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Assessment of the effectiveness of structural and non-structural measures to cope with global change impacts in Barcelona

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Abstract: In a context of high uncertainty of hydro-climatic variables, the development of updated methods to assess climate change impacts is as important as the provision of improved climate change data. This paper presents the impacts of climate change on the flooding problems concerning a critical area of Barcelona: the Raval district. For this purpose a specific study tackling climate change influence on extreme precipitation in Barcelona and a detailed 1D/2D coupled model were used. Once the model was developed and calibrated, several scenarios of adaptation measures were considered to cope with climate change effects for the 2050 horizon. Results concerning these scenarios were compared to a defined "Business as usual scenario". Climate change impacts were assessed in terms of flood hazard and risk maps concerning vehicular and pedestrian circulation for several return periods (1, 10 and 100 years) for all the considered scenarios. Additionally direct tangible damages were estimated using depth-damage curves. Combining hazard and vulnerability levels by using a GIS-based toolbox, the expected annual damage of the area is obtained. By undertaking a cost-benefit analysis, the effectiveness of the strategies is assessed, and a prioritization of the most adequate ones for each scenario is carried out.

Keywords: 1D/2D model, climate change, cost-benefit analysis, depth damage curves, flood resilience strategies, urban flooding.

INTRODUCTION

Urban areas are, due to the concentration of population and economic activities, one of the most sensitive regions to natural hazards. Trends show that world's population is moving to cities: currently 50 % of the global population lives in urban areas, and by 2030 at least 61 % of the world's population will be living in cities (IBRD/WB 2009). In Europe, such values present even more extreme situations: 83 % of the population is expected to live in cities by 2050 (EC 2010).

The concentration of people in cities increases their vulnerabilities to natural hazards and climate change impacts (Djordjević *et al*. 2011). Consequently, the assessment of urban flood impacts is an issue of high interest, specially taking into account the regulations that have been established with the European Flood Directive (EC 2007).

In the last few years and in agreement with the European Flood Directive, the traditional "flood control approach" has been partially replaced by "flood risk management" (Merz *et al*. 2010a). The focus in this paradigm shift is put in flood risk instead of flood hazard. Therefore, nowadays vulnerability is considered as important as hazard. Flood damage assessments are gaining more importance within this evolving context of decision-making related to flood risk management (Merz *et al*. 2010b).

Previous work developed on 7th Framework Programme Project CORFU (Collaborative Research on Flood Resilience in Urban areas) aimed to establish a framework to assess flood damages, and more generally flood risk, in urban areas starting from scratch (Velasco *et al*. 2015, Russo *et al*. 2015). By combining flood maps and depth damage curves, flood damage maps can be obtained, allowing to identify the most critical spots in a given area. By calculating the costs for different return periods, the expected annual damage (EAD) of the studied domain can be obtained, being able to express the extension of flooded areas and the related flow parameters (flow depth and velocity).

As stated in the 5th Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented ~~over decades to millennia~~ in the temperature records over the past few thousand years (IPCC 2013). AR5 states that human influence on the climate system is clear, because the increasing greenhouse gas concentrations in the atmosphere have led to warming of the atmosphere and the ocean, changes in the global water cycle, reductions in snow and ice, global mean ~~sea~~ sea-level rise and changes in some climate extremes. Specifically related to changing climate extremes, the IPCC (2012) issued a report focused on managing disasters caused by them and proposed strategies for adaptation.

Flood risk has increased over recent decades, and so have the associated damages. Increased flood risk and losses in recent decades have been attributed mostly to increasing exposure and vulnerability (Barredo 2009; Barredo *et al*. 2012; Bouwer 2011; IPCC 2012). The evidence shows that societal change and economic development are the principal factors responsible for increasing flood risk. This situation enhances the relevance of flood risk management practices because it is in the socio-economic domain where most of the actions should be implemented.

In this paper, the methodology and models defined previously in early stages of this work (Velasco *et al*. 2015, Russo *et al*. 2015) will be fed with future scenarios of socioeconomic and climate changes. By doing this, the future flood impacts can be obtained and the need for adaptation measures can be identified.

Then, several structural and non-structural measures to cope with global change impacts are implemented, and their effectiveness is assessed. By comparing risk levels with and without implementing adaptation strategies, and using a cost-benefit analysis to properly take into account the economic aspects, their effectiveness can be adequately assessed. This will be applied in the Raval district of Barcelona, a case study area which suffer from urban floods with important social impacts and economic damages.

MATERIALS AND METHODS

Case study

Barcelona, with a population of 1,620,943 within its administrative limits on a land area of 101.4 Km^2, is located in Catalonia, on the Northeast coast of the Iberian Peninsula. It is facing the Mediterranean Sea, on a plateau limited by the mountain range of Collserola, the Llobregat river to the south-west and the Besòs river to the north east (Figure 1~~Figure 1~~).

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Barcelona presents a classic Mediterranean climate with cool winters and warmer summers, occasionally suffering heavy rainfalls of great intensities and flash flood events. The yearly average rainfall is 600 mm, but the maximum intensity in 5 minutes corresponding to a return period of 10 years is 202.5 mm/h and it is not rare that 50 % of the annual precipitation occurs during two or three rainfall events. The Intensity Duration Frequency (IDF) curves were recently updated on the basis of a rainfall series data of 81 years (from 1927 to 1992 and from 1995 to 2009). On the basis of these IDFs, new project storms with several return periods were obtained for the design of the sewer network (Rodríguez *et al*. 2013).

The morphology of Barcelona presents areas close to Collserola Mountain with high gradients (with an average of 4% and maximum values of 15-20%) and other flat areas near to the Mediterranean Sea with mild slopes (close to 0-1 %) or even areas below the sea level, susceptible to floods. Figure 1~~Figure 1~~ shows the longitudinal profile of the city including the Raval district. Barcelona primarily suffers from flash flooding combined with pluvial flooding that results from high intensity rainfall over short periods of time, and where drainage systems are unable to cope with the storm runoff (Barrera et al. 2006).

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The Raval District of Barcelona is located in a flat area of the city. With almost 50,000 inhabitants in an area of 1.09 km^2, it is one of the most densely populated areas in Europe (approx. 44,000 inh./km^2). The district area is highly impervious with several highly vulnerable elements (such as schools, hospitals, museums, historic buildings, etc.).

This area suffers from flooding problems when heavy storm events occur. These problems are caused by the excess of surface runoff not adequately conveyed into the underground network and the poor capacity of the sewer system in some of the upstream basins in the city. In addition, the hydrological response time of Raval District catchment is very short (less than 30 minutes). As a result, there is a significant hazard for the vehicular and pedestrian circulation, and economic damages in terms of goods and properties often occur.

