (Direction Générale de la Prévention des Risques, 2011). In this regard, public action aims to promote the adaptation of residents in flood-prone areas through various means: (i) Regulatory measures in flood risk management plans (*plans de prévention des risques naturels d'inondation*, or PPRIs in French), which may be either compulsory or mandatory depending on whether the buildings are already constructed; (ii) Full subsidies for "individual" vulnerability assessments, listing the various property-level flood risk adaptation (PLFRA) measures to be considered; (iii) Subsidies of varying amounts for the investments required for PLFRA measures to be taken on existing buildings.

Various institutional levels are involved in implementing this public policy, from the national level, which defines the main guidelines to be followed and the funding framework, to territorial risk managers, who carry out local implementations, particularly through the 'Alabri' programmes for residents. The development of this policy has also given rise to a professional ecosystem comprising experts who carry out individual vulnerability assessments and make recommendations regarding PLFRA measures, as well as building professionals who develop, install and commercialise PLFRA technical solutions (which are still evolving).

This policy has not yet been deemed effective; numerous studies demonstrate that the implementation of PLFRA measures among exposed residents remains underdeveloped (Poussin, Botzen, and Aerts 2013; Richert, Erdlenbruch, and Figuières 2017; Richert, Erdlenbruch, and Grelot 2019). Following the recommendations of the Protection Motivation Theory, knowledge and subsidies have been provided to address the reasons for this underdevelopment, enabling the implementation of 'Alabri' programmes and, ultimately, compliance among residents. Numerous guides have been produced to advise on the measures and their expected effects (see, for example, CEPRI (2010a) and CEPRI (2010b)), and many adjustments have been made in terms of subsidies and funding in recent years.

However, the assessment of the effectiveness of the proposed PLFRA measures in reducing the vulnerability of people and property remains underdeveloped (Kuhlicke et al. 2020), despite being identified as a priority. Professionals, especially those conducting vulnerability assessments, lack the tools to evaluate the validity of their recommendations. Several studies demonstrate that assessing effectiveness can call into question the validity of programmes designed based on broad principles but applied to specific areas (Richert, Boisgontier, and Grelot 2019).

In this paper, we propose filling this gap by combining hydraulic and economic models at the building level. This coupled model can be used to evaluate the effectiveness of the most common PLFRA measures proposed in vulnerability diagnostics, and can be transferred to operational actors in this field. This coupled model is innovative in itself, as it enables ex-ante assessment of the effectiveness of measures. This makes it possible to question the implementation of innovative PLFRA measures to reduce flood risk more broadly.

The paper is organised as follows: Section 2 reviews different innovations for dealing with flood risk and the associated need for evaluation. Section 3 briefly presents the model, the case study and the experimental design used to demonstrate the methodology's potential. Section 4 analyses the obtained results, and Section 5 provides conclusions and a discussion.

2 Innovation and flood resilient buildings

A paradigm shift has occurred in flood risk management. Rather than relying solely on grey infrastructure (i.e. dikes, embankments, dams, weirs and other structures) to reduce the probability of flooding, more holistic approaches of "flood risk management" are being adopted to reduce the residual flood risk by adapting the urban environment to mitigate the consequences of flood events (Gralepois et al. 2016; White et al. 2018; Davids, Priest, and Hartmann 2023; Hooimeijer et al. 2024).

This shift has been accompanied by numerous innovations in a variety of areas within flood risk management strategies. For instance, studies such as Wehn and Evers (2015) and Wehn et al. (2015) explore the potential of new technologies in local citizen observatories and their impact on flood risk communication and governance. Scholars such as Fournier et al. (2016), Hegger et al. (2016) or Mees et al. (2016) focus on innovations and ways of flood risk governance. Studies such as Davids, Priest, and Hartmann (2023) explore how flood risk management professional should contribute to flood risk communication to encourage the implementation of PLFRA measures. Authors such as Lendering et al. (2019), Lendering et al. (2020), Connelly et al. (2015) or Iliadis, Glenis, and Kilsby (2024) examine technological innovations aimed at mitigating the impact of floods. Interested readers can find systematic reviews of innovations in flood risk management in studies such as those by Cvetkovic and Martinović (2020) and Guerriero and Penning-Rowsell (2021).

The integration of innovations in flood management does not happen automatically. In fact, it is subject to a variety of factors that can hinder or encourage the adoption of innovations (Mees et al. 2016; White et al. 2018; Attems 2020; Guerriero and Penning-Rowsell 2021; Webber et al. 2021). One area of flood risk management in which innovations have been implemented is the development of property-level protection/resilience measures, or more generally, property-level flood risk adaptation (PLFRA) measures (Guerriero and Penning-Rowsell 2021). These measures help homeowners to increase their resilience (Davids, Priest, and Hartmann 2023; Webber et al. 2021) by reducing or mitigating material damage, increasing human safety and enabling quicker recovery. PLFRA measures can be divided into different groups, such as:

- general elevation of buildings;
- creation of shelters for people;
- preventing water intrusion inside buildings (with temporary obstruction systems);
- targeted elevation of building components (electrical or heating equipment);
- choice of materials in contact with water (walls, floors and their coverings);

The first group of measures is the most effective, but also the most difficult to implement in the case of existing buildings. The second and third groups include measures that prioritise human safety. It is generally assumed that the presence of a shelter guarantees the safety of a dwelling's occupants. However, this is only valid if people move to safety before the water enters the dwelling. If people only reach the shelter once the water has started to infiltrate, the interior layout of the dwelling and the placement of the shelter access point may play a crucial role in the effectiveness of the measures. Using temporary obstructive devices to prevent water intrusion can delay infiltration and give people more time to reach the shelter. However, these devices can also have dramatic consequences if they are exceeded by the flood event, leaving occupants of a building unexpectedly exposed to sudden flooding when they thought they were safe.

