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Effectiveness of flood damage mitigation measures: Empirical evidence from French flood disasters

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ABSTRACT

Recent destructive flood events and projected increases in flood risks as a result of climate change in many regions around the world demonstrate the importance of improving flood risk management. Flood-proofing of buildings is often advocated as an effective strategy for limiting damage caused by floods. However, few empirical studies have estimated the damage that can be avoided by implementing such flood damage mitigation measures. This study estimates potential damage savings and the cost-effectiveness of specific flood damage mitigation measures that were implemented by households during major flood events in France. For this purpose, data about flood damage experienced and household flood preparedness were collected using a survey of 885 French households in three flood-prone regions that face different flood hazards. Four main conclusions can be drawn from this study. First, using regression analysis results in improved estimates of the effectiveness of mitigation measures than methods used by earlier studies that compare mean damage suffered between households who have, and who have not, taken these measures. Second, this study has provided empirical insights showing that some mitigation measures can substantially reduce damage during floods. Third, the effectiveness of the mitigation measures is very regional dependent, which can be explained by the different characteristics of the flood hazard in our sample areas that experience either slow onset river flooding or more rapid flash and coastal flooding. Fourth, the cost-efficiency of the flood damage mitigation measures depends strongly on the flood probability faced by households.

1. Introduction

The importance of designing adequate flood risk management strategies has been illustrated by recent global flood events, such as Hurricane Sandy in the USA in 2012, or the large river floods in Germany and the UK in 2013, and 2014, respectively. Climate change may increase flood risks in many places around the world, which requires the implementation of strategies to manage current and future flood risks (IPCC, 2012). Such strategies include the provision of flood protection such as storm surge barriers and dykes as well as measures that reduce flood impacts (Botzen and van den Bergh, 2009). Recent studies have shown that an adequate implementation of flood damage mitigation measures at the household level, with the aim of flood-proofing individual buildings, can decrease the costs of floods (Kreibich and Thieken, 2009; Bubeck et al., 2012). Examples of such measures are installing flood barriers or anti-backflow valves, and elevation of the ground floor. Estimates of the effectiveness of such measures have been obtained by simulating flood risk reduction through flood risk assessment models (e.g. Dawson et al., 2011; Poussin et al., 2012), using expert judgment (ICPR, 2002; ABI, 2003; Defra, 2008), and empirical studies on avoided flood damage conducted after flood events (Kreibich et al., 2005; Kreibich and Thieken, 2009).

The few empirical analyses of flood damage avoided by private mitigation measures find that such savings can be large. After the Meuse floods in The Netherlands in 1993 and 1995, Wind et al. (1999) showed that the implementation of flood damage mitigation measures by households after 1993 decreased their flood losses by 35 per cent during the similar flood of 1995. Bubeck et al. (2012) collected survey data on household flood preparedness during the Rhine floods of 1993 and 1995. They showed that flood damage to households was reduced by up to 50 percent during the 1995 flood as a result of implementing measures. Several studies conducted after the 2002, 2005, and 2006 floods of the Elbe river in

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Germany have also concluded that mitigation measures substantially reduce flood damage (Kreibich et al., 2005, 2011, 2012; Olfert and Schanze, 2008; Kreibich and Thieken, 2009). Kreibich et al. (2005) and Kreibich and Thieken (2009) estimated that the use of flood adaption for buildings and furnishing reduced the flood damage to buildings by between 46 and 53 per cent, and the flood damage to home contents by between 48 and 53 per cent. Installing heating and electrical utilities on higher floors, adapting the structure of the home to floods, and water barriers, respectively reduced the damage to buildings by 36, 24, and 29 per cent (Kreibich et al., 2005; Kreibich and Thieken, 2009).

Although the aforementioned studies provide useful insights into the potential damage savings from flood damage mitigation measures, it is evident that this empirical literature is scarce and focused on a few river basins, which are located in a few countries (mainly Germany). Moreover, few studies examined the cost-effectiveness of these measures. Kreibich et al. (2011, 2012) estimate benefit–cost (B/C) ratios of adapting buildings to floods in Germany, which depend on the type of measures and homes as well as on the probability of flooding. In particular, securing oil tanks and installing water barriers turn out to be very cost effective with B/C ratios between 5.61 and 539.96, and between 1.12 and 61.14, respectively (Kreibich et al., 2011, 2012). These B/C ratios are calculated using values of flood loss reductions that are based on a comparison of means of flood damage suffered between groups of households who have, and who have not, taken flood damage mitigation measures. Applying regression analysis may be more suitable for estimating the independent effect of damage mitigation measures by controlling for other effects on flood damage, such as flood water heights (Wooldridge, 2003).

Further empirical research is needed on the (cost-)effectiveness of individual flood damage mitigation measures. Such information is imperative for policy-makers who are involved in the design of flood risk management policies, insurance companies who are interested in reducing flood vulnerability of their policyholders, and households and businesses who want to reduce the flood risk to their property (e.g. Kull et al., 2013). This study, therefore, aims to provide data on the (cost-)effectiveness of 11 different flood damage mitigation measures. Flood damage savings are estimated using regression models of data gathered by means of a survey of households who have experienced floods. This survey was conducted in three regions of France that face different flood risks. In total 885 households replied to the survey.

The remainder of this paper is structured as follows: Section 2 describes the survey and methodology; Section 3 presents the results of the potential flood damage that can be avoided by the 11 flood damage mitigation measures, and the (cost-)effectiveness of these measures; and Section 4 provides a discussion and conclusion of the main findings of this study and their implications for flood risk management policies.