~~Following~~Next, data and methodologies applied to assess effectiveness of resilience measures are presented. Given that most of this information was already described in previous papers such as Russo *et al*. (2015) and Velasco *et al*. (2015), only brief descriptions have been included in this paper.

1D/2D coupled model

A detailed 1D/2D coupled model, simulating surface and sewer flows was developed using Infoworks ICM version 3.0 by Innovyze (2013). ICM solves the complete 2D Saint Venant equations in a finite volume semi-implicit scheme (Godunov, 1959) with a Riemann solver (Alcrudo and Mulet-Martí, 2005).

The estimation of flood depth in a very accurate way is crucial for a micro scale hydraulic assessment as the one described here. Therefore, there was a need for a coupled 1D/2D approach in order to take into account surface flows coming from upstream catchments and the interactions between the two drainage layers (the sewer network and the streets, sidewalks, squares, etc.) through the surface drainage system.

Special attention was paid to the hydraulic characterization of the inlet systems (representing the interface between surface and underground flows) using experimental expressions developed by Gómez and Russo (2011).

In order to consider surface and sewer flows coming into the Raval District from upstream catchments, an extended area was included in the study. Only main sewers were modelled for these catchments, while main and secondary networks were taken into account for Raval District and its proximity. The final model considered a total area of 44 km^2 with 3,874 nodes, 241 km of total pipe length and 6 major storage facilities with a total capacity of 170,000 m^3.

A 2D mesh covered the whole analyzed domain with 403,822 triangles. Parks and other green areas were represented in the same 2D mesh, through “2D infiltration zones” characterized by their specific hydrological, physical and geometric parameters, while buildings were represented as void areas. Runoff produced in the building areas was estimated considering an approximation of single non-linear reservoir and directly conveyed into the sewer network. This goes in accordance with local practice in Barcelona, where roofs and terraces (approximately corresponding to 50% of the whole analyzed domain) are directly connected to the underground sewers.

The sewer model was calibrated and validated using data regarding 4 critical rainfall events occurred in 2011. These data concerned 11 rain gages, 29 limnimeters and several time series related to real time control devices. Moreover, other data collected in the post events emergency reports (elaborated by policemen and firemen), and amateur videos recorded during the selected storm events were used to calibrate surface flow. Detailed information about the features of the model can be found in Russo *et al.* (2015).

Damage calculation

A methodology to determine flood damages was developed in early stages of the CORFU project (Velasco *et al.*, 2015). In order to carry out an urban flood damage assessment, three key elements are required: depth damage curves, detailed flood depth maps and land-use maps. It is worth noting that, the outputs of the model described in the previous section (i.e. water depth in the streets) have been converted into water depth inside the buildings. Furthermore, to ease the calculation of the final flood damage maps, a GIS-based toolbox has been developed (Hammond *et al*., 2012). This toolbox enables to automatize the three following steps, increasing the speed of the post processing data and so, easing the simulation of several events (Figure 2~~Figure 2~~):

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1. Simulation of three flood events to obtain the flood depths in the area.
2. Assign a water depth to each building.
3. Interpolate this value in the depth damage curve to obtain the relative cost.
4. Multiply the relative cost by the area, obtaining the total damage value per each block.
5. Sum of all the blocks damages' to obtain the total damages of each event.
6. Calculation of the EAD by weighting the damages of each event with its probability.

This methodology can be directly applied for the calculation of the current damages. However, to determine the damages for the future scenarios, some changes have to be applied in order to update socio-economic and climate inputs. Regarding rainfall, the new hyetographs obtained by using the climate change factors must be fed into the 1D-2D coupled model. Regarding the depth damage curves, a ratio of exposed assets is applied to the initial curves so they can be upscaled. The calculation of current and future damages with this methodology is presented graphically in Figure 2~~Figure 2~~.

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In order to see the depth damage curves that were created for the Raval district, and to see more details about this whole methodology, the reader is referred to Velasco *et al.* (2015).

Expected annual damage

By calculating the damages for different return periods, the expected annual damage (EAD) of the studied domain can be obtained, being an extensively used indicator to calculate to which extent is the area affected by floods.

EAD is an estimate of the average flood damages computed over a number of years (Arnell, 1989) and it is obtained by integrating the relationship between the expected damage for an event and its probability (Dawson *et al*., 2008).

Since it is difficult to accurately define the relationship between the probability of a flood event and the damage it would cause, the most common methodology to calculate EAD consists on simulating several events of different return periods (which means that they have a different probability associated) and calculate the damages for each case.

Then, by calculating the area under the curve defined by these points, the EAD can be obtained.

Although it is generally recommended that EAD is better addressed by simulating the maximum number of events, recent studies (Olsen *et al.* 2014; Velasco *et al*. 2015) have shown that by properly choosing three events, EAD estimates can be very accurate. Olsen *et al.* (2014) ~~These studies~~ showed that a log-linear relationship existed in the damage – probability curves. However, they also found a shift in the curves, where smaller events followed one log-linear relationship and the larger events followed a different one. This breaking point was identified as the design standard of the network. For the Raval district, in Velasco *et al*. (2015) the breaking point was obtained for a 10 year return period.

For this case, the three events correspond to an extreme event (T = 100 years), a precipitation event that starts to create some damage (T = 1 year) and the design of the sewer system one (that in Barcelona is T = 10 years). Such rainfall events have been simulated by using the hyetographs developed from the IDF curves (Rodríguez *et al*., 2013).

Using the methodology ~~Given that the log linear relationship~~ described by Olsen *et al.* (2014)~~ and Velasco *et al*. (2015) exists~~, the damage functions between 1 and 10 years and 10 and 100 years can be expressed as presented in equation (1).

$$Damages = a \cdot \log(probability) + b \quad (1)$$

Since the integral of this function can be calculated analytically, the exact areas below these curves can be obtained. Therefore, the calculation of damages with two different procedures can be compared: (i) a first approach in which a five point integral (including the return periods of 5 and 20 years in addition to the other three) using the trapezoidal rule is applied and (ii) the approach that will be followed in this study, where the analytical integral of the two logarithmic functions are calculated.

In Figure 3~~Figure 3~~ and Table 1~~Table 1~~, the comparison of these two approaches applied to the baseline scenario of the Raval district can be seen. The EAD values obtained are (i) 1,116,~~079~~ 000 and (ii) 1,~~173~~174,~~597~~ 000 €, which corresponds to a 5 % error. Therefore, given that the errors obtained are considered limited for this type of study, the methodology considering only three events will be used, in order to avoid a large number of simulations.

