Economic assessment of measures aimed at reducing flood damage to buildings using computer modelling and expert judgement

Richert, Claire [1], Boisgontier, Hélène [1], and Grelot, Frédéric [1]

[1]UMR G-EAU, Irstea, Université de Montpellier

Correspondence: Claire Richert (claire.richert@irstea.fr)

Abstract. To limit the losses due to floods, public authorities can try to foster the adoption of private measures aimed at reducing the vulnerability of the dwellings. However, the efficacy and cost-efficiency to reduce material losses of such measures are not well-known. In particular, a better understanding of the influence of buildings characteristics and flood parameters on these variables would help identify the measures that are relevant to implement in specific contexts. We examined this topic for three

5   groups of measures taken on existing dwellings: one consists in elevating the dwelling, one in dry-proofing it, and one in using construction materials that are resistant to water or cheap to replace. We combined expert judgement and computer modelling to assess their cost, efficacy, and cost-efficiency for a wide range of flood depth and duration, building characteristics, and level of exposure. We found that the value of the building components has a positive effect on the efficacy of dry-proofing and elevating a dwelling. Both the efficacy and cost of these two groups of measures increase with the size of the dwelling.

10 Moreover, according to our results, dry-proofing and elevating a dwelling are unlikely to be cost-efficient for dwellings that are not exposed to floods with a return period lower than 100 and 30 years, respectively. Our findings also highlight that it is often less expensive to use the adapted than the original materials when rebuilding a damaged dwelling. Moreover, adapting the materials of an intact dwelling is unlikely to be cost-efficient for dwellings that are not exposed to floods with a return period lower than 20 years.

1   Introduction

15 A flood risk can be defined as the combination of a hazard and the vulnerability of the people who are exposed to it (e.g. Apel et al. (2009)). Thus, mitigating such a phenomenon boils down to reducing one or both of these two components. Throughout the twentieth century, it was largely preferred in several countries to only target the hazard component of flood risks through the building of physical defences (e.g. in the Netherlands (Vis et al., 2003), in the United Kingdom (Werritty, 2006), or in the

20 United States (Tobin, 1995)). Nowadays, several authors report that flood risk management policies are increasingly combining flood defences with measures aimed at reducing people's vulnerability (Klijn and Samuels, 2008; Merz et al., 2010). This tendency is driven by the awareness that physical defences can harm ecosystems and that levee failures can have catastrophic consequences (Klijn and Samuels, 2008), and by the increasing uncertainty regarding the risks of floods due to climate change (Merz et al., 2010). Thus, in countries such as England, France, Hungary, or Germany, recent policies were designed to limit

25 development in flood prone areas, provide more efficient insurance schemes, raise people's awareness of the risk, or foster the

adoption of measures aimed at reducing the vulnerability of dwellings (Klijn and Samuels, 2008). Policy-makers need to be able to compare these different means of reducing the vulnerability to floods in order to efficiently allocate public funds among them, in terms of subsidies and communication.

5   We focused on measures aimed at reducing the vulnerability of existing dwellings to floods, which we call "precautionary measures", and analysed their efficacy, cost, and cost-efficiency. We define the cost-efficiency of a measure as the discounted sum of the difference between its annual expected efficacy and its annual cost over its lifespan. The efficacy of a precautionary measure indicates the extent to which it reduces the level of damage to dwellings. It depends on the flood intensity. The annual expected efficacy is thus the probability-weighted average of the values of efficacy computed for all possible flood intensities.

So far, the efficacy of precautionary measures has been examined at the household level using mainly empirical approaches

10 and expert judgement (see Kreibich et al. (2015) for a review). For instance, the International Commission for the Protection of the Rhine relied on expert judgement to assess the efficacy of flood proofing measures (International Commission for the Protection of the Rhine (ICPR), 2002). On the other hand, Kreibich et al. (2005) surveyed people who were affected by the flood that took place in 2002 in the Elbe river basin. They compared damage to the building and contents of dwellings with and without different types of precautionary measures. Their results suggest that installing flood barriers and adapting the building

15 structure, use and layout to floods were effective measures to reduce material damage in their case study. The same conclusion was reached by Kreibich and Thieken (2009) after comparing the levels of damage due to different floods that occurred in a given area in Germany and between which the proportion of inhabitants who took measures had increased. Using a similar approach on another case study in Germany, Bubeck et al. (2012) also suggest that implementing precautionary measures significantly reduces material damage.

20 All these studies assessed the efficacy of precautionary measures for particular flood events. However, the comparison of the cost and efficacy of a measure requires to estimate its annual expected efficacy. Kreibich et al. (2011); Poussin et al. (2015); Xian et al. (2017) proposed various methods to assess the annual expected efficacy of some measures. Kreibich et al. (2011) surveyed people who were affected by floods in Germany. They assumed that the mean efficacy of a measure was the difference between the mean amount of damage suffered by those who lived in houses where the measure was not implemented and the

25 mean amount of damage suffered by the others. They multiplied the estimated mean efficacies by several frequencies to obtain annual expected efficacies that relate to various flood return periods. Poussin et al. (2015) conducted a survey in France to assess the cost-efficiency of some precautionary measures. They used ordinary least square regression models to explain the relationship between the amount of damage and several independent variables, such as the presence of some precautionary measures and the flood depth. They then assumed that the mean efficacy of a measure is the difference between the estimated

30 levels of damage suffered by an average home without and with this measure. To assess the annual expected efficacy, they proceeded in the same way as Kreibich et al. (2011). Xian et al. (2017), assumed that the annual expected efficacy of elevating a dwelling is the reduction in risk-based annual insurance premium due to this measure, which they computed following the guidelines of the Federal Emergency Management Agency (FEMA, 2014, 2018). As explained in a report of the National Research Council (2015), the risk-based annual insurance premium takes into account the average annual expected damage,

35 which is averaged across classes of buildings which are in the same flood zone and share some characteristics, including their

elevation. The values of average annual expected damage are computed using two types of depth-damage functions: some were obtained by using claims data and others come from the U.S. Army Corps of Engineers but the method used to obtain them is not well-documented, according to the National Research Council (2015). Thus, Xian et al. (2017) ultimately relied partly on empirical data and partly on data of unknown nature to assess the annual expected efficacy of elevating a dwelling.

5 While empirical studies analyse precautionary measures in realistic settings, the results they provide are largely context-dependent, as reported by Poussin et al. (2015) and Kreibich et al. (2015). Moreover, since they do not control for all the parameters that influence the amount of damage, they cannot be used to anticipate the efficacy or cost-efficiency of precautionary measures in other contexts. In particular, they do not take into account the relationship between the material used for the components of the buildings and the vulnerability to floods of these latter, which could partly explain the variance in the
10 amount of damage (National Research Council, 2015). As for the reports based on expert judgement, since they contain little methodological information, it is difficult to evaluate their reliability in specific contexts.

To gain insights regarding the variability of the cost-efficiency of precautionary measures, we combined data based on expert judgement and computer modelling to analyse three types of measures (elevation, dry-proofing, and component adaptations) for a wide range of flood intensities and dwellings' characteristics, including the material used for their components. The aim
15 of our study was then to assess ranges of cost and efficacy of the measures and to provide a range of exposure levels for which it is unlikely that the precautionary measures could be cost-efficient, independently of the dwelling's characteristics.

