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Socio-Economic Assessment of Green Infrastructure for Climate Change Adaptation in the Context of Urban Drainage Planning

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Abstract: Green infrastructure (GI) contributes to improve urban drainage and also has other societal and environmental benefits that grey infrastructure usually does not have. Economic assessment for urban drainage planning and decision making often focuses on flood criteria. This study presents an economic assessment of GI based on a conventional cost-benefit analysis (CBA) that includes several benefits related to urban drainage (floods, combined sewer overflows and waste water treatment), environmental impacts (receiving water bodies) and additional societal and environmental benefits associated with GI (air quality improvements, aesthetic values, etc.). Benefits from flood damage reduction are monetized based on the widely used concept of Expected Annual Damage (EAD) that was calculated using a 1D/2D urban drainage model together with design storms and a damage model based on tailored flood depth–damage curves. Benefits from Combined Sewer Overflows (CSO) damage reduction were monetized using a 1D urban drainage model with continuous rainfall simulations and prices per cubic meter of spilled combined sewage water estimated from literature; other societal benefits were estimated using unit prices also estimated from literature. This economic assessment was applied to two different case studies: the Spanish cities of Barcelona and Badalona. The results are useful for decision making and also underline the relevancy of including not only flood damages in CBA of GI.

Keywords: urban flood; water quality; cost-benefit analysis; modelling; combined sewer overflows

1. Introduction

Green infrastructure (GI)—also recognized with the acronyms NBS (Nature-Based Solutions), SUDS (Sustainable Urban Drainage Systems), LID (Low Impact Development), BMP (Best Management Practices), WSUD (Water Sensitive Urban Design) and many others [1]—contributes to improve urban stormwater management and has several other societal benefits like air quality improvements, reduction of heat island effects, aesthetic and recreational values, and others [2]. Socio-economic assessment of GI is an important tool for urban drainage planning and decision making of climate change adaptation strategies [3].

Several studies have presented socio-economic assessments of different climate change adaptation options focusing on direct and indirect benefits derived from flood damage reduction capacity of GI. Velasco et al. [4] presented a cost-benefit analysis where only direct benefits were included in terms of avoided flood damages obtained by different adaptation scenarios in Barcelona: structural measures (pipe enlargement and stormwater tanks), GI, flood barriers for ground floor doors of businesses and private buildings and early-warning systems. Zhou et al. [3,5] presented a framework and its application to a Danish case study for economic assessment of different climate adaptation options focusing on flood impacts. The economical assessment was based on a cost-benefit analysis (CBA) with direct and indirect benefits derived from flood damage reduction that were monetized using flood models together with damage costs for houses, basements, sewers, roads, lakes and people health and also administrative and traffic delay costs. The damage costs were calculated using unit costs reported from case-specific literature. In these papers, flood adaptation options based on pipe enlargements were compared to stormwater infiltration through GI focusing on flood reduction benefits.

Further studies present socio-economic assessments including additional benefits not only related to direct or indirect flood damages [6]. Löwe et al. [7] presented a cost-benefit analysis (CBA) for comparing different flood adaptation options in Australia. The flood adaptation options consisting of pipe enlargement, flood zoning and rainwater harvesting through GI were compared including flood reduction benefits and also additional benefits derived from reduction of drinking water consumption. Zhou et al. [8] presented an integrated hydrological cost-benefit analysis for comparison of different climate adaptation options such as open urban drainage systems, pipe enlargement and local stormwater infiltration. Here, benefits derived from flood damage reduction were integrated with additional monetized benefits derived from increased property values in the areas where GI was planned and the consequent increase in property taxes. Finally, Cooper et al. [9] presented an integrated costs-benefits analysis of a berm (sea wall) to mitigate the effects of coastal flooding from sea storms. Here, the monetized benefits of the project included: avoided costs derived from building damages, management expenses, fatalities, debris removal, utility and municipal damages; benefits derived from recreational and health value and indirect costs derived from interruption of key transportation and commercial infrastructure located in the area. The recreational and health values were linked to the ecosystem services and health benefits to the surrounding community generated by the planned green areas along the berm.

Further studies underlined the importance of analyzing GI with a multidisciplinary approach. Venkataramanan et al. [10] presented a multidisciplinary literature review focusing on the interaction between human dimensions and socio-ecological-technical systems that are involved with GI in the context of flood risk management. Additionally, Wilkerson et al. [11] analyzed the role of socio-economic factors involved in the planning and management of urban ecosystem services.

The aim of this paper is to present a cost-benefit analysis that includes multiple benefits derived from green infrastructure in the context of urban drainage planning. The novelty of this study is the integration of water quantity and quality and other socio-economic benefits into CBA of GI in the context of urban drainage planning. The application of this analysis to two different case studies can also be considered as novel since the application of CBA is generally used for comparing different adaptation measures within the case study. GI benefits are calculated from direct and indirect flood impacts reduction, water quality related benefits and additional societal benefits. Benefits of flood damage reduction are calculated as avoided direct and indirect flood damage costs to buildings, vehicles, urban infrastructure and indirect costs. Flood damage costs are calculated using coupled 1D urban drainage and 2D surface runoff models together with tailored depth–damage and permeability coefficients functions. Water quality related benefits derived from CSO and waste water treatment cost reduction are calculated using a 1D urban drainage model and costs of wastewater treatment and CSO spills obtained from literature. Finally, additional societal benefits like increased aesthetic value, air quality improvement, habitat provision and reduced urban heat island effect and energy consumption, are calculated based on unit costs from literature. The socio-economic assessment is applied to two different case studies: the Spanish municipalities of Barcelona and Badalona. These two case studies were part of the two European H2020 research projects: BINGO (Bringing Innovation to onGOing water management. www.projectbingo.eu) and RESCCUE (Resilience to Cope with Climate Change in Urban Areas. www.resccue.eu). The aim of presenting two cases is mainly to show that the methodology can be applied to different cases. Nevertheless, the comparison can also bring new points of view in the discussion of GI in the context of urban drainage planning. The methodology proposed can be considered generally applicable to other cities in the context of green infrastructure and urban drainage planning.

2. Materials and Methods

2.1. The Two Case Studies

2.1.1. The Case Study of Barcelona

Barcelona (Figure 1) has an extension of approximately 100 km^2, 1,619,000 inhabitants and it is highly urbanized. An important part of its urban development lies in a flat area up to few tens of meters above mean sea level. The city faces the Mediterranean Sea and approximately half of its coast line is occupied by the harbor and the remaining by sandy beaches. In the opposite side of the sea, there are hills with significant slopes towards the urban area. The great majority of the drainage system is a combined one and Barcelona experiences urban pluvial floods due to intense rainfalls, steep slopes towards the flat urban area, high degree of imperviousness and, in recent years, expansion of new urban areas draining into an older drainage system. The mean annual rainfall is 612 mm/y, the degree of imperviousness is estimated to be approximately 70% of the whole municipal area even though it can reach much higher percentages in the urban areas (see for instance the two zoom-in areas in Figure 1). The city also experiences Combined Sewer Overflows (CSO) that generally occur during rainfall events larger than a few millimeters. CSOs pollute the river Besos (that coincides with the north-eastern boundary of the municipal area shown in Figure 1) and the sea water both in front of the beaches and in the harbor. Figure 1 also shows the planned GI that will be described in Section 2.2.1.