2. Description of the survey and methodology

2.1. Survey method and description of the sample

A mail survey was conducted in France in 2011 in three flood-prone areas: the French Ardennes; the Var; and the West Coast (Fig. 1). These three areas differ with respect to their flood history, the types of floods they are subject to, their existing regulations against floods, their local "flood cultures" and flood management approaches. The Ardennes are mainly subject to large river floods, which occur regularly and can cause considerable damage, such as €120 million and €240 million in 1993 and 1995, respectively (EPTB, 2011). In the Var, households are regularly threatened by flash floods. In 2010, an extreme event occurred that caused €600 million and 23 deaths (FFSA, 2011). The West region faces coastal

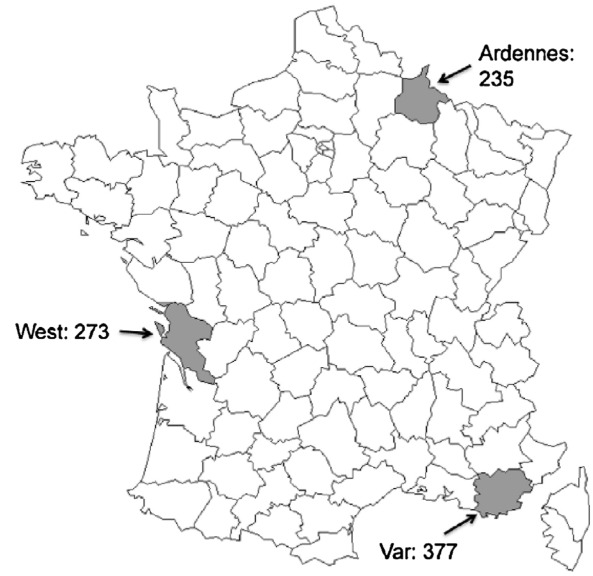

Fig. 1. Geographical location of the three French regions surveyed and the respective number of respondents to the survey.

floods, which occur rarely. In 2010, the storm Xynthia caused €1.5 billion in damages, including €700 million flood damage, and 47 deaths (Anziani, 2010). More information can be found in Poussin et al. (2013). The survey was conducted in villages and towns that were carefully selected on the basis of having experienced flood event(s) in the past. The survey was pre-tested in the same sample areas that were used for the final survey (Poussin et al., 2013). The final survey was sent by IPSOS, a French professional survey research company, by postal mail to 8201 households, which were equally divided over the 3 regions. In total, 885 respondents returned the mail survey, of which 530 have been personally flooded at least once in their home.

A comparison between the demographic statistics from the actual population of the three regions, and the socio-economic characteristics of the respondents who experienced flood damage can be found in Poussin et al. (2013). The sample is approximately representative with respect to certain characteristics, such as gender and education, while it slightly under-represents home-owners and over-represents high income and older households. Most age groups of adults are well represented in our sample, but higher age groups are slightly over-represented. As an illustration, the percentages of our regional samples that fall in the age group 60–74 years are 28%, 24% and 37% in the Ardennes, the Var and the West, while in the actual population these percentages are 14%, 18% and 17%. In general, older individuals in France tend to take more flood risk mitigation measures (Poussin et al., 2014). But, there is no reason to suspect that age affects the flood damage avoided per mitigation measure, which is the main focus of this paper.

2.2. Overview of the main variables included in the regression models

A variety of variables have been used to assess the effectiveness of the mitigation measures in reducing flood damage. The effects of several variables that potentially influence the level of flood damage are estimated using ordinary least squares (OLS) regression models. Linear regressions are calculated in a stepwise manner, thus excluding explanatory variables (Table 1) that are insignificant.

Table 1 contains a description of the dependent and explanatory variables that are included in the final regression models. The two

Table 1
Overview of the variables used in the statistical analysis and their coding.

Dependent variables	
Damage to buildings[a]	Continuous variable of the flood damage to building divided by the market value of the home, in Euros
Damage to home contents[a]	Continuous variable of the flood damage to home contents divided by the value of home contents, in Euros
Explanatory variables	
Characteristics of the flood:	
Water height in the cellar	Continuous variable of the maximum water height attained in the cellar during the last flood, in cm
Water height on the ground floor[c]	Continuous variable of the maximum water height attained in the ground floor during the last flood, in cm
Characteristics of the home:	
Close to source of the flood[c]	Dummy variable, 1 = home of the respondent is located less than or up to 100 m from the source of the flood (river or coast), 0 = otherwise
House	Dummy variable, 1 = house, 0 = apartment
Cellar	Dummy variable, 1 = respondent has a cellar, 0 = otherwise
Mitigation measures:	Dummy variables, 1 = measure was implemented in the home of the respondent before his/her last flood, 0 = otherwise
Elevated ground floor[d]	The level of the ground floor is elevated above the most likely flood level
Foundations strengthened[b,c]	The foundations of the home are strengthened against water pressures
Walls and equipment made of water-resistant materials[c]	The walls and equipment of the ground floor have been constructed using water-resistant materials
Floor of ground floor made of water-resistant materials[b]	The ground level floor is made of water-resistant materials
Raised electricity meter[b,c]	The electricity meter is above the most likely flood level or on an upper floor
Raised power sockets on ground floor[b,c]	On the ground floor of the home, the power sockets are above the most likely flood level
Anti-backflow valves[b,c]	Anti-backflow valves are installed on pipes to stop flood-waters from entering the home through the pipes
Elevated boiler[b,c]	The boiler or heater is above the most likely flood level or on an upper floor
Sandbags[c]	The respondent owns sandbags or other water barriers
Raised electrical appliances[b,c]	The washing machine and dryer are above the most likely flood level or on an upper floor
Furniture adapted[b,c]	In flood-prone parts of home, the furniture is chosen and placed to avoid flood damage

Notes:
[a] These variables include observations of respondents who were personally flooded but replied that they had no financial damage, as well as respondents who replied that they were not personally flooded while their neighbors were flooded. These respondents may have not experienced damage or been personally flooded because of mitigation measures taken prior to the flood, which is why these responses were included in the analyses as having zero flood damage.
[b] The regression models include interactions of this variable with the variable of closeness to the source of the flood.
[c] The regression models include an interaction of this variable with the variable of the water height at the ground floor.
[d] This measure is excluded from the regression analyses because it has a direct effect on water depth and only an indirect effect on the damage.

dependent variables are the level of financial flood damage experienced by respondents to their home (the building) and to its contents. This damage data was elicited by asking respondents to give the monetary value of the damage they had experienced during their (last) flood. In line with Kreibich et al. (2005), we determine the damage ratio of the assets and of the contents by dividing the level of flood damage to the building or to the contents by the market value of the home or the value of contents respectively. In total, 374 and 357 observations were obtained for calculating damage ratios Y/a, for the buildings and the home contents, respectively, where, Y is the flood damage experienced to the building or home contents and a is the value of the building or the home contents.