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Risk assessment

In addition to the economic damages, the flooding problems that occur in the Raval produce significant hazard for the vehicular and pedestrian circulation. Besides the economic damage assessment that has been presented, an intangible evaluation to determine the impacts to people and vehicles has also been included in this study.

Risk is defined as the probability or threat of a hazard occurring in a vulnerable area and that may be avoided or minimised through preventive actions. For the three different categories (pedestrians, vehicles and goods), flood risk is assessed in the same way. Flood risk maps related to each specific scenario and return period are obtained by combining hazard maps and vulnerability maps.

As explained, for the direct tangible damages, risk is expressed in terms of monetary values thanks to the ~~depths~~ depth-damage curves. For the other two categories, risk maps are created multiplying the vulnerability index (1, 2 or 3, corresponding to low, moderate and high vulnerability) by the hazard index (1, 2 or 3, corresponding to low, moderate and high hazard) obtaining a risk matrix. Finally the total risk varies from 1 to 9 where higher levels indicate higher risk.

Scenarios framework

The future scenarios used in this study represent a mid-term time frame. This is done in order to be able to represent a future in which adaptation strategies can be implemented with less uncertainty than long-term scenarios would imply. Therefore, the future scenarios presented in this study are centred in the year 2050. For the case of Barcelona, and more specifically for the Raval District, a combination of different future scenarios of climate and socioeconomic aspects are developed.

In addition to climate and socioeconomic changes, the framework to assess future flood risk adaptation includes a set of scenarios to represent different levels of adaptive capacity, including structural and non-structural strategies. By this, the business as usual (BAU) scenarios, in which no adaptation strategies would be implemented, can be compared to the adaptation scenarios. Of course, these scenarios must be related and compared to the current situation or baseline scenario, which represents the nowadays flood risk situation in the Raval District.

Taking into account that the studied area (as well as its upstream basins) is totally developed and highly consolidated, is not likely to vary essentially in 2050, this is the reason why scenarios of land-use changes will not be considered. Considering this, the total number of possible combinations is presented in Table 2~~Table 2~~.

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Adaptive capacity

Three different levels of adaptive capacity have been defined for this study, being low, medium and high. Following, a brief description of each one of them is provided.

The low adaptive capacity scenario dedicates a low level of resources to the improvement of this adaptive capacity. Measures implemented in this scenario are non-structural, and only focusing on vulnerability reduction.

Given that in the Raval district there is a long history of flooding, it is common that the owners protect their own properties. The most common strategy is to use wooden panels called flood boards or flood barriers (with an approximate height of 50-55 cm) that prevent water entering into the properties. The consideration of these protection measures in the methodology adopted is done by updating depth damage curves. It has been considered that there will be no damages until 50 cm, and once the board is overtopped, the damages will grow linearly until the damages of the original curve for 55 cm are reached. After this point, the new damage curve will follow the same pattern as the original curve (Figure 4~~Figure 4~~).

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The implementation of such protection measures depends on the behavior of the population, on their experience and on the location of their property. Obviously, if the population in flood prone areas is aware of the existing risks, they will act differently in order to protect themselves. This is why these strategies were jointly considered to an early warning system (EWS) in order to maximize the implementation of this strategy. In terms of risk for pedestrian and vehicular circulation, an EWS will also have considerable effects: people that are warned will probably act accordingly and will not go to the area affected and hence, the vulnerability level will be considerably reduced. It is worth noting that these measures do not have any incidence in modifying hazard levels but only in vulnerability ones.

Given that the effectiveness of an EWS can vary, several subscenarios have been created to represent this (Table 3~~Table 3~~). They are applied to the low adaptive capacity level, and thus, this applies to both Adaptation 1 and 4 scenarios. These subscenarios imply different usage percentages of the flood boards, as well as changes in human vulnerability and vehicular flow intensity.

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Regarding the flood board implementation, a 100 % of use has been considered as a utopic case. Then, a low, medium and high effectiveness of the EWS has been assigned to usages of the flood board of 25, 50 and 75%. These cases represent the real situations, where floods can occur at night or the warnings might not reach the population, considerably reducing the self-protection level of the population.

Summarizing, the low adaptive capacity scenario implies the implementation of the following strategies, that are considered together in order to enhance their effectiveness. Thus, when doing the cost-benefit analysis, the costs of these strategies must be considered:

- Development and maintenance of an EWS;
- Construction and use of the flood boards;
- Intervention of response teams (fire-fighters, civil protection, etc.) to close streets and flood prone areas when a warning is issued.

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The medium level of adaptive capacity consists of implementing SUDS (Sustainable Urban Drainage Systems), and specifically green roofs in the studied area. Green roofs have been the selected technique in this work because the Barcelona Municipality promoted and implemented them during the last decade in several areas of the city. Moreover, the Agència d'Ecologia Urbana de Barcelona (Urban Ecology Agency of

Barcelona city) published a specific study about the potential implementation of urban roofs in Barcelona.

In Figure 5~~Figure 5~~, the location of green roofs in Barcelona is shown differentiating their typology. Potential green roofs (existing + planned green roofs) with extensive vegetation cover a surface of 33.26 Ha, while green roofs with semi-intensive and intensive vegetation cover surfaces of 0.27~~68~~ Ha and 17.13~~29~~ Ha respectively. It is possible to observe that, according to this study, only a limited area can be occupied by green roofs respect to the whole analysed domain (1.1%).

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These green roofs were introduced into the model specifying their surface portion in each subcatchment and by defining their infiltration losses parameters (Table 4~~Table 4~~).

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Finally, the high level of adaptive capacity considers classical structural measures (new pipes and one storage tank, in this case) to reduce flooding problems in the Raval district. Specifically, the new simulated structural measures are the following (Figure 6~~Figure 6~~):

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- 3 pipes in the upper part of the city to reduce runoff coming from upstream areas;
- 3 pipes in Poble Sec district to reduce runoff in the Raval coming from Parallel St.;
- A storage tank of 23,000 m^3 to store local runoff generated in the Raval district.

Climate change inputs

Climate change factors can be defined as the ratio between the rainfall intensity with a return period T and a duration d for a future climate scenario ($I(T/d)_{Future}$) and the corresponding rainfall intensity in the present climate ($I(T/d)_{Present}$) (Arnberg-Nielsen 2012; Larsen et al. 2009):

$$c_f = \frac{I(T,d)_{Future}}{I(T,d)_{Present}}$$

Climate change factors become an easy and handy method to describe the potential change in rainfall intensity due to climate change. They have been recommended by Willems et al. (2012) as the methodology to assess future changes in rainfall extremes when studying urban drainage systems.

