Assessing the Co-Benefits of green-blue-grey infrastructure for sustainable urban flood risk management

Alves, Alida; Gersonius, Berry; Kapelan, Zoran; Vojinovic, Zoran; Sanchez, Arlex

DOI
10.1016/j.jenvman.2019.03.036

Publication date
2019

Document Version
Accepted author manuscript

Published in
Journal of Environmental Management

Citation (APA)
Alves, A., Gersonius, B., Kapelan, Z., Vojinovic, Z., & Sanchez, A. (2019). Assessing the Co-Benefits of green-blue-grey infrastructure for sustainable urban flood risk management. *Journal of Environmental Management*, *239*, 244-254. https://doi.org/10.1016/j.jenvman.2019.03.036

INTRODUCING CO-BENEFITS OF GREEN-BLUE-GREY INFRASTRUCTURE FOR SUSTAINABLE URBAN FLOOD RISK MANAGEMENT

Alida Alves[a], Berry Gersonius[b], Zoran Kapelan[c,d], Zoran Vojinovic[a], Arlex Sanchez[a]

[a] Department of Environmental Engineering and Water Technology, IHE-Delft, The Netherlands

[b] Department of Water Engineering, IHE-Delft, The Netherlands

[c] Centre for Water Systems, College of Engineering, University of Exeter, United Kingdom

[d] Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands

Alida Alves: a.alves@un-ihe.org

Abstract

Green-blue infrastructures in urban spaces offer several co-benefits besides flood risk reduction, such as water savings, energy savings due to less cooling usage, air quality improvement and carbon sequestration. Traditionally, these co-benefits were not included in decision making processes for flood risk management. In this work we present a method to introduce the monetary analysis of these co-benefits into a cost-benefits analysis of flood risk mitigation measures. This approach was applied to a case study, comparing costs and benefits with and without co-benefits. Different intervention strategies were considered, using green, blue and grey measures and combinations of them. The results obtained illustrate the importance of assessing co-benefits when identifying best adaptation strategies to improve urban flood risk management. Otherwise green infrastructure is likely to appear inferior than more conventional grey infrastructure. Moreover, a mix of green, blue and grey infrastructures is likely to result in the best adaptation strategy as these three alternatives tend to complement each other. Grey infrastructure has good performance at reducing the risk of flooding, whilst green infrastructure brings in multiple additional benefits that grey infrastructure cannot offer.

Keywords: sustainable urban drainage; green-blue-grey infrastructure; flood risk management; co-benefits; decision making; cost-benefits analysis.

1- Introduction

Currently, most people in the world live in cities and urban population is expected to continue growing in the future (United Nations 2014). We need to enhance liveability and sustainability in cities, ensuring that urban spaces are safe and attractive places for living and working. However, climate change and urbanisation are putting this at risk, through problems such as increasing flood risk, heat stress, water shortages and air pollution (IPCC 2012). Green and blue infrastructure (GBI) offer a multifunctional approach which can reduce vulnerability and increase resilience in front of these multiple threats (European Commission 2012a).

Traditionally, flood management was focused on grey or traditional solutions, such as pipes. Nowadays, it is understood that this approach offers low sustainability (Vojinovic 2015). Therefore, decision makers are increasingly considering GBI as an option for climate adaptation. However, even if multi-functionality is recognised as their main strength, these technologies are often evaluated from a single goal perspective, such as storm water management (Engström et al. 2018). But it is through a comprehensive analysis of their multiple benefits that the complete net-benefits of GBI can be understood (Foster et al. 2011). The secondary benefits, besides flood management, are called here co-benefits and are the positive side effects for people and the environment obtained from GBI application.