Table 1 lists three categories of explanatory variables: the characteristics of the flood; the characteristics of the home; and the mitigation measures. The floods experienced by the respondents are defined by two characteristics: the maximum water height attained in the cellar and the maximum water height attained on the ground floor. The possible effect of the characteristics of the home of the respondents on the damage are accounted for by using three variables which are: living in a home within 100 m of the source of the flood; living in a house (instead of in an apartment); and whether the home of the respondent includes a cellar. Water velocity is not included directly, which means that this effect is captured indirectly by the distance to the source of the flood variable. Interaction variables of the measures and the water height, and of the measures and the closeness to the source of the flood, are included in the regressions to assess the effect of the water depth and the distance to the source of the flood on the damage experienced by households who have, or have not, implemented flood damage mitigation measures. For two measures (i.e. walls and equipment made of water-resistant materials, and owning sandbags or water barriers), the interaction variables with the closeness to the source of the flood are not used in the regressions in order to avoid problems with multi-collinearity. These interaction variables have a Pearson coefficient of correlation larger than 0.7 with the variables of the measures themselves, which is a high level of correlation that can cause multi-collinearity (Bryman and Cramer, 1994). Since potential damage savings from having the ground level floor made of water-resistant materials does not depend on the water depth, the interaction variable of this measure with the water height on the ground floor is not used in the regressions.

In the final survey, respondents were asked whether or not twenty one mitigation measures were implemented in their homes (Poussin et al., 2013). These measures were selected using literature review (ICPR, 2002; ABI, 2003; Boulet-Desbareau et al., 2005; Defra, 2008) and the survey pre-test. Ten measures were not included in the regression models: seven measures were excluded because of the very low number of respondents who replied that they had implemented them, and three measures were excluded because they cannot directly reduce flood damage. Also, elevating the ground floor is not included in the regression analyses, because it is the only measure that has a direct effect on the water height in the home by limiting the amount of water which can enter the ground floor. Thereby, it only has an indirect effect on the damage itself. Results of the (cost-)effectiveness of this measure are presented jointly with the results for the other measures. The ten remaining measures which are included in the models are described in Table 1.

2.3. Methodology used to assess the (cost-)effectiveness of the mitigation measures

First, a comparison of means of flood damage suffered by households who have, or have not, implemented a specific mitigation measure was conducted. The significance of differences in mean damage ratios was assessed using the non-parametric Mann–Whitney *U* test which does not rely on the assumption of normally distributed variables, which is an assumption made by the *t*-test (Siegel, 1957). Data on the flood damage variables and damage ratios were found to be not normally distributed. In a second step, regression models were estimated in which all the explanatory variables of Table 1 were included (Section 3.2). These regression models were conducted to assess the effectiveness of the measures in reducing damage independently of other factors that can have a significant impact on the damage, such as the water height or the distance of the homes to the river or the sea. In a third step, using the coefficients of the regression models represented by Eq. (1), the effect of the implementation of each of the mitigation measures on the damage to buildings and to home contents was assessed for an average respondent (Section 3.3, Table 5).

$$Y/a = \beta_0 + \beta_1 \times X_1 + \beta_2 \times X_2 + \beta_3 \times X_1 \times X_2 + \beta_4 \times Z_1 + \beta_5 \times Z_1 \times X_1 + \beta_6 \times Z_1 \times X_2 + \beta_7 \times Z_2 + \beta_8 \times Z_2 \times X_1 + \beta_9 \times Z_2 \times X_2 + \beta_{10} \times Z_3 + \beta_{11} \times Z_3 \times X_1 + \beta_{12} \times Z_3 \times X_2 + \cdots + \beta_n \times Z_n + \beta_n \times Z_n \times X_1 + \beta_n \times Z_n \times X_2 + \epsilon \quad (1)$$

where 'Y' is the flood damage, 'a' is the value of the home or of the home contents, 'β_0' is the constant, the other betas are the unstandardized coefficients of the linear regression, 'X_1' is the water height, 'X_2' is the distance to the source of the flood, and the 'Z' are the dummy variables of the mitigation measures, which take on the value 1 when the mitigation measure is implemented by the respondent, and 0 otherwise. ε is the error term. The impact of a mitigation measure on flood damage was assessed using Eq. (1) without the error term by estimating the effect on the damage ratio Y/a of changing the level of the mitigation measure variable from 0 to 1, while keeping all other variables at their sample average values. Changes in the damage ratio were translated to absolute values of flood damage avoided using the average value of the home or home contents.

In a fourth stage, the values of damage avoided by the measures which were found to significantly reduce flood damage were used in a benefit–cost analysis to assess the cost-effectiveness of the measures (Section 3.3, Table 6). Total discounted benefits over the life-time of the flood damage mitigation measures ('$B_{lifetime}$') were calculated using Eq. (2): the average values of damage avoided obtained with Eq. (1) which correspond to the benefits for a flood event ('B_{flood}') were multiplied by the flood probability 'P' to obtain values of average flood losses reduced per year, defined as B_t. These flood losses were discounted using the discount rate 'r' and the year 't' over the time horizon 'T' for which the measure is in place. The discounted flood losses reduced per year were then added over the life-time of the measure ('$B_{lifetime}$'). The obtained value corresponds to the maximum value the measures can cost to remain cost-effective.

$$B_{lifetime} = \sum_{t=1}^{T} \frac{(B_t)}{(1+r)^t} \quad (2)$$

The flood probabilities selected for these calculations are 1/1, 1/10, and 1/50 years (Kreibich et al., 2011, 2012). Flood probabilities differ considerably between locations in French floodplains (Poussin et al., 2013). The broad range used here is representative for many inhabitants of floodplains in our sample areas. The applied discount rate is 4.5 per cent, which corresponds to the current discount rate in use in France since 1996 (Banque de France, 1997–2004; Banque de France, 2005–2013). The time horizon, or life-time of the measures, was set to 10 or 50 years depending on the life time of the specific measure (Table 6). Estimates of total costs of implementing the measures are provided, which were used to calculate Benefit–Cost (BC) ratios for the different mitigation measures per flood probability and region. When the cost of the measures is provided as a range, then the BC ratios were calculated for both the low and the high value of the range.