Measures belonging to the third group also aim to reduce material damage by preventing water from entering buildings. In this sense, they can be combined with measures in groups 4 and 5, which only address material damage. Their effectiveness is also assessed based on precise knowledge of the layout of the components involved, in order to determine the conditions under which they are flooded.

Despite being perceived by professionals and regulators as a solution to increase flood resilience at property level within flood risk management strategies (White et al. 2018) and having been available for quite some time already, the implementation of PLFRA measures is not as widespread as we might anticipate. White et al. (2018) identify several factors that hinder the implementation of PLFRA measures, relating to trust, transparency, and the availability of information (e.g. trust in weather warning systems, usability for the elderly, or device performance). One key factor of reluctance among both insurance professionals and homeowners is the lack of adequate cost-benefit analysis on which to base decisions regarding performance, investment or loss and risk reduction calculations.

Scholars have also emphasised the need to assess the performance of PLFRA measures (see, for example, Golz, Schinke, and Naumann (2015) and Lendering et al. (2019)). The standard method of estimating the effectiveness of PLFRA measures aimed at reducing material damage relies on comparing damage levels before and after the measures are implemented. To achieve this, "depth-damage function" vulnerability models are required. There are two main approaches to implementing a depth-damage function (Molinari et al. 2020; Brémond et al. 2022): the statistical approach, which uses disaster data to link observed damage to flood parameters and key building characteristics; and the process-based approach, which relies on expert knowledge and a characterisation of the vulnerability of elementary building components. Studies such as Richert, Boisgontier, and Grelot (2019) show that the second approach is particularly well suited to evaluating of the performance of PLFRA measures in terms of damage reduction as it permits a more precise definition of the targeted measures.

Studies such as Nortes Martínez et al. (2022) also demonstrate that the process-based modelling approaches of depth-damage functions can be coupled with hydraulic models at the building level. This coupling enables the simulation of hydraulic dynamics within a building based on the flood conditions outside, addressing the issue of opening permeability and allowing a more accurate estimation of flood damage. This modelling approach is highly relevant in the case of flash floods or runoff flood events. Though they are receiving increasing attention, hydraulic models addressing the exchanges between the exterior and interior of buildings are seldom in the current literature (Zhu et al. 2022; Choley et al. 2021; Mejía-Morales et al. 2021). This type of hydraulic models coupled with depth-damage models are rarer to find (see, for example Nortes Martínez et al. (2024)), particularly at building level.

Yet, this type of models has great potential for evaluating PLFRA measures, as they allow the simulation of how such measures would affect the hydraulic dynamics of the building, which, in turn, enables the estimation of damage and the possibility of performing cost-benefit analyses of PLFRA measures. Furthermore, the possibility of modelling and analysing internal hydraulic dynamics implies that such models can also be used to simulate the dangerousness of the access to flood shelters. Building on this, we propose combining the model developed in Nortes Martínez et al. (2022) with a danger index based on pedestrian stability in the event of flooding, in order to evaluate PLFRA measures aimed at ensuring human safety.

Currently, there is no methodology in place to measure the effectiveness of PLFRA measures in mitigating property damage and reducing danger by combining hydraulic and depth-damage models. Furthermore, we intend for this coupled model to be integrated into the common practices and methodologies employed by vulnerability diagnostics professionals. In this context, our proposed methodology is innovative in terms of both its potential to assess the effectiveness of PLFRA measures and its multidisciplinary nature, offering novel approaches to each discipline involved while being transferable to operational actors in the vulnerability diagnostics sector.

3 Method and application

We propose a coupled hydraulic-economic model to evaluate the effectiveness of the PLFRA measures, using the model developed in Nortes Martínez et al. (2022) and combining it with a dangerousness index, based on the stability of pedestrians in case of flooding.

3.1 The floodam.building model

The model presented in Nortes Martínez et al. (2022) is implemented as an R library, called *floodam.building* (Grelot et al. 2024; Grelot and Richert 2019). It combines a process-based vulnerability model with an ad-hoc hydraulic model at a building scale.

The library *floodam.building* uses a highly detailed building survey to produce several intermediary and final outputs that are mobilized by its two main modules: the vulnerability module and the hydraulic module. We propose a so-called *dangerousness index* to be able to estimate the effectiveness of measures targeting human safety, and we also mobilize the vulnerability module to estimate the effectiveness of measures targeting the reduction of material damage.

3.1.1 Vulnerability module

The goal of this module of *floodam.building* is to estimate a damage function specific to the surveyed building. To achieve this, the model uses two types of input: an accurate 3D representation of the building's geometry (floor plan) with precise measurements along the XYZ axes, and an exhaustive survey of the building's components (walls, ceilings, furniture, etc.), their materials, and their placement along the XYZ axes.

To determine the damage that a flood could cause to a building, the *floodam.building* model proceeds as follows for each of the elementary components that constitute a building (walls, coating, painting, etc):

1. Before any flood event, all elementary components are assumed to be in a normal state (i.e. functioning as they should).
2. When a flood hits the building, the affected elementary component switches to a different state (e.g. dirty, damaged or destroyed). The sensitivity of the elementary components to flooding is defined based on expert knowledge.
3. In order to return to normal, one or more actions should be taken, e.g. cleaning, repairing, or replacing.
4. The sum of all the costs in which we should incur to get an elementary component back to the normal situation is the monetary valuation of the damage to that component.

Thanks to the highly detailed information, *floodam.building* is able to locate each elementary component within the building in a three-dimensional coordinate system. Thus, by combining the damage functions of the elementary components located in a given space, we can determine the damage function associated with that space. This feature prevents the model from overestimating damage, since it only includes the elementary components associated with specific XYZ locations.