In the following section, we present the measures that we focus on. We describe the method used to assess their efficacy, cost, and cost-efficiency in Sect. 3. Then, we present the results in Sect. 4. We discuss them in Sect. 5 and conclude in Sect. 6.

2 Precautionary measures studied

20 We reviewed the measures recommended to reduce the vulnerability of dwellings to floods in a joint report of the French ministries in charge of environment and housing (Ministère de l'égalité des Territoires et du Logement Ministère de l'écologie du Développement durable et de l'énergie, 2012), a report of the European Center for Flood Risk Prevention (CEPRI, 2010), and a report of the Doubs and Saône catchment management agency (EPTB Saône et Doubs, 2015).

The measures described in these reports can be classified into three categories: some aim at avoiding damage by elevating
25 the house, storing valuables upstairs, or elevating heating and electrical utilities for example, some at preventing the water from entering into the dwelling, and some at limiting the costs of repair and replacement of the components of the building.

We analysed the measure that consists in elevating the house, and those that aim at preventing the water from entering into the dwelling or at limiting the costs of repair and replacement of the building components. We refer to the first measure as the elevation strategy, to the second group of measures as the dry-proofing strategy, and to the third group of measures as the
30 component adaptations strategy.

2.1 Elevation

To avoid damage up to a given flood depth, the dwellings can sometimes be elevated. According to a report of the FEMA (2009), if the dwelling is built on a basement, a crawlspace, or on open foundations, the first step to elevate it consists generally in separating it from its foundations and raising it on hydraulic jacks while it is held by a temporary support. Then, the existing foundations can be extended or new ones can be built. However, if the dwelling has slab-on-grade foundations, they are lifted together and new foundations are constructed below the slab.[1] In both cases, an external staircase must be built to access the dwelling and utility lines must be extended.

We analysed the efficacy, cost, and cost-efficiency of elevating dwellings by 50 cm, 100 cm, and 250 cm. We assumed that only single storey houses can be elevated because other types of dwellings are too large.

2.2 Dry-proofing

Measures can be taken to prevent the water from entering into a dwelling if the flood depth stays below 1 m and the flood lasts less than 48 hours. For higher flood depths or longer flood durations, the pressure on the vertical elements of the building structure can cause severe damage.

For a dwelling without basement, the following measures must be taken together and dimensioned consistently to prevent the water from entering up to a chosen threshold: installing flood barriers, repairing faulty seals in the external walls, waterproofing the external walls, treating cracks in the external walls, installing removable covers on small openings that are below the chosen threshold, installing anti-backflow valves, ensuring that the electrical cable sleeves are watertight, and buying a pumping device.[2] Following Poussin et al. (2012), we call "dry-proofing" the combination of these measures. We assessed the efficacy, cost, and cost-efficiency of dry-proofing a dwelling without basement in the cases where it prevents the water from entering up to flood depths of 50 cm and 1 m.

2.3 Component adaptations

We call "component adaptation" a measure which consists in using building materials that are resistant to water or cheap to repair. Component adaptations aim to limit the costs of repair and replacement of building materials after a flood. We studied together component adaptations which pertain to the ceilings, the walls, the floors, and the openings. We detail in Table 1 the component adaptations that pertain to each of these building components.

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[1]Note that it is also possible to leave the slab on the ground and to construct a new floor after lifting the house.

[2]For dwelling with a basement, additional measures must be taken. We only analysed the measures which aim to prevent the water from entering into a dwelling without basement.

3 Method

3.1 Overview

We used a computer tool called *floodam* (Grelot and Richert, 2019) and developed in R language (R Core Team, 2017) to assess the efficacy of the strategies aimed at reducing the vulnerability of existing dwellings. *floodam* requires as input a numerical

5 model of building and produces a function which associates a level of damage to several combinations of flood depth and duration. We call damage function this type of outputs.

The efficacy and the cost of the strategies aimed at reducing the vulnerability of existing dwellings were assessed for several numerical models of dwellings. The cost of each strategy depends on the geometry of the dwellings and, in some cases, on whether the strategy is taken on an intact or damaged building and on the building materials. Its efficacy is assessed by

10 comparing the damage functions of the dwellings obtained with and without the strategy. It depends on the flood depth and duration, on the geometry of the dwellings, and on the building materials.

In this section, we describe the numerical models used as inputs, we provide an overview of how *floodam* works, and we explain how we modelled the strategies. We then explain how we assessed the cost, the efficacy, and the cost-efficiency of each strategy.

15 3.2 Numerical models of dwellings

Each numerical model of dwelling is made up of an xml file and a csv file. The former indicates the ground floor height above ground level, the layout and size of the rooms, and the construction materials used for the building. Figure 1 provides a graphical interpretation of the xml file of a numerical model of dwelling. The csv file indicates the pieces of furniture that are present in each room and their height above the floor. For instance, Table 2 shows the information contained in the csv file of a

20 numerical model of dwelling that pertains to a bedroom.

Originally, we had three numerical models which represent real dwellings: we visited an apartment to establish its plan and make an inventory of its furniture, the European Center for Flood Risk Prevention did the same with a single storey house (CEPRI, 2013) and gave us access to their data, and we used the architectural plan of a double storey house. Since we have no real data regarding the furniture of the double storey house, we first allocated the pieces of furniture of the single storey

25 house in the corresponding rooms of the double storey house. Then, we added pieces of furniture in one room which had no correspondence in the single storey house (a home office) and in two dressing rooms. More specifically, we assumed that the home office contained a desk, a chair, and a cupboard in chipboard and that the dressing rooms each contained a variety of small items.

In order to be able to generalize our results, we developed several versions of these three numerical models of dwelling by

30 modifying the combination of the components of the building listed in Table 3. These components were chosen because they are widely used in French buildings according to a report of the agency of building quality (Agence Qualité Construction, 2009). Each version contains only one variant of each component listed in Table 3. Since there are 1 728 possible combinations

of all components, we developed the same number of versions for each of the three original numerical models of dwellings. In total, we thus have 5 184 numerical models of dwellings.

3.3 Overview of *floodam*

We define the damage suffered by a good as the expected cost of the actions that must be performed after a flood in order to
5 bring it back to its pre-flood state. Using this definition, *floodam* relies on two main assumptions: 1) the damage suffered by a building is the sum of the levels of damage suffered by its components, and 2) the levels of damage of the components are independent.

floodam relies on a database of 431 elementary damage function. An elementary damage function associates a level of damage suffered by an elementary component to several combinations of flood depth and duration. A partition wall in plaster
10 or a washing machine are examples of elementary components. The elementary damage functions come from interviews with insurance and construction experts. We used elementary damage functions with data points at immersion depth values from 0 to 500 cm (included) in 10 cm increment, and immersion duration values from 0 to 144 hours (included) in 12 hours increment.