3. Survey results

3.1. Comparison of means of damage ratios

Table 2 provides a comparison of means of damage ratios, respectively, for the damage to buildings and to home contents experienced by respondents who did, or did not, implement a specific mitigation measure. In cases where the difference of means is significant, the table also provides the differences in flood

Table 2
Difference in average flood damage ratios of buildings and home contents, absolute amounts of damage avoided, and percentage reduction in damage ratios for respondents who did, or did not, implement a specific flood mitigation measure (N = number of respondents).

Flood damage mitigation measures	Damage to buildings (N = 301–350) Mean differences in ratios (mean differences in damage[a]): percentage reduction	Damage to home contents (N = 290–333) Mean differences in ratios (mean differences in damage[a]): percentage reduction
Elevated ground floor	−0.03*** (€−7172): 48%	−0.10*** (€−5424): 56%
Foundations strengthened	−0.01	−0.002
Walls and equipment made of water-resistant materials	0.02	0.01
Floor made of water-resistant materials	−0.02	−0.04
Raised electricity meter	−0.04*** (€−11,365): 54%	−0.16*** (€−8885): 63%
Raised power sockets on ground floor	−0.07*** (€−18,971): 84%	−0.18*** (€−10,038): 77%
Anti-backflow valves	−0.03** (€−8585): 65%	−0.05* (€−2923): 38%
Elevated boiler	−0.04*** (€−11,492): 60%	−0.12*** (€−6953): 63%
Sandbags	−0.01	−0.06
Raised electrical appliances	*n.a.*	−0.14*** (€−8056): 77%
Furniture adapted	*n.a.*	−0.04

Notes:
* sig < 0.1.
** sig < 0.05.
*** sig < 0.01 estimated using the Mann–Whitney *U* test.
n.a. stands for not applicable.
[a] The mean differences in flood damage experienced are calculated by multiplying the mean differences in ratios with the value of an average home, for each measure and type of flood damage.

damage to an average home in Euros and the percentage of the average reduction in the damage ratio that may be obtained by implementing the flood damage mitigation measure. The table shows that elevating the ground floor decreases both the damage ratio to buildings and to home contents by 48 per cent to 56 per cent, respectively. This damage saving is caused by a reduction in the water depth on the ground floor. In particular, elevation decreases the water depth in flooded homes on average by 0.26 m for the entire sample, which is statistically significant (p-value <0.001). Raising the electricity meter, the power sockets, and the boiler also significantly decreases the level of the damage ratio to both buildings and home contents from 54 per cent to up to 84 per cent. Anti-backflow valves decrease the damage ratio to buildings by 65 per cent and to home contents by 38 per cent, while raising the electrical appliances significantly reduces the level of the damage ratio to home contents by 77 per cent. The other measures do not significantly reduce the average flood damage. The differences in flood damage range from €2923 to €18,971 per household. The highest reductions in damage caused to both the building (over €10,000) and home contents (over €6000) are observed when the electricity meter, the power sockets, the boiler, and electrical appliances are raised.

3.2. Results of the regression models of flood damage to buildings and flood damage to home contents

Tables 3 and 4 show the results of the regression models that include the variables that are significant in explaining the variations in the level of flood damage among our respondents, for the whole sample, and for each region separately. In Table 3, the variables explain between 36 per cent and 79 per cent of the variance in the damage. In Table 4 the variables explain between 62 per cent and 85 per cent of the variance in the damage. Overall, these results indicate that the models provide a good fit of the data.

3.2.1. Damage to buildings

3.2.1.1. Overall sample. The results from Table 3 show that the water height on the ground floor is strongly and directly related to an increase in damage. This finding is in line with various research using flood damage models, which shows that water depth is the main factor determining flood damage (Klijn et al., 2007; Bouwer et al., 2009, 2010; Aerts and Botzen, 2011; De Moel et al., 2011; Te Linde et al., 2011; Ward et al., 2011; Poussin et al., 2012). Moreover, the results show that the effect of water depth on damage is slightly higher for respondents who live close to the source of the flood.

Strengthening the foundations has a negative, but insignificant effect on flood damage, while respondents with strengthened foundations who live close to the source of the flood have higher flood damage. This suggests that this measure is not effective in the overall sample.

Having the walls and equipment made of water-resistant materials does not decrease the damage to buildings. In contrast, it increases damage in the overall sample, especially when the water depth on the ground floor is high. This finding can reflect the strong correlation of the implementation of this measure with the variable living close by the source of flooding, which cannot be accounted for by an interaction variable because of the aforementioned problems with multi-collinearity. This means that the higher damage experienced by buildings made of water-resistant materials can occur because these buildings are generally located close by the river and the sea where flow-velocities are high. Alternatively, this result can arise if buildings made of water-resistant materials collapse in case of high flood water depths, as has been identified as a drawback of this measure by others (FEMA, 2009).

Using water-resistant materials for the ground level floor of the home does not significantly reduce the damage to buildings for the

Table 3
Influence of mitigation measures and other variables on the level of flood damage to buildings in three flood-prone areas in France.