3.1.2 Hydraulic module

The aim of this module is to estimate how flood depth changes over time in each room of the building, as well as how water flows in and out through openings (i.e. exchange discharges) and how fast it is moving (i.e. water velocity). To estimate these magnitudes, *floodam.building* uses information on the building's geometry as the main input. Specifically, the module uses the following as its main inputs:

- The areas of the rooms.

- The XYZ position of each opening connecting the interior of the building with the exterior, as well as each interior space with another.
- Limnigraphs (one for each opening connecting the interior of the building with the exterior). These provide the evolution of floodwater depth around the building over time. They also determine the duration of the flood event during each simulation.

The hydraulic module uses the classical weir law to determine the water flow exchange between the exterior and interior of the building, as well as between rooms. The module is able to take into account the state of each opening (open or closed) and adjust the water flow passing through accordingly.

3.1.3 Dangerousness index

Using the output of the hydraulic module — specifically, flood depth and flow velocity within the building — we propose a danger module that aims to evaluate the likelihood of reaching a safe location within the building when water reaches a certain level in a given room. The safety of a path is assessed using a four-level criterion based on pedestrian stability in flood flows (see Mejía-Morales et al. 2021), determined by the product of the water depth and the flow velocity (Russo, Gómez, and Macchione 2013) along the path from the room set as the starting point to the shelter.

According to this criterion, when the product of the flood depth and the flow velocity (v×h) falls within the following intervals:

- [0, 0.3] interval, few pedestrians show instability and the dangerousness is considered **low**
- (0.3, 0.7] interval, few pedestrians show instability and the dangerousness is considered **moderate**
- (0.7, 1] interval, few pedestrians show instability and the dangerousness is considered **important**
- > 1, most pedestrians show instability and the dangerousness is **high**

3.2 Case study

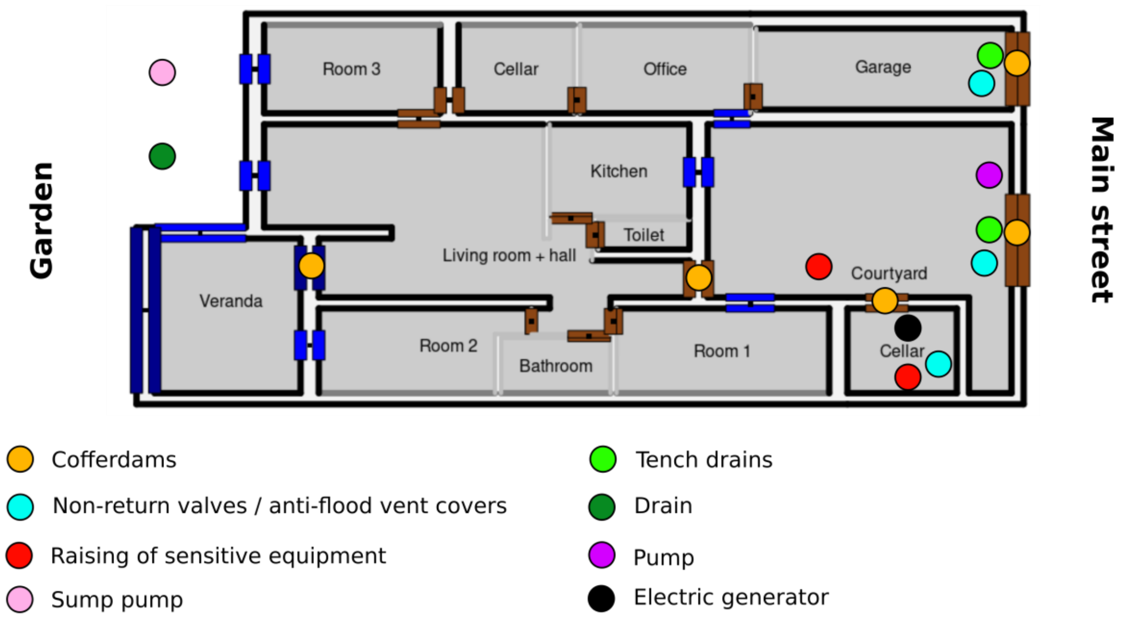
To showcase the application of *floodam.building* in estimating the effectiveness of measures, we have selected a real building as a case study. This building has undergone a vulnerability diagnosis, during which several PLFRA measures have either been implemented or proposed. Data on this building was collected through a study that included field surveys and qualitative interviews with the homeowners.

The building's layout is shown in Figure 3.1. This building is a terraced house connected to similar properties on the right and left (the right and left sides of the house correspond to the top and bottom of the plan). The house is mainly exposed to flooding through its front façade, although the rear façade may also be exposed.

Figure 3.1 also shows the nature and schematic location of the numerous PLFRA measures implemented in or proposed for this house. These measures can be classified into four well-differentiated strategies:

- First strategy: *flood resistance* strategy, designed to keep the water out of the property. This strategy includes cofferdams, non-return valves and anti-flood cover vents.
- Second strategy: *floodwater drainage*, designed to remove water from the property. This strategy involves installing drains and pumps, as well as independent generators to provide energy in case of electrical failure.
- Third strategy: *equipment and furniture raising*. This strategy is designed to reduce the material damage to sensitive equipments
- Fourth strategy: *human physical safety*. This strategy is designed to ensure the security of people. This category includes access to a shelter, for example. In the case of this building, the shelter would be located on the roof, with access via the courtyard (see Figure 3.2).

Figure 3.1: Adaptation measures deployed in our case study



The estimated cost of the PLFRA measures implemented in the building is shown in Table 3.1

Table 3.1: Cost of implemented flood adaptation measures in our study case building

strategy	cost
flood resistance	7 000
floodwater drainage	4 000
equipment and furniture raising	negligible
human physical safety	Not implemented

3.3 Experimental design

We propose an experimental design to evaluate the effectiveness of different flood adaptation strategies in achieving the two main goals of flood adaptation: reducing material damage and increasing human safety. The design comprises two experiments.