Since this work is dealing with the management of extreme events, one of the scenarios used will be a pessimistic scenario. This scenario will be obtained by using the highest climate change factors obtained from the climate data assessment which will be later presented.

Besides this pessimistic scenario, an optimistic scenario must also be developed in order to describe the best situation in the future. This optimistic scenario will be obtained by using the minimum climate change factors.

In order to quantify the impacts of climate changes on the Raval District for the horizon 2050, the results of a local study done in Barcelona were used (Rodriguez et al. 2013). In this study, 84 daily rainfall series were simulated for the period 2000-2099 in Barcelona. These series were obtained for six stations located in the metropolitan area of Barcelona using the information provided by five general circulation models under four future climate scenarios of greenhouse gas emissions (from the Fourth Assessment Report of IPCC (IPCC 2007)) and applying statistical downscaling methods.

The pessimistic scenario was considered as the one with the highest extremes from Rodríguez et al. (2013). On the other hand, since the effects of climate change are uncertain, and some of the scenarios obtained even considered reductions in extreme precipitation, the optimistic scenario was considered as if there would be no change in extreme precipitations due to climate change (which means that this scenario is the same as the baseline in terms of climate). These two climate futures and its climate change factors are the ones presented in Table 5~~Table 5~~. The effects of the future scenarios of extreme rainfall will be obtained by multiplying design storms with its corresponding uplift factor. Moreover a sea rise of 0.2 m was considered for the pessimistic scenario.

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Cost-benefit analysis

A cost-benefit analysis should include all the costs and benefits of the different adaptation measures. Nevertheless, here we assume as benefits only the avoided damages obtained by implementing the adaptation strategies. Results from this cost-benefit analysis provide insights on the economic efficiency of the different adaptation measures against the background of the different scenarios. The economic value of the potential impacts is analysed jointly with the costs of implementing and maintaining the adaptation measures.

Within the scope of this analysis, benefits are defined as the reduction in the EAD to buildings and their contents that presumably is going to be achieved by implementing the considered adaptation measures. Costs are analysed by including the initial expenditures of setting up or constructing the respective measure – the capital costs (CAPEX) – and any costs that are required to operate and maintain the adaptation measure (OPEX).

To assess the impact of the different adaptation measures on the EAD separately from the impact of other scenario parameters (such as different socio-economic pathways or different climate scenarios), the BAU scenarios are compared to the different adaptation scenarios with the same parameters except for the adaptive capacity. For example, for obtaining the benefits of the scenarios Adaptation 1, the EAD is compared to those of BAU1, while for estimating the benefits of Adaptation 4, the scenario used is BAU2.

Flood protection and adaptation measures at the same time reduce damages and require expenditures throughout the entire considered time horizon (i.e. the year 2050). In order to be able to compare costs and benefits of the adaptation measures and to evaluate their cost-effectiveness, the cost-benefit analysis thus is based on the Annual Equivalent Costs and Benefits. To calculate the Annual Equivalent Costs and Benefits, in a first step, the Total Present Value of the costs and the benefits must be obtained, using a discount rate of 4.0% that in this analysis seems to be feasible. In a second step, the Annual Equivalent Costs and Annual Equivalent Benefits of each scenario are calculated and then, the Net Benefits of an adaptation strategy can be obtained as the difference of the benefits (considered as avoided damages) and costs of the different scenarios.

RESULTS AND DISCUSSION

Simulations with the 1D/2D model generate flood hazard maps (Figure 7~~Figure 7~~) and flood risk maps (Figure 8~~Figure 8~~) for different return periods (T1, T10 and T100) and the several current, future and adaptation scenarios. As it can be seen from the figures, hazard assessment was carried out for each cell of the 2D domain in the Raval, while vulnerability and risk assessment was carried out for each census area of the district according to the available data provided by Barcelona's municipality. In fact, flood hazard criteria proposed by Russo *et al*. (2013) were adopted for hazard assessment concerning pedestrian circulation, while the vulnerability assessment takes into account several social indicators (population density, density of people with critical age, presence of sensitive buildings, etc.) which only exist at that spatial resolution.

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Results of Figure 7~~Figure 7~~ and Figure 8~~Figure 8~~ can be explained because scenario Adaptation 1 only tackles vulnerability, whereas the structural strategies from Adaptation 3 only focus on hazard reduction. By assessing results according to these two different points of view, a deeper understanding of the efficiencies of each strategy can be obtained.

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Regarding economic losses, Table 6~~Table 6~~ and Figure 9~~Figure 9~~ present the several EAD values obtained, as well as the graphic representation of damage maps. Comparing the EAD of the baseline scenario and the two BAU scenarios, considerably high increases are observed. This means that the combined effects of climate and socioeconomic changes might imply increases in the levels of hazard and vulnerability in the area, and hence, flood risk. This justifies the implementation of adaptation strategies that aim to decrease either hazard or vulnerability, and consequently risk.

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The effectiveness of the applied measures can be assessed using the values from Table 6~~Table 6~~. As it can be seen from the results of Adaptation 1 and Adaptation 4 scenarios, the non-structural strategies are highly efficient for events with low return period. On the other hand, for events of higher return periods, such strategies are not able to prevent flood damages so efficiently. Otherwise, scenarios Adaptation 3 and Adaptation 6 show that structural strategies are able to cope with flood impacts at all levels. Specifically, it can be observed that these measures reduce the damages for a 100 year event to values which are even lower than the ones obtained for the baseline scenario.

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Concerning the Adaptation 2 and Adaptation 5 scenarios it is useful to remark that their effectiveness is limited from the beginning due to the limited suitable area.

Comparing the EAD values of the six adaptation scenarios and in agreement with Figure 9~~Figure 9~~, it can be clearly concluded that the highest adaptive capacity level implies higher benefits. This means that the flood impacts are more efficiently reduced with structural strategies compared to the non-structural ones. Nevertheless, given that the benefits based on avoided damages of these strategies must be compared to their costs, a cost-benefit analysis was also carried out for the Raval District (this assessment has the limitation that the costs of the structural measures were fully computed, whereas their benefits were only measured in the Raval District, although they could benefit a much larger area of Barcelona).