For each numerical model of dwelling, *floodam* computes the height above the ground of all elementary components and the size of the elementary components of the building. Then, for each combination of depth and duration of immersion of
15 the dwelling, it 1) computes the depth of immersion of each elementary component, 2) retrieves the corresponding levels of damage by measurement unit for the duration of immersion considered, 3) multiplies each level of damage by the size/quantity of the corresponding elementary component, 4) sums the obtained values to obtain the level of damage at the scale of the dwelling. The damage function of the numerical model of dwelling considered is made up of the levels of damage computed for each combination of immersion depth and duration.
20 A more detailed description of *floodam* can be found in Grelot and Richert (2019).

3.4 Modelling of the strategies

3.4.1 Elevation

Modelling the elevation of a numerical model of dwelling consists in choosing a threshold of flood depth below which damage should be avoided. The cost and efficacy of the strategy are deduced from this threshold.

25 ### 3.4.2 Dry-proofing

To model the dry-proofing of a dwelling, a threshold below which the water should be prevented from entering must first be chosen. The number of openings that are below the threshold is the number of flood barriers that must be installed. Then, the perimeter of the dwelling, from which the quantity of removable covers that must be installed is deduced, is computed. The perimeter is multiplied by the threshold to obtain the surface on which faulty seals and cracks in the external walls must be
30 repaired, and on which the external walls must be waterproofed.

3.4.3 Component adaptations

Adapting a given component of a numerical model of dwelling boils down to replacing its original variant by the recommended one (cf Table 1) if the latter is different from the former.

3.5 Analysis

3.5.1 Assessment of the cost

Elevation

To assess the cost of elevating a dwelling, we relied on the estimates provided by the FEMA (2009) and reported in Table 4. We first converted each of these estimates in 2017 Euros by square foot. To do so, we multiplied them by the ratio between the construction prices in France and the United States (0.97, cf https://www.fgould.com), the exchange rate between the US dollar and the euro in 2009 (0.72), and an index that gives the construction price development in France between 2009 and December 2017 (1670 \((1507 + 1502 + 1498 + 1503)\4), cf https://www.insee.fr).

Once the costs were in Euros by square foot, we converted them in Euros by square meter by dividing them by 0.3048^2 ft²/m² (1 ft = 0.3048 m). After that, we computed the cost for heights of elevation of 50 cm, 100 cm, and 250 cm by assuming that the cost increases linearly between 50 cm and 250 cm. Finally, we used the costs indicated in Table 5.

Dry-proofing

The cost of each measure that must be implemented to dry-proof a dwelling was assessed by a construction expert for the single storey house. Knowing the characteristics of this dwelling, we estimated the cost of each measure by measurement unit. For each numerical model of dwelling, they were multiplied by the quantities on which the measures must be applied. Table 6 indicates the cost of each measure and their measurement units.

Component adaptations

A given component can be destroyed or intact when the adaptation takes place. At the level of a dwelling, we consider 2 situations: either all the components are destroyed or they are all intact when the adaptation takes place. In the first case, which we call the repair context, the adaptation cost is the difference between the costs of installing the recommended and the original variants of the components. In the second case, which we call the prevention context, the adaptation cost is the sum of the costs of installing the recommended variant of the components (if they are different from the original ones) and of reinstalling the original coatings (of the walls, floors, and ceilings).

3.5.2 Assessment of the efficacy

We define the efficacy of a strategy for a given numerical model of dwelling as the difference between the damage functions computed without and with the strategy.

Elevation

When a dwelling is elevated of x centimetres, its damage function (f) which depends on the flood depth (de) and duration (du) becomes $g(de, du)$ such as :

$$g(de, du) = \begin{cases} f(de - x, du), & \text{if } de - x \geq 0 \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

5   Therefore, the efficacy of elevating a given numerical model of dwelling depends on the immersion depth and duration. For example, elevating the original version of the single storey house by 1 m can reduce the damage by up to €30 000 approximately, as shown in Fig. 2.

Dry-proofing

The damage function of a numerical model of dwelling where the dry-proofing strategy is installed is equal to zero for com-

10   binations of immersion depths below or equal to the threshold and immersion durations less or equal to 48 hours. For greater immersion depths, dry-proofing has no effect on the damage function. For example, Fig. 2 shows the damage functions of the original version of the single storey house without and with the dry-proofing strategy with a threshold of 1 m, and the resulting efficacy. For this dwelling, the maximum avoided damage due to dry-proofing is approximately €25 000.

Component adaptations

15   The efficacy of a component adaptation to reduce the vulnerability of a numerical model of dwelling is the difference between the damage functions computed with the original and recommended variants of the component. Hence, the efficacy depends on the immersion depth and duration. For instance, Fig. 2 shows that the maximum avoided damage due to the adaptation of the walls of the original single storey house reaches approximately €2 500.

3.5.3   Assessment of the maximum cost-efficiency

20   The maximum cost-efficiency of a strategy for a given type of dwelling (single-storey house, double-storey house, apartment) is defined as the maximum cost-efficiency computed for the version for which the strategy is the most cost-efficient. In this section, we mathematically define the cost-efficiency and maximum cost-efficiency of a strategy for a given numerical model of dwelling.

The cost-efficiency (CE) of a strategy can be defined as the discounted sum of the differences between the annual expected

25   efficacy (AEE) and the cost of the strategy over a defined time horizon (H) :

$$CE(H) = \sum_{1 \leq i \leq H} \frac{AEE - AEC}{(1 + r)^i} - IC \tag{2}$$

where r is the discount rate, AEC the annual expected maintenance cost of the strategy, and IC its installation cost. A strategy is cost-efficient if $CE > 0$, that-is-to-say if :

$$\frac{IC}{AEE - AEC} < \sum_{1 \leq i \leq H} \frac{1}{(1+r)^i} \tag{3}$$

Moreover, the annual expected efficiency of a strategy is equal to:

$$5 \quad AEE = \int_0^1 f \times E(f) df \tag{4}$$

with f the flood frequency and E the efficacy.

What we call maximum cost-efficiency is in fact an upper boundary of the cost-efficiency. To compute the maximum cost-efficiency of a strategy s for a given numerical model of dwelling d, we used a lower boundary of the cost by taking only the installation cost into account.

10   To compute the maximum cost-efficiency of s for d, we used the following upper boundary of annual expected efficiency:

$$AEE_{max}^{sd}(f_{max}) = f_{max} \times E_{max}^{sd} \tag{5}$$
$$= \frac{E_{max}^{sd}}{T_{min}} \tag{6}$$

with f_{max} the frequency of the flood that affects d the most often, T_{min} the return period of the flood that affects d the most often, and E_{max}^{sd} the highest value of efficacy of s for d.

15   Thus, we define the maximum cost-efficiency of s for d as follows:

$$CE_{max}^{sd}(T_{min}, H) = \frac{E_{max}^{sd}}{T_{min}} \sum_{1 \leq i \leq H} \frac{1}{(1+r)^i} - IC^{sd} \tag{7}$$

The maximum cost-efficiency of a strategy s for a given type of dwelling is then the cost-efficiency computed for the version of the dwelling for which the ratio $\frac{IC^{sd}}{AEE_{max}^{sd}}$ is the lowest.

