Civil Engineering Works versus Self-protection measures for the mitigation of floods economic risk. A case study from a new classification criterion for Cost-Benefit Analysis.

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ABSTRACT

The application of classical cost-benefit analysis to flood risk mitigation measures can be improved by incorporating new comparative parameters, such as the risk-cost ratio, which is defined here for the first time. In addition, applying these analyses not only to the typical public structural measures (dams, dredging, flood storage reservoirs, transverse drainage works), but also to non-structural measures and self-protection (improving housing resistance to flooding, insurance policies), broadens the range of active risk management options. Last two categories are measures with lower initial investment (thus reducing costs) and visual and environmental impact, making them compatible with the EU Water Framework Directives and flood risk management. All these analyses of economic flood risk have been tested in a small Spanish village in the central Iberian Peninsula. For different flooding scenarios, new proposed RCR criterion allow us a rapid and effective quantification of the efficiency of each of the measures, allowing the ordered classification of the same; as well as the weighting of the results according to the particular needs of the decision makers (prioritizing well the reduction of damages, or the necessary economic investment). Thus, the RCR reveals itself as a powerful tool for flood risk management.

Keywords: Cost-Benefit Analysis; Flood risk; Risk-Cost criterion; Self-protection measures; Spain.

1. INTRODUCTION

According to the results presented by the Centre for Research on the Epidemiology of Disasters (CRED, 1988), floods are the natural hazard which generate the greatest financial losses worldwide, with the exception of years when a catastrophic event occurs, such as a major earthquake or exceptional marine storm. This scenario has led politicians over recent decades to prefer the implementation of structural and non-structural defences in an attempt to mitigate the increasing risk of river flooding. Since the early 21st century the focus has shifted from flood protection to a more ambitious flood risk management approach (Plate, 2002; Schanze, 2006; Loucks et al. 2008), upon the recognising that is necessary a wide portfolio of structural and non-structural options to prevent, defend, prepare, mitigate, respond and recover from flood events; with the intention of minimising both the likelihood and consequences of flood events. Along with this evolution and since the mid-20th century, as for example in the US National Flood Insurance Program (NFIP), flood insurance policies have been actively promoted (Platt, 1999; FEMA, 2004), with a different focus in each country (Swiss Re, 1998; Barraque, 2000; Graff, 2001; Prettenthaler and Vetters, 2003; von Ungern-Sternberg, 2004).

Within the flood risk management approach, while recognising that it is impossible in financial and technical terms to achieve zero flood risk, it is deemed essential to maximise risk reduction through selecting the most efficient actions. In response to this perceived need, a cost-benefit analysis (CBA; Prest and Turvey, 1965) of different risk mitigation measures is often used (Tung, 2002), to analyse the advantages and disadvantages of each and so maximize the overall benefit (Kopp et al, 1997; Rackwitz et al, 2005; Zhu and Lund, 2009).

Nevertheless, according to Brouwer and Pearce (2005), although the lack of information on profitability (net benefit) of the mitigation measures has not prevented the application of CBA, this factor has often made it more difficult to use in flood management programs. Therefore, an appropriate application of CBA must always be based on a precise estimate of economic losses from flooding, to ensure maximum confidence in the decisions adopted. The vulnerability of the elements exposed (in this case the quantification of the direct tangible damage) is usually approached by using magnitude-damage functions (Merz et al., 2010), using the depth variable to define the flood magnitude; although in other cases different variables have been used, such as flow velocity, duration or a combination of variables. Within the vulnerability models, there are those who consider only the damage to the content (e.g. Garrote et al., 2016), the content and structure (e.g. USACE, 2000 and 2003; Ross, 2003). To these models, which consider housing as a unit of measure, it is necessary to add those that consider the damage to a lower level (e.g. Kelman, 2002; Mazorana et al., 2014; Custer and Nishijima, 2015), Analyzing the response of the different components in its interaction with the water and the intensity of the flooding process.

CBA have been used in different places and at different working scales for their capacity to produce results not skewed by external factors (Dawson et al., 2011; Broekx et al., 2011; Ballesteros et al., 2013; Kind, 2014; Penning-Rowsell et al., 2014; Kousky and Walls, 2014; de Moel et al., 2014; Feuillette et al., 2016; Ocio et al., 2016; Li et al., 2016; Dong and Frangopol, 2017; Ward et al., 2017; Arrighi et al., 2018). The above cases reveal the great potential of this type of analysis. However, to develop a CBA it is essential to make a correct estimation of the damages, a process which involves many analytical techniques, leading to different uncertainties in the results obtained. In addition, there is no general consensus on the main source of error or uncertainty in the results: this may be attributed to analyses of flow frequency, to hydraulic models, to damage models or to the study scale (Messner et al. 2007; Apel et al. 2009; Merz et al. 2009; Eleuterio et al. 2014; Garrote et al. 2016); or even to the benefit-cost ratio (BCR) and marginal cost (MC) criteria used to select the optimal mitigation measure (Špačková and Straub, 2015). To carry out a CBA correctly, therefore, it is essential to consider, and attempt to reduce as far as possible, all these uncertainties in the damage estimate (de Blois and Wind, 1995; Merz et al. 2009).

About CBA criteria, there are three key metrics of economic efficiency (Brent, 1998): the benefit-to-cost ratio (BCR) or cost-benefit ratio (CBR), the internal rate of return (IRR), and net present value (NPV), which in most circumstances are equivalent (Kull et al., 2013). Shreve and Kellman (2014) highlight the BCR, as it is commonly used to communicate with decision makers. Nevertheless, the use of the BCR (or CBR) presents certain limitations (principally in its formulation as BCR_{mean}, which is calculated as the total benefits over total cost associated with each project), by not taking into consideration the residual risk after the implementation of the defense measures. Other formulations (like the BCR_{inc}, that is when the mitigation measure cost are used as primary criterion for measure consideration. This approach is sometimes called marginal BCR, and should be used for selection from mutually exclusive projects) solve partly this problem, but they present major difficulties at the time of comparing all the considered measurements between them, generating a classification of economic efficiency of defense measures. And these limitations can complicate decision makers' performance, limiting the advantages of applying CBA to flood risk management.

Taking all the above into account, in this present study CBA is proposed to choose the most effective risk mitigation measure in small piedmont town. As a criterion for classification of the efficiency of the measures will be used the CBR, from the two formulations previously raised. Also, in order to overcome the limitations of the method, a new approach is proposed for BCR, which takes into account both the residual risk and the costs of implementing the defense measures. This new proposed formulation, named risk-cost ratio (RCR), it preserves the advantages associated with the CBA-BCR, overcoming the limitations shown by previous approaches.

The choice of a small piedmont town for the case study is precisely because of the dilemma which may arise in this situation: whether or not it is viable in economic terms to propose the construction of costly structural measures for flood defence, to protect the small number of people and properties involved. In addition, the geographical location of these towns significantly defines the type of flash floods, with a very pronounced maximum flood peak and a limited concentration time, making other measures such as meteorological forecasting or early warning non-viable.

The present work constitutes the first study of CBA carried out in Spain that considers both measures of a structural type, as non-structural type. Including among the mentioned, self-protection and insurance policies measures against floods. The analysis highlights the utility and cost-effectiveness of self-protection measures against floods for small towns, which can be quickly observed from the results of the new proposed CBR, the RCR index. Furthermore, combination of self-protection and insurance policies improve the results of any more expensive structural mitigation measure, and should be considered as the most suitable scenario for flood risk mitigation in small towns.

2. STUDY AREA

The village of Pajares de Pedraza (Segovia, Spain) is located on the floodplain of the Cega river (Figure 1). Repeated flash flood events occur in this small village because of its upstream catchment area, mountainous character and impermeable lithology, which reduce concentration time to just a few hours. River overbank flow has frequently caused flooding and damage to homes and rural properties, most notably in 1927, 1991, 1996, 2001, 2013 and 2014 (peak flow and associated T-year return period of these floods are shown in Table I). The spatial distribution of rural and urban areas is asymmetric, with a rural area of 6.1 km^2, and an urban area of only 0.2 km^2.

Flood Date	Peak Flow ($m^3 s^{-1}$)	T-year Return period
1948	112.6	< 50 year
1991	122.2	≈ 50 year
1996	147.3	≈ 100 year
2001	57.8	≈ 5 year
2013	80.3	≈ 10 year
2014	51.9	< 5 year

Table I

It has a population of only 14 people during autumn and winter; but it can multiply by 20 in Eastern Holidays, July and August, reaching more than 300-350 people, because of rural tourism. The predominant typology of houses is one floor without stores, or two floors. Most of the permanent inhabitants are retired and ancient people (more than 60 years old), high rates of social dependency (chronic illness), with a low perception of flood risk even they have suffered at least two or three catastrophic flood events during their lives.