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As it can be seen in Figure 10~~Figure 10~~, the total present value of costs and benefits of the six adaptation strategies have been calculated. Benefits represent the reduction of the EAD compared to the corresponding BAU scenarios, whereas the costs refer to the addition of the CAPEX and OPEX costs. Observing these two variables, one conclusion can be directly extracted: structural strategies imply higher benefits than the non-structural ones, but their costs are also much greater than the other ones. Consequently, the net benefits of the non-structural strategies (Adaptation 1.4 and 4.4) are larger.

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Given that the costs of the strategies analysed do not depend on the climate scenario, the net benefits of each pair of scenarios present rather different values. For the adaptation 1.4 and 4.4 scenarios (pessimistic and optimistic climate change scenarios respectively), the first one reaches a net benefit of 25,~~993~~994,~~978~~ 000 €, whereas the second one achieves a value of 19,~~541~~542,~~755~~ 000 €. On the other hand, given that the costs of the structural strategies are very significant, their net benefits are very different: adaptation 3 presents a value of 5,~~455~~456,~~729~~ 000 €; whereas adaptation 6 presents negative "benefits" of -12,~~221~~222,~~800~~ 000 €. Again, in this second case, the analysis only considers the benefits in the Raval District, while these infrastructures benefit a much bigger area.

The cost-efficiency of the early warning system is highly dependent on its degree of effectiveness. The aforementioned net benefits that can be achieved by a purely theoretical 100%-effective early warning system are substantially reduced when considering lower degrees of effectiveness. For instance, a 25%-effective system (represented by scenario Adaptation 4.1) yields a corresponding value of net benefits of 6,498,~~484~~ 000 €.

It is important to note that the results of the ~~cost~~ cost-benefit analysis strongly depend on the discount rate considered. The reason is that the types of investments that have to be done are very different for each of the strategies. Structural measures will imply a high initial investment (with the benefits split throughout its life span). On the other hand, non-structural strategies will have smaller but recurrent investments. Consequently, a sensitivity analysis of this variable was done.

In this analysis it was observed that a high discount rate puts relatively more weight on the initial investment but less weight on future and recurrent costs. In an analogue manner, the value of the EADs over time is also subject to discounting: a higher discount rate gives more importance to present than to future damages, which also affects the estimated values of the net benefits. In the case of the structural strategies, a high discount rate gives relatively more importance to the very high initial investment and it gives less importance to future benefits, which without discounting exceed those ones achieved by non-structural measures, such as SUDS and the early warning system, by far.

This is why when considering discount rates smaller than 2%, the structural measures of Adaptation 6 achieve positive net benefits. Furthermore, when reaching discount rates of approximately 0%, Adaptation 3 is the most cost-effective strategy and Adaptation 6 performs quite well, only being surpassed by Adaptation 4.3 (slightly) and Adaptation 4.4. For this reason, it is important to include a sensitivity analysis of discount rate.

CONCLUSIONS

Impacts of climate change have been analyzed in the Raval district of Barcelona by using a detailed 1D/2D coupled model and local damage curves. By simulating future scenarios, the need for adaptation was identified. Therefore, several adaptation strategies were implemented and their costs and benefits were calculated.

Results of simulations and the elaboration of the hazard and risk maps demonstrate that non-structural measures provide a significant mitigation of flood risk and damage only for low return periods, while, for high return periods, structural measures are more effective in terms of hazard, risk reduction and prevention of economic losses. Structural strategies can better cope with flood impacts but at higher costs. Nevertheless, the economic benefits of these strategies have been only quantified in the Raval District. By extending the domain analysed, results obtained would be different, being expected benefits higher in this case.

SUDS measures have limited effects due to the lack of suitable area to locate this type of systems. This is a comment that can be extrapolated to other Spanish Mediterranean consolidated urban areas where the urban pattern with an extremely high level of imperviousness and people density make it difficult to implement these types of measures.

The choice of the most appropriate adaptation measures depends on one hand on the established selection criteria and on the other hand on the relative importance given to current and future costs and benefits (i.e. the choice of the discount rate). If the absolute reduction of EADs is the crucial objective, structural measures seem to be the best available alternative since they achieve the largest reduction in EADs and the highest benefits. However, when regarding the cost-effectiveness of the measures, early warning systems and the use of flood barriers are the most efficient measures if high discount rates are considered. Notwithstanding, when considering low interest rates (lower than the 4% used in this study) the structural adaptation measures turn out to be the most cost-effective adaptation measures.

The paper demonstrates that pioneer and promising methods and tools can be used to develop accurate and detailed Drainage Master Plans in our modern cities contributing to build more resilient cities in a context of global change. Furthermore, this type of methodology allows decision-makers to distinguish among different technical proposals on the basis of a set of parameters (social and economic risk in their cities) and cost benefit analysis providing more elements to address municipal policy in terms of measures prioritization.

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Tables

Table 1 Comparison of the two methods of calculating the EAD, using the results of the Raval district for the baseline scenario.

	Return periods				
	1	5	10	20	100
Damages (€)	7879,8460 00	606607,9050 00	1,615616,7380 00	6,825,0810 00	19,156,1960 00
EAD with trapezoidal rule (5 points)	Trapezium 1		Trapezium 2	Trapezium 3	Trapezium 4
	274,300000		111,132000	211,021	519,626
	1,116,079 000 €				
EAD with logarithmic functions	Function 1			Function 2	
	517518,990000			655656,607000	
	1,173174,597 000 €				

Table 2. Combinations of the possible scenarios for the Raval district.

Combined scenario	Climate scenario	Socioeconomic scenario	Adaptive capacity
Business as usual 1	Pessimistic	Medium	None
Adaptation 1	Pessimistic	Medium	Low
Adaptation 2	Pessimistic	Medium	Medium
Adaptation 3	Pessimistic	Medium	High
Business as usual 2	Optimistic	Medium	None
Adaptation 4	Optimistic	Medium	Low
Adaptation 5	Optimistic	Medium	Medium
Adaptation 6	Optimistic	Medium	High

Table 3. Different levels of use of the flood board related to the effectiveness of an EWS. The same considerations are given for the adaptation 4 sub-scenarios, so Adaptation 1.1 and Adaptation 4.1 are applied analogously.

Sub-scenarios	EWS effectiveness	Percentage of flood boards	Human vulnerability reduction	Vehicular flow intensity reduction
Adaptation 1.1	Low	25 %	0.25	25 %
Adaptation 1.2	Medium	50 %	0.5	50 %
Adaptation 1.3	High	75 %	0.75	75 %
Adaptation 1.4	Total	100 %	1.5	100 %

Table 4. Different green roofs type and their main characteristics.