	All regions	Ardennes	Var	West
	$N=228$ $R^2=0.36$	$N=66$ $R^2=0.57$	$N=126$ $R^2=0.51$	$N=52$ $R^2=0.79$
	Regression coefficients β			
Characteristics of the flood:				
Water height in the cellar	*n.s.*	*n.s.*	*n.s.*	0.22**
Water height on the ground floor	0.08***	0.12***	0.07***	0.22***
Characteristics of the home:				
Close to source of flood	0.004	0.03	−0.002	−0.02
Close to source of the flood × water height ground floor	−0.05**	0.16***	*n.s.*	1.11***
Mitigation measures:				
Foundations strengthened	−0.005	−0.006	−0.002	*n.s.*
Foundations strengthened × water height ground floor	*n.s.*	−0.35***	*n.s.*	
Foundations strengthened × close to source of the flood	0.05*	0.14***	0.10***	
Walls and equipment made of water-resistant materials	0.02	*n.s.*	*n.s.*	−0.004
Walls and equipment × water height ground floor	0.04**			0.08*
Floor made of water-resistant materials	*n.s.*	−0.06***	−0.03*	*n.s.*
Raised electricity meter	−0.02*	0.04	*n.s.*	*n.s.*
Electricity × water height ground floor	*n.s.*	*n.s.*		
Electricity × close to source of the flood	*n.s.*	−0.10**		
Raised power sockets on ground floor	−0.02*	0.02	−0.007	−0.02
Power sockets × water height ground floor	−0.06***	−0.11***	−0.15***	0.12**
Power sockets × close to source of the flood	*n.s.*	*n.s.*	0.06*	*n.s.*
Anti-backflow valves	−0.02	*n.s.*	*n.s.*	−0.03
Anti-backflow valves × water height ground floor	0.10*			−1.10***
Elevated boiler	*n.s.*	−0.03	−0.002	−0.008
Boiler × water height ground floor		*n.s.*	0.12***	−0.24***
Boiler × close to source of the flood		0.06*	−0.12***	*n.s.*

* $p<0.1$.
** $p<0.05$.
*** $p<0.01$.
n.s. = not significant.

Table 4
Influence of mitigation measures and other variables on the level of flood damage to home contents in three flood-prone areas in France.

	All regions	Ardennes	Var	West
	$N=244$	$N=70$	$N=100$	$N=73$
	$R^2=0.62$	$R^2=0.85$	$R^2=0.72$	$R^2=0.69$
	Regression coefficients β			
Characteristics of the flood:				
Water height in the cellar	0.05***	0.05***	*n.s.*	−0.15**
Water height on the ground floor	0.31***	0.31***	0.09**	0.39***
Characteristics of the home:				
Close to source of flood	−0.26***	0.09	−0.57***	0.05
Close to source of the flood × water height ground floor	−0.08**	−0.20**	*n.s.*	0.33*
Mitigation measures:				
Foundations strengthened	0.009	*n.s.*	0.07**	*n.s.*
Foundations strengthened × water height ground floor	0.08*		*n.s.*	
Walls and equipment made of water-resistant materials	0.001	−0.01	*n.s.*	*n.s.*
Walls and equipment × water height ground floor	0.08*	0.53***		
Floor made of water-resistant materials	−0.04	*n.s.*	−0.13***	*n.s.*
Floor × close to source of the flood	0.11**		0.28***	
Raised electricity meter	−0.13***	0.31***	−0.40***	−0.11**
Electricity × water height ground floor	*n.s.*	−0.32***	0.16***	*n.s.*
Electricity × close to source of the flood	0.18***	−0.30***	0.30***	*n.s.*
Raised power sockets on ground floor	−0.03	−0.19***	−0.05	*n.s.*
Power sockets × water height ground floor	−0.11***	*n.s.*	−0.11**	
Power sockets × close to source of the flood	*n.s.*	0.18***	*n.s.*	
Anti-backflow valves	*n.s.*	−0.17**	−0.11**	*n.s.*
Anti-backflow valves × water height ground floor		0.42***	*n.s.*	
Elevated boiler	*n.s.*	−0.04	*n.s.*	*n.s.*
Elevated boiler × water height ground floor		0.27**		
Sandbags	*n.s.*	0.14**	*n.s.*	*n.s.*
Sandbags × water height ground floor		−1.22***		
Raised electrical appliances	−0.03	−0.01	*n.s.*	*n.s.*
Electrical appliances × water height ground floor	−0.13***	−0.35***		
Furniture adapted	*n.s.*	−0.03	−0.15***	*n.s.*
Furniture × water height ground floor		0.31***	*n.s.*	
Furniture × close to source of the flood		*n.s.*	0.31***	

* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.
n.s. = not significant.

overall sample. A more effective measure is to raise the electricity meter which significantly reduces flood damage. Moreover, raising the power sockets on the ground floor significantly reduces the damage in the overall sample and it limits the negative effects on damage of high water levels.

Installing anti-backflow valves on pipes has an insignificant negative effect on flood damage in the overall sample, however, the effect of water depth is (weakly significantly) higher for respondents who implemented this measure. Elevating the boiler has an insignificant effect on flood damage in the overall sample.

3.2.1.2. Regional sub-samples. The sub-sample results confirm the significant influence of the water height on flood damage (Table 3). Moreover, the effect of water depth on damage is significantly higher for respondents who live close to the source of the flood in the Ardennes and the West.

Table 3 shows that, in the Ardennes, the effect of water depth on the ground floor on flood damage is smaller for households who strengthened the foundations of their home against water pressures than for other respondents. However, in the Ardennes, and the Var, this measure's effectiveness is strongly reduced when households live close to the flood source. This suggests that strengthening the foundations is insufficient to prevent flood damage in areas close by a river or the sea where flow velocities of flood waters are high.

The positive influence on flood damage of having the walls and equipment made of water-resistant materials found for the overall sample appears to be driven by the West where this coefficient is significant and positive. This measure has a non-significant influence on flood damage in the other regions.

Using water-resistant materials for the ground level floor of the home significantly reduces the damage in the Ardennes and the Var, while this measure was not significant in the overall sample. The damage reducing effect in the overall sample of raising the electricity meter appears to come from the Ardennes where it negatively reduces flood damage of respondents who live close to the source of the flood.

Raising the power sockets on the ground floor significantly compensates the effect of water depth on damage in the Ardennes and is related with a reduction in damage for higher water depths in the Var. In contrast, in the West this measure causes a slight increase in the effect of water depth on damage. This can be related to the speed of the flow during a coastal flood, making this measure less effective at high water levels. This effect can be mitigated in the West by installing anti-backflow valves on pipes since the effect of water depth on damage is smaller in the West for respondents who take this measure.