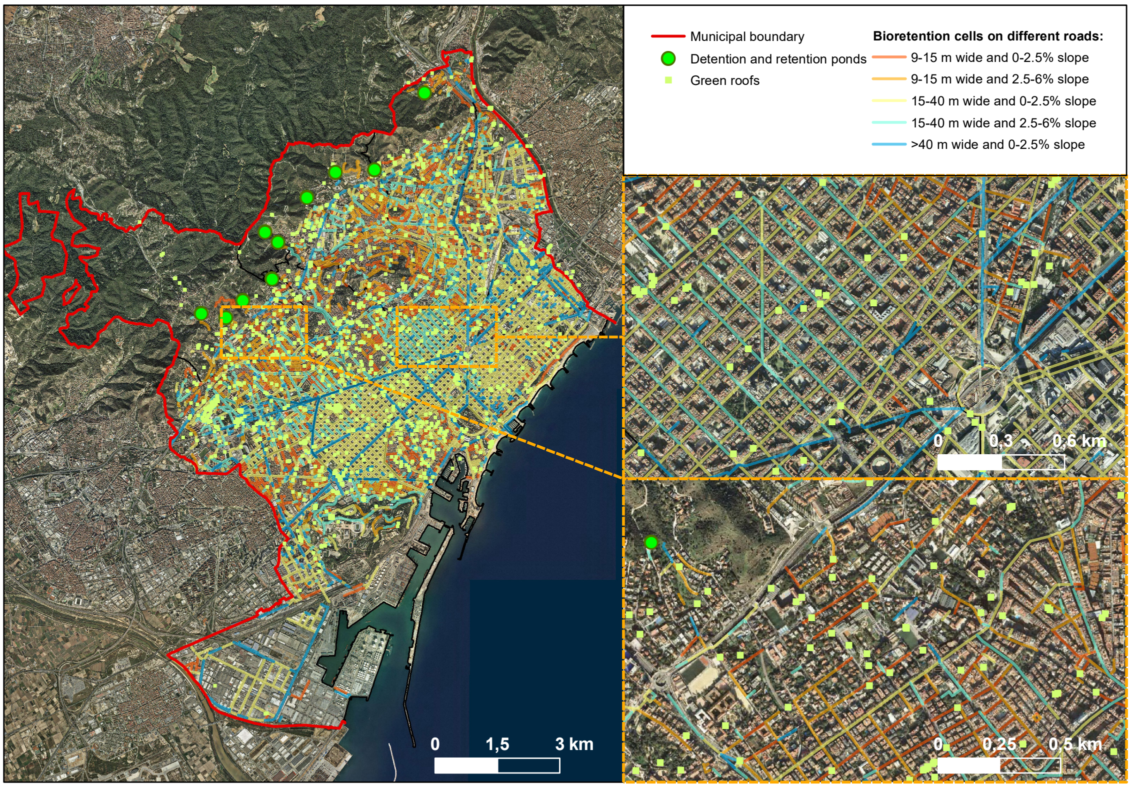

Figure 1. Plan view of Barcelona with all the planned GI: ponds, green roofs and bioretention cells. The colored lines show the classification of five different kind of streets where bioretention cells are planned (a different spatial allocation of bioretention cells was proposed as a function of the different street slope and width).

2.1.2. The Case Study of Badalona

Badalona (Figure 2), within the Barcelona Metropolitan Area, has an extension of approximately 21 km^2, 215,000 inhabitants (the fourth most populated city in Catalonia) and it is highly urbanized. An important part of its urban development lies in a flat area up to few tens of meters above mean sea level. In the north and north-western part of the municipality there are hills with significant slopes towards the urban area. On the opposite side the city has approximately 5 km of sandy beaches facing the Mediterranean Sea. Badalona experiences urban pluvial floods due to intense rainfalls, steep slopes towards the flat urban areas, high degree of imperviousness and, in recent years, expansion of new urban areas draining into an older drainage system. The mean annual rainfall is 568 mm/y, the degree of imperviousness is estimated to be approximately 57% of the whole municipal area even though it can reach much higher percentages in the urban areas (see for instance the two zoom-in areas in Figure 2). Almost all the drainage system is a combined one and CSOs that generally occur during rainfall events larger than a few millimeters pollute the sea water. Figure 2 also shows the planned GI that will be described in Section 2.2.3.

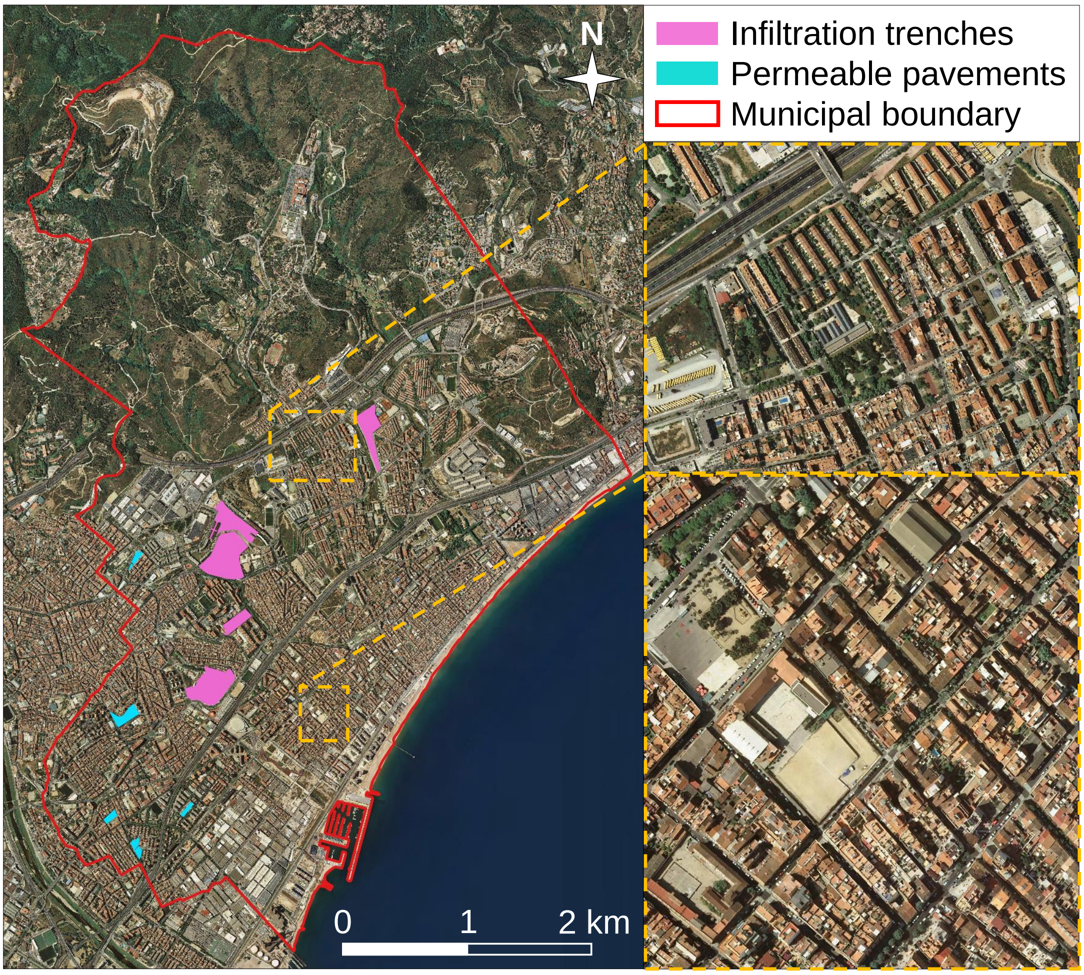

Figure 2. Plan view of Badalona with the planned green infrastructure (green roofs are not shown) and two zoom-in areas for better visualization of the urban environment.