Green roof type	Type of vegetation	Thickness (cm)	Wet weight (Kg/m2)	Storage capacity (mm)
Extensive	Sedum	90-13	95-150	25
	Herbaceous	11	115	25
	Inclined	12	175	64

Semi-intensive	Aromatic	16-28	195-280	70
Intensive	Garden, Yard	27-80	350-815	113

Table 5 Uplift factors of selected scenarios of climate change for 2050.

	Return periods		
Scenario	1	10	100
Pessimistic	1.08	1.12	1.15
Optimistic	1.00	1.00	1.00

Table 6. Damages and EAD of several scenarios for the Raval district.

Return period (years)	1	10	100	EAD
Probability	1	0.1	0.01	
Damage for baseline scenario	~~78~~79,~~846~~ 000 €	1,~~615~~616,~~738~~ 000 €	19,156,~~196~~ 000 €	1,697,~~299~~ 000 €
Damage for BAU 1 scenario	~~211~~212,~~846~~ 000 €	8,369,~~323~~ 000 €	45,642,~~494~~ 000 €	6,292,~~056~~ 000 €
Damage for Adaptation 1.1	~~158~~159,~~884~~000 €	7,~~093~~094,~~660~~000 €	43,097,~~160~~000 €	5,522,~~232~~000 €
Damage for Adaptation 1.2	~~105~~106,~~923~~000 €	5,~~817~~818,~~996~~000 €	40,~~551~~552,~~825~~000 €	4,752,000 €~~406~~
Damage for Adaptation 1.3	~~52~~53,~~961~~000 €	4,542,~~333~~000 €	38,006,~~491~~000 €	3,~~982~~983,000 €~~580~~
Damage for Adaptation 1.4	0 €	3,~~266~~267,~~670~~000 €	35,461,~~156~~000 €	3,~~212~~213,000 €~~754~~
Damage for Adaptation 2	56,~~143~~ 000 €	6,398,~~101~~ 000 €	44,402,~~370~~ 000 €	5,190,000~~431~~ €
Damage for Adaptation 3	7,~~005~~ 000 €	275,~~258~~ 000 €	10,478,~~002~~ 000 €	~~610~~611,000~~915~~ €
Damage for BAU 2 scenario	~~131~~132,~~654~~ 000 €	2,718,~~048~~ 000 €	32,400,~~065~~ 000 €	2,~~862~~863,000~~681~~ €
Damage for Adaptation 4.1	~~98~~99,~~741~~000 €	2,086,~~404~~000 €	30,243,~~330~~000 €	2,438,000 €~~153~~
Damage for Adaptation 4.2	~~65~~66,~~827~~000 €	1,~~454~~455,~~759~~000 €	28,~~086~~087,~~594~~000 €	2,~~013~~014,000 €~~625~~
Damage for Adaptation 4.3	~~32~~33,~~914~~000 €	823,~~115~~000 €	25,~~929~~930,~~858~~000 €	1,589,~~096~~000 €
Damage for Adaptation 4.4	0 €	191,~~470~~000 €	23,773,~~122~~000 €	1,~~164~~165,~~568~~000 €
Damage for Adaptation 5	24,~~278~~ 000 €	2,030,~~046~~ 000 €	28,695,~~007~~ 000 €	2,307,~~073~~ 000 €
Damage for Adaptation 6	~~5~~6,~~818~~ 000 €	~~71~~72,~~540~~ 000 €	3,253,~~262~~ 000 €	184,~~427~~ 000 €

Figures

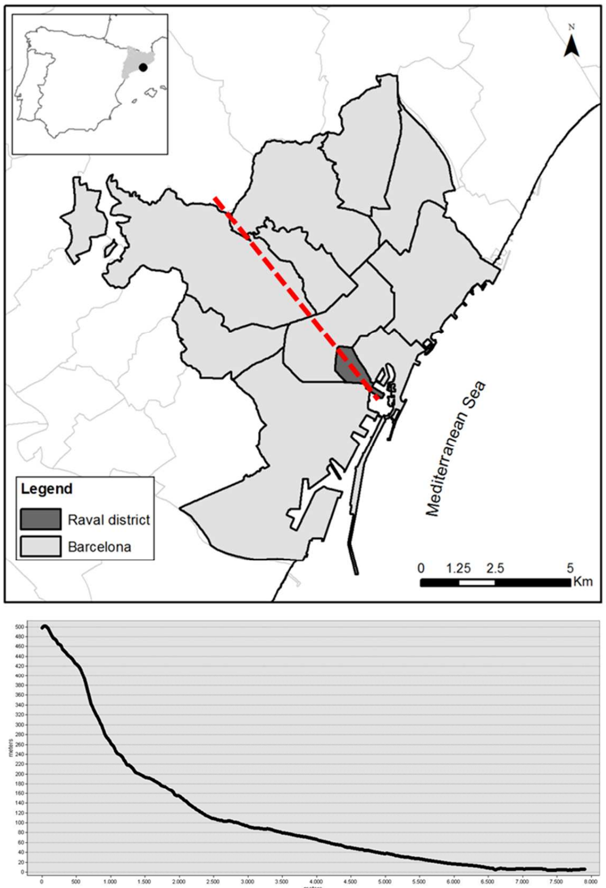

Figure 1. Administrative limits of Barcelona and representation of the case study area, the Raval District (top). On the bottom, longitudinal profile of Barcelona, from the Collserola Mountain to the Old Port. From Km-5 until the Old Port, the profile shown corresponds to the Raval district. The elevations there oscillate between 20 m (in Universitat Square) and 1 m (in the Old Port).