We used a discount rate of 2.5%, which is the value recommended to assess public investments in France (Commissariat

20   général à la stratégie et à la prospective, 2013).

For each type of dwelling, we computed the maximum cost-efficiency for values of H from 1 to 50 (for dry-proofing and component adaptations) or 100 years (for elevation) in 1 year increment and T from 1 to 120 years in 1 year increment. H can be considered as the lifespan of the strategy.

For each strategy and type of dwelling, we searched for the combinations of time horizon and return period for which the

25   maximum cost-efficiency is negative. In these contexts, our results suggest that the strategy is unlikely to be cost-efficient.

4   Results

We present the ranges of efficacies and costs and the maximum cost-efficiency of elevation, dry-proofing and of the combination of all component adaptations.

4.1   Range of efficacy

5   Figure 3 shows the ranges of efficacy obtained for each strategy. The efficacy of a strategy depends on the type and components of the dwelling, on the immersion depth and duration, and sometimes on some characteristics of the strategy.

More specifically, the efficacy of elevating a dwelling increases with the height of elevation and with the value of the components of the dwelling. For this strategy, the highest efficacy is obtained for numerical models of dwellings which contain a lot of wooden components (joist boards, parquet, and opening frames and shutters in wood). The highest efficacy is observed

10   for an immersion depth equal to the elevation height.

As for dry-proofing, its efficacy increases with the threshold, the value of the components of the dwelling, and the floor area. The highest maximum efficacies relate to the single storey house and the lowest to the double storey house because the former has the largest floor area (133.5 m²) and the latter the smallest (98 m²). For a given numerical model of dwelling, the efficacy of dry-proofing increases up to an immersion depth equal to the threshold and an immersion duration of 48 hours. In keeping

15   with the assumptions used when modelling dry-proofing, the efficacy is equal to zero for higher immersion depths and longer immersion durations.

Adapting all components can sometimes generate the same or a higher level of damage than keeping all original components. This is the case for the 576 versions of each type of dwelling which originally have masonry internal walls and tiles or textile as coatings of floors. There is indeed a probability greater than zero that the adapted walls in plaster must be replaced for

20   depths of immersion greater than or equal to 30 cm, no matter the immersion duration. On the contrary, the probability that masonry walls must be replaced for immersion durations lower than 72 hours is equal to zero. This type of walls needs only to be repaired in such cases. As a consequence, for some immersion depths, the elementary damage function of an internal wall in plaster is above the one of a masonry internal wall for immersion durations lower than 72 hours. Negative levels of efficacy are observed only for dwellings which originally have tiles or textile as coatings of floors because the high efficacy of replacing

25   parquet floors by sealed tiling floors compensates the negative efficacy of replacing masonry walls by walls in plaster. The efficacy of adapting all components is always positive for immersion durations higher than or equal to 72 hours. The variance of the efficacy increases with the quantity of building components to adapt.

Table 7 shows the distribution of the efficacy of each measure. The efficacy of elevating a dwelling lies between €0 and k€65. Dry-proofing a dwelling leads to a reduction of damage comprised between €0 and k€36 and the efficacy of adapting

30   all the components of the building is between k€-14 and k€54. These results highlight the high variability of the efficacy of each strategy.

4.2 Range of cost

As shown in Table 8, the cost of a given strategy does not depend on the immersion depth and duration. It always varies with the type of dwelling and the characteristic of the strategy (the height of elevation, the threshold, or the adaptation context). In the specific case of the component adaptations strategy, it also depends on the original variant used for the building components.

5   The cost of elevating a single storey house lies between k€66 and k€109. Thus, it is always higher that the highest value of efficacy for this strategy. It increases with the height of elevation and is always the highest for dwellings that have slab-on-grade foundations.

    The cost of dry-proofing a dwelling ranges from k€6 to k€10. For a given threshold, the cost of dry-proofing is always maximum for the single storey house and minimum for the double storey house. This is due to the fact that the single storey

10   house has the greatest perimeter (54 m) and the double storey house the smallest (40 m). The surface on which some measures must be applied increases with the threshold. Thus, the cost of dry-proofing is greater when the threshold is 100 cm than when it is 50 cm.

    Regarding the adaptation of all building components, if it takes place on a damaged building (repair context), it is often less expensive to adapt the dwelling than to install again the original variants of the components. More precisely, it is the

15   case for 91% of the 5 184 numerical models of dwellings. On the opposite, if the dwelling is intact when the adaptation takes place (prevention context), the mean cost of adapting all components is approximately four times higher than the cost of dry-proofing. In the prevention context, the minimum costs relate to versions of the dwellings for which the original variants of the components are highly similar to the recommended ones. Note that we did not compute numerical models of dwellings that were made up of all the recommended variants of the components. The cost and efficacy of adapting all building components of

20   such dwellings would be null. The highest adaptation costs relate to versions of the dwellings for which almost all components must be adapted.

4.3 Maximum cost-efficiency

Figure 4 indicates the maximum cost-efficiency of each strategy, depending on the type of dwelling and on some characteristics of the strategy (the height of elevation, the threshold, or the adaptation context), and for several combinations of time horizon

25   and return period.

    For the analysed values of time horizon, it is never cost-efficient to elevate a single storey house which is only exposed to floods with a return period higher than 30 years. If the dwelling has slab-on-grade foundations, the minimum return period for which it could be cost-efficient to elevate a dwelling is 20 years approximately.

    Similarly, according to our results, adapting all building components is never cost-efficient for intact dwellings that are

30   not exposed to floods that have a return period of less than 20 years. However, when component adaptations take place on a damaged dwelling, our results do not indicate ranges of time horizons and return periods for which this strategy is never cost-efficient.

Regarding dry-proofing, the results are similar for the three types of dwellings and are not affected by the threshold. They suggest that dry-proofing is never cost-efficient for dwellings that are not exposed to floods with a return period of a hundred years or less.

Except in the case of adapting all the building components of a damaged building, we observe that the maximum return
5 period for which a strategy is cost-efficient increases with the time horizon. For instance, for a dwelling that must be entirely dry-proofed again after twenty years and that is not exposed to floods with a return period of less than 60 years, this strategy will never be cost-efficient.

5 Discussion

We assessed the efficacy and cost of some precautionary measures by taking into account some characteristics of the dwellings
10 (their building components and size) and parameters of the measures, grouped in strategies (their dimension or implementation context). Then, we computed the maximum cost-efficiency of each strategy for several combinations of time horizon and return period. We could thus identify exposure levels for which it is unlikely that the strategies could be cost-efficient.