2.2. The Climate Change Adaptation Scenarios

Green infrastructure was one out of the several climate change adaptation options (do nothing, pipe enlargement, new pipes and detention storages and early-warning systems) proposed and analyzed in agreement with the different local stakeholders. In this study, two different adaptation scenarios with future rainfalls are presented: the business as usual (BAU) scenario where no adaptation is considered, and the GI scenario. The BAU scenario is used as a reference scenario when calculating benefits as part of the cost-benefit analysis. Both BAU and GI scenarios were based on future simulated rainfalls. Two kinds of future rainfalls were estimated for each of the two case studies: a future design storm event relevant for single event flood simulations and a future continuous rainfall time series relevant for continuous urban water simulations that aimed at stimulating combined sewer overflows, water quality impacts on the Mediterranean Sea and annual combined sewer water fluxes at waste water treatment plants. The future design storm events were calculated by applying climate factors (CF) to current design storm events according to Arnbjerg-Nielsen et al. [12]. It is noted that significantly different approaches were used in Barcelona and Badalona in order to derive CF. In Barcelona the 50th percentiles of all Representative Concentration Pathways (RCP) 8.5 and 4.5 scenarios were used to compute CF as a function of both different return periods and rainfall durations. Instead, in Badalona the average values of RCP 8.5 were used to compute CF as a function of different return periods. Nevertheless, the obtained climate values are in both cases within the range proposed in other local studies [13]. Details on the derivation of CF and future rainfall time series are provided in the following. Further future climate variables like temperature, sea level rise, wind, solar radiation, etc., were not considered in the current climate change adaptation scenarios even though they likely impact the future urban drainage systems and GI performances [14].

2.2.1. Green Infrastructure in Barcelona

The proposed GI in Barcelona was agreed with local project stakeholders and it was mostly derived from a study of the Municipality of Barcelona [15] that aimed at increasing stormwater exploitation in the city. Three different types of GI were proposed: green roofs, bioretention cells and retention and detention basins. Figure 1 shows the location of GI throughout Barcelona. Extensive green roofs are assumed to be retrofitted to approximately 5% (143 ha) of all the roof area of Barcelona. This percentage was derived from a study for the Municipality of Barcelona [16] that analyzed the roof areas suitable for green roof retrofitting. Bioretention cells with a total area of approximately 181 ha are supposed to be implemented in almost all the streets of Barcelona as shown in Figure 1. The location and preliminary design of these bioretention systems were proposed in a study for the Municipality of Barcelona [15] that suggested five different spatial distribution and capacity of bioretention systems depending on street slope and width (the five street types classified were presented in Figure 1). The proposed systems are made of a top soil and vegetation layer and a deeper layer of more porous material for water detention and infiltration into the underlying soil. The bioretention cells are devised for managing stormwater runoff from part or the whole streets where they are built. Finally, ten retention and detention basins with a total volume of 128,700 m^3 are supposed to be located at the upstream parts of the urban area in order to collect stormwater runoff from the upstream rural areas for a 10-year return period design storm. Approximately half of the basin volume is allocated to retention with infiltration into the ground and the rest to detention and reduction of peak stormwater runoff. Other examples of the combination of retention and detention volumes can be found in the literature [17].

Overall, the GI implementation in Barcelona would reduce the total impervious area by approximately 14% for all the modelled area. Nevertheless, this reduction is higher in the city center reaching approximately 29%. It is noted that bioretention cells and retention and detention basins do manage stormwater runoff from their associated catchment areas (larger areas compared to their physical construction areas).

2.2.2. The Future Rainfalls in Barcelona

The future rainfalls in Barcelona were computed based on the results of CMIP5 climate models considering the RCP scenarios 8.5 and 4.5. Downscaling methods were then applied and verified using both the ERA-Interim re-analysis as a reference for reproducing the past climate variables and other statistical indicators. Future rainfalls were finally derived using both rainfall observations from local rain gauges and different atmospheric circulation models: ACCESS1, BCC-CSM1, CanESM2,

CNRM-CM5, GFDL-ESM2M, HADGEM2-CC, MIROC-ESM-CHEM, MPI-ESM-MR, MRI-CGCM3 and NorESM1. Each model provided past (1951–2005) and future (2021–2100) rainfall time series.

The CF used for flood simulations were computed for both different rainfall durations (5, 10, 15 min, etc.) and different return periods (T = 1, 10, 50, 100 and 500 y) by calculating the rainfall intensity ratio between the simulated future (2071–2010) and simulated historical period (1976–2005). The computed CF were in the range between 1.07 and 1.26 and corresponded to the 50th percentile of the predicted RCP 8.5 and 4.5 scenarios.

The future rainfall time series used for continuous urban water simulations was selected to be the same as the actual one. This choice came after analyzing the predicted future rainfall volume and annual number of rainfall events. The 50th percentile of the latter two variables did not show an increase in the future and therefore, together with the project stakeholders, it was decided to keep the current rainfall time series for continuous urban water simulations of the future climate change adaptation scenarios.

2.2.3. Green Infrastructure in Badalona

The proposed GI in Badalona was agreed together with local project stakeholders that spotted realistic near-future implementation areas. Three different types of GI were selected for the adaptation scenario: green roofs, permeable pavements and infiltration trenches (Figure 2). Extensive green roofs are assumed to be retrofitted to 5% of all the roof area of Badalona. Permeable pavements with a total area of 47,000 m^2 are supposed to be implemented in 7 different public squares and parks. Infiltration trenches are supposed to be implemented in 5 different public parks that have a total area of 298,372 m^2. These trenches are supposed to retain and infiltrate into the ground both the impervious and pervious stormwater runoff from the parks (mostly pervious areas) generated by a design storm of 10 years return period. A total trench volume of 1923 m^3 was estimated (assuming a 95% porosity of the trench filling material).

Overall, the planned GI implementation in Badalona would reduce the total impervious area by approximately 2%. It is noted that infiltration trenches do not reduce impervious areas; however, they do manage stormwater runoff from their associated catchment areas.

2.2.4. The Future Rainfalls in Badalona

Two different sources of future climate data were used in the case of Badalona. The future design storm events for flood simulations were obtained from climate projections results of the EURO-CORDEX project (www.euro-cordex.net) while the future rainfall time series for continuous urban water simulations were obtained from the decadal climate predictions of the Miklip project (www.fona-miklip.de) that were derived from the model MPI-ESM (www.mpimet.mpg.de/en/science/models/mpi-esm/).

The CF used for flood simulations were obtained by calculating the 24 h rainfall intensity ratio between future projections (2051–2100) and historical simulated rainfall (1951–2005). Three different RCP scenarios were analyzed: 8.5, 4.5 and 2.6. The CF obtained with average rainfall intensities from RCP 8.5 scenarios were the ones selected together with the project stakeholders for flood simulations. A CF of 1.15 for the 2-year return period design storm was obtained, 1.07 for the 10-year, 1.02 for the 100-year and 1.01 for the 500-year. In this case, the same climate factor is applied to all rainfall durations. Calculating climate factors from 24 h rainfall intensity ratio can be a limitation [18].