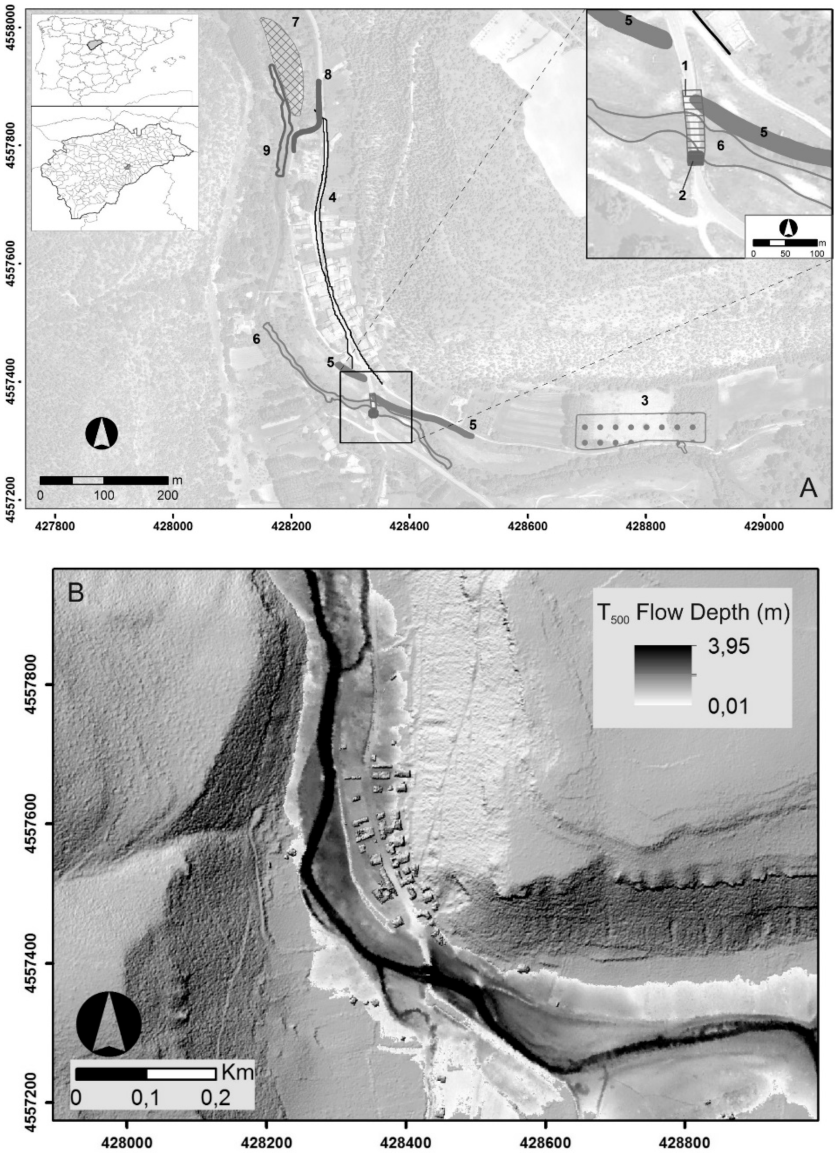


Figure 1

Previous studies of floods in Pajares de Pedraza have examined the flood hazard using dendrogeomorphological techniques (Ballesteros et al., 2015) and economic estimation of flood risk using ultra-detailed stage-damage functions (Garrote et al., 2016).

3. DATA SOURCES AND METHODS

A classic factorial flood risk analysis for a set of proposed mitigation measures has been applied to the village of Pajares de Pedraza. The risk analysis was focused exclusively on direct tangible impacts, i.e. on those exposed elements with a (tangible) market value and that are the (direct) result of the destruction or damage caused by an event (Merz et al., 2010). Data sources and methods (Figure 2) used were the usual for this kind of flood risk analysis, and will be explained in the following sections.

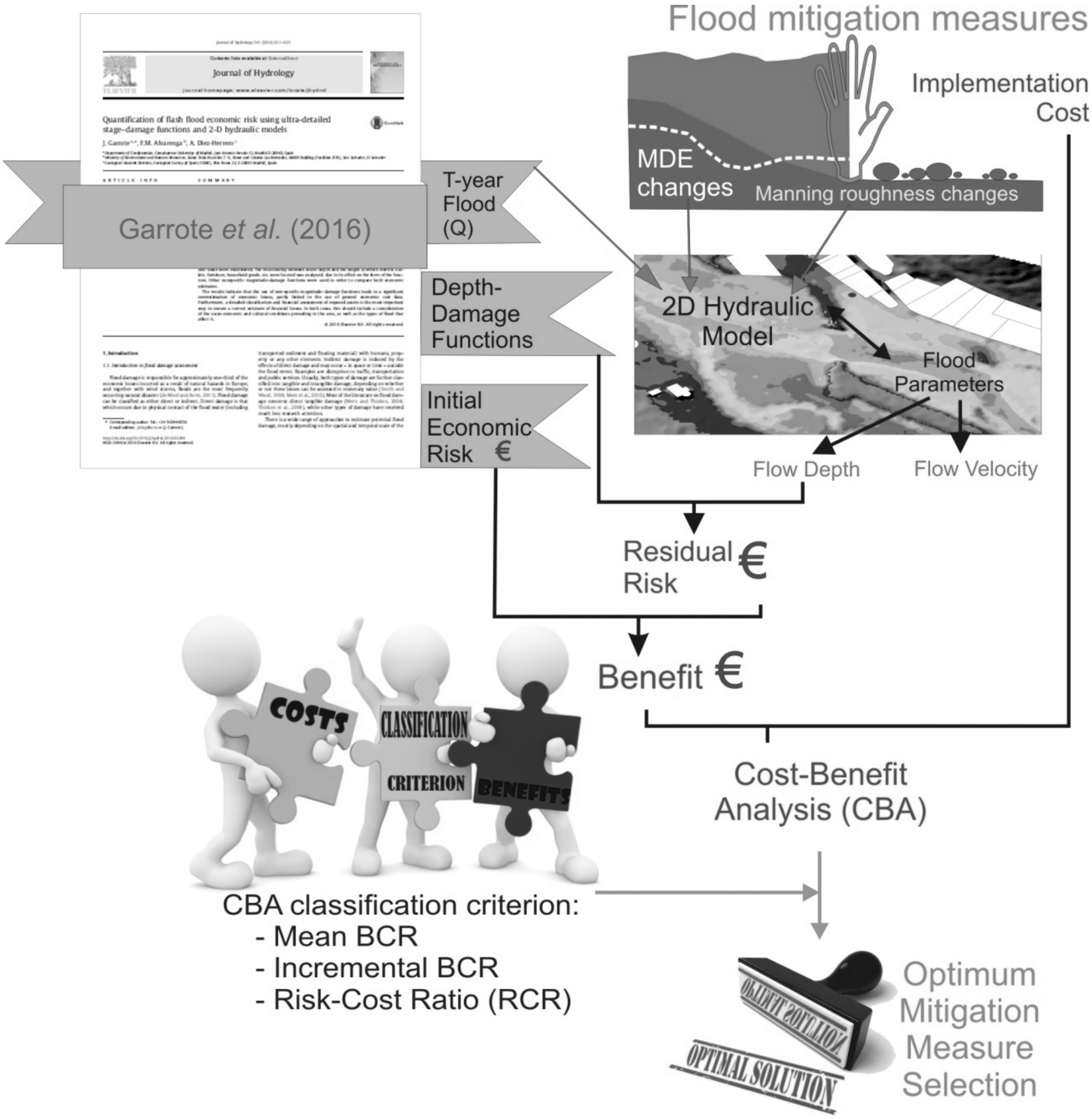


Figure 2

3.1. Data Sources

The data sources used for the flood risk analysis focus on those required for simulating the hydraulic model settings (including topography, terrain roughness, peak flows, hydraulic boundary conditions), and the damage model settings (magnitude – damage function), linked to all mitigation measures considered. Estimation of the financial costs of the implementation of each of these measures is the other main source of information needed for this study (Figure 2).

The set of mitigation measures was developed from an original hydraulic model, similar to that used by Garrote et al. (2016). In summary, the topography is provided by a 1x1 m Digital Terrain Model (DTM), generated from LiDAR data (CNIG, 2010). Manning roughness coefficient values were obtained by photo-interpretation on 0.25 m resolution orthophotos, with subsequent fieldwork for value adjustments. Peak flows (5, 25, 50, 100, and 500-year return periods) were obtained by flood frequency analysis from an annual maximum data series; using several extreme value frequency functions (GEV, LPIII…) and different parameter estimation methods (LMOM, ML…); with the GEV-ML combination like the best fit option.