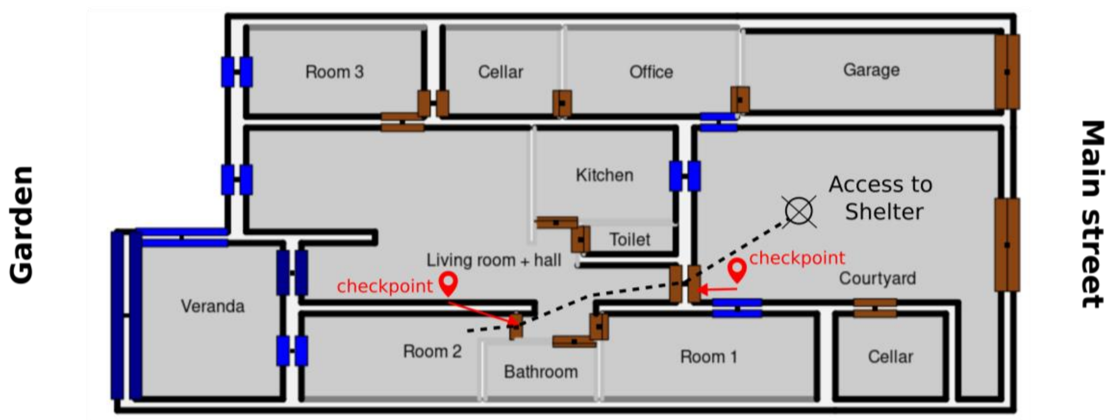
The first experiment focuses on the effectiveness of PLFRA measures in reducing material damage. Two strategies implemented in our study case building are considered here: the *flood resistance* strategy and the *equipment and furniture raising* strategy. For this experiment, we will assume that 80 cm-high cofferdams are placed at the points shown in Figure 3.1, and that non-return valves and anti-flood vent covers are installed. We will also assume that two household electrical appliances, one located in the cellar and one in the courtyard, are raised by 10 and 40 cm, respectively.

The effects of these two strategies will be evaluated separately and in combination against a baseline scenario in which no PLFRA measures are implemented. Damage functions will be calculated for flood events up to 4 metres high, and following the official French methodology for flood damage appraisal, for events lasting up to 48 hours (short events) and over 48 hours (long events).

The second experiment focuses on the effectiveness of PLFRA measures targeting human safety. It evaluates whether having access to a shelter increases people's safety. To do so, we will evaluate how safe a given path is for reaching the shelter and how much time people in the house have to reach the shelter before the path becomes too dangerous.

For this experiment, we will assume that the people in the house are in the bedroom and should go to the courtyard, where access to an elevated shelter is located (see Figure 3.2). To set a timer, we will use the time at which the flood depth in the bedroom reaches 1 cm as the initial time (t_0). The dangerousness of the path is evaluated at the two checkpoints shown in Figure 3.2: the bedroom door and the main door (access to the courtyard).

Figure 3.2: Location of access shelter and path to safety from room 2 (bedroom)



Throughout the simulation, all openings in the house are considered closed, i.e. they hold during all simulated flood events. Openings are not watertight, with a clearance of 3mm through which water can enter the courtyard and the interior of the house. Cofferdams or other devices designed to prevent water entry or drain floodwaters inside the house are not considered.

We test two flood durations: One-hour and two-hour events. These durations include the time taken for the water to rise and recede. For each duration, we test three different maximum flood heights outside the building: 0.5 metres, 1 metre and 1.5 metres. The combination of durations and heights gives us a total of six different flood scenarios, all of which are symmetrical, i.e. the times taken for the water to rise and recede are equal. Figure 3.3 shows a summary of the evolution of floodwater heights against time.

Figure 3.3: Evolution of floodwater depth outside the building in a 2-hour long flood event