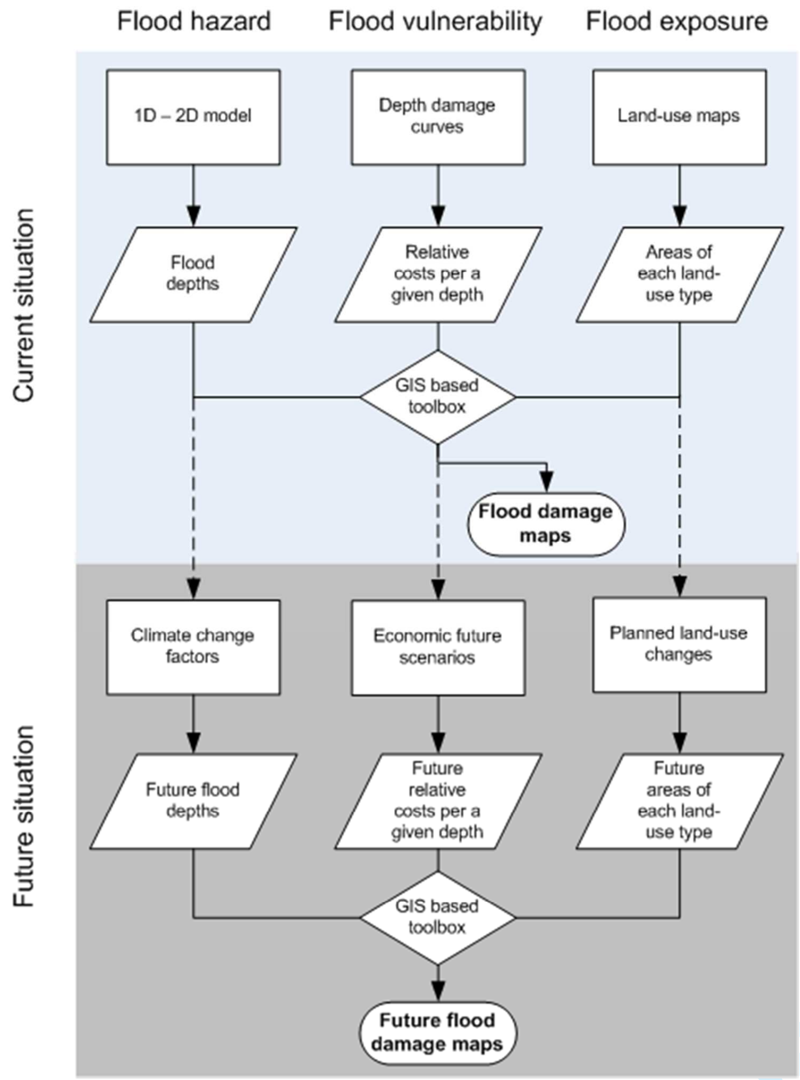

Figure 2 Schematic representation of the methodology used to calculate current and future flood damages for the Raval district.

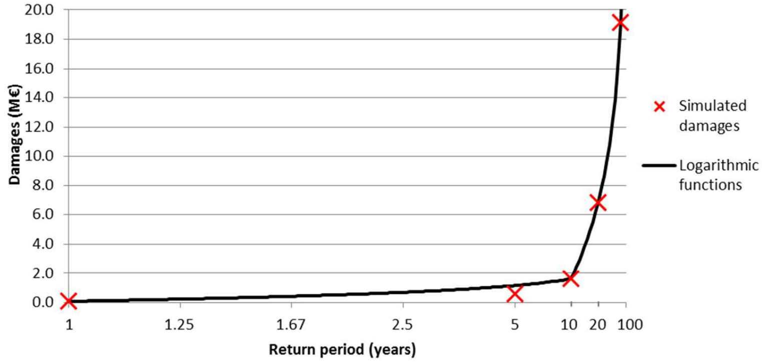

Figure 3 Damage – probability curve for the whole Raval district for the baseline scenario. The area under this curve expresses the EAD of the region. The red markers represent the five simulated events, whereas the black lines are the two logarithmic functions between 1 and 10 and 10 and 100 years of return period.

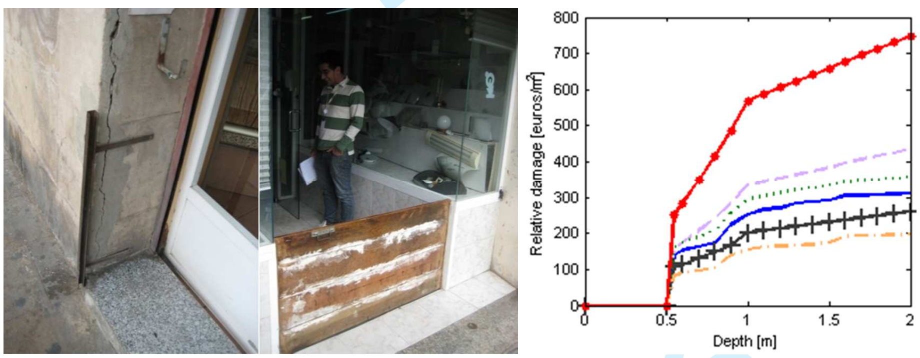

Figure 4. Flood properties prevention using flood boards: on the left and on the centre, some details (frame and board) of a sliding panel currently used by an inhabitant of the Raval district. On the right, the modified DDC for the Raval district when implementing such strategies.

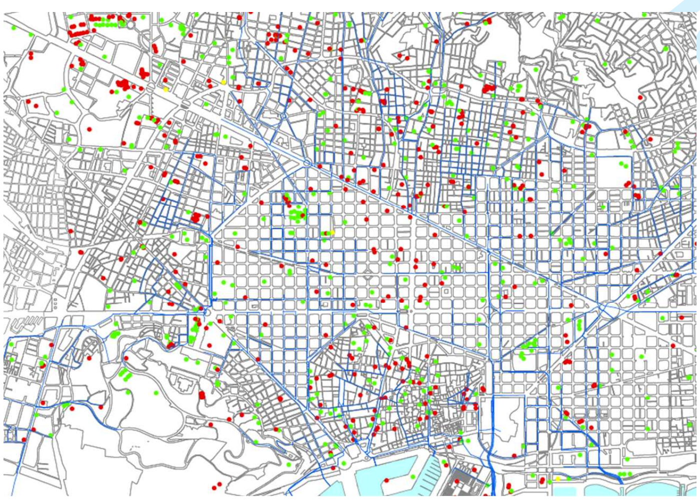

Figure 5. Potential green roofs location in Barcelona, identified by the Urban Ecology Agency. Green, yellow and red represent different types of green roofs, being respectively extensive, semi-intensive and intensive.

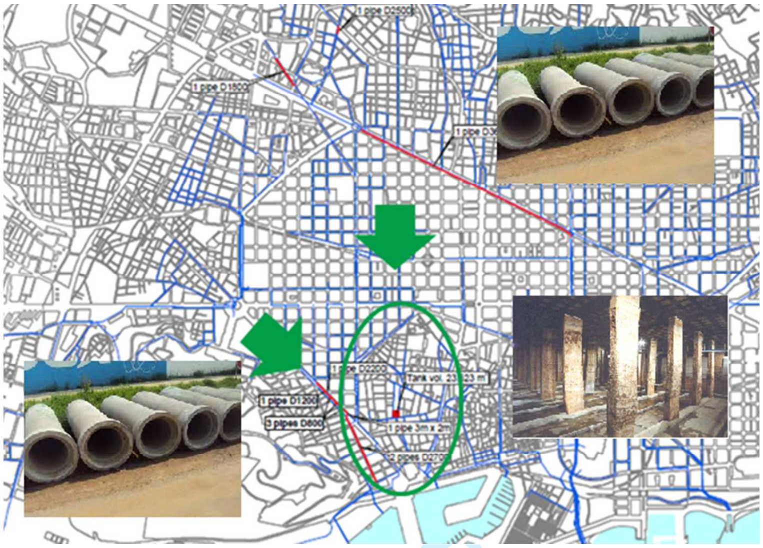

Figure 6. Existing and proposed sewers (respectively in blue and red) for the high adaptive capacity level. Green arrows indicate the runoff reaching the Raval (in the circle) in case of storms.