The exposed elements are made up of around 80 houses, which were grouped into four categories according to two variables: number of stores and type of temporary occupancy. In such a way that the types of housing were constituted by houses of one store and continuous occupation; house of one store and discontinuous occupation; houses of more than one store and continuous occupation; and houses of more than one store and discontinuous occupation. In addition, two types of special construction were considered: churches and isolated small farmhouses.

For every housing type ultra-detailed magnitude-damage functions, developed for a single-house scale, specifically developed for Pajares de Pedraza (Garrote et al., 2016) were applied to the damage model used; the typological classification of the buildings was carried out from the official cartography and databases of the Spanish *Ministry of Finance and Public Administrations*, using several building characteristics (main residence, second home, number of floors, …).

In addition, a fieldwork campaign collected data on the dimensioning and spatial location (Figure 1) of each structural mitigation measure considered in the risk analysis. Finally, several civil engineering companies in the study area were consulted, to establish the financial cost of implementing each individual flood risk mitigation measure.

3.2. Methods

For the selection and implementation of mitigation measures, the methodology used can be summarized in the following points:

- Selection of a wide range of structural, non-structural and self-protection mitigation measures appropriate to the characteristics of the study area. The set of mitigation measures was selected in accordance with those proposed in the flood risk management plan of the Duero river basin (PGRI; Demarcación Hidrográfica del Duero, 2016), and they are shown in Table II. A third group of flood risk mitigation measures, which would encompass tasks such as the over-elevation of houses or their buy out by the Spanish government, is not considered in this study because of the conditions set out below. In the case of over-elevation of dwellings, it is considered that it is not an available approach due to the age and construction model on the study area; even considering this option as very interesting for new houses in flood risk areas (this measure is proposed and required in the new urban planning of the town, approved in 2017 and which took into account the results of the hydraulic studies carried out by the authors of this manuscript). On the other hand, the houses buy out by the Spanish government has not been considered for its high economic cost and for not being a measure with previous historical examples in Spain.

Measures			Dimensions	Roughness
Public works	Bridge (M1)		34 m length x 10 m width	0.12 to 0.04
	Concrete frame		2 m height x 3 m width x 4 m length	0.12 to 0.01
	Water drainage		1 m width x 1 m depth x 450 m length	0.013
	Flood retention basin (M2)		204 m length x 49 m width	Steady
	Felling of trees		197 m length x 44 m width	0.07 to 0.04
	Levee	Upstream	7 m base width x 1.25 m height x 226 m lenght	Steady
		Downstream (M3)	3.3 m base width x 1.5 m height x 135 m lenght	Steady
	Dredging	Upstream	1 m depth x 380 m length	Steady
		Downstream (M4)	160 m length x 0.3 m depth	Steady
	Combinations	M3+M4	-	-
		M1 + (M3+M4)	-	-
		M2 + (M3 + M4)	-	-
Self - protection	Floodgates in houses		0.77 m width x 0.65 m height	
	Insurance policies		-	

Measures description: Bridge: A new bridge with greater flow capacity, without bridge piles.
Concrete frame: Adjacent to the bridge to allow an increase in flow capacity
Water drainage: Two water drainage alongside the main road/street crossing the town of Pajares de Pedraza
Dredging: River bed dredging to increase the area of the cross section of the channel

Table II

- Detailed manual corrections in the DTM cell elevation values were carried out to simulate conditions of implementing each structural risk mitigation measure. The dimensions and spatial location of structural mitigation measures can be seen in Table II and Figure 1.
- The non-structural mitigation measures were implemented by modifying surface terrain roughness coefficient values (Arcement and Schneider, 1989). This modification aims to simulate the clearing of river bed and riparian vegetation in two locations, upstream and downstream of the Pajares de Pedraza village.
- 2D hydraulic modeling of 50, 100, and 500-year return period peak flows (Iber software; Blade et al., 2014) for each flood risk mitigation measure scenario considered. Return periods used here are those which caused the greatest economic losses in Pajares de Pedraza (Garrote et al., 2016) for the pre-mitigation risk scenario.

- No changes were needed in the hydraulic model to simulate the self-protection measures considered, because the effect of these measures is a change in the damage model. Thus, the hydraulic model settings were the same as used by Garrote et al. (2016), which were taken as the starting point of the analysis.

3.2.1 Cost-Benefit Analysis (CBA)

Cost-benefit analysis is a financial tool that measures the relationship between the costs and benefits associated with an investment project to assess its profitability (FEMA, 2007; Shreve and Kelman, 2014). In this study, this tool has been used to calculate profitability resulting from the implementation of the proposed risk mitigation measures, presented in the previous section.

The cost of implementing each mitigation measure was estimated after consultation with civil engineering companies. In the case of the structural measures, these costs are derived from the work and materials needed to implement the measure (not including financial costs). The annual maintenance costs were estimated as being about 2% of the construction cost (as proposed by Arrighi et al., 2018). For non-structural mitigation measures the costs will be related to clearing the river bed and riparian vegetation. The costs of the self-protection measures are for the materials and installation of removable door barriers or the cost of a flood insurance policy; in both cases, these are estimated for each building in Pajares de Pedraza.

In the specific case of the self-protection measure involving taking out insurance to cover flood damage, the methodological approach differs from the other mitigation measures. In Spain, all housing insurance policies cover this eventuality with the *Consorcio de Compensación de Seguros* (CCS), i.e. the Spanish official public insurance consortium. In this case, first the pre-mitigation measure economic losses were considered, to estimate the expected annual damages (EAD) until the longest return period considered (Arnell, 1989; Koks et al., 2015), in this case 500 years. EAD results were calculated both for the whole village, and for individual buildings. Then, through consultation with different insurance companies, a financial valuation was obtained for insurance policies covering EAD values for standard type housing in Pajares de Pedraza. This valuation allowed us to compute the implementation cost of this measure for the village as a whole.

As well as the financial costs, we also need to know the economic benefit linked to each mitigation measure considered. The value of this benefit is related to the difference in residual economic damages between the pre- and post-implementation scenarios for each mitigation measure. Pre- and post-implementation residual economic damage were obtained using specific, ultra-detailed, magnitude-damage functions (Garrote et al., 2016) for each building type, where flood depth (for all return periods considered) was used as the magnitude variable. These flood depth maps are one of the outputs of the 2D hydraulic modelling carried out previously.

After the financial cost and benefits (EAD value) for each mitigation measure considered had been calculated, the CBA was performed according to the classification criteria selected. First, two widely used criteria (Shreve and Kelman, 2014; Špačková and Straub, 2015) were selected: the mean Benefit-Cost Ratio (BCR_{mean}), and the incremental Benefit-Cost Ratio (BCR_{inc}). The first one allows to select from projects that are not mutually exclusive, so several projects can be implemented in parallel; against this, the second approach should be used for selection from mutually exclusive projects, that is, in situations where one selects only one project from available options. And later, a new criterion called Risk-Cost Ratio (RCR), which will be described in the following section. CBA classification criteria values were obtained for the complete time period considered (EAD value), as well as for 50, 100, and 500-year return periods single floods.

3.2.2. Risk-Cost Ratio criterion

With the use of BCR indices, situations can occur in which the value of the index is clearly optimal, and yet the implementation of the risk mitigation measure associated with that BCR value causes the residual economic damages to remain significantly high. These situations occur when a mitigation measure has small implementation costs, clearly lower than the implementation costs of the rest of the measures. In this way, a limited reduction of the post-implantation economic losses of the measure gives rise to a very good BCR index value.

On the other hand, the availability of economic funds for investment in risk mitigation measures is limited. In such a way, even when setting the scenario in which with an unlimited investment a residual risk equal to zero was obtained, this situation is not realistic. And even less when the number of goods and people to be protected is small, as it occurs in populations such as those analyzed in this study. For this reason, it is important to analyze and assess the amount of economic investment. Moreover, this analysis is directly related to cost efficiency. This cost efficiency in the field of mitigation of natural risks (specifically in the face of floods in this study) translates into maximizing the reduction of residual damages from the lowest possible economic investment. Therefore, this approach must be the starting point for any Benefit-Cost Index (BCR).

To take into account both the reduction of the economic damage linked to adopting a specific mitigation measure (residual risk), and the magnitude of the financial investment required to implement this measure, a new criterion for mitigation measure effectiveness is required.