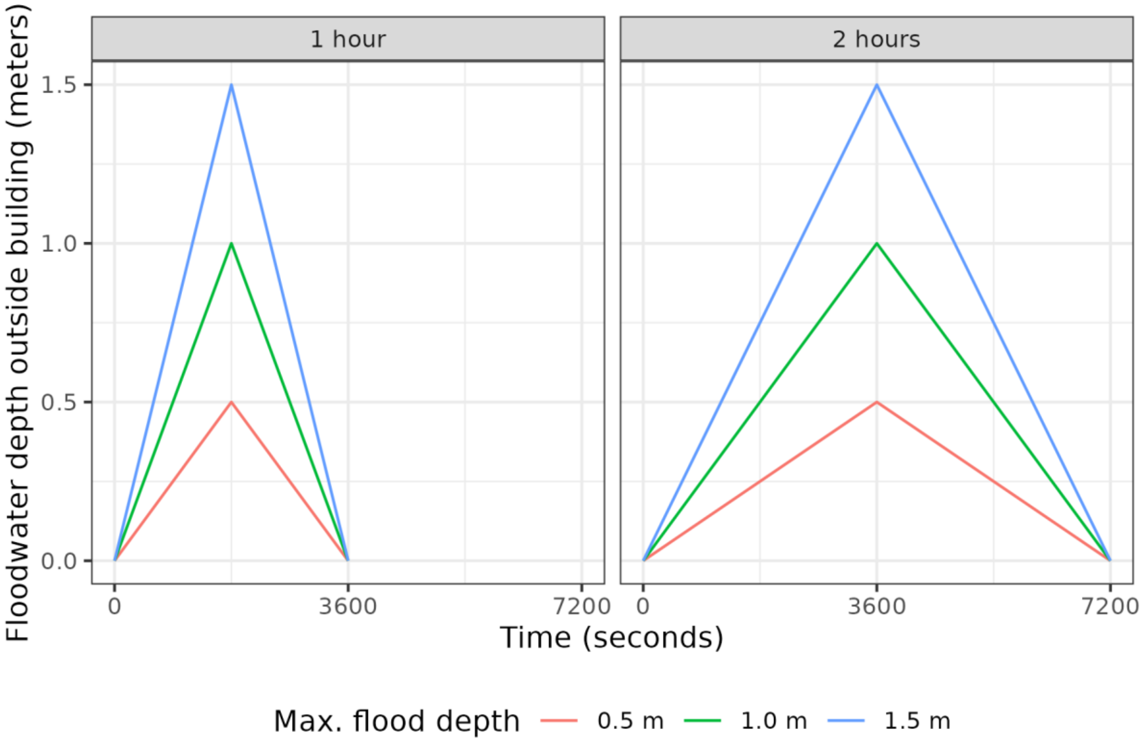


Table 3.2 summarizes the key features of our experimental design:

Table 3.2: Summary of experiment features

feature	experiment_1	experiment_2
Goal	Test efficacy	Test efficacy
Strategy	resist & raising	shelter
Openings	indifferent	closed
flood duration	up to 4m	0.5m | 1m | 1.5m
flood height	0-48h | >48h	1h | 2h

4 Results

The results are presented in accordance with the order of the experiments in the experimental design. This allows us to analyse the effectiveness of achieving the two goals of flood adaptation policy separately.

4.1 Experiment 1: effectiveness of PLFRA measures targeting the reduction of material damage

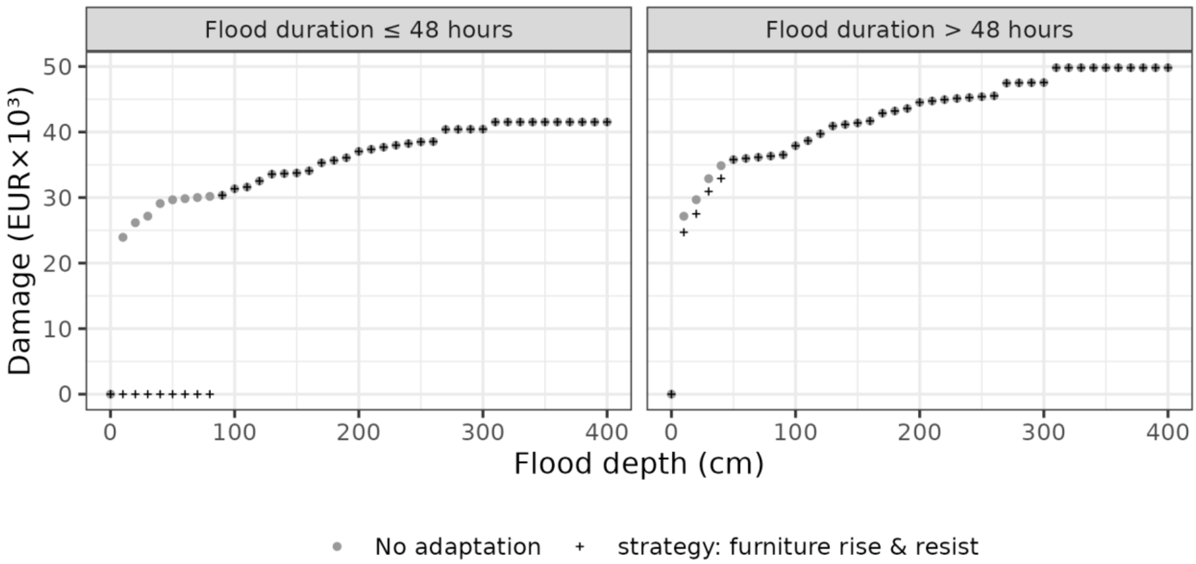
Figure 4.1 shows the damage functions obtained for the simulated scenarios, distinguishing between short (flood duration ≤ 48 hours) and long (flood duration > 48 hours) flood events. Generally, the damage functions represent a direct relationship between the monetary value of the flood damage and the flood depth: as flood depth increases, so does the monetary value of damage. This relationship, however, is not monotonic along the “curve”, i.e. the sensitivity with which material damage reacts to variations in flood height is not constant.

As shown in figure 4.1, the damage functions of our baseline scenario (i.e. the *no adaptation* scenario) show greater sensitivity of damage to changes in flood depth in the (0, 50] cm interval than in the (50, 260] cm or (260, 400] cm intervals, for both short (flood duration ≤ 48 hours) and long (flood duration > 48 hours) flood events. Furthermore, monetary damage is most sensitive to changes in flood depth in the (0, 50] cm interval for both flood durations. The magnitude of monetary damage differs between short (flood duration ≤ 48 hours) and long (flood duration > 48 hours) events though, with the latter being higher for any given flood depth.

Comparing the baseline scenario with a scenario in which the strategies *flood resistance* and *equipment and furniture raising* are combined shows how implementing these strategies reduces the sensitivity of monetary damage to changes in flood depth, reflecting a reduction in vulnerability to flooding. However, this reduction in vulnerability is not generalised, reflecting the fact that the adopted strategies are only effective within very specific ranges of flood depth and duration.