5.1 Main results

The value of the building components by square meter has a positive effect on the efficacy of dry-proofing and elevating a
15 dwelling while it does not affect the cost of these strategies. Hence, the more expensive the components of a dwelling, the more relevant it can be to elevate or dry-proof it. By contrast, both the efficacy and the cost of dry-proofing and elevation increase with the flood depth below which damage must be avoided and with the size of the dwelling. Consequently, these parameters do not affect the maximum cost-efficiency of dry-proofing and elevation. According to our results, these strategies are unlikely to be cost-efficient for dwellings only exposed to floods with a return period higher than 100 and 30 years, respectively.
20 The efficacy of adapting the building components strongly depends on their original materials. It can even be negative for floods that last less than 72 hours if the internal walls are originally in masonry. The cost of adapting the building components is influenced by the adaptation context and by the original materials. If the adaptation takes place on an already damaged building, it is most of the time less expensive to adapt it than to reinstall the original variants of the components. However, it costs approximately €40 000 on average to adapt an intact building. Since the cost and efficacy both increase with the quantity
25 of components to adapt, the maximum cost-efficiency does not depend on the size of the dwelling. It is unlikely that adapting an intact dwelling could be cost-efficient if this latter is not exposed to floods with a return period lower than 20 years. In a repair context, we could not identify exposure levels for which it is never cost-efficient to adapt all building components.

Note that the cost-efficiency of all strategies increases with their lifespan and with the level of exposure in terms of frequency of floods.

5.2 Comparison with previous studies

5.2.1 Elevation

According to Poussin et al. (2015), the mean efficacy of elevating the ground floor is €8 000 approximately and the cost of this strategy for existing building lies between €25 000 and €69 000. The range of cost comes from an article written by Aerts et al. (2013). These authors also used the data from the report of the FEMA (2009) to estimate the costs of elevating dwellings. Thus, our estimates of the cost of elevation are of the same order of magnitude as those reported by Poussin et al. (2015), even if they are higher on average (€87 000). Moreover, the mean efficacy estimated by these authors lies in the range of efficacy that we found (between €0 and €65 000). Poussin et al. (2015) also found that elevating an existing building is only cost-efficient for dwellings exposed to floods with a return period lower than 10 years. This result is compatible with our study.

Similarly to our results, those of Xian et al. (2017) indicate that the cost-efficiency of elevating a dwelling is positively affected by the value by square meter of this latter, the frequency of floods, and the lifespan of the strategy.

5.2.2 Dry-proofing

To our knowledge, there is no empirical study that analyses the combination of all the measures required to dry-proof a dwelling. However, Poussin et al. (2015) and Kreibich et al. (2011) studied the efficacy, cost, and cost-efficiency of installing flood barriers.

The average efficacy of flood barriers estimated by Kreibich et al. (2011) is €23 491 and the estimated cost of this measure is €6 100 for an average house. As explained in Sect. 3, flood barriers must be completed by other measures to dry-proof a dwelling. Since Kreibich et al. (2011) only asked whether flood barriers were installed, it is likely that the average efficacy they found is lower than the one that would have been observed for completely dry-proofed dwellings. Moreover, since the flood depth which affected the dwellings of the respondents is not known, we cannot precisely compare our results with this average efficacy. However, it lies in the range of efficacy that we found for the measure that consists in dry-proofing the dwellings. Moreover, we found an average cost for the installation of flood barriers only of €3 100, which is two times lower than the one used by Kreibich et al. (2011) but stays in the same order of magnitude. According to the results of Kreibich et al. (2011), flood barriers are only cost-efficient for dwellings affected by floods with a return period lower than 40 years approximately. This result is compatible with ours since we found that it is unlikely that dry-proofing could be cost-efficient for dwellings only exposed to floods with a return period higher than 100 years.

Poussin et al. (2015) found that flood barriers did not significantly reduce material damage in their whole sample. However, they highlight that this result may not be reliable because of multi-collinearity issues.

5.2.3 Component adaptations

We did not find studies which analyse specifically the efficacy, cost, or cost-efficiency of adapting all the building components. However, Kreibich et al. (2005) studied the efficacy of the combination of using waterproof building materials and having mostly movable pieces of furniture on the ground floor. They found that this strategy reduced the total damage by €39 000 on average. In line with this result, our estimates of the efficacy of adapting all building components are comprised between €-14 000 and €54 000.

According to Poussin et al. (2015), adapting the walls and equipment increases the damage by €2 000 on average. This result is compatible with our finding that adapting the walls can lead to negative levels of efficacy. These authors found that adapting the floors could reduce the damage by €400 to €10 000. They used a cost for this measure that lies between €800 and €7 250. They do not specify the adaptation context for which this cost was estimated, but given that it is always positive, we assume that it was assessed for an intact building. To adapt only the floors, we found costs in a prevention context comprised between €10 000 and €23 000. These values are higher than those used by Poussin et al. (2015) but stay in the same order of magnitude. As for the efficacy of adapting only the floor, we estimate that it lies between €0 and €16 000 depending on the flood depth and duration. These values are in line with those found by Poussin et al. (2015).

5.3 Recommendations based on our results

Our results seem reliable since they are in line with previous studies. They suggest that elevating or adapting the building components of intact dwellings that are not exposed to frequent floods (i.e. with a return period lower than 30 years) should not be fostered by policy-makers who wish to limit material damage due to floods. However, after a flood, it could be efficient to take advantage of the reconstruction phase to adapt the building components, since it is often less expensive to install the recommended components than to rebuild dwellings as they were before the event. Given that the post-disaster recovery often occurs in a climate of urgency, it could be useful to design in advance policy tools to help people adapt their dwelling during this phase.

Moreover, besides the level of exposure, the building components should be taken into account to assess the vulnerability of the dwellings, and thus the relevance of implementing precautionary measures that sometimes generate higher costs than benefits.

5.4 Limits

Decisions regarding the allocation of public funds to communicate about the strategies considered here or to subsidize their installation cannot be based solely on the present study. Indeed, we only took into account the damage in terms of monetary losses and did not consider the impact of the strategies on the damage related to human health. While this latter is unlikely to be influenced by component adaptations, it could be reduced by dry-proofing and even more by elevating the dwelling.

Moreover, our results cannot be used to identify a range of exposure for which it is likely that the studied precautionary measures would efficiently reduce monetary losses. Contextualised studies are required to finely relate the efficiency of precautionary measures to the characteristics of a dwelling and its level of exposure to floods.

Also, our results are mainly relevant for relatively slow riverine flood. Indeed, to compute the damage functions, we assumed
5   that the pieces of furniture are never moved by the water during a flood and that the salinity level of the water is negligible.

Finally, note that dry-proofing was only analysed for dwellings that do not contain a basement.

6 Conclusions

By using a novel approach that combines expert judgement and computer modelling, we were able to analyse three types of precautionary measures for a wide range of flood intensities and frequencies and characteristics of dwellings. In particular,
10   we found that adapting all the building components or elevating an existing dwelling are unlikely to be cost-efficient if the probability of occurrence of floods is lower than 1/30 per year. As for dry-proofing, this measure is unlikely to be cost-efficient for dwellings exposed only to floods with a return period higher than a hundred years.

Code availability. *floodam* is developed as a R library. It is available upon request through a git repository maintained by Irstea, and under certain conditions.

15   *Data availability.* Data at building levels used within *floodam* are available upon request through a git repository maintained by Irstea, and under certain conditions.

Author contributions. Claire Richert modelled the elevation strategy, analysed the data, and wrote the article. Hélène Boisgontier modelled the other strategies. Frédéric Grelot developed *floodam*, supervised the project, and proofread the article.