The future rainfall time series used for continuous urban water simulations were obtained in two steps: first, the daily rainfall was obtained using the Daily Spatio-Temporal Stochastic Precipitation Generator [19]; then, disaggregation of daily rainfall into 5 min values was made using a stochastic method that combined both the Bartlett–Lewis process [20] and further procedures (included into the R package 'HyetosMinute') in order to reproduce the 5 min rainfall observations from local rain gauges. This procedure provided an ensemble of 10 different time series with both historical and future rainfall. Only a single time series representing average future rainfall conditions was selected and used for continuous simulations with the urban drainage and the sea water quality model (presented in Section 2.3.2).

2.3. The Cost-Benefit Analysis

2.3.1. Costs

The capital (CAPEX) and operation and maintenance (OPEX) costs of the planned green infrastructure are based on unit costs obtained from both literature and local experience. The costs ranges found in provider websites, unpublished documents and literature have generally a large spread. In this cost-benefit analysis (CBA) the costs were derived partly from literature [21] and partly from unpublished documents and internal research projects. The different costs were converted into the same year value using consumer price indices. The CAPEX of extensive green roofs are assumed to be 80 €/m^2 and the OPEX 2.33 €/m^2/y. Bianchini et al. [22] reported a CAPEX range of 120–152 €/m^2 and an OPEX one of 1–12 €/m^2 for extensive green roofs. The CAPEX of bioretention cells are 45 €/m^2 plus 2.25 €/m^2 for plant implementation and the OPEX 0.45 €/m^3/y. The CAPEX of detention and retention ponds are 100 €/m^2 and the annual OPEX is 1.49% of the CAPEX. The CAPEX of permeable pavements are 49.5 €/m^2 and the OPEX 1.375 €/m^3/y. The CAPEX of infiltration trenches are assumed to be 185 €/m^3 and additional 742 €/m^3 the OPEX 50 €/m^3/y. The additional CAPEX of infiltration trenches in this case include the costs of additional manholes, inlets and pipes that need to be constructed since these systems are supposed to be constructed into a public park area where existing drainage connections are limited. The estimated CAPEX of the infiltration trenches proposed in Badalona are similar to the costs paid by the municipality for an executed project. Zhou et al. [8,23] used investment costs of infiltration trenches in the range between 16 and 91 €/m^2. Alves et al. [6] estimated annual OPEX as 3% of CAPEX costs.

The lifetime of an infrastructure can vary depending on Its maintenance: the higher the maintenance costs the longer the lifetime [24]. In Badalona extraordinary maintenance was assumed to be carried out every 20 years with a cost equal to the 23% of the CAPEX at each intervention. Similarly, in Barcelona it was assumed every 20 years for bioretention cells and 50 years for green roofs and retention and detention ponds with a cost equal to the 50% of the CAPEX at each intervention.

Residual GI value at the end of the project evaluation period was also considered according to European recommendations for evaluations of investments [25]. This reflects the value of the remaining potential use of GI since its services will be provided further beyond the end of the CBA evaluation period [25]. In this study, it was considered as a negative cost but it could also be considered as a benefit as the choice does not affect the net present value Equation (1) (it only affects the graphical presentation of cost and benefits).

2.3.2. Benefits

Several benefits can be included into CBA of green infrastructure [5,9,14]. Benefits can be direct and indirect, tangible (i.e., that can be quantified in monetary values) and intangibles [26]. In this study, direct and indirect tangible benefits are taken into consideration. The benefits of the GI scenario were calculated as avoided damages (or added values) compared to the BAU scenario that is considered to be the reference as typically done in similar CBA [3,5]. In this study, the benefits were organized into 3 different categories for a better representation and discussion of the results:

- Benefits derived from flood damage reduction. Benefits are defined as avoided direct and indirect flood damage costs. Flood damage costs were quantified in terms of Expected Annual Damage (EAD) using a 1D/2D urban drainage model together with design storms and a damage model based on tailored flood depth–damage curves [27]. The direct flood damages were quantified for infrastructure, vehicles, buildings and assets, while the indirect damages for business interruption.
- Benefits derived from water quality improvements. Benefits are defined as avoided direct and indirect damage costs. The direct damages are quantified as environmental costs produced by

CSO spills to receiving water bodies and for avoided costs of combined sewage treatment. Indirect damages are monetized for coastal economies that are affected by the polluted water.

- Additional benefits. Additional indirect benefits are monetized considering: increased aesthetic value, air quality improvement, reduction of the urban heat island effect and energy consumption, and habitat provision [22,24].

Direct flood damages in both Barcelona and Badalona were quantified using coupled 1D/2D (urban drainage/overland flow) models and damage models based on tailored flood damage curves (developed for indoor flood water levels) and permeability coefficient curves that were developed together with flood insurance experts [27]. The damage model takes as inputs the deterministic and spatially distributed values of maximum flood depth simulated with the 1D/2D urban drainage model. The simulated flood depth from the 1D/2D model (considered as outdoor flood depth) is converted into building indoor water levels using the permeability coefficient curves and then the flood damage curves are applied to indoor water levels. In the case of buildings with basements further model parameters control the indoor flood water exchange from ground floor to lower floors. Both the flood models and the damage models (of Barcelona and Badalona) were calibrated and validated using historical data. The flood models used water level data in the drainage network, rain gauge data and photos of urban floods during different past rain events. The damage models used flood insurance compensation data from different flood events during the last few decades [27]. The most influential model parameters of the 1D/2D model were the roughness coefficients of pipes and urban surfaces and of the damage model the parameters controlling the indoor flood water level exchange from ground floor to lower floors [27].

The 1D/2D model provides the maximum simulated flood depth for different design storms of different return periods between 1 and 500 years: 1, 10, 50, 100 and 500 years for Barcelona and 2, 10, 100 and 500 for Badalona. For each return period, the total flood damages at the urban scale were calculated by multiplying the maximum simulated flood depth at each cadastral parcel by permeability coefficients and flood depth–damage curves that were specifically tailored for Badalona and Barcelona for different land uses (hotels, warehouses, restaurants, dwellings, car parks, etc.) and vehicles [28]. The permeability coefficient curves were used to transform the 2D simulated flood levels on the urban floodable area into indoor water levels. Finally, Expected Annual Damage (EAD) was calculated including both direct and indirect damages as detailed in a previous study of Badalona [27]. Indirect flood damages due to business interruptions were estimated at 29% of the total direct damages using an input–output model [27]. This percentage is in the range of other studies that proposed 19–39% [29,30].

The 1D/2D hydrodynamic models were developed with InfoWorks ICM (www.innovyze.com) and calibrated and validated using local rainfall and water level data. The 1D sewer model of Badalona includes approximately 368 km of pipes, 11,338 manholes, 11,954 sub-catchments, 62 weirs, 4 sluice gates, and 1 detention tank of 30,000 m^3. The 2D model has 199,338 cells that form an unstructured mesh generated from a digital terrain model (DTM) of 2 m^2 resolution obtained by a LIDAR with a precision of approximately 15 cm for the altitudes. The size of the 2D cells is in the range of 16–64 m^2 in the urban areas where most of the flood damages occur. The 1D sewer model of Barcelona includes approximately 2041 km of pipes, 85,834 manholes, 980 weirs, 44 sluice gates, 75 pumps and 285 storage nodes representing different kinds of chambers and 10 detention tanks with a total volume of more than 400,000 m^3. The 2D model has 1,361,324 cells that form an unstructured mesh generated from a digital terrain model (DTM) of 2 m^2 resolution obtained from a LIDAR. The size of the 2D cells is in the range of 25–100 m^2.