The risk-cost ratio (RCR) is proposed as this new criterion to take these two factors into account. The financial damage reduction is considered based on the ratio of residual risk (post-mitigation scenario) to initial risk (pre-mitigation scenario) values. On the other hand, the magnitude of the financial investment is considered with the ratio of the cost of implementing each mitigation measure to the cost of the most expensive mitigation measure. The limits for each of the proposed ratios are 0 and 1, so the limits for RCR values are 0 and 2. Thus, the lowest RCR value denotes the most effective mitigation measure.

This simple approach to the assessing the effectiveness of different mitigation measures can be improved by a weighting factor giving more importance to economic risk reduction or to the financial investment required. Taking this weighting into account, the proposed formula (now with limits 0 and 1) is expressed as follows:

$$RCR = p_1 \cdot \frac{EAD_m}{EAD_i} + p_2 \cdot \frac{C_m}{C_{max}}$$

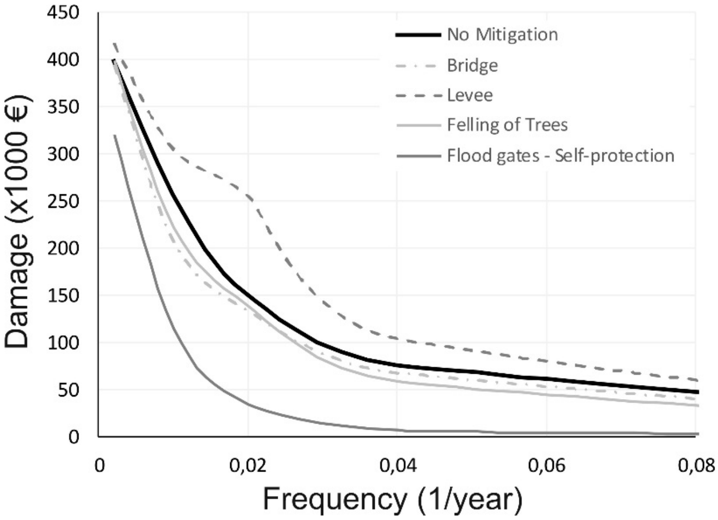
where *RCR* is Risk-Cost ratio; p_1 is 'economic risk reduction' weighting factor; p_2 is 'financial investment' weighting factor ($p_1 + p_2 = 1$); EAD_m is Residual Risk (Expected Annual Damage, or the integral of the risk curve considering mitigation measure); EAD_i is Initial Risk (Expected Annual Damage, or the integral of the risk curve considering the pre-mitigation scenario); C_m is the cost of each mitigation measure considered; and C_{max} is the cost of the most expensive mitigation measure considered. After the RCR values have been estimated for a set of mitigation measures, sorting in ascending order quickly gives a full view of its effectiveness.

As for BCR_{inc}, RCR should be mainly used for selecting mutually exclusive projects, i.e. in situations where only one mitigation measure can be selected from the available options (Irving, 1978). However, this does not exclude the possibility of considering combinations of mitigation measures in the Benefit-Cost analysis.

4. RESULTS AND DISCUSSION

4.1 Financial losses associated with each mitigation measure considered

In general, the results offered by the various mitigation measures considered are not very positive, regardless of whether the EAD values or the values associated with single floods are considered. (Figure 3 and Table III).



MITIGATION MEASURE	EAD (€)
No Mitigation	*15786,44*
Bridge	*11568,63*
Concrete Frame	*12524,63*
Flood retention basin	*13631,24*
Water drainage	*11885,62*
Levee	*17630,66*
Dredging	*10472,17*
Downstream Levee + Dredging	*8617,29*
Combination 1	*8410,51*
Combination 2	*9693,83*
Felling of Trees	*11041,57*
Floodgates - Self protection	*4138,30*

Figure 3

	Measures	Initial Losses	Cost	Residual Risk	Benefit	Average BCR	Incremental BCR	Risk - Cost Ratio
T 50	Bridge	150.765	400.000	133.530	17.235	0,04	-0,26	0,93
	Concrete frame	150.765	25.000	141.515	9.250	0,37	-0,60	0,50
	Flood retention basin	150.765	277.567	140.858	9.907	0,04	-0,43	0,81
	Water drainage	150.765	300.000	144.325	6.440	0,02	-0,40	0,84
	Levee	150.765	16.502	254.789	-104.025	-6,30	-15,48	0,87
	Dredging	150.765	8.544	131.593	19.172	2,24	1,22	0,45
	Levee + Dredging	150.765	10.043	138.914	11.851	1,18	-4,88	0,47
	Combination 1	150.765	287.611	136.392	14.373	0,05	-0,39	0,80
	Combination 2	150.765	410.043	132.291	18.474	0,05	-0,25	0,94
	Felling + Cleaning	150.765	1.608	140.039	10.726	**6,67**	-	0,47
	Floodgates in houses	150.765	30.146	35.558	115.207	3,82	**4,45**	**0,15**
T 100	Bridge	257.160	400.000	206.975	50.185	0,13	-0,25	0,89
	Concrete frame	257.160	25.000	214.379	42.781	1,71	-0,45	0,45
	Flood retention basin	257.160	277.567	225.010	32.150	0,12	-0,44	0,78
	Water drainage	257.160	300.000	201.878	55.281	0,18	-0,32	0,76
	Levee	257.160	16.502	304.218	-47.058	-2,85	-12,22	0,61
	Dredging	257.160	8.544	206.981	50.178	5,87	2,27	0,41
	Levee + Dredging	257.160	10.043	234.944	22.216	2,21	-18,65	0,47
	Combination 1	257.160	287.611	235.294	21.866	0,08	-0,47	0,81
	Combination 2	257.160	410.043	216.359	40.801	0,10	-0,27	0,92
	Felling + Cleaning	257.160	1.608	222.755	34.405	**21,40**	-	0,44
	Floodgates in houses	257.160	30.146	115.422	141.738	4,70	**4,24**	**0,26**
T 500	Bridge	400.450	400.000	393.504	6.945	0,02	-0,20	0,98
	Concrete frame	400.450	25.000	395.702	4.748	0,19	0,16	0,52
	Flood retention basin	400.450	277.567	397.620	2.829	0,01	-0,31	0,83
	Water drainage	400.450	300.000	399.475	974	0,00	-0,29	0,86
	Levee	400.450	16.502	416.137	-15.688	-0,95	-1,12	0,54
	Dredging	400.450	8.544	395.966	4.483	0,52	0,50	0,50
	Levee + Dredging	400.450	10.043	410.737	-10.288	-1,02	-1,34	0,53
	Combination 1	400.450	287.611	410.484	-10.034	-0,03	-0,35	0,86
	Combination 2	400.450	410.043	399.586	863	0,00	-0,21	1,00
	Felling + Cleaning	400.450	1.608	399.472	978	0,61	-	0,50
	Floodgates in houses	400.450	30.146	320.794	79.655	**2,64**	**2,76**	**0,44**

Table III

None of the mitigation measures with the highest implementation costs (bridge, pipelines, flood storage reservoirs, or combinations including these measures), offers the best results in terms of reducing tangible direct flood damage. Even some of these measures, such as the levee upstream of the population, cause negative effects on the direct economic damages due to floods (Figure 3). In this particular case, it is possible that a poor design of the levee conditions these results to a certain extent. However, due to the geographical complexity of the area, a more accurate design of the levee would require modifications in other structures such as the bridge over the river, or the location of a dirt road access to agricultural parcels.

Due to the not too positive results obtained from the combination of mitigation measures (combination 1 and 2), it was not proceeded to analyse all the possible combinations of mitigation measures in search of the one that provided the most optimal results. Instead of this approach, we opted to analyse individually the effects of each mitigation measure, seeking to contrast the effect of structural measures against non-structural measures (including in this last group the self-protection and insurance policy). This approach is also supported by the significant difference in economic costs associated with the implementation of both kinds of measures, with the costs associated with the non-structural measures being significantly lower. All that in an environment of small towns in mid-mountain areas.

The best results in terms of risk reduction are obtained with self-defence measures protecting access to buildings (Figure 3). Since implementing these measures did not involve new hydraulic simulations, the impact of tangible direct damages associated with floods with lower return periods was analysed (Figure 4), as these floods, despite causing minor economic damage, can have significant impact on homeowners due to their recurrence. These values exceed the 75% reduction for return periods of up to 50 years;

are reduced by around 50% for the 100-year return period, and finally fall to 20% for the maximum 500-year return period considered.