Economic valuation, including all relevant costs and benefits, is an important tool to support decision-making when planning GBI, particularly when comparing different types of infrastructures investment options (Wild et al. 2017). A frequently used method to estimate the efficiency of projects is cost-benefit analysis (CBA), being the project attractive if the benefits are higher than the costs. In the case of flood management, the comparison is typically between the cost of measures to increase safety and the reduction of expected damages. This method offers significant rational information for decision makers when choosing among different solutions (Jonkman et al. 2004).

Despite the challenges to monetise co-benefits it is recognised that monetary valuation helps to raise policy makers awareness regarding the economic importance of these associated benefits (Chenoweth et al. 2018; Saarikoski et al. 2016). Very few works use net present value assessment over the lifespan of measures to compare sustainable and traditional flood management strategies from a holistic perspective, this is including the multiple benefits offered by GBI. For instance, Urrestarazu Vincent et al. (2017) shown that the economic feasibility of GBI is significantly improved if multiple benefits are considered. A similar result was obtained by and Ossa-Moreno et al. (2017) but working only with sustainable measures.

There is still the need to better understand how costs and benefits change when GBI are combined with grey solutions (Foster et al. 2011). In this paper we address this gap comparing the economic viability of green, blue and grey flood risk reduction strategies, focusing on the combination of different measures. We present a method to perform monetization of co-benefits and to include this into a cost-benefits analysis. Besides the primary benefit of flood risk reduction, several secondary benefits, or co-benefits, are considered in this work. An analysis with and without co-benefits consideration is applied in a case study comparing different strategies combining green, blue and grey measures. The work performed falls into the framework of EC-founded PEARL (www.pearl-fp7.eu; Vojinovic 2015) and RECONECT (www.reconect.eu) projects.

2- Methodology

In a traditional flood management measures assessment, only the primary benefit of flood damages reduction is considered. In this work, several secondary benefits or co-benefits are included, such as heat stress reduction, air quality improvement and water savings. These co-benefits are associated with the application of green and blue measures. Figure 1 summarises the whole methodological process.

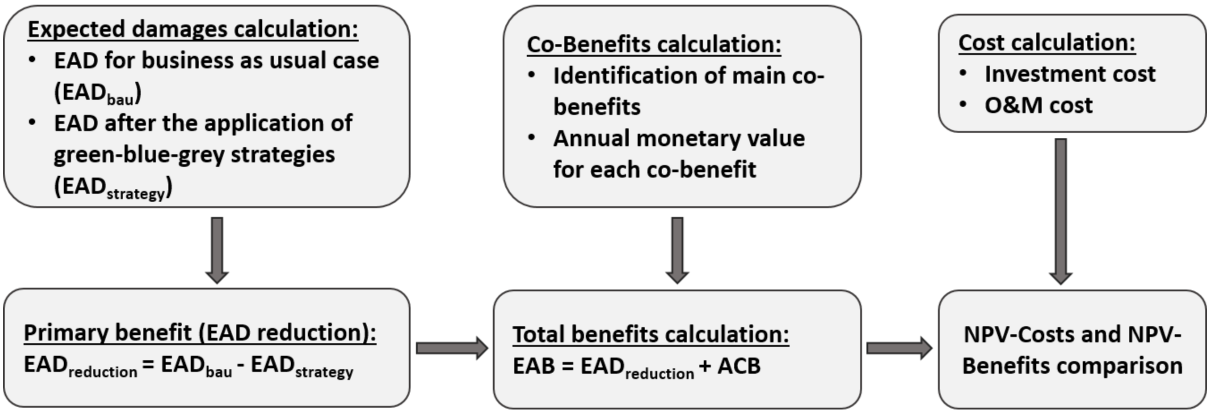

Figure 1: Methodology for total benefits and costs comparison.

The primary benefit, seen here as the benefit obtained from flood damages reduction, is estimated by expected annual damage (EAD). EAD is the probabilistic expected flood damage cost per year for all possible flooding events and is expressed in monetary terms (Delelegn et al. 2011). The flood damages reduction is then calculated as the difference between EAD in the case of business as usual (without measures), and EAD after the application of flood reduction measures.