Direct and indirect water quality benefits were computed using continuous simulation of a 1D urban drainage model to estimate annual volumes of CSO and combined sewage water sent at the treatment plant. The urban drainage models used were the 1D/2D models presented earlier but without the 2D overland flow model. The urban drainage models were then coupled to a sea water quality model [31] to simulate the sea water contamination from CSOs and to estimate the average duration of insufficient bathing water quality. The duration of insufficient bathing water quality was used as an input to a coastal economy model that estimates indirect damages to coastal economies caused by pollution of bathing waters and the consequent reduction of sea related leisure, sport and restoration activities. The coastal economy model includes different contributions. First, the daily direct added value of the coastal economy was calculated by selecting the expected business sectors affected by a beach closure (restaurants, small retails and maritime sector). This selection was based on the results of a field study based on surveys to beach goers and personal interviews to coastal business owners carried out in Barcelona and Badalona (see both H2020 BINGO and RESCCUE projects). Second, based on data from Barcelona's economic annual report [32] a 50% share of the annual coastal economic added value was assumed to come from the bathing season [33], which lasts approximately 3–4 months in Badalona and Barcelona. Only the direct added value of coastal districts (identified by comparing the CSO spill points with the districts maps) affected by CSO spills were included. Furthermore, assumptions of the magnitude of the impact per sector were made based on the results of the local surveys: 50% impact to restaurants, 25% to retails and 25% to maritime sector (water sport and private fishing). The daily economic impact obtained by dividing the value added by the number of days of the bathing season, was finally multiplied by the average number of sea water pollution days (where the beaches could potentially be closed to bathing) to estimate the potential annual indirect damages to the coastal economy.

The different GI systems were simulated in both the 1D and the 1D/2D drainage models by converting the planned GI areas from impervious areas into pervious areas with hydrological losses. This simplified approach was also used by Velasco et al. [4]. However, to the knowledge of the authors, this method was not validated with hydrological data and can be a limitation.

The direct damages produced by CSO spills to receiving water bodies were calculated using a reparation cost method, which assumes that the value of the damage is equal to the cost of repairing it [34]. The direct damage produced by CSO spills was obtained multiplying the average annual CSO volume by the unit CSO damage cost of 0.7 €/m^3 in Badalona. Instead, in the case of Barcelona different values were used: 2.69 €/m^3 for CSOs to the sea and 1.50 €/m^3 to the river and the harbor according to a Spanish regional normative devised for industrial spills [35]. Another benefit considered was the reduction of the sewage water to be treated by the wastewater treatment plants (WWTPs). The monetization of this benefit was calculated as the avoided costs of combined sewer water treatment that were estimated by multiplying the average treated annual volumes from the urban drainage model with a selected unit treatment cost of 0.12 €/m^3 that is considered reasonable for local WWTPs based on local expertise. The tangible indirect damages (and the consequent benefits calculated as avoided damages) to coastal economies were estimated using the pollution time from the sea water quality model and the coastal economy model explained before.

The additional indirect benefits considered are based on four contributions. The first is aesthetic value which is monetized as the willingness to pay for properties nearby, or that include green infrastructure, is measured through the increase of the value of these properties. This value could also include the increased property taxes acquired by the taxation authorities [8]. In this case, the benefits were estimated with a benefit transfer method to be the 3% of the CAPEX of GI [22]. The benefits derived from the reduction of energetic consumption (for indoor heating and cooling) and heat island effect are quantified using 0.049 €/m^2/y per green roof unit surface [24]. Benefits derived from urban heat island reduction obtained with bioretention cells (that in Barcelona are planned) were not included and this can be a limitation. The air quality benefits are derived from both emission reduction (of CO_2 and Nox) capacity of GI that was estimated to be 0.072 ton/ha and the cost of emissions of 3051 €/ton [24,36]. The habitat provision was based on the potential increase of urban ecosystems that support wildlife and it was estimated to be 2.8 €/m^2 for both case studies. This was estimated using a benefit transfer method from a study that assumed the value of habitat creation could be estimated at 15% of the value of natural land [22].

2.3.3. Net Benefits

The net present value (NPV) is calculated using Equation (1)).

$$NPV = \sum_{t=1}^{T} \frac{B_t - C_t}{(1+i)^t} \quad (1)$$

where B_t and C_t are the benefits and costs at each year t, i is the discount rate, T is the project evaluation period.

3. Results

3.1. Costs

Table 1 summarizes CAPEX and OPEX of the green infrastructure proposed in Badalona and Barcelona. The table shows that in the case of Badalona the total costs are approximately an order of magnitude lower compared to Barcelona. Barcelona has a bigger area and a much more ambitious implementation plan compared to Badalona. Further, the total GI costs of Badalona are dominated by green roofs. This is because green roofs are assumed to be retrofitted onto 5% of the total roof area of Badalona, whereas infiltration trenches are placed only on 7 different parks and infiltration pavements on 5 different parks and public squares.

Table 1. CAPEX and OPEX of the analyzed green infrastructure.

	Badalona		**Barcelona**	
	CAPEX [€]	**OPEX [€/y]**	**CAPEX [€]**	**OPEX [€/y]**
Green roofs	14,534,788	405,157	114,752,240	3,342,159
Infiltration trenches	1,783,561	96,150		
Permeable pavements	1,739,183	48,311		
Bioretention cells			85,509,743	1,357,298
Detention and retention ponds			12,870,000	191,763
TOTAL	18,057,531	549,618	213,131,983	4,891,220

3.2. Benefits

The first step in order to estimate benefits derived from flood damage reduction obtained by GI implementation is the estimation of EAD for both the BAU and the GI scenarios. Table 2 shows the EAD results. Generally, the EAD of these two BAU scenarios are considered to be overestimated, particularly in the case of Barcelona (see the Discussion section). Figure 3 shows the flood damage costs simulated as a function of different exceedance probabilities for the two case studies. The EAD that is the area below the curve of Figure 3 was calculated using simple trapezoidal contributions adopting the linear interpolation between the discrete points represented Figure 3.

Table 2. Flood Expected Annual Damage including both direct and indirect damages.