Competing interests. The authors declare that they have no conflict of interest.

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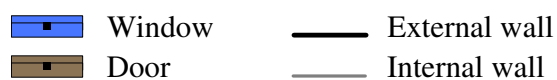
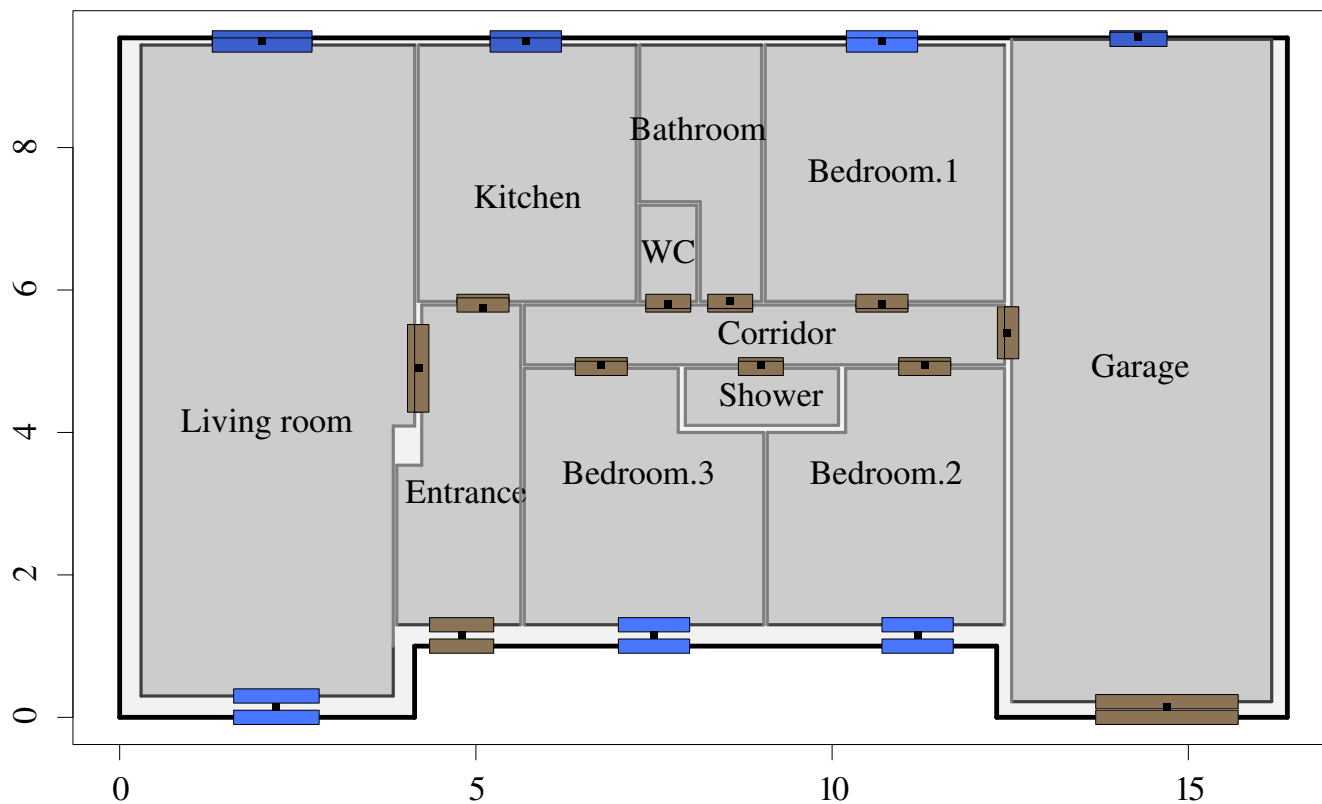


Figure 1. Top view of the single storey house. The external walls are in black, the internal walls in grey, the doors in brown, and the windows in blue.

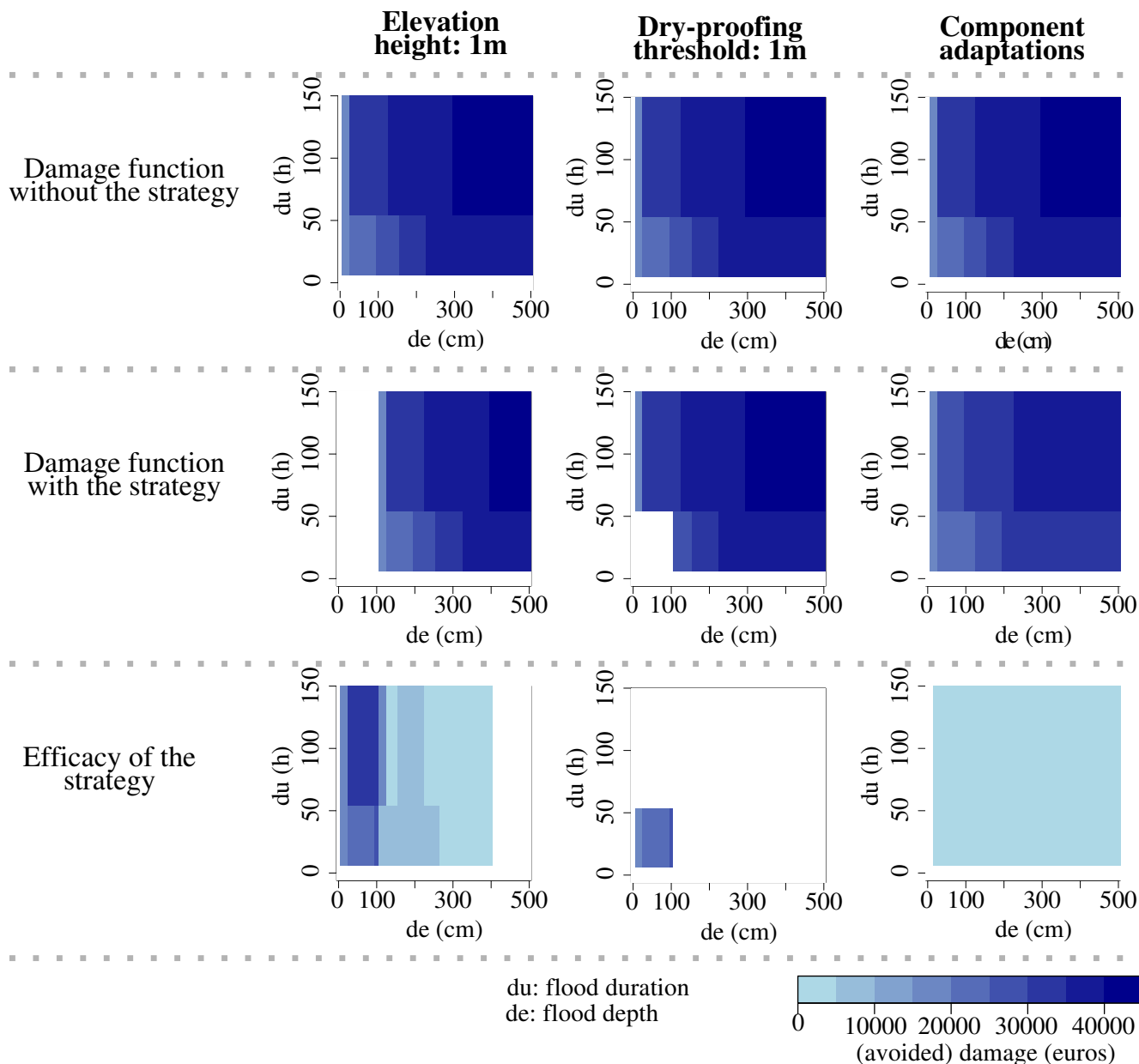



Figure 2. Efficacy of the elevation, dry-proofing and component adaptations strategies implemented on the original version of the single storey house. The two top panels show damage in euros while the lower panel shows avoided damage in euros.