Since CBA requires the quantification of all costs and benefits in monetary terms, it is necessary to calculate the value of co-benefits. In the present work, every relevant benefit obtained from GBI application (besides the primary benefit) is calculated in monetary terms per year. The addition of EAD reduction and annual co-benefits (ACB), both due to the application of a specific measure or measures combination, is the value of expected annual benefits (EAB).

Regarding costs calculation, investment and maintenance costs of every applied measure are considered here. Once total benefits and costs are estimated, both are converted to the net present value (NPV). This allows the comparison of these figures, seen as present values of costs and benefits, and to stablish which is higher over the project lifespan.

2.1- EAD calculation

An extensively used method to calculate flood damages comprises the use of 2D hydrodynamic models and depth-damages curves. In practice, the damages of flooding are influenced by several factors, but usually water depth is the most influential factor in the case of small scale urban catchments (Delelegn et al. 2011).

Due to the requirements on computational resources and time of 2D models, in this case we estimate damages using a surrogate model. A surrogate model is a model that approximates a more complex and too computationally expensive model, allowing faster approximations (Udoh and Wang 2009). In this case, the surrogate model emulates the original 2D one and is composed by a much simpler 1D-1D model and look-up curves.

To develop the look-up curves, the relation between water depth and the number of affected buildings in several points of the drainage system (look-up points) is needed. Then, combining the use of these look-up curves and depth-damages curves for the area, the value of damages can be estimated for each one of these points. Adding the damages for all the look-up points, the total buildings damage is calculated for a given return period rainfall event. Using this method it is not necessary to run the 2D model for each green-blue-grey strategy and each rainfall event, instead the damages are calculated using water depth results from the 1D-1D model, look-up curves and depth damages curves (see Figure 2).

Once total damages for different rainfall events are estimated, the expected annual damage is calculated using next equation:

$$EAD = \sum_{i=1}^{n}\left(\frac{D_i + D_{i+1}}{2}\right) * \left(\frac{1}{RP_i} - \frac{1}{RP_{i+1}}\right) \qquad (1)$$

where D_i is the damage corresponding to the event of return period RP_i, and n is the number of return periods considered. The damage D is calculated as the addition of damages in the different look-up points.

To apply the concept of EAD, the return periods considered should cover a range going from frequent and not so damaging events, to a very rare event. Moreover, n should be as large as possible in order to have a good scatter of events (Delelegn et al. 2011).