Elevating the boiler is insignificant in the whole sample, but has mixed regional results. In the Ardennes, this measure slightly reduces the damage. In the West, this measure reduces the effect of the water depth on the damage. In the Var, elevating the boiler reduces flood damage for respondents who live close by the source of flooding, but also increases the negative effects of water depths on damage, suggesting that it is ineffective if water levels are high.

3.2.2. Damage to home contents

3.2.2.1. Overall sample. The results from Table 4 show that higher water depths on the ground floor and in the cellar are significantly and directly related to an increase in the damage to home contents.

Moreover, respondents who live close to the source of the flood have, in general, a lower flood damage level than respondents who live farther away from the river or the sea and the effect of water depth on damage is smaller for this former group of respondents.

Strengthening the foundations of the home against water pressures is not effective in reducing the damage to home contents. In fact, in the overall sample, the effect of the water height on the damage is higher for respondents who implemented this measure. This is consistent with results in the previous section showing that this measure is not effective in reducing flood damage to buildings.

Results show that using water-resistant materials for the walls and equipment reduces overall damage in the model of the whole sample, but this effect is not significant, while similarly as for the damage to buildings, this measure increases the effect of water depth on damage to home contents. Using water-resistant materials for the floor on the ground floor has a negative, but insignificant, effect on the overall flood damage for the overall sample, while this damage reducing effect is not present for households who live closer to the source of the flood.

Raising the electricity meter above the most likely flood level significantly reduces the flood damage to home contents in the overall sample, but this measure is ineffective for respondents who live close to the source of the flood. Anti-backflow valves do not significantly influence flood damage in the overall sample.

A priori we do not know whether people count damage to their boiler as building or contents damage which is why we include this measure in both regressions. It appears that elevating the boiler is not significantly related to the damage to home contents. A similar result is found for installing sandbags. Raising electrical appliances significantly reduces flood damage for the overall sample as a function of water depth.

3.2.2.2. Regional sub-samples. The significant positive effect of higher water depths on the ground floor is consistent for all the three regions. Moreover, in the Var, respondents who live close to the source of the flood have, in general, a lower flood damage level than respondents who live farther from the river or the sea. For respondents who live close to the source of the flood, the effect of water depth on damage is smaller in the Ardennes, while it is higher in the West. In the Ardennes and the Var, the findings can be the result of the high frequency of flooding in these regions that made respondents in flood-prone areas adapted to the risk.

It appears from Table 4 that the water depth in the cellar is associated with an increase in damage in the Ardennes. In the West, a higher water depth in the cellar is related to a reduction in damage to home contents. In particular, of the 73 respondents in this region, the 61 households who were not flooded in the cellar experienced more damage than the 12 households who were flooded in their cellar. This is probably due to the high number of households in this region that have flood-proofed their cellars.

The ineffective result of strengthening the foundations of the home against water pressures for the overall sample appears to be driven by the Var where this measure directly increases the level of damage experienced by households. The Ardennes appears to drive the ineffective result of using water-resistant materials for the walls and equipment which increases damage at high water levels. Using water-resistant materials for the floor on the ground floor reduces the overall flood damage in the Var, except for households who live closer to the source of the flood.

Raising the electricity meter above the most likely flood level significantly reduces the flood damage to home contents in the Var, and the West. The effect of the water level on the damage for respondents who implemented this measure is smaller compared to other respondents in the Ardennes. In the Var, the effect of the water level is higher when this measure is implemented, but the reducing effect of the measure itself means that even when the water level is high, the measure remains effective in reducing the damage to home contents. In the Var, this measure is less effective for respondents who live close to the source of the flood.

The damage reducing effect of raising the power sockets observed in the overall sample is driven by the Var and the Ardennes, but this measure is not effective in the Ardennes for people who live close by the river. Moreover, in the Var, the measure significantly compensates the effect of water levels on the damage to home contents.

Although anti-backflow valves were insignificant in the overall sample regression, this measure significantly reduces flood damage in the Ardennes and the Var, but is less effective in the Ardennes if flood depths are high. Sandbags effectively reduce the damage in the Ardennes, as a function of flood depths, while this measure is not significant in the other regional models.

Adapting the furniture in flood-prone parts of the home only reduces the damage in the Var for respondents who live farther than 100 m away from the source of the flood. That measure is not effective in the Ardennes, where raising electrical appliances does reduce flood damage as a function of water depth.

Overall it is apparent from the regional models of flood damage to buildings and contents that none of the measures that involve

Table 5
Effect of the measures on reducing flood damage to buildings and to home contents of an average home, in Euros.

Measures\type of damage and regions	Flood damage to buildings (€)				Flood damage to home contents (€)			
	All regions	Ardennes	Var	West	All regions	Ardennes	Var	West
Average value	272,917	171,818	309,615	326,705	54,674	57,885	53,289	56,801
Elevated ground floor[a]	−5051	−1703	−5547	*n.s.*	−2995	−3778	−1051	−6529
Foundations strengthened	423	−303	1139	*n.s.*	329	*n.s.*	710	*n.s.*
Walls and equipment made of water-resistant materials	1864	*n.s.*	*n.s.*	2056	350	1055	*n.s.*	*n.s.*
Floor made of water-resistant materials	*n.s.*	−6184	−8223	*n.s.*	−394	*n.s.*	−2055	*n.s.*
Raised electricity meter	−4771	−338	*n.s.*	*n.s.*	−3237	4476	−11,291	−4294
Power sockets on ground floor heightened	−4738	303	−3906	−1373	−1599	−3385	−2411	*n.s.*
Anti-backflow valves	−72	*n.s.*	*n.s.*	−9052	*n.s.*	235	−403	*n.s.*
Elevated boiler	*n.s.*	275	2469	−9481	*n.s.*	223	*n.s.*	*n.s.*
Sandbags	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	−464	*n.s.*	*n.s.*
Raised electrical appliances	*n.a.*	*n.a.*	*n.a.*	*n.a.*	−1379	−1475	*n.s.*	*n.s*
Furniture adapted	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.s.*	1042	−523	*n.s.*

Notes: *n.s.* not significant ($p < 0.1$); *n.a.* = not applicable.
[a] The effect of this measure on the damage is calculated by comparing for each sample the damage to an average home using the average water height reduction during a flood (which is significant with the Mann–Whitney *U* test), when the measure is implemented and when the measure is not implemented.