D RATION OF IMMERSION: 24   **D RATION OF IMMERSION: 24**

Elevation

height: 50 cm   height: 100 cm   height: 250 cm   height: 50 cm   height: 100 cm   height: 250 cm

Dry-proofing threshold: 100 cm

Single storey house   Double storey house   Apartment   Single storey house   Double storey house   Apartment

Component adaptations

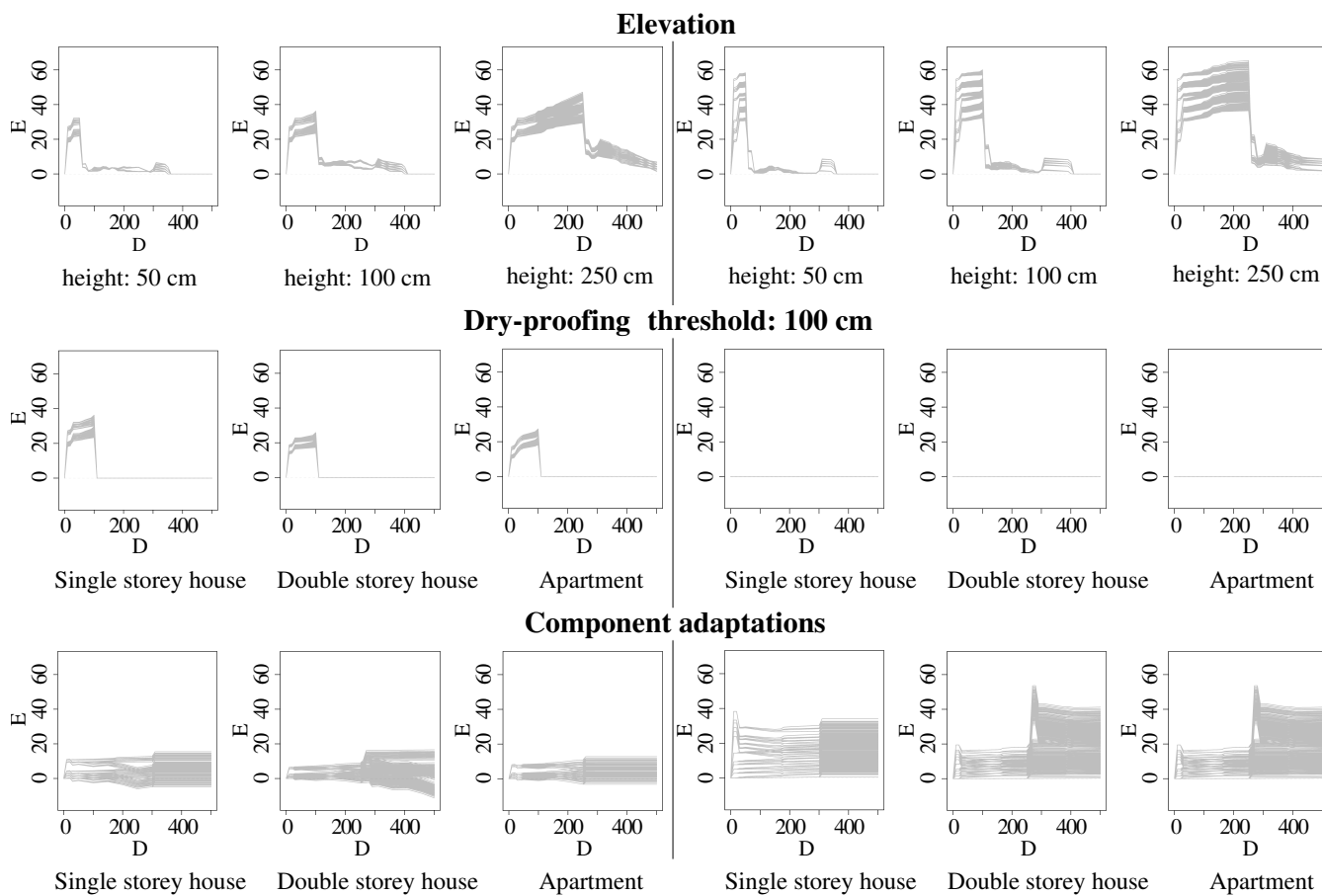
Single storey house   Double storey house   Apartment   Single storey house   Double storey house   Apartment

D: immersion depth in cm   ——— : Efficacy of the strategy considered for one version of the dwelling considered
E: efficacy in k

Figure 3. Efficacy of the three strategies for a duration of immersion of 24 or 72 hours