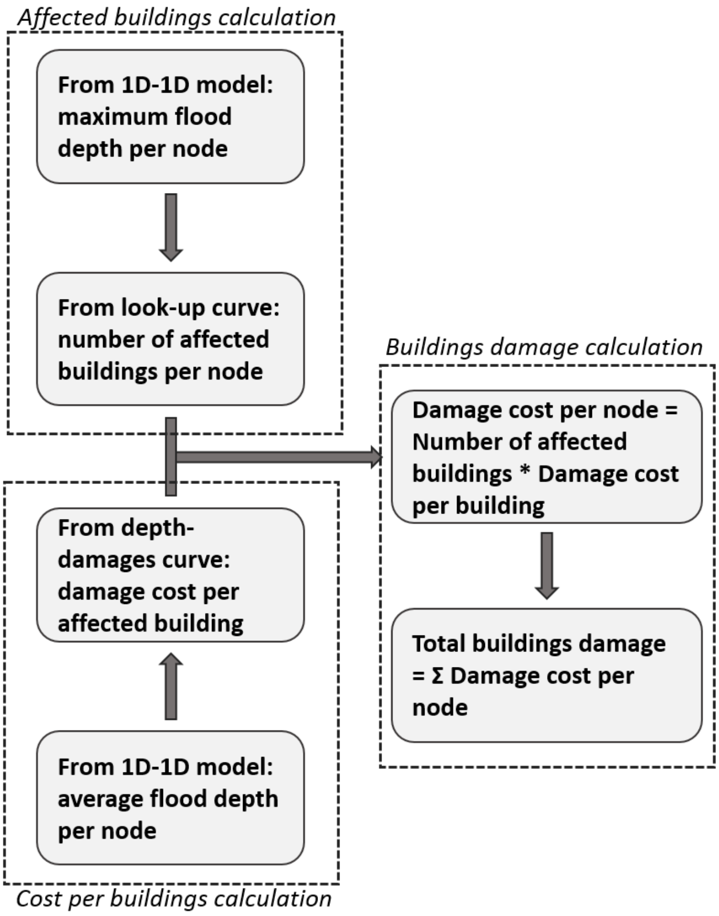

Figure 2: Process for buildings damage calculation.

2.2- Co-benefits calculation

The first step to estimate co-benefits is the identification of locally relevant benefits and the applicable measures to achieve these benefits. To accomplish this, a multi criteria method for measures selection is applied (Alves et al. 2018). This method is based on questions regarding local characteristics and preferred benefits, with the answers given by decision makers a ranking of green-blue and grey measures is built. From this ranking, different combinations of measures are selected for further analysis in this work.

After the selection of measures, and the identification of benefits from them provided, the next step is the calculation of the economic value of these benefits. To achieve this, it is needed to understand the relation between impacts on the environment and the consequent human welfare. A good description of these interactions is provided by Defra (2007) through the concept of impact pathways (see Figure 3).