The self-protection measures provide a significant reduction in the number of houses affected (Fig ~~3A~~4A) and the total amount of economic damage caused in the whole town (Fig ~~3B~~ 4B upper). The same pattern of economic loss reduction can be observed when we consider only the houses that are affected by flooding in the scenario without mitigation measures (Fig ~~3B~~ 4B lower). In such a way that those houses that are still affected by the floods in spite of the self-protection measures (Fig ~~3B~~ 4B middle) can be considered as the worse located house, and where the economic damages will be maximum in any scenario considered.

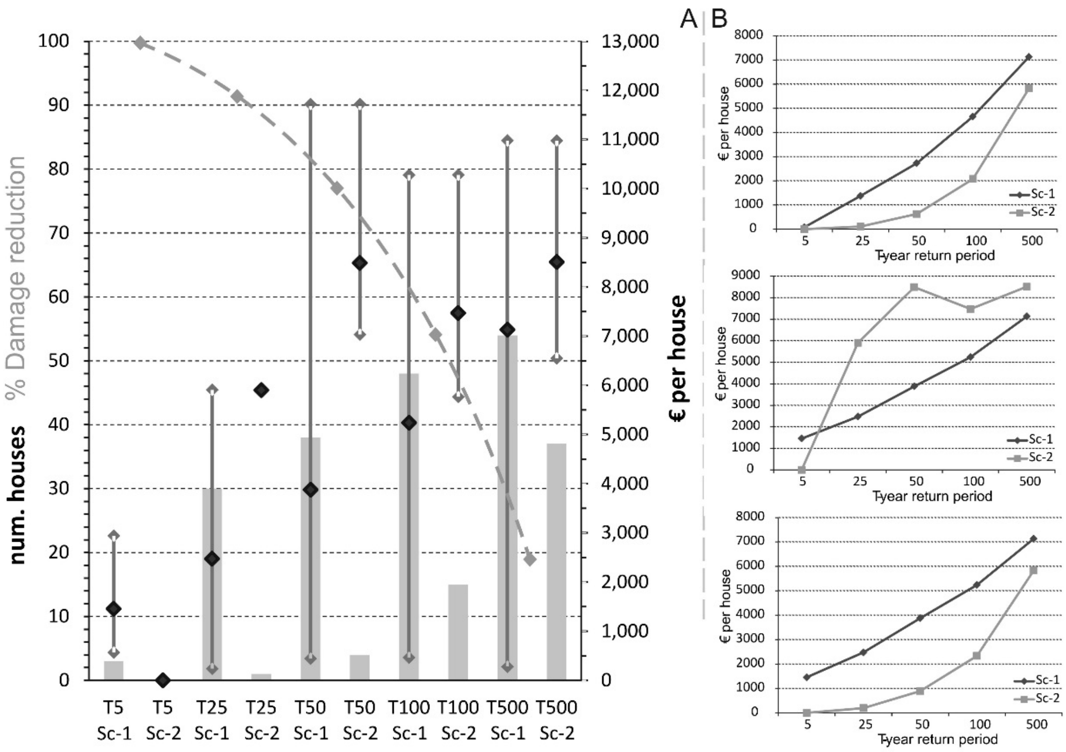


Figure 4

4.1.1. Results obtained with insurance as a self-defence measure

As a starting point for the analysis of this mitigation measure, Expected Annual Damage (EAD) was calculated for the time interval until the maximum return period considered (500 years). The results are shown in Figure 5. For the whole population, tangible direct damages amount to approximately €13,500 per year, resulting in damage per household of around €175 per year.

The cost of implementing this measure for the whole population would be around €9,300 considering only the households affected in the hydraulic model for the 500-year return period. The cost of this implementation rises to €11,200 if all homes in the village are considered. These implementation costs have been estimated based on standard housing with area 100 m^2.

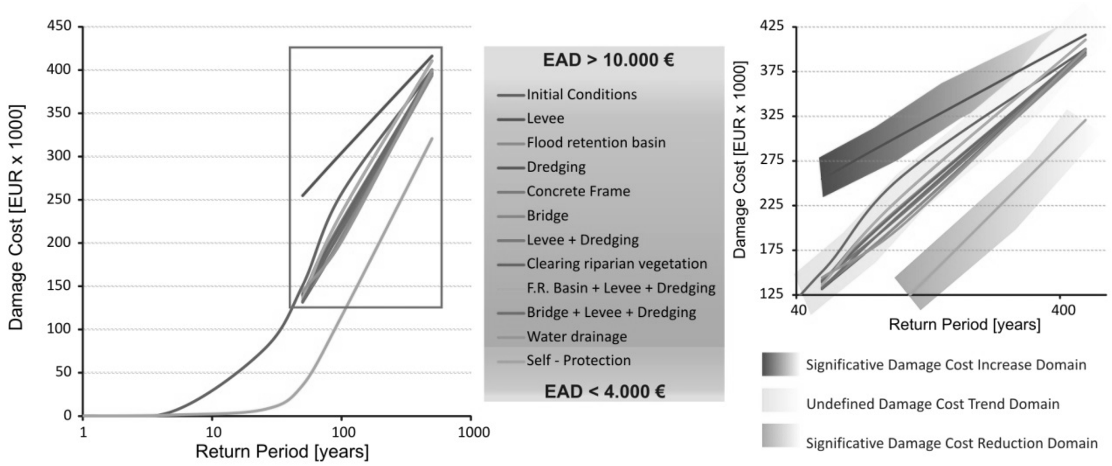


Figure 5

Due to the particular characteristics of house insurance in Spain, an insurance policy cannot be contracted solely and exclusively covering flood risk. Thus, the insurance premium covers multiple damages to the housing (both structure and contents), as well as theft. In fact, in the case of extraordinary flood damage it is not the insurance company which has to bear the costs of claims, but instead the CCS, financed by a small percentage of insurance premiums obtained from all insurance policies contracted in Spain.

The analysis carried out shows (Table III) that there is no direct relationship between financial investment in a mitigation measure and the reduction of the residual risk that this measure achieves. This situation is already observed in the results showed by other studies (e.g. Dedeurwaerdere, 1998; Khogali and Zewdu, 2009; Ballesteros et al., 2013), but nevertheless cannot be considered as certain in a generalized way. As in other cases (e.g. Khan et al., 2008) the efficiency of structural measures is shown higher. Shreve and Kelman (2014) make a compilation of studies on the effectiveness of mitigation measures whose results clearly highlight this variability.

The study shows that for small populations in piedmont areas with low population density, self-defence measures are the most effective to reduce residual flood risk (Figure 5). The efficiency of these self-defence measures is independent of the return period considered (Figure 4). The efficiency shown by self-protection measures are consistent with those shown by Kreibich and Thieken (2009), Bubeck et al. (2012), or Poussin et al. (2015). Further, the reduction of economic losses (%) can be considered similar to those already mentioned by other authors (e.g. Kreibich et al., 2005; Kreibich and Thieken, 2009), taking into account the magnitude of the flood considered in each case.

Given that the different defence measures considered are shown to be unable to reduce the residual risk to zero, insurance covering flood damage is postulated as a different approach to the treatment of tangible direct damages. The decision to insure does not imply a reduction in flood damage, but rather another way to deal with its impact. Thus, this study shows how in this type of populations (with their socio-economic particularities) taking out an insurance policy with a premium under €150 per year/per household, would allow homeowners to claim compensation for damages caused by flooding with a return period of up to 500 years.

However, it must be taken into account that the efficiency of such measures, as indicated by Thieken et al. (2006), depends on the level of awareness of the homeowners, which in turn will partly be determined by the involvement of insurance companies and the relevant public bodies in promoting this type of measure.

4.2. Cost-Benefit analysis

The suitability of the different mitigation measures considered in the Cost-Benefit analysis can be determined from several classification criteria. The approach used in this paper is the mean Benefit-Cost Ratio (BCR_{mean}; Rose et al. 2007), the incremental Benefit-Cost Ratio (BCR_{inc}; e.g.: Lee and Jones, 2004 or Špačková and Straub, 2015); and the new proposed criteria: the Risk- Cost Ratio.

The results obtained using the BCR_{mean} method (Table III) show that non-structural measures within a general action plan (clearing riparian vegetation) would be the optimal choice to reduce the direct tangible damages caused by floods in Pajares de Pedraza. For the 500-year period, the longest return period analysed, there is only one measure with a ratio value greater than 1: the self -protection measure consisting of flood barriers at the main entrance to properties.

On the other hand, the BCR_{mean} ratio results indicate that the most common structural measures within the general action scope (bridge, flood storage reservoir, levee and water drainage channels) as well as the two proposed combinations, they are not the most economically viable options in any of the return periods considered.