		M€/y
Barcelona	EAD. BAU	62.65
	EAD. GI	33.90
	Flood damage reduction	28.75
Badalona	EAD. BAU	1.93
	EAD. GI	1.86
	Flood damage reduction	0.07

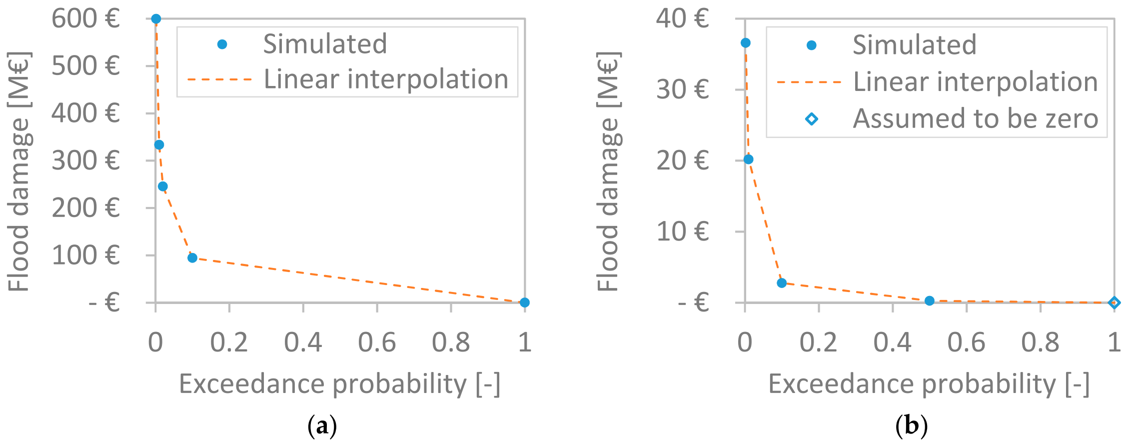

Figure 3. Flood damage as a function of the exceedance probability for Barcelona (**a**) and Badalona (**b**).

Table 3 shows the details of the monetized annual (not discounted) benefits for each of the three categories proposed and their percentage contribution to the total benefits in Barcelona and Badalona. The table shows that the benefits derived from reduced combined sewage treatment costs; from reduced indirect damages to coastal economies; from air quality improvement and from reduction of the urban heat island effect and energetic consumption are in the range of 0–1%.

Table 3. Annual value of benefits (not discounted).

		Barcelona			Badalona		
Benefit Category	**Description**	**Value [€]**	**Percentage**	**Aggregated Percentages**	**Value [€]**	**Percentage**	**Aggregated Percentages**
Benefits derived from flood damage reduction	Avoided direct and indirect flood damage costs	28,745,795	56%	56%	66,536	6%	6%
Benefits derived from water quality improvements	Avoided environmental damage due to CSO to receiving waters	11,876,496	23%	24%	44,306	4%	5%
	Avoided cost of combined waste water treatment	274,985	1%		945	0%	
	Avoided indirect damages to coastal economies	270,474	1%		9043	1%	
Additional benefits	Added aesthetic value	6,393,959	12%	20%	436,044	40%	89%
	Air quality improvement	71,272	0%		3992	0%	
	Habitat provision	4,016,328	8%		508,718	47%	
	Reduction of urban heat island effect and energy consumption	85,031	0%		10,770	1%	
TOTAL		51,734,342			1,080,354		

Figure 4 provides a graphical representation of the contribution of each of the three benefit categories proposed to the total benefits. Overall, significant differences are shown in the percentages of Barcelona and Badalona. In the case of Barcelona, the benefits derived from flood damage reduction are 56% of the total and in Badalona 6%. Additionally, water quality benefits have a larger share in Barcelona compared to Badalona. This is probably because of the widespread GI implementation of Barcelona compared to Badalona where a significantly less ambitious GI implementation plan was considered. A different GI location in Badalona could result in higher water related benefits. Cooper et al. [9] also looked into the contribution of multiple benefits associated to green infrastructure (considered as a coastal flood adaptation measure) showing that benefits from reduced residential damages were 69% of the total, recreational and health benefits 12% and avoided commercial damages 12%.

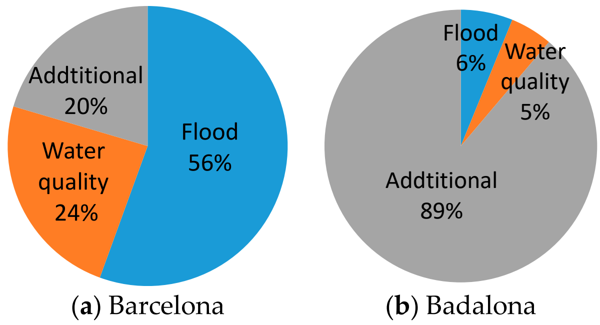

Figure 4. Contribution of each of the three different benefit categories to the total green infrastructure benefits. (**a**) Barcelona and (**b**) Badalona.

Figure 5 shows the discounted benefits during the study evaluation period (80 years, from 2020 to 2100 for the considered scenarios). The results show that the benefits reach their maximum when all GI are implemented: after 20 years in Barcelona and 5 years in Badalona.

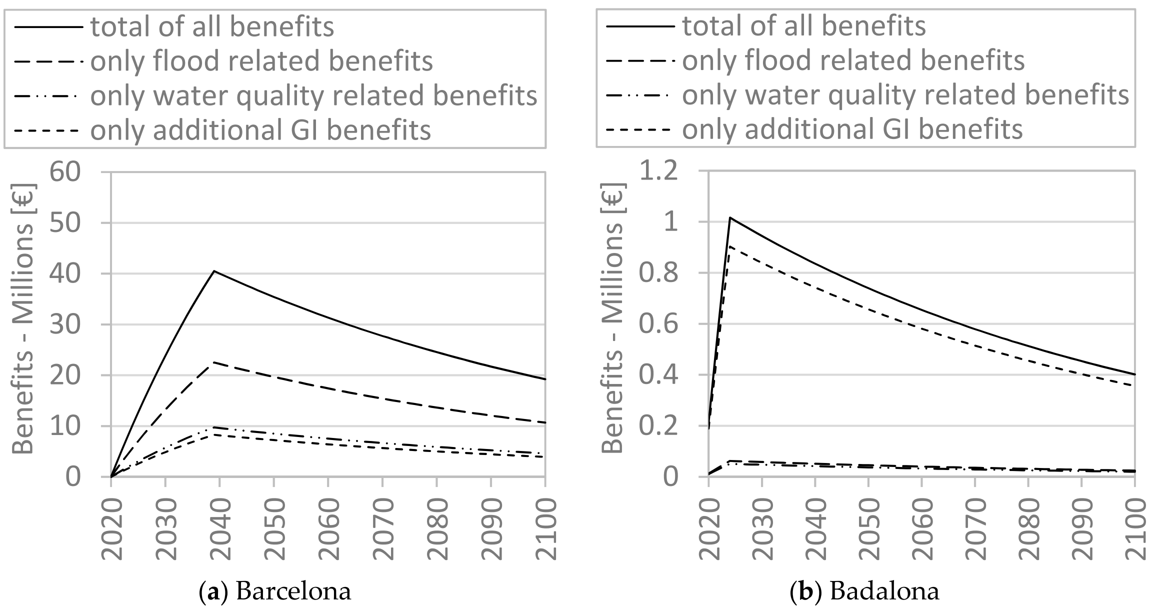

Figure 5. Contributions of the different benefit categories to the total green infrastructure benefits (Discount rate = 1.23%). (**a**) Barcelona and (**b**) Badalona.

3.3. Net benefits

Figure 6 shows the discounted (rate of 1.23%) costs and benefits. Note that the y-axes of Barcelona is approximately an order of magnitude higher than the Badalona one. This figure helps visualizing that the ratio between benefits and costs is generally higher in Barcelona compared to Badalona.