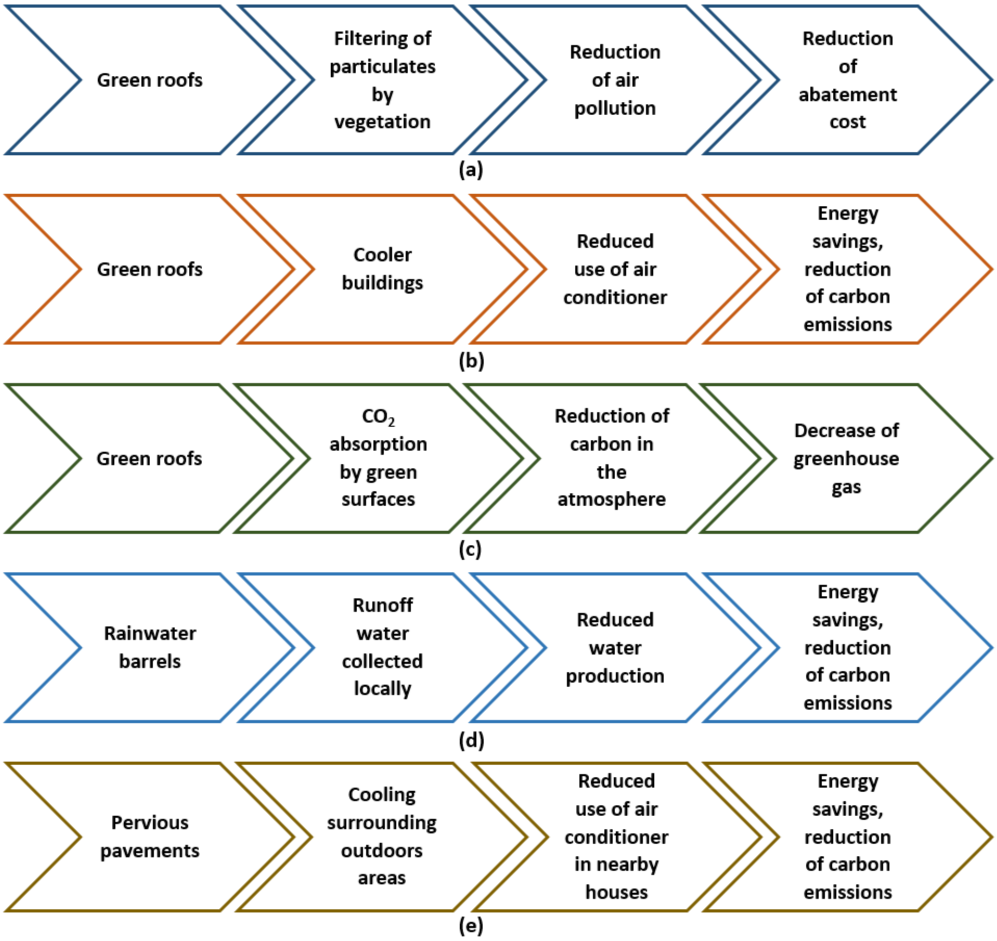

Figure 3: Conceptual analysis of five co-benefits monetization: (a) air quality, (b) buildings temperature reduction, (c) carbon sequestration, (d) rainwater harvesting, (e) heat stress reduction (adapted from Horton et al. 2016).

Always when possible, the economic values of benefits are estimated based on local data, for instance energy and water prices. When local data is not available, general information form literature review is used. There are several published works on co-benefits values estimation, such as Horton et al. (2016), Center for Neighborhood Technology (2010), NYC Environmental Protection (2013), CRC for Water Sensitive Cities (2016), among other. The values of co-benefits are calculated per unit of area of green infrastructure and per year.

2.3- Costs calculation

Costs calculation is based on local prices and literature review. Afterwards, the obtained values are compared with values from other works for validation. Investment and maintenance for the lifespan period are considered. All amounts are converted to the same year valuations using the consumer price index (CPI). Moreover, all values are converted to present values using NPV for the lifespan period of the measures. Next, equations for these two conversions are presented.

$$Value_{year\ A} = Value_{year\ B} * \left(CPI_{year\ A}/CPI_{year\ B}\right) \tag{2}$$

$$NPV = \sum_{i=1}^{m} \frac{Value\ per\ year}{(1+dr/100)^{i}} \tag{3}$$

3- Case Study

3.1- Description

The methodology here presented was applied in a case study in the Dutch side of Sint Maarten Island, located in the Caribbean region. This part of the island covers an area of approximately 3380ha. Elevation ranges from near sea level at the southern end, to hilly areas with until 380m at the northern borderline. Stormwater catchments and streams have several characteristics contributing to severe flood related impacts. For instance, urban areas are situated on low-lying zones, with not good stormwater drainage infrastructure. Besides, streets in residential areas are usually narrow allowing very limited further enlargement of stormwater channels (see also Vojinovic and van Teeffelen 2007).

The catchment selected for this study is called Cul De Sac, which is one of the most vulnerable areas to flooding. This catchment has an area of 509Ha and the land use is predominantly residential, with some dispersed commercial areas in the lower part. During small rainfall events usual impacts include inconveniences such as disruption to transportation systems. However, heavy rainfall causes large-scale flooding with damages to residential and commercial buildings (UNDP 2012).

The local currency is Netherlands Antillean Guilder. However, in practice USD, Euros and the local currency are accepted. Regarding the data used in this work, damage curves are given in Euros, while other information for costs and co-benefits calculations is either in Euros or USD. In this work all values are given in Euros.

3.2- Measures selection and benefits screening

The multi-criteria analysis introduced by Alves et al. (2018) was used to choose the measures to be studied in this work. To apply this method a questionnaire was answered by local decision-makers. The questionnaire was focused on the obtention of local physical characteristics data, such as soil type and water table depth. The respondents also had to define local preferences regarding co-benefits, for instance choosing which benefit is more important between water quality and liveability. The answers were used to develop a ranking of green-blue-grey measures. From this ranking, five measures were selected. Green roofs, pervious pavements and rainwater barrels (as green infrastructure) were chosen to be applied in the flat and more urbanised area of the catchment. Open detention basins (as blue infrastructure) and pipes (as grey infrastructure) were selected to manage runoff from steep areas and for increase the capacity of the existent drainage system, respectively. This analysis considers the existing channels system working properly.