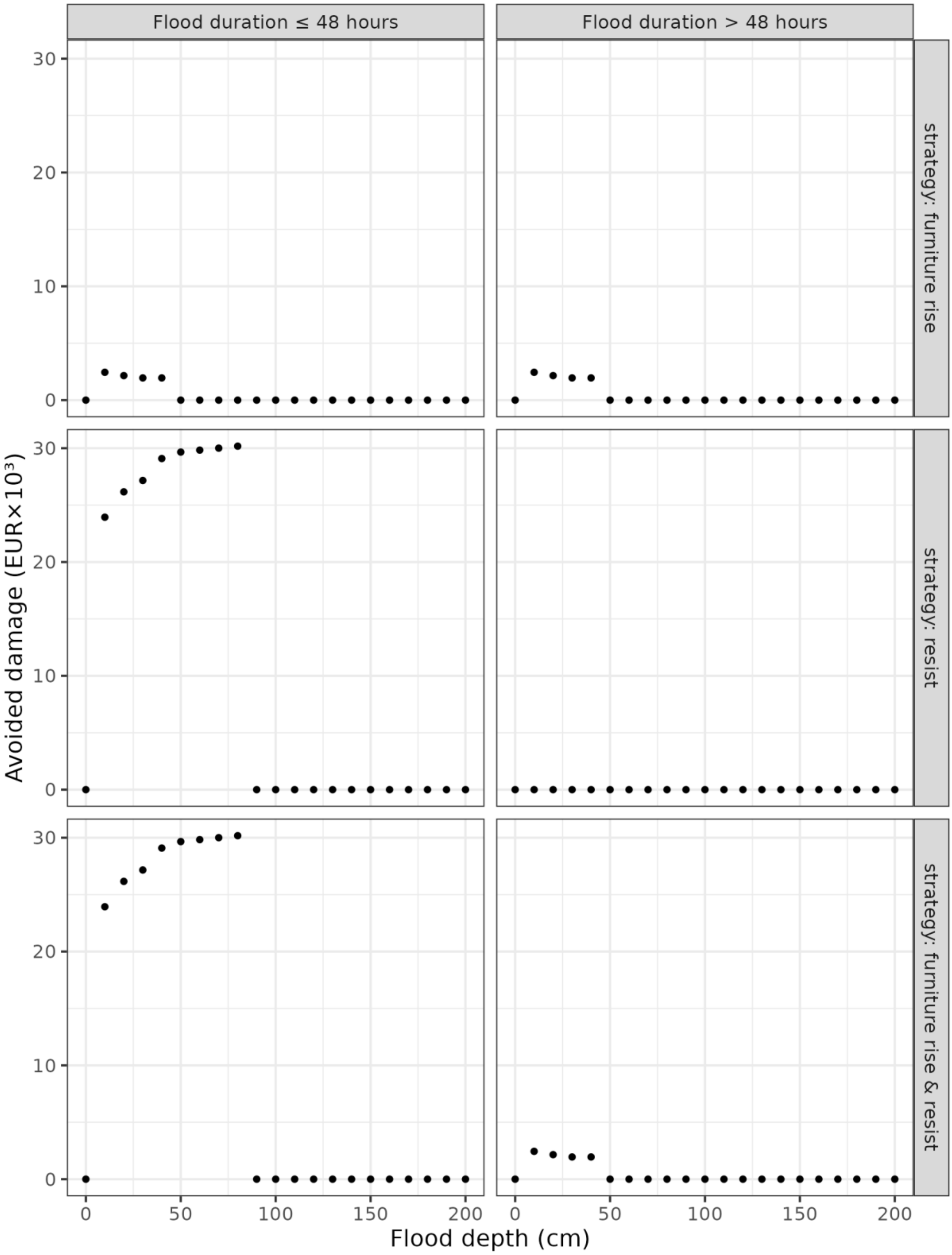
Specifically, implementing the combination of PLFRA measures helps to avoid up to EUR 30 000 of damage in the (0, 80] cm flood depth interval in the case of short flood events. For long flood events, the maximum avoided damage is EUR 2 500 in the (0, 40] cm flood depth interval.

Figure 4.1: Comparison of the damage function before and after adoption flood adaptation measures



These differences are illustrated more clearly in Figure 4.2. As you can see, the effects of each strategy depend on both flood depth and duration. The *equipment and furniture raising* strategy is equally effective for short and long flood events, with a maximum avoided monetary damage of EUR 2 500, but is ineffective for flood depths higher than 40 cm. Indeed, the household appliances were risen 10 and 40 cm respectively, so the strategy is most effective for flood depths lower than 10cm. The effectiveness of the strategy decreases gradually within the (10, 40] cm interval until it becomes ineffective.

Figure 4.2: Comparison of the effectiveness of each adaptation strategy



The *flood resistance* strategy is effective for short flood events (up to 48 hours) and for flood depths in the [0, 80] cm interval (the height of the cofferdam). It can prevent up to 30 000 EUR. However, the strategy becomes ineffective once the cofferdams' capacity to resist water intrusion is exceeded, either by the duration or depth of the flood event.