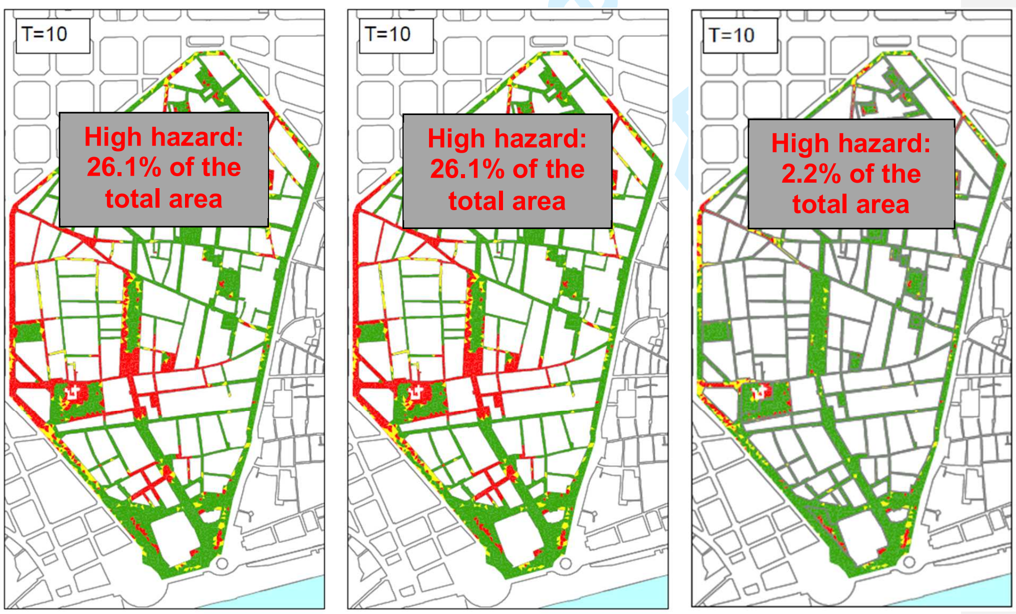

Figure 7. Flood hazard maps for a 10 year return period for the BAU1 scenario (left), Adaptation 1 scenario (centre) and Adaptation 3 scenario (on the right). In red, yellow and green colours, high, moderate and low hazard conditions are respectively shown. Note that since the scenario Adaptation 1 only tackles vulnerability, the hazard maps on the left and centre are exactly the same.

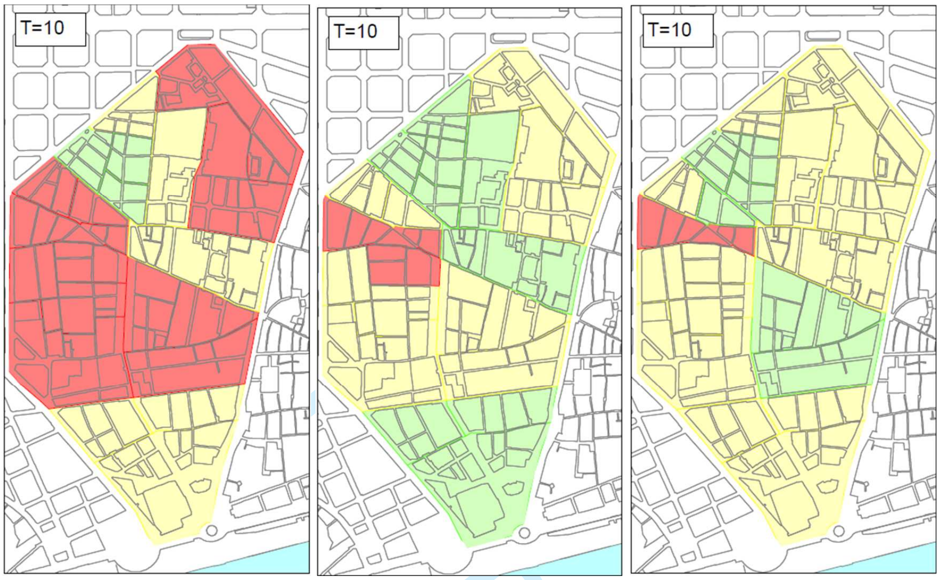

Figure 8. Flood risk maps for BAU1 scenario (on the left), Adaptation 1 scenario (in the centre) and Adaptation 3 scenario (on the right). In red, yellow and green colours, high, moderate and low hazard conditions are respectively shown.

Figure 9.Flood damages for a rain event of 100 year return period in the Raval district, for the baseline scenario (left), the BAU 1 scenario (centre) and the adaptation 3 scenario (right).

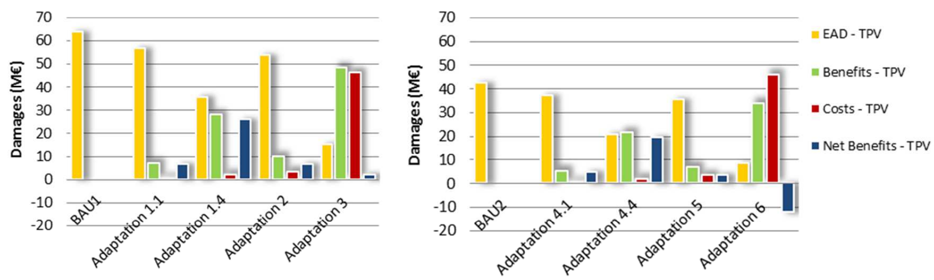

Figure 10.Results of the cost-benefit analysis: Total Present Value of EADs, benefits, costs and net benefits of the several scenarios for the horizon 2050 and a discount rate of 4.0%. Benefits are only focused in Raval District while in some cases they have a wider extension. Scenarios 1.2 and 1.3 (as well as 4.2 and 4.3) are not plotted for the sake of clarity.