Next, we analyse the main co-benefits obtained through the selected measures and their importance for the case under study. Green roofs offer several benefits besides runoff reduction, such as thermal insulation of buildings and consequently energy savings, air pollution reduction and carbon sequestration, as well as less waste materials due to longer lifespan than traditional roofs (Bianchini and Hewage 2012; Kosareo and Ries 2007; Rowe 2011). Buildings insulation is crucial in this island, which has high temperatures and consequently high energy consumption for cooling. Furthermore, energy savings is very important since the island has expensive energy production. The energy production depends on imported fossil fuel which implies high carbon footprint and air pollutants emission. Additionally, the island has one of the highest regional electricity prices and energy consumption rates (Radjouki and Hooft Graafland 2014).

The installation of rainwater harvesting barrels at household level is a useful measure which allows the reduction of drinking water consumption and water shortages. This is an important benefit in an area where water production and cost have been increasing notoriously in the last 10 years (CENTRALE BANK CURAÇAO EN SINT MAARTEN 2017). The production of water in the island is based on reverse osmosis, an expensive technology which implies high energy consumption (Elimelech and Phillip 2011). Moreover, the Dutch part of the island experiences water shortages during peak consumption hours (European Commission 2012b).

Regarding the installation of pervious pavements, this measure allows urban cooling through lower reflection and higher evaporation (Foster et al. 2011). The reduction of surface temperature due to pervious pavements installation, can reach between 8 and 3 Celsius degrees during day and night respectively (Charlesworth 2010). Benefits obtained from this reduction are energy savings and associated carbon dioxide and air pollutants reduction (USEPA 2012). This temperature reduction is especially important for an area with tropical weather and high average temperatures, resulting in increased cooling energy consumption due to heat stress. In these cases the increment of energy consumption can reach 2 to 4% per each Celsius degree of higher temperature (Akbari et al. 2001; Santamouris 2014).

In a previous work, open detention ponds (ODP) were identified as applicable flood management alternatives in Cul De Sac catchment (UNDP 2012). This was reaffirmed through the measures selection process applied for this case. As a result, in this work we analyse the application of several of these structures in available spaces upstream the flat and more densely populated area. Although multi-functionality can be considered for this measure, allowing co-benefits as recreation and liveability enhancement, this benefit was not included for the present study.

Finally, as grey measure, pipes were chosen to increase the capacity of the existent drainage system in the catchment. This existent system is composed by open channels with limited capacity to convey the excess of rainfall runoff. Several of these channels are located in narrow streets which do not allow their enlargement (UNDP 2012). A single line of big pipes is planned to follow the main channels path from the mid area of the catchment until its discharge downstream.

3.3- Damage calculation

In the present work, the 1D-1D flood estimation model was developed in Storm Water Management Model (SWMM), version 5.0 (Rossman 2010). It includes the main drainage channels in the area, linked to streets and surfaces which represent the floodplain. This model was calibrated with results from an existent 2D model developed in DHI software Mike FLOOD (UNDP 2012). Values of water depths from the previously mentioned 2D model were registered in several points of the drainage system (look-up points) to develop look-up curves (Water Depth-Buildings Damaged curves). The construction of the curves was done obtaining the number of affected buildings for different flood depths in those points.

The look-up points have the same location than the nodes in the 1D-1D model. One look-up curve was built for each of these nodes. Figure 4 shows an example of how to construct look-up curves, it presents a node location, flooding surfaces for different return periods, buildings in the area, and the resultant curve for that node. Once the look-up curves were constructed, the procedure used to calculate damages was as follows. Firstly, changes were made to the 1D-1D model, adding the selected measures for flood risk management. Secondly, the model was run and maximum water depths in each node were registered. With this data, the number of affected buildings per node were obtained from the curves previously built.