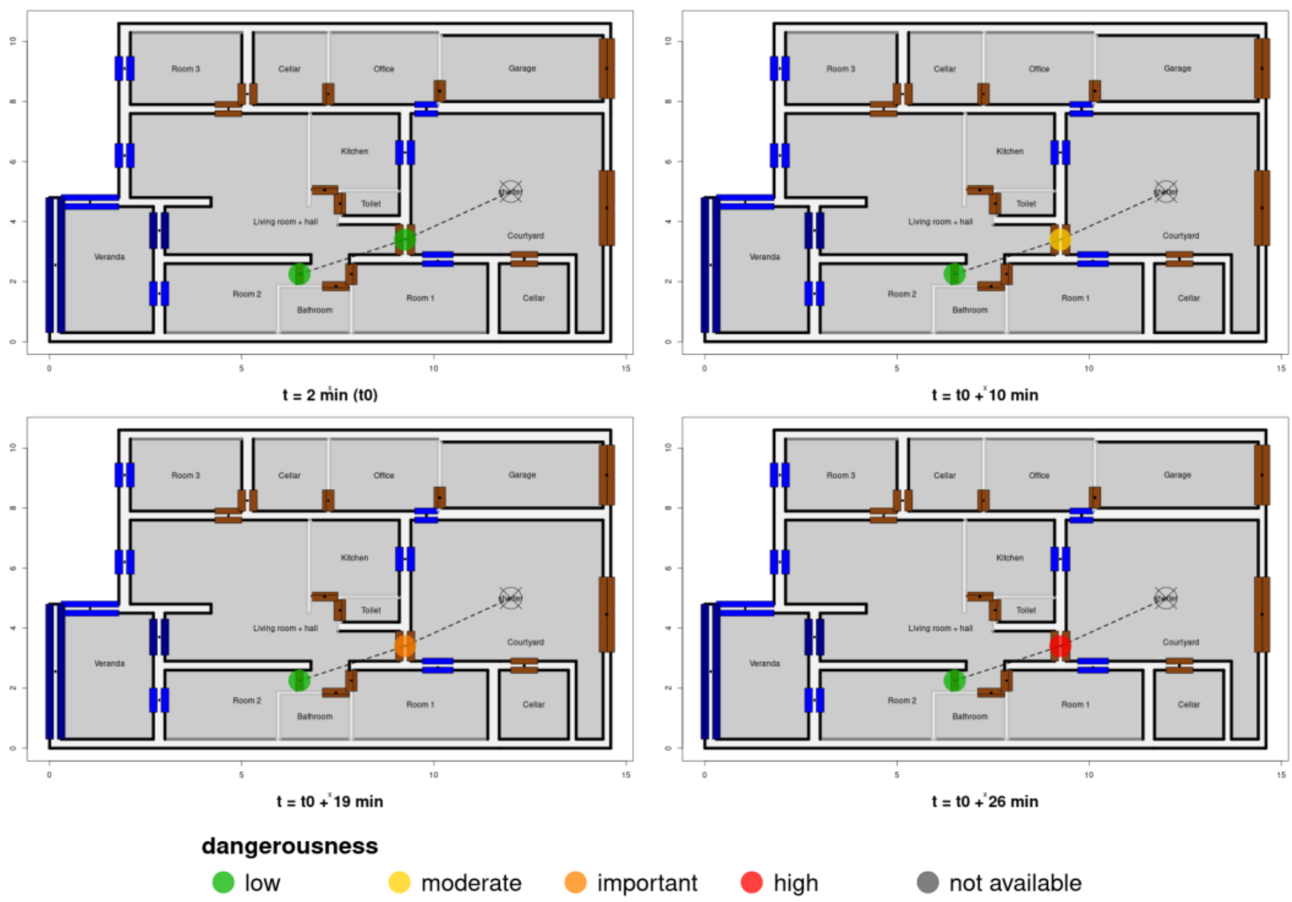
Interestingly, our results also show that the effectiveness of the combination of strategies depends on the type of flood event targeted. During short floods, when the *flood resistance* strategy is effective, combining strategies is redundant as it does not reduce the building's vulnerability more than implementing the *flood resistance* strategy alone. However, once the duration of the flood event renders the *flood resistance* strategy ineffective, the *equipment and furniture raising* strategy can still effectively prevent flood damage within its own limits of effectiveness.

In any case, comparing the amount of monetary damage avoided by each strategy with its implementation cost (see Table 3.1) shows that the monetary damage avoided by implementing the evaluated PLFRA measures exceeds the implementation cost.

4.2 Experiment 2: effectiveness of PLFRA measures targeting human safety

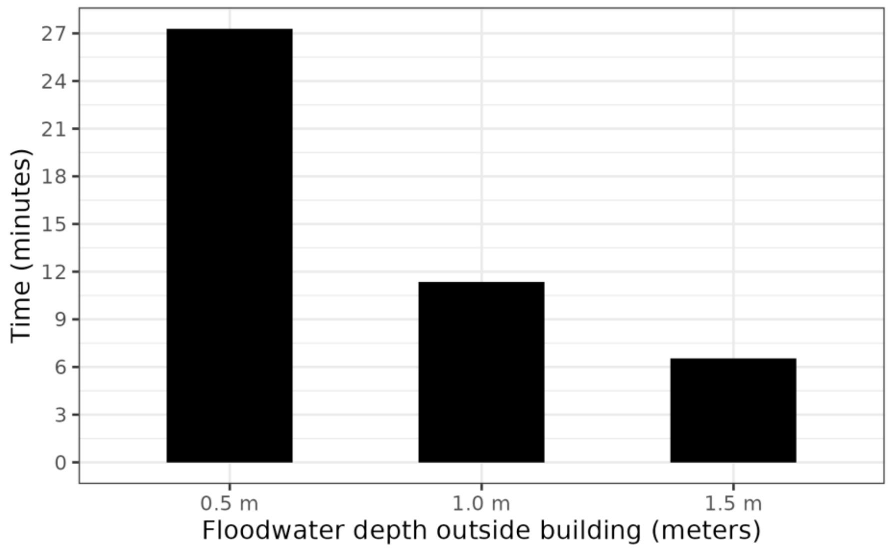
To analyse the effectiveness of this PLFRA measures, a simulation of a 2-hour flood event with a maximum depth of 0.5 m outside the building is set as the baseline. As can be seen in Figure 4.3, the timer (t_0) is set two minutes after the flood begins. From t_0, the occupants of the house have ten minutes to reach the shelter before the level of dangerousness at the main door of the building increases from *low* to *moderate*; a further nine minutes before it becomes *important*; and a further seven minutes before it reaches the maximum level on our scale. Overall, people in the building have 28 minutes from the start of the flood to reach the shelter before the situation becomes too dangerous.