Taking into account the analysis of the different risk mitigation measures, the most appropriate method used is BCR_{inc}. This is because the optimal mitigation measure choice excludes the rest of the choices (Irvin, 1978; Hendrickson and Matthews, 2011; Špačková and Straub, 2015). The values obtained for BCR_{inc} vary considerably compared with previous results, as they are homogeneous, independently of the return period considered. Following this method, the best option is the self-protection measure that consists of installing flood barriers at the main entrance to properties.

According to the results (Table III) achieved in the BCR_{inc} (considering the measures used as a reference), the dredging of the river channel would be the second reference measure for 50 and 100-year return periods, while for the 500-year return period the second reference measure would be the felling and clearing of riverbank vegetation. This option is the most economical one and, consequently, it would be the standard reference for that return period.

For economists, the problem of choosing between mutually exclusive projects for flood mitigation can be solved by choose the project with the highest net present value (or *NPV*) which equals the *PV* of project benefits minus the *PV* of costs. Where there is risk, if the decision makers believe they should behave as if risk neutral, then the economists consider the correct approach is the same except that one should compute de *expected NPV*. However, the *expected NPV* applied to the analysis of mitigation measures against T-year return periods floods has not given satisfactory results, as shown in Table IV. In the opinion of the authors, the index gives great importance to the cost of the mitigation measure, downplaying the efficiency of the measure. As can be seen in Table IV, for a hypothetical mitigation measure that eliminates the residual risk, the cost of this measure will continue to condition the efficiency that the *expected NPV* to grant it. Therefore, it does not seem the most suitable index for situations like those studied in the present assessment.

	Measures	Initial Losses	Cost	Residual Risk	Benefit	Expected NPV
T 50	Bridge	150,765	400,000	133,530	17,235	-395075.81
	Concrete frame	150,765	25,000	141,515	9,250	-22357.27
	Flood retention basin	150,765	277,567	140,858	9,907	-274736.56
	Dredging	150,765	8,544	131,593	19,172	-3066.19
	Felling + Cleaning	150,765	1,608	140,039	10,726	**1456.46**
	Floodgates in houses	150,765	30,146	35,558	115,207	2769.75
	Hypothetical mitigation measure	150,765	150,000	0	150,765	-106924.30
T 100	Bridge	257,160	400,000	206,975	50,185	-392830.73
	Concrete frame	257,160	25,000	214,379	42,781	-18888.44
	Flood retention basin	257,160	277,567	225,010	32,150	-272974.20
	Dredging	257,160	8,544	206,981	50,178	-1375.68
	Felling + Cleaning	257,160	1,608	222,755	34,405	**3307.02**
	Floodgates in houses	257,160	30,146	115,422	141,738	-9898.09
	Hypothetical mitigation measure	257,160	150,000	0	257,160	-113262.86
T 500	Bridge	400,450	400,000	393,504	6,945	-399801.56
	Concrete frame	400,450	25,000	395,702	4,748	-24864.36
	Flood retention basin	400,450	277,567	397,620	2,829	-277486.16
	Dredging	400,450	8,544	395,966	4,483	-8415.90
	Felling + Cleaning	400,450	1,608	399,472	978	**-1580.06**
	Floodgates in houses	400,450	30,146	320,794	79,655	-27870.53
	Hypothetical mitigation measure	400,450	150,000	0	400,450	-138558.57

Table IV

Finally, using the new CBA classification criteria (RCR) proposed here, results are usually similar to BCR_{inc} values (Table III). In any return period considered, the self-protection measure consisting of the installation of flood barriers at the main entrance to properties is the optimal choice. Furthermore, the similarity to BCR_{inc} also affects the choice of the second and third preferred measures.

As the limits for this new ratio are 0 and 1 (inverse relationship between the value and the efficiency), the comparison of these results and those obtained by other authors using BCR ratios is particularly difficult. However, this point should not be a limiting factor to their use. First, because as Shreve and Kelman (2014) shown in their work, the values of BCR ratio are highly variable in general. In this respect, there are no defined thresholds establishing the suitability of a mitigation measure; beyond that, as discussed in Holub and Fuchs (2008) or Špačková and Straub (2015), the BCR value must be greater than 1 (when the benefits begin to exceed the costs), considered then the measured as efficient.

Secondly, because BCR_{mean} and BCR_{inc} values obtained in this study are within the range of values analyzed by Shreve and Kelman (2014).

Nevertheless, it is more difficult to relate the effectiveness when the mitigation measure considered is housing insurance policies. This is more complex because of the specific characteristics of these policies in Spain, which are applied by transferring responsibilities from the homeowner to the state, without this causing an effective reduction of damages. On this basis, the mitigation measure of housing insurance policies becomes the option that offers the best results because it reduces the residual risk for homeowners to zero if they have insured their personal assets, with an annual investment required of less than €15,800 for the whole village (± €205 /year/house).

It is significant that the non-structural measures (mainly self-protection ones) are most efficient than structural measures (Figure 6 and 7; both figures share the same legend). Table V shows the variation of flow depth for the whole housing location at Pajares de Pedraza for each mitigation measure and T-year return period scenario considered. Most of mitigation measure show reduction values lower than 0.1 meter, but self-protection mitigation measure shows reduction values up to 0.26 meter. This situation was already observed in the results of various previous works (Tucci and Villanueva, 1999; Dedeurwaerdere, 1998; Khogali and Zewdu, 2009), and may be directly related to the concept of integrated flood risk management (Hall et al. 2003); advocating the involvement of owner´s personal exposed assets in the risk management (Kron, 2005; Kreibich et al., 2007).

	50-year Flood	100-year Flood	500-year Flood
Concrete Frame	-0,01	-0,08	-0,01
Flood retention basin	-0,01	-0,07	-0,01
Water drainage	0,01	-0,12	-0,01
Combination C1	-0,03	-0,08	0,00
Combination C2	-0,01	-0,04	0,03
Levee	0,21	0,11	0,04
Levee + Dredging	-0,01	-0,04	0,03
Dredging	-0,03	-0,10	-0,02
New Bridge	-0,03	-0,10	-0,02
Felling of trees	-0,01	-0,08	-0,01
Self-Protection	-0,26	-0,26	-0,14

Table V

In general, the CBA use the risk or annual average loss (in the form of EAD) and not to single scenarios. So, the effectiveness of a measure for its reduction of risk is based upon the whole span of possible scenarios (i.e. probabilities), not just for one single scenario. As EAD value represent the integral of the risk curve (Figure 3) for the whole range of considered probabilities, it is not allow to define the range of probabilities where the mitigation measure is really effective. To solve this problem, may be the consideration of single scenario could be useful. In our study, the most effective mitigation measure (self-protection by floodgates) shows a high mitigation effectivity until 100-year return period floods (Table III and Figure 4), but this mitigation effectivity drops significantly for 500-year return period floods. Which it is not so clear from EAD data (Figure 3). Anyway, as shows the Table VI the most efficient mitigation measure (using EAD values) is the self-protection measure by using floodgates.

	EAD (€)	Benefit (50 year)	Cost (50 year)	BCRmean	RCR
No Mitigation	15786,4				
New Bridge	11568,6	210890	600000	0,35	0,85
Concrete Frame	12524,6	163091	50000	3,26	0,43
Flood retention basin	13631,2	107760	555134	0,19	0,77
Water drainage	11885,6	195041	600000	0,33	0,74
Levee	17630,7	-92211	33004	-2,79	0,58
Dredging	10472,2	265714	115344	2,30	0,34
Levee + Dredging	8617,3	358457	135581	2,64	0,29
Combination 1	8410,5	368797	575222	0,64	0,62
Combination 2	9693,8	304630	820086	0,37	0,81
Felling of trees	11041,6	237244	61908	3,83	0,35
Self-Protection	4138,3	582407	60293	**9,66**	**0,17**