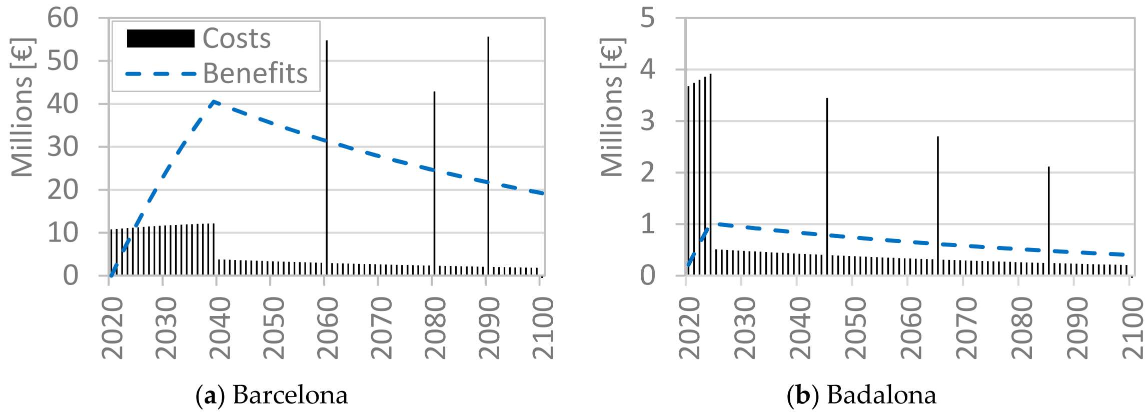

Figure 6. Discounted (i = 1.23%) costs and benefits of green infrastructure. (**a**) Barcelona and (**b**) Badalona.

The evaluation period T in this study was selected to be 80 years in both cases. Similar studies performing CBA for climate change adaptation measures in the context of urban drainage planning used 90 years [23]; 50 years [7] and 35 years [4].

Figure 7 shows the discounted marginal benefits during the project evaluation period. Both Barcelona and Badalona and two different discount rates (1.23% and 4%) were applied. Additionally, three different combinations of benefits are included and shown. First, only benefits derived from flood damage reduction are included, then flood together with water quality benefits and finally all benefits from the three categories proposed: flood, water quality and additional benefits. These three different combinations show that including multiple GI benefits significantly affects the results and this is relevant for decision making of urban drainage planning. In the case of Barcelona, the NPV obtained considering only benefits derived from flood damage reduction and a discount rate of 1.23% (Figure 7a) increases by a factor of 1.74 when including flood and water quality benefits and by 2.37 when including all the three benefits categories. Instead, with a discount rate of 4.00% (Figure 7b), the NPV obtained considering only benefits derived from flood damage reduction increases by a factor of 1.95 when including flood and water quality benefits and by 2.76 when including all the three benefits categories. In the case of Badalona, the NPV also increases significantly by including multiple benefits. In this case, factors of increase of NPV are considered misleading because the NPV is mostly negative. The NPV in Badalona becomes positive only at the last five years of the study evaluation period (Figure 7c).

In the two cases analyzed in this study two different discount rates were considered: the 1.23% that was recommended for climate change adaptation projects in the region of Catalonia [37] where the two considered cities are located and the 4% that was used in another CBA of climate change adaptation measures of Barcelona [4]. The discount rate is a controversial topic in economic valuation of policies, in particular in the context of climate change as it involves intergenerational and social valuation issues (Atkinson et al., 2018). In addition CBA results are very sensitive to the discount rate, particularly for projects with a long time horizon, where small changes of discount rate can influence the suggested decisions [38]. High discount rates imply that future economic impacts would have a lower weight compared to today's value, and could lead to an underestimation of future benefits derived from damage reduction measures [39,40]. A CBA of GI for the case study of Melbourne used 1.4% [7] and the range of 1 to 4% for GI Danish case studies of [3,5]. Some literature also proposed a 1% discount rate (Aaheim, 2010; Lopez, 2008; Stern, 2007). Different public institutions propose different discount rates. For instance, in Denmark, the Danish Environmental Protection Agency (EPA) recommended a 3% for environmental projects while the Department of Finance suggested 5% [5]. The US EPA recommended 2–3% while the American office of management and budget proposed 7% [5]. For developing countries the World Bank recommend 10% because of the significant GDP growth [38,41]. The UK Government proposed 3.5% for project evaluation periods of 1–30 years, 3%

for 31–75 years, 2.5% for 76–125 years, 2% for 125–200 years, 1.5% for 201–300 years and 1% for larger periods [42]. Generally, it is recommendable to consider different discount rates in order to quantify favorable and unfavorable scenarios.

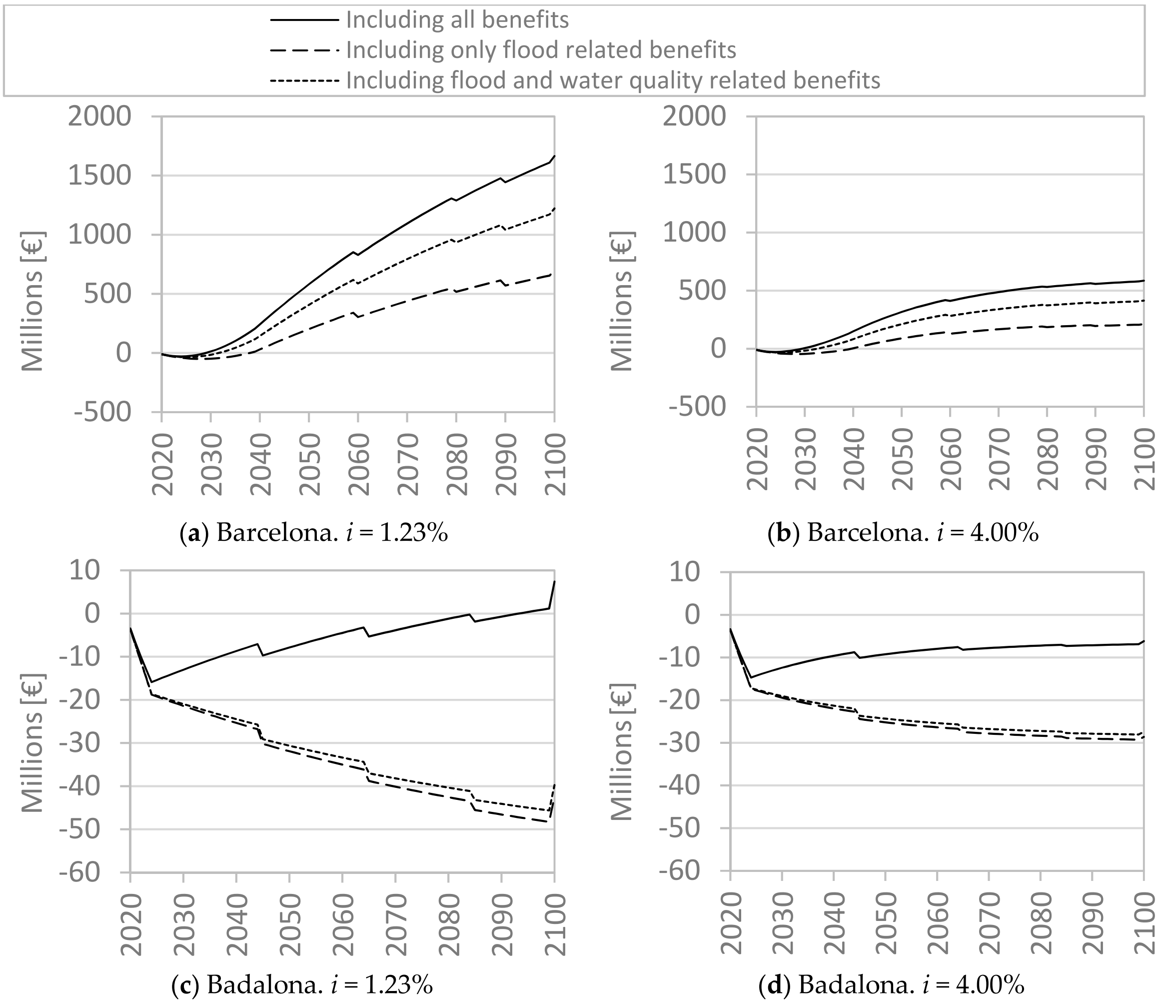

Figure 7. Accumulated marginal benefits of the proposed green infrastructure including different benefit categories and two different discount rates. (**a**) Barcelona with $i = 1.23\%$; (**b**) Barcelona with $i = 4.00\%$; (**c**) Badalona with $i = 1.23\%$; (**d**) Badalona with $i = 4.00\%$.