Figure 4.3: Evolution of the dangerousness of the path to safety in the 2-hour long flood event with a maximum flood depth of 0.5 m outside the building



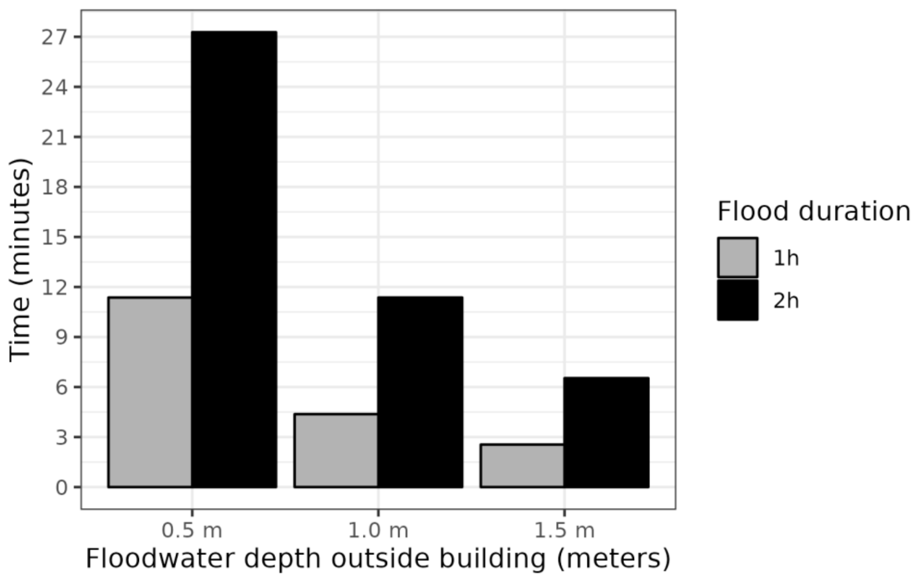
The time available to reach the shelter in a 2-hour flood event decreases as the maximum flood depth outside the building increases. As shown in Figure 4.4, in a one-meter flood event, the total time to reach the shelter is reduced by more than half (11 minutes) when flooding peaks outside the building. In the case of the 1.5 m flood event, people have a total of seven minutes from the start of the flood event before the dangerousness of the path to safety becomes *high*.

Figure 4.4: Overall evacuation time per scenario of floodwater depth in a 2-hour long flood



If the duration of each flood event is reduced, while keeping the peaks constant, provoking shorter, more sudden flood events, the overall times to reach the shelter are even shorter. Figure 4.5 shows a comparison between all simulated scenarios. As can be seen, when the flood duration is 1 hour and the flood peak is 0.5 m, the time available to seek refuge (11 minutes) is less than half that in the 2-hour event (28 minutes). If the peak reaches 1 m or 1.5 m, the overall times are reduced to 5 and 3 minutes, respectively.

Figure 4.5: Comparison of evacuation times per scenario of floodwater depth in a 2-hour and 1-hour long flood



5 Discussion and conclusion

Property-level flood risk adaptation (PLFRA) has become a key part of modern flood risk reduction strategies. As flooding becomes more frequent and severe due to climate change, there is a growing emphasis on promoting these measures as an effective complement to large-scale, state-led infrastructure projects.

However, despite being a central pillar of current flood risk governance, the adoption of PLFRA measures remains limited due to homeowners' reluctance to implement them without knowledge of their effectiveness in mitigating flood damage and enhancing human safety.

Effectiveness and efficiency assessments are not merely technical exercises. As has been pointed out, it is essential to build trust and transparency, and to improve the available information needed to encourage the widespread implementation of PLFRA measures. Indeed, assessing the effectiveness of PLFRA measures is necessary to determine whether the recommended measures are fit for purpose, i.e. whether adaptation is occurring, where it is failing and where additional support is needed. Consequently, assessments are necessary to facilitate the adoption of PLFRA innovations.

The *floodam.building* tool (Grelot et al. 2024; Grelot and Richert 2019) has been successfully applied to estimate the effectiveness of flood adaptation measures aimed at reducing material damage. The tool allows us to estimate the magnitude of the potential avoided monetary damage for each individual measure, as well as the avoided monetary damage of the combination of individual measures.

When installation costs are available, efficiency analysis and estimations can be performed by comparing the magnitude of the avoided monetary damage and the installation (and eventually maintenance) cost.

The *floodam.building* tool has also been successfully combined with a dangerousness index based on the stability of pedestrians in flood flows, allowing us to apply the *floodam.building* tool to the evaluation of the effectiveness of the measures aimed at increasing human safety. Specifically to the estimation of the dangerousness of a given path to a shelter during a flood event. In addition, we have been successfully able to estimate the total amount of time that potential residents have to get to the shelter once a given signal is detected, and how this total time is closely tied to the intensity of the flood event.

Therefore, the *floodam.building* tool combined with the dangerousness index is able to provide pertinent information regarding, human safety, material damage and pertinence of flood adaptation measures for an specific building. In this sense, the combination of *floodam.building* and the dangerousness index can be used as an ex-ante laboratory to simulate the effectiveness, efficiency and pertinence of flood adaptation measures.

In addition, the workflow and the level of exhaustibility in the building surveys demanded by the *floodam.building* tool is similar to the workflow and level of detail of the approaches already employed by the professionals carrying out diagnoses of vulnerability of buildings. In this sense, the implementation of *floodam.building* is compatible with the methodologies already used by professionals, which in turn can allow the valorisation of already existing databases. Furthermore, we consider that the results shown by *floodam.building* would allow homeowners and citizens to easily integrate the effectiveness assessments into their decision-making process, including: i) understanding the relative benefit of different PLFRA measures; ii) evaluating cost-effectiveness and personal risk reduction; iii) deciding whether and how to invest in specific adaptations.

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