Table VI

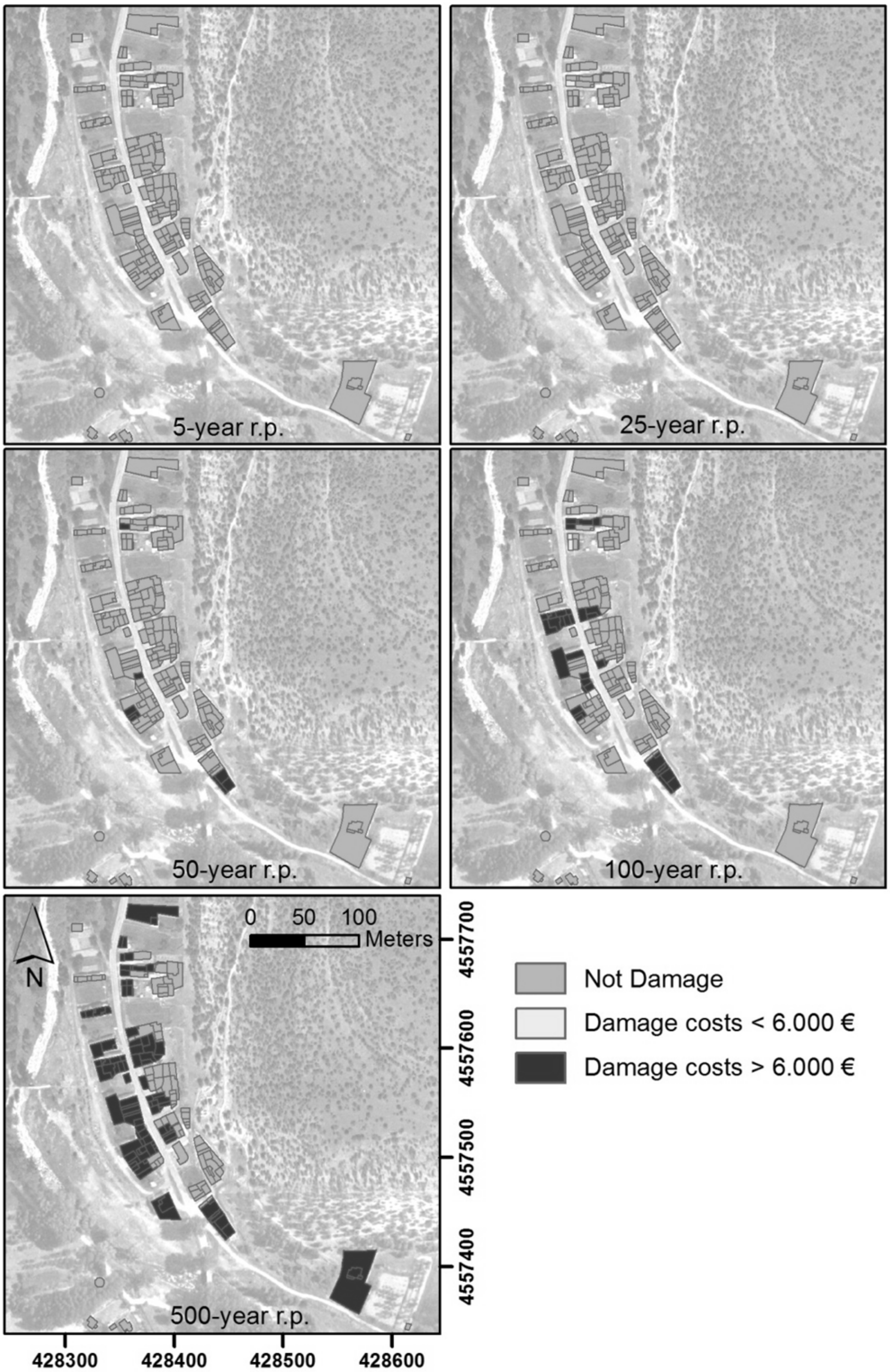


Figure 6

The RCR criterion involves a considerable improvement in the CBA because it supposes an update of the classification approach within BCR or CBR criteria, being the most appropriates or required by decision-makers, according to Shreve and Kelman (2014).

According to the results obtained (Figure 4, 5, and 6), the implementation of self-protection measures is the optimum approach in the flood risk management in mid-mountain towns. As was point out by Botzen and Van den Bergh (2008), the combination of these measures with housing insurance policies (according to the residual risk related damage) would eliminate the residual risk to homeowners and also reduce the financial cost to the entity responsible. The fact that homeowners do not take on the responsibility for the cost of housing rehabilitation, should have a positive impact on the resilience of inhabitants after flood events (Botzen and Van den Bergh, 2009).

Some aspects related to implementing self-protection measures may not initially be positive, especially those requiring homeowner involvement, in terms of both participation and financial implications. This is a key point, but as highlight Mees et al. (2016) in their analysis in Flanders (Belgium) the majority of residents consider flood protection as an almost exclusive government responsibility. Information and advice, together with tax and financial incentives on the part of insurance companies and the relevant authorities, should encourage the implementation of flood self-protection measures (Thieken et al., 2006; Botzen and Van den Bergh, 2008). However, as proposed by Thieken et al. (2006), involvement of the insurance companies may be conditioned by financial considerations, and their profit margin may be reduced because of increased expenditure due to the analysis and control of the self-protection measures implemented and the quality of materials used. In this respect, previous experiences can be cited, such as in the UK, where a quality certificate for flooding self-protection products was implemented in 2003, resulting in an important consideration taken into account by insurance companies to improve the terms of insurance policies in certified houses (Wordsworth and Bithell, 2004).

Regrettably, CBA analysis not appear to be the solution to those aspects. Neither the previously proposed ratios, nor the RCR index are capable of resolving the above-mentioned issues on their own. In fact, it does not seem easy for such questions to be solved solely from a mathematical equation. It seems more feasible for CBAs to consider self-protection measures as another option for mitigating risks, and that mitigation measures such as floodgates, insurance policies, or house lifting will be considered and analyzed in the CBA. Following this second approach, the use of the RCR may be a useful tool both by the consideration of residual damages and cost investment; and second by the option of different weighting according to each specific case.

Looking for an optimal solution for flood risk management, Botzen and Van den Bergh (2008) identify the positive and negative aspects of private management in flood insurance policies and consider different ways to overcome constraints of these management models, proposing a mixed management model of public and private institutions as the best alternative. Surminski and Thieken (2017) analyze the role of insurance against floods in flood risk management in England and Germany. In both cases, and even identifying positive aspects, the future viability of insurance in the management of flood risk is questioned, given the need to persevere in the necessary efforts by both the insurance companies and the risk managers.

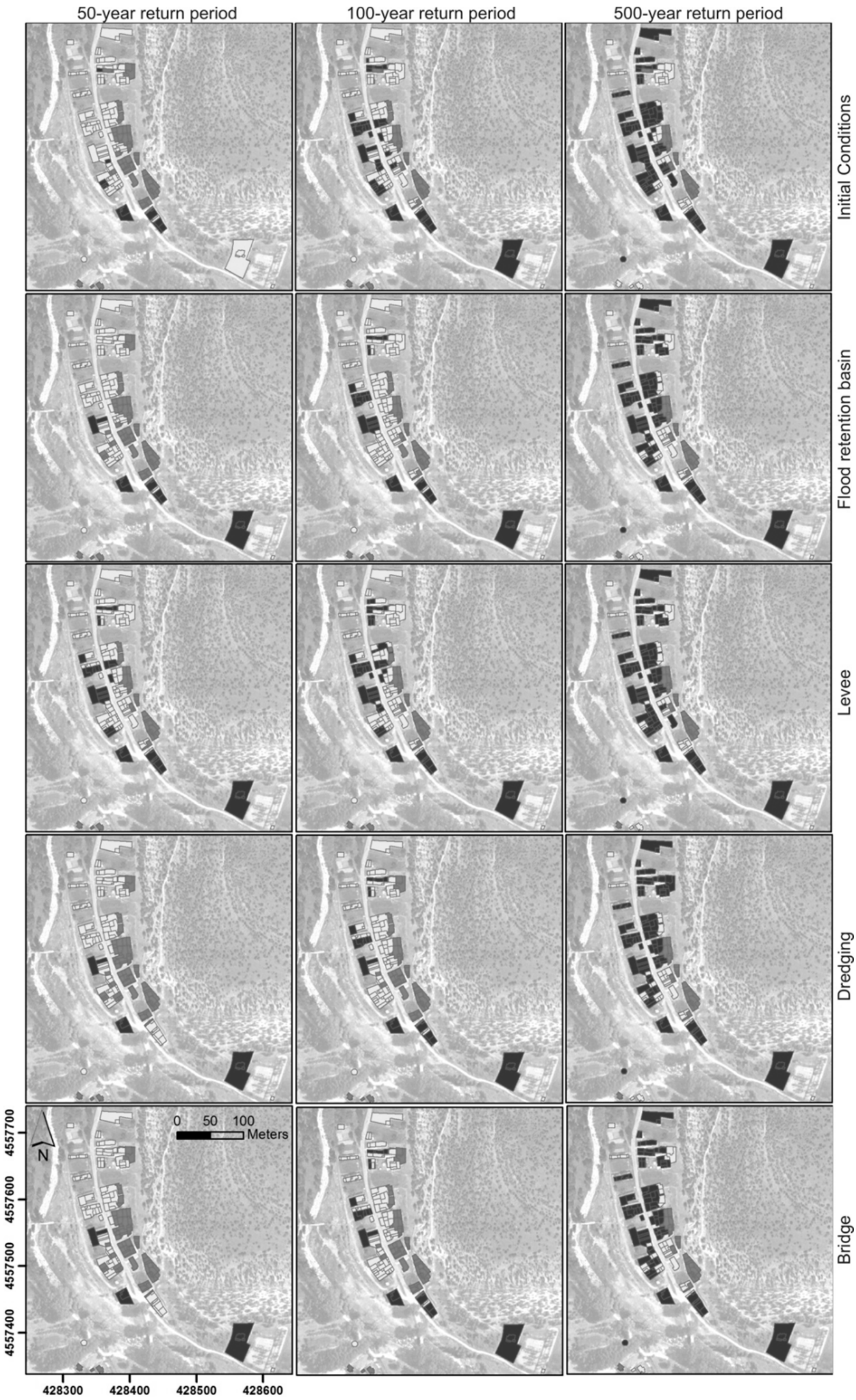

50-year return period
100-year return period
500-year return period
Initial Conditions
Flood retention basin
Levee
Dredging
Bridge
0
50
100
Meters
N
4557700
4557600
4557500
4557400
428300
428400
428500
428600