The cumulative NPV including all benefits in Barcelona becomes positive after 10 years with a discount rate of 1.23% (Figure 7a) and after 11 years with a discount rate of 4.0% (Figure 7b). In Badalona it becomes positive after 75 years with a discount rate of 1.23% (Figure 7c) and it remains negative with a discount rate of 4.0% (Figure 7d). Overall, the GI planning scenario of Barcelona seems to be a better socio-economical option compared to inaction. Instead, the GI planning scenario in Badalona seems to be a worse socio-economical option compared to inaction. Similarly, Zhou et al. [5] presented several stormwater infiltration scenarios that can be considered as GI scenarios showing positive NPV at discount rates of 1% and both positive and negative NPV at discount rates of both 3 and 5%. Zhou et al. [23] presented a negative 50th percentile of the NPV of their stormwater infiltration adaptation scenario. Alves et al. [6] obtained negative NPV for both a green roof and a permeable pavements adaptation scenario and a positive NPV for rainwater harvesting. Zhou et al. [3] reported a positive NPV for their stormwater infiltration scenario.

4. Discussion

This study presented a CBA to evaluate the socio-economic viability of selected GI applied to two different case studies: Barcelona and Badalona. The results are significantly different among the two cases: Barcelona has higher NPV compared to Badalona. Additionally, the accumulated marginal benefits (Figure 7) of Barcelona are mostly positive and become positive after tens of years compared to Badalona where they are mostly negative during the 80 years project evaluation period. The dominating GI benefits (Figure 4) in Barcelona are from flood damage reduction while in Badalona from additional benefits (mostly aesthetic and habitat provision). Direct comparison between the two case studies is difficult for several reasons: the scale difference (Barcelona is much bigger than Badalona), the current situation (Barcelona has much higher flood damage costs than Badalona), the different approaches used to derive CF and the differences of GI planning (Barcelona has an intensive GI implementation plan while Badalona has a sparse one). The fact of having a sparse implementation plan that was not devised to solve particular urban water problems might result in the lower socio-economic performance of the case of Badalona compared to Barcelona. Further comparison between the results obtained in Badalona and Barcelona is considered out of the scope of this study.

Generally, CBA are sensitive to parameter uncertainty and model assumptions. Therefore, quantifying uncertainty of NPV estimations of climate change adaptation options is relevant and in this study only uncertainty related to discount rate was addressed as also done in other studies [9]. Uncertainty is often quantified by analyzing different present and future climate scenarios [4,5,7] and by analyzing different investment options [3]. Zhou et al. [23], instead of using a scenario approach where variables are changed individually, quantified the NPV uncertainties using a Monte Carlo approach to fully explore the propagation of uncertainty from different models and variables choices to the final NPV. A significant source of uncertainty also comes from the hydrological performance of GI [43–45].

Additionally, in this study the EAD is considered to be overestimated, particularly for the case of Barcelona (Table 2) where EAD seems to be high when compared to flood damage compensations data. From 1996 to 2018, pluvial floods, only in the city of Barcelona, have caused more than EUR 34 million in compensations, for industries, offices, dwellings, vehicles and civil works, according to the classification adopted by the Spanish Insurance Compensation Consortium (CCS). In 2018, damages caused by four heavy rainfalls amounted to around EUR 5.5 million. It was the third most damaging year in terms of insurance indemnifications within the last 22 years. The first two years were 1999 and 2002, which compensations amounted to EUR 7.3 million and EUR 6.5 million respectively. Such values only include compensations that the CCS paid. Therefore, total damages (including also indirect damages) are usually higher. Three main contributions were identified to produce the EAD overestimation:

(a) The hyetographs design storms (for all the considered return periods) were obtained from few rain gauges and uniformly applied to the whole catchment area in Barcelona. When calculating flood damages, it can be relevant to use design storms obtained by spatially averaged (over the catchment area) Intensity Duration Frequency (IDF) curves or multiply the rainfall intensity by a reduction coefficient that is a function of the catchment area: the larger the area, the lower the coefficient. In the case of Badalona, the project storm hyetographs presented blocks with maximum rainfall intensity corresponding to different return periods in order to take into account the correspondence of the project storms intensities with the observed rainfall data for extreme events [46].

(b) The discretization used in the flood damage vs exceedance probability curve and the integration method used to compute EAD (the integral of the flood damage curve over the exceedance probability domain) introduced a significant numerical error with consequent overestimation, particularly for the case of Barcelona. Figure 3 showed the flood damage vs exceedance probability for the case of Barcelona together with the linear interpolation lines that were used for the calculation of the area below the curve that corresponds to the EAD. The figure shows that the selected simulated points might not be enough to properly describe the non-linear relation between flood damages and exceedance probability, particularly for the case of Barcelona (Figure 3a) for the range of exceedance probability between 0.1 (10 year return period) and 1 (1 year return period). By introducing new simulation points (for instance at 0.2 exceedance probability) the EAD (the area below the curve) might significantly reduce [4,47].

Even though the EAD is considered overestimated and two main different causes were identified, the EADs for Barcelona were not re-calculated as these values were included in the latest drainage master plan of Barcelona.

5. Conclusions

This study presented a cost-benefit analysis to evaluate the socio-economic viability of GI, which was considered as a climate change adaptation option in the cities of Badalona and Barcelona. The GI planning of the two cities is significantly different: Barcelona proposed a widespread GI implementation plan while Badalona proposed a much lower degree of implementation. CBA is relevant for decision making of urban drainage planning and is useful for comparing different scenarios: in this case a business as usual (BAU) and the GI scenario were compared. Multiple benefits derived from GI implementation were considered and they were grouped into three different categories: benefits derived from flood damage reduction, from water quality improvements and from additional benefits. For each categories both direct and indirect tangible (that can be monetized) benefits were defined and quantified. The largest share of GI benefits in Barcelona was from reduced flood damages (56%), while in Badalona was from additional benefits like added value of properties and habitat provision (89%). The GI benefits derived from reduced sewage treatment costs; from reduced indirect damages to coastal economies; from air quality improvement and from reduction of the heat island effect and energy consumption resulted in the range of 0–1% playing an insignificant role in the socio-economic assessment. The calculated cumulative net present value (NPV) in Barcelona became positive after 10–11 years considering all benefits, whereas in Badalona was mostly negative. Overall, this study presented and quantified how different multiple benefits that can contribute to net present value as part of CBA. The details provided in this paper guarantee the replicability of the presented CBA to other case studies.

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