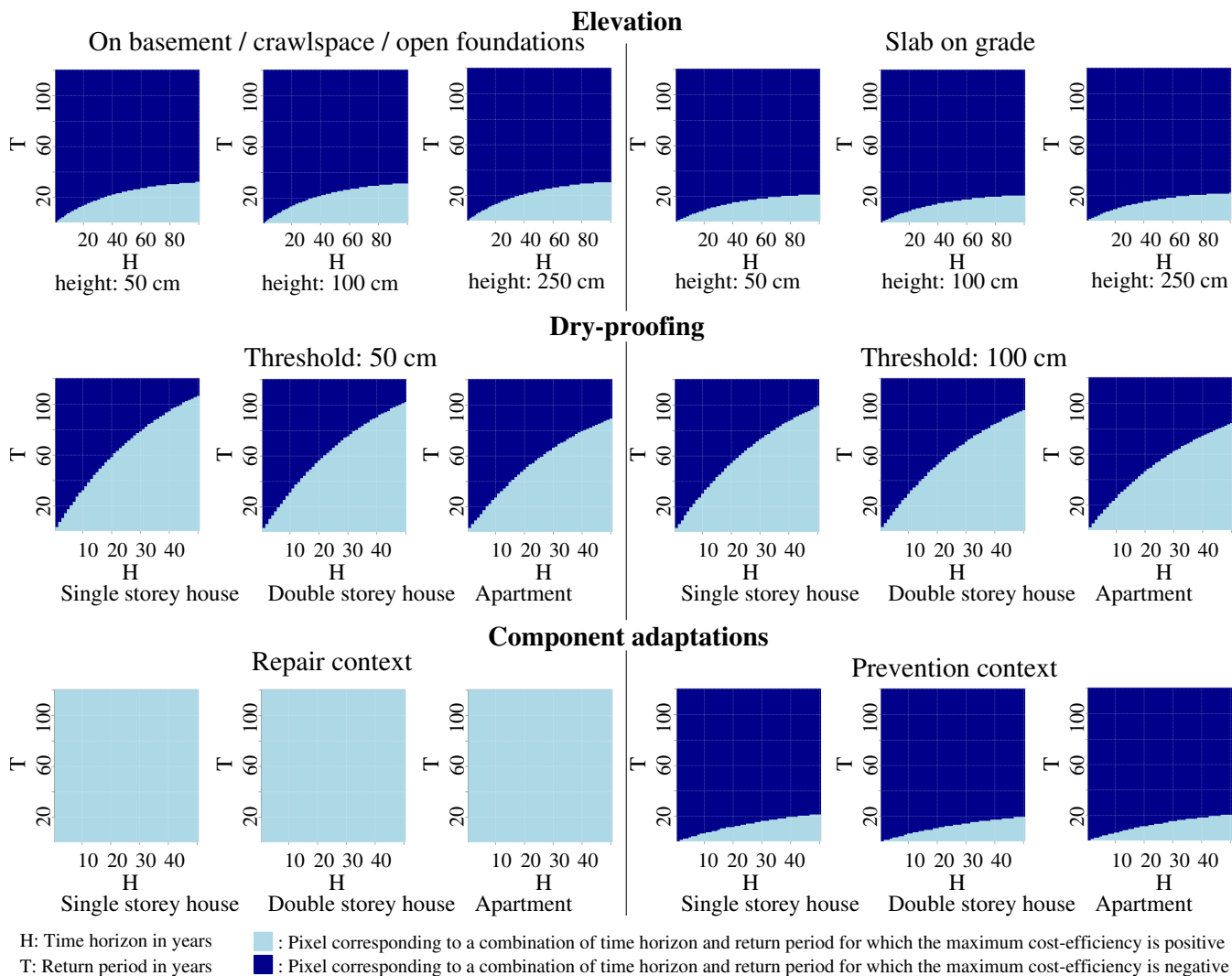



Figure 4. Sign of the maximum cost-efficiency of each strategy

Table 1. Materials that limit the costs of repair or replacement after a flood

Component	Material
Ceilings	Plaster boards and metal frame
Insulation of ceilings	Cellular plastic
Internal walls	Plaster boards and metal frame
Insulation of walls	Cellular plastic
Floors	Concrete
Coatings of floors	Sealed tiling
Internal door frames	Metal
External door frames	PVC or metal
Window frames	PVC
Shutters	PVC

Table 2. Pieces of furniture contained in Bedroom.1 of the single storey house (see Fig. 1)

Item	Height above the floor (cm)	Quantity
Single bed in solid wood	0	1
Stock of linen (value: €2675)	0	1
Various furniture in chipboard	0	3
Small items (value: €1500)	0	0.3
Small items (value: €1500)	120	0.7
Stock of toys (value: €900)	120	1

Table 3. Components of the building used to develop the versions of the numerical models of dwellings

Component	Number of variants	variant
External walls	3	brick, reinforced concrete, concrete blocks
External walls render	1	Cement
Internal walls	2	plaster boards/metal frame, masonry
Insulation	2	mineral wool, plastic
Coatings of walls	2	paint, paper
Ceilings	3	wood planks and frame, plaster boards/metal frame, concrete
Coatings of ceilings	1	paint
Floors	2	concrete, joist board
Coatings of floors	3	tiles, parquet, textile
Opening frames	2	PVC, wood
Shutters	2	PVC, wood

Table 4. Costs of elevating a masonry dwelling as reported by FEMA (2009)

Type of foundations	Height (feet)	Cost (US$/foot^2)
Basement / crawlspace / open	2	60
Basement / crawlspace / open	4	63
Slab on grade	2	88
Slab on grade	4	91

The costs by square foot are in 2009 US$

Table 5. Costs of elevating a masonry dwelling used in our study

Type of foundations	Height (cm)	Cost (€/m^2)
Basement / crawlspace / open	50	497
Basement / crawlspace / open	100	517
Basement / crawlspace / open	250	579
Slab on grade	50	731
Slab on grade	100	751
Slab on grade	250	813

The costs by square meter are in 2017 €

Table 6. Costs of the dry-proofing measures

Measure	Cost by measurement unit	Quantity
Flood barriers	775 €/unit	N of O
Removable covers	15.5 €/m	P
Repair of faulty seals	35 €/m^2	P × T
Treatment of cracks	3 €/m^2	P × T
Waterproofing of the walls	30 €/m^2	P × T
Watertight electrical sleeves	€550	NA
Pumping device	€820	NA
Anti-backflow valves	€650	NA

N of 0: Number of openings; P: Perimeter; T: threshold; NA: we assume that
the cost of the measure is fixed.

Table 7. Distribution of efficacy in k€ across all numerical models of dwellings and all combinations of immersion depth and duration

Strategy	Case	Minimum	Mean	Maximum	Standard deviation
Elevation	50 cm	0.0	4.5	58.3	10.1
	100 cm	0.0	9.0	60.1	13.8
	250 cm	0.0	22.1	65.4	18.2
Dry-proofing (Threshold: 50 cm)	Single storey house	0.0	0.7	32.3	4.2
	Double storey house	0.0	0.5	22.9	3.1
	Apartment	0.0	0.5	23.9	2.8
Dry-proofing (Threshold: 100 cm)	Single storey house	0.0	1.6	36.3	6.2
	Double storey house	0.0	1.1	25.9	4.5
	Apartment	0.0	1.1	27.4	4.5
Component adaptations	Single storey house	-8.9	9.5	38.3	8.9
	Double storey house	-13.3	8.8	53.6	10.0
	Apartment	-5.6	7.6	26.7	6.5

Table 8. Distribution of the cost in k€ across all numerical models of dwellings

Strategy	Case	Minimum	Mean	Maximum	Standard deviation
Elevation	50 cm	66.3	66.3	66.3	0.0
(On basement / crawlspace /	100 cm	69.1	69.1	69.1	0.0
open foundations)	250 cm	77.3	77.3	77.3	0.0
Elevation	50 cm	97.5	97.5	97.5	0.0
(Slab on grade)	100 cm	100.3	100.3	100.3	0.0
	250 cm	108.5	108.5	108.5	0.0
Dry-proofing	Single storey house	8.6	8.6	8.6	0.0
(Threshold: 50 cm)	Double storey house	6.3	6.3	6.3	0.0
	Apartment	7.6	7.6	7.6	0.0
Dry-proofing	Single storey house	10.4	10.4	10.4	0.0
(Threshold: 100 cm)	Double storey house	7.7	7.7	7.7	0.0
	Apartment	9.2	9.2	9.2	0.0
Component adaptations	Single storey house	-33.2	-12.6	8	9.9
(Repair context)	Double storey house	-45.5	-18.2	8.9	13.1
	Apartment	-28.4	-11.4	5.5	7.7
Component adaptations	Single storey house	2.6	40.2	74.0	17.2
(Prevention context)	Double storey house	1.8	53.9	102.2	24.9
	Apartment	0.3	30.0	57.1	13.4