Figure 7

5. EPILOGUE: Public Works vs. Self-protection measures for financial flood risk mitigation in Spain.

Traditionally, mitigation of flood risk in Spain was restricted to the adoption of structural measures until the end of the 20th century (Ayala, 2002). These traditional structural measures, including dams, levees and dikes, dredging, and hydrological-forestry adaptation, with high project and execution costs, frequently require public funding and are promoted by the central, regional, provincial or local government. Until approximately twenty years ago, managers of the basin water authorities did not include any self-protection measures for financial flood risk mitigation in national hydrological plans and river basin authority plans. Proof of this is the study by Romero and Maurandi (2000), which reveals the absence of requirements for the evaluation and repair of flood damage in Spanish water law. However, after the flood events of 1987, the Government promulgated a law, which envisaged that the public re-insurance institution (CCS) would pay compensation for the damages caused by the floods in that year.

Traditionally, the owners of rural properties in Spain adopted rudimentary self-protection measures for their properties, although these were not adequately coordinated and were often counterproductive for other exposed properties nearby. From the 1980s onwards the approach to risk mitigation began to change, with feasibility studies of standard non-structural measures such as early warning systems (e.g. hydrological information automatic system –SAIH-, weather radar), civil protection preventive planning, territorial and urban planning and risk education.

However, it was not until the publication of the EU Directive on the assessment and management of flood risk and its transposition into Spanish law that other mitigation measures were considered, not only those related to public works. The recently approved flood risk management plan for Spain (PGRI), in accordance with the EU Directive, including self-protection measures and the first general aim of the PGRI is to increase flood risk perception.

Faced with this lack of official proposals for self-protection measures to mitigate economic risk, research by De Mora and Díez-Herrero (2008) showed the importance of estimating financial risk in a 18th century building in Toledo (Central Spain), to calculate accurately the cost of applying self-protection measures, as an insurance policy to cover flood damage. The Ph.D. thesis of Salazar (2013) provided another interesting study covering flood risk analysis and reduction in the Rambla del Poyo (Valencia, Spain).

However, it was only with the recent publication of modifications to the regulation of the Public Hydraulic Domain, that we find the first official initiative encouraging self-protection against the financial risk of flooding. It states that, for existing buildings, the competent authorities must promote the adoption of measures to reduce vulnerability and improve self-protection. Additionally, developers must sign a declaration stating clearly that the existing risk and civil protection measures applicable to each case are understood and assumed; and undertake to transfer that information to the persons potentially affected, regardless of any additional measures deemed appropriate and adopted for their protection (Sánchez et al., 2012). These regulations are implemented by a Flood Working Group with the publication of a Guide to adapting buildings for flood risk protection and the consequences of climate change (Manrique et al., 2017). Self-protection guidelines for buildings are divided into four types: i) avoiding flooding of the building (levees, walls and barriers); ii) resisting and preventing water from entering the house (by sealing doors and windows, waterproofing basements and lower floors, and protecting drains); iii) tolerating flooding in parts of the building where it causes the least damage (wet rooms, adapted access, resistant materials); iv) abandoning the building (transfer of equipment and site, demolition, etc.).

This context and evolution over time is the framework of this present study, which makes an original additional contribution to earlier studies carried out in Spain. The case study serves as a practical application to a small town of some of the self-protection actions in the new CCS/DGA Guide (Manrique et al., 2017), in an analysis compared with the classic official initiatives using structural measures.

6. CONCLUSIONS

From the use of the new RCR criterion in a CBA which consider all: structural, non-structural, and self-protection measures, the main findings and contributions of this paper are:

1. The new approach to cost-benefit analysis, known as RCR, meet the requirements and limitations observed in the measurement criteria of the mitigation measures effectiveness (in a CBA context).
2. Results obtained using the RCR criterion are similar to those reached through BCR_{inc} improving in this case the profits, both on speed calculation and on the control of the quantity and type of the variables employed. Furthermore, RCR criterion allows for variable weighting associated with the particular conditions of each analysis (prioritizing the economic costs, or the damages reduction).
3. The results of the CBA carried out in the little village of Pajares de Pedraza (Central Spain) show the limited economic viability of classic structural mitigation measures for the torrential flash-floods that occur in mid-mountain towns in the central Iberian Peninsula.
4. The self-protection measures against the financial risk of flooding are put forward as essential flood risk mitigation options which must be considered in any CBA

project, as a priority when these CBA are carried out in small towns similar to the one analyzed in the present study.

5. Considering these results, self-protection measures and insurance policies against floods have been shown to be much more viable options, both from the financial point of view and for their effectiveness in reducing residual risks.
6. The results show the importance of not only considering the CBA analysis from the value of the integral of the risk curve (EAD), but also considering the results associated with single scenarios. So, it is the latter that best show us the scope (return period, or probabilities) of the effectiveness of mitigation measures against risk.
7. Finally, the results obtained in this study show that if significant implication is achieved of homeowners, insurance companies, authorities, and other agents involved in the economic management of flood risk, promoting self-protection measures and insurance policies should become the main risk mitigation strategy for governments.

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FIGURE AND TABLE CAPTIONS

Figure 1: Location map and spatial distribution of mitigation measures (A): Bridge (1); Concrete frame (2); Flood retention basin (3); Water drainage (4); Upstream Levee (5); Upstream Dredging (6); Clearing riparian vegetation (7); Downstream Levee (8); Downstream Dredging (9). Pre-mitigation measure flow depth map (B) for the 500-year return period flood.

Figure 2: Representative flow diagram of both, data sources and analysis procedures and established relationships between them, designed to estimate the Cost – Benefit Analysis.

Figure 3: Risk curve in the actual condition (no mitigation) and with some of the most relevant mitigation measures. EAD (€) value for the whole set of flood mitigation measures.

Figure 4: Economic losses vs. return period evolution (A) both under initial conditions scenario (Sc-1, no mitigation measures), and with the adoption of self-protection measures scenario (Sc-2) against floods. Blue vertical bars show the number of flooding houses in each scenario; black-red diamonds show the mean economic losses per house; red diamonds and lines show the range and extremes values for economic losses per house; green line and diamonds show the reduction (%) of economic losses related to the different T-year return periods considered. Economic losses vs. return period evolution (B) considering all houses of Pajares de Pedraza (upper); considering the number of flooding houses with economic losses for each scenario Sc-1 and Sc-2 (middle); and finally considering the number of flooding houses with economic losses for the Sc-1

scenario (lower). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Figure 5: Damage costs versus T-year return period results for the considered mitigation measures, including the EAD value for each of them.

Figure 6: Damage cost classification results for houses in Pajares de Pedraza from self-protection mitigation measure scenario.

Figure 7: Damage cost classification results for houses in Pajares de Pedraza from some structural mitigation measure scenarios. The limits of the different classes are the same as those used in Figure 6.

Table I: Peak flow and associated T-year return period for the most important flooding events in Pajares de Pedraza.

Table II: Mitigation measures characteristics, dimensions, and related changes in roughness coefficient.

Table III: Cost-Benefit Data and classification criterion results for the considered mitigation measures against floods. RCR values have been obtained with $p_1 = p_2 = 0.5$.

Table IV: Cost-Benefit Data and *expected NPV* classification criterion results against floods.

Table V: Flow depth variation at housing places for each mitigation measure and T-year return period scenario. Flow depth variation values in meters.

Table VI: CBA results using the EAD values for benefits linked to each flood risk mitigation measure.