Table 6
Flood damage avoided to buildings and to home contents over the life-time of the mitigation measures.

Measures (estimated lifetime)\region	Flood probability of 1/1 yr				Flood probability of 1/10 yrs				Flood probability of 1/50 yrs				Costs of the measures (in Euros) (ABI, 2003; Aerts et al., 2013; FEMA, 2009)
	All regions	Ardennes	Var	West	All regions	Ardennes	Var	West	All regions	Ardennes	Var	West	
Benefits to buildings (in Euros)													
Elevated ground floor (50 yrs)	99,818	33,655	109,620		9982	3365	10,962		1996	673	2192		25,000–69,000 for existing buildings, 1900 to 9800 for new buildings
Floor made of water-resistant materials (50 yrs)		122,208	162,503			12,221	16,250			2444	3250		800–7250
Raised electricity meter (50 yrs)	94,285	6680			9428	668			1886	134			1750
Raised power sockets (50 yrs)	93,632		77,190	27,133	9363		7719	2713	1873		1544	543	800–1300
Anti-backflow valves (10 yrs)	570			71,626	57			7163	11			1433	800–1750
Elevated boiler (50 yrs)				187,364				18,736				3747	1200
Benefits to home contents (in Euros)													
Elevated ground floor (50 yrs)	59,187	74,661	20,770	129,026	5919	7466	2077	12,903	1184	1493	415	2581	25,000–69,000 for existing buildings, 1900 to 9800 for new buildings
Floor made of water-resistant materials (50 yrs)	7786		40,611		779		4061		156		812		800–7250
Raised electricity meter (50 yrs)	63,970		223,133	84,858	6397		22,313	8486	1279		4463	1697	1750
Raised power sockets (50 yrs)	31,599	66,894	47,646		3160	6689	4765		632	1338	953		800–1300
Anti-backflow valves (10 yrs)			3189				319				64		800–1750
Sandbags or water barriers (50 yrs)		9170				917				183			265–845 for wood or metal barriers
Raised electrical appliances (50 yrs)	27,252	29,149			2725	2915			545	583			700
Furniture adapted (10 yrs)			4138				414				83		*No reference found*

Table 7
Summary of the cost–benefit analysis of the mitigation measures for different flood probabilities.

Measures\flood probability	1/1 yr	1/10 yrs	1/50 yrs
Elevated ground floor (50 yrs)	In existing homes: ++ for buildings, +− for contents; During construction: ++	In existing homes: −−; During construction: ++ for buildings, +− for contents	In existing homes: −−; During construction: +− for buildings, −− for contents
Foundations strengthened (50 years)	−−	−−	−−
Walls and equipment made of water-resistant materials (50 years)	−−	−−	−−
Floor made of water-resistant materials (50 yrs)	++	++ for buildings +− for contents	+−
Raised electricity meter (50 yrs)	++	+− for buildings ++ for contents	+−
Raised power sockets (50 yrs)	++	++	+−
Anti-backflow valves (10 yrs)	+− for buildings ++ for contents	+− for buildings −− for contents	+− for buildings −− for contents
Elevated boiler (50 yrs)	++	++	++
Sandbags or water barriers (50 yrs)	++	++	−−
Raised electrical appliances (50 yrs)	++	++	−−
Furniture adapted (10 yrs)[a]	++	+−	−−

Notes: ++: cost-effective; +−: moderately cost-effective; −−: not cost-effective.
[a] The estimation of the cost-effectiveness of this measure is based on expert judgment.

using water-resistant materials significantly reduces damage in the West, where mainly coastal floods occur. These results imply the greater corrosiveness of saltwater compared with freshwater.

3.3. Assessment of the effectiveness and cost-effectiveness of the mitigation measures in reducing flood damage

Using the methodology described in Section 2.3 we calculated the average damage avoided per flood by effective mitigation measures (Table 5), the flood damage avoided over the life-time of a flood damage mitigation measure and their costs (Table 6), which are inputs for the cost–benefit analysis (Table 7).

Table 5 shows that the average effects of the mitigation measures vary considerably between regions and types of damage. Some measures, such as elevating the ground floor, appear to be very effective in reducing the damage to both the buildings and the home contents. Flood damage can be reduced by €1000 to up to €6500. Using water-resistant materials can reduce damage to buildings up to about €8200. Raising the electricity meter reduces the damage to buildings by €4700, and the damage to home contents up to over €11,000. Raising the power sockets also significantly reduces the damage by up to €4700. Anti-backflow valves and elevating the boiler also substantially reduce the flood damage to buildings in the West up to about €9000, although these two measures have mixed results depending on the regions. Installing sandbags or other water barriers does not result in large damage savings, except for a small reduction in flood damage to home contents in the Ardennes. An explanation for the limited effectiveness of sandbags may be that they can overtop or collapse during high flood depths, which can cause substantial damage as other studies have shown (FEMA, 2009; Kreibich et al., 2011, 2012). This finding may also reflect the strong correlation between the implementation of this measure with the variable living close by the source of flooding, which cannot be accounted for by an interaction variable because of the aforementioned problems with multi-collinearity. Raising electrical appliances reduced the damage to home contents in the overall sample and in the Ardennes by almost €1500.

The results of the discounted life-time benefits of implementing effective flood damage mitigation measures are shown in Table 6 along with estimated total costs of the measures. These cost values are approximations based on unit costs from US and British studies, which means that they provide a rough approximation of the cost of the mitigation measures. Most of these values are provided as ranges of costs because the actual costs of the implementation of the measures can vary depending on various factors such as the age, the state, and the type of homes in which the measure is installed. Following Table 6, a summary table (Table 7) provides the results of a qualitative ranking of the cost-effectiveness of the measures. Such a qualitative instead of a quantitative analysis is in order here, because the implied precision of the latter may be deceptive given the uncertainty of our cost-estimates. Measures are categorized as being cost-effective (++) if more than 75 per cent of the BC ratios are above 1, moderately cost-effective (+−) if between 25 per cent and 75 per cent of the BC ratios are above 1, and not cost-effective (−−) if less than 25 per cent of the BC ratios are above 1.

Two of the eleven measures considered in this study, namely strengthening the foundations and using water-resistant materials for the walls, are not cost-effective. Installing sandbags, raising electrical appliances, and adapting the furniture are measures which can be cost-effective, but mostly in areas where flood probabilities are high. The reason is that life-time damage savings are high when floods occur frequently. Installing anti-backflow valves has mixed results. It can be cost-effective for damage to buildings even for low probability floods, but for damage to home contents it is a measure that is only cost-effective in areas with very high flood probabilities (1/1 yr). A few measures are cost-effective, such as elevating the ground floor. Even when flood probabilities are low, discounted life-time damage savings of elevation are substantial (about €20,000). It should be noted that elevation of homes is especially cost-effective when buildings are newly constructed, but not for existing buildings since elevating the latter is more expensive (Aerts et al., 2014). Using water-resistant materials for the floor, raising the electricity meter, the power sockets, and the boiler in the West are three measures, which are cost-effective for high-probability floods, and can be cost-effective for low-probability floods. These are relatively low-cost measures that can save large amounts of money during a flood (Table 6).

4. Discussion of the results and main conclusions

Flood-proofing of homes has often been proposed as an effective strategy to limit future increases in flood damage that may be caused by climate change. An obstacle for the design of policies to flood-proof buildings is that few empirical studies have estimated the effectiveness of household flood damage mitigation measures. As a result, little is known about what specific measures are effective in reducing losses during floods, and about how much damage can be avoided by implementing them. Moreover, few studies have examined the cost-effectiveness of installing flood damage mitigation measures, while such information can be important for prioritizing measures that have a good economic return.

A novelty of our study is the application of regressions models to estimate the independent effect of flood damage avoided for specific mitigation measures in regions with different flood characteristics, and the use of these estimates in an analysis that examines the cost-effectiveness of these measures. To the best of our knowledge this the first study that examines the (cost-)effectiveness of flood risk mitigation measures in France. Our methodological approach of using survey data about individual flood preparation activities and flood damage experience and of estimating reduced flood damage and costs and benefits of flood risk mitigation is, in principle, generic and transferable to other regions.

Previous studies have assessed the effectiveness of private flood damage mitigation measures with a simple comparison of means of flood damage suffered by people who have, or have not, implemented such measures. The application of regression models in this study to estimate damage savings by mitigation allows for controlling for the effects of the water height and other variables on flood damage, and, therefore, can more accurately assess the independent effectiveness of specific flood damage mitigation measures. For this purpose a unique data set was collected by surveying 885 households about their flood preparedness and flood experiences in three flood-prone regions in France, including 530 households who have previously been flooded in their homes. Regression models were estimated separately for the damage to buildings and the damage to home contents, and for the different regions in which the survey was conducted. To control for the effectiveness of the measures in reducing the damage, variables of the mitigation measures were included in the models, along with variables of the water depth and the characteristics of the home. Moreover, the survey was conducted such that it allowed for evaluating individual mitigation measures rather than a few groups of measures. It was, therefore, possible to assess the effectiveness and cost-effectiveness of 11 specific flood damage mitigation measures. Four main conclusions can be drawn from this study.

First, using regression analysis results in improved estimates of the effectiveness of mitigation measures compared with a comparison of mean damage used by earlier studies. For example, it is clear from the results that the water depth and the distance to the source of the flood are important variables that explain a large part of the variations in the recorded flood damage, and in several instances interact significantly with the effects of the mitigation measures. Moreover, the regression models show that a variety of mitigation measures have a significant influence on flood damage. When the effects of these variables on the damage are not controlled for, then the damage reduced by a specific mitigation measures may not correspond to the independent effect the measure has on the damage. When the results in Tables 2 and 5 are compared, it is apparent that the mean damage always results in greater damage avoidance than the independent effects of damage saved per measure resulting from the regression models.

Second, this study has provided empirical insights showing that some mitigation measures can substantially reduce flood damage. This is important information for the design of flood risk management policy, and shows that stimulating the adoption of flood damage mitigation measures, for example through building codes, can provide substantial complementary benefits of reduced flood risk to traditional flood protection infrastructure.

Third, the effectiveness of the mitigation measures is very regional-dependent. This can be explained by the different characteristics of the flood hazard in our sample areas that experience either slow onset river flooding (the Ardennes) or more rapid flash flooding (the Var) or coastal flooding (the West). Overall these findings imply that care should be taken with designing flood risk management policies, such as building codes, since measures that work well in one region may not be effective in another region that faces a different kind of flood hazard. Nevertheless, some measures appear to be effective in all of the regions considered here.

Fourth, the cost-efficiency of the flood damage mitigation measures depends strongly on the flood probability faced by households. Therefore there is a high degree of variation in the efficiency and effectiveness of the measures in each region, depending on its flood hazard characteristics. A high flood frequency is required before costly investments in the flood-proofing of homes pays off. This suggests that strategies of reducing flood risks through flood-proofing of buildings become more economically attractive if climate change increases flood frequencies, as has been projected for many regions worldwide (IPCC, 2012). Most of the flood damage mitigation measures are cost-effective in areas where flood probabilities are larger than 1/10 year. Nevertheless, some measures have been identified that can be cost-effective in areas with lower flood frequencies (1-in-50 year flood probability).

It can be concluded that policy makers should not only advise households to implement mitigation measures, but they should also provide advice on which measures to install. The provision of such information could ensure that households take measures that are effective and efficient in the region in which they live and for the type and frequency of floods they face. Flood management strategies which focus on the household level should be fitted to the local conditions. Further research on the costs and the (cost-)effectiveness of individual mitigation measures in regions subject to different types of floods could provide improved knowledge to policy makers around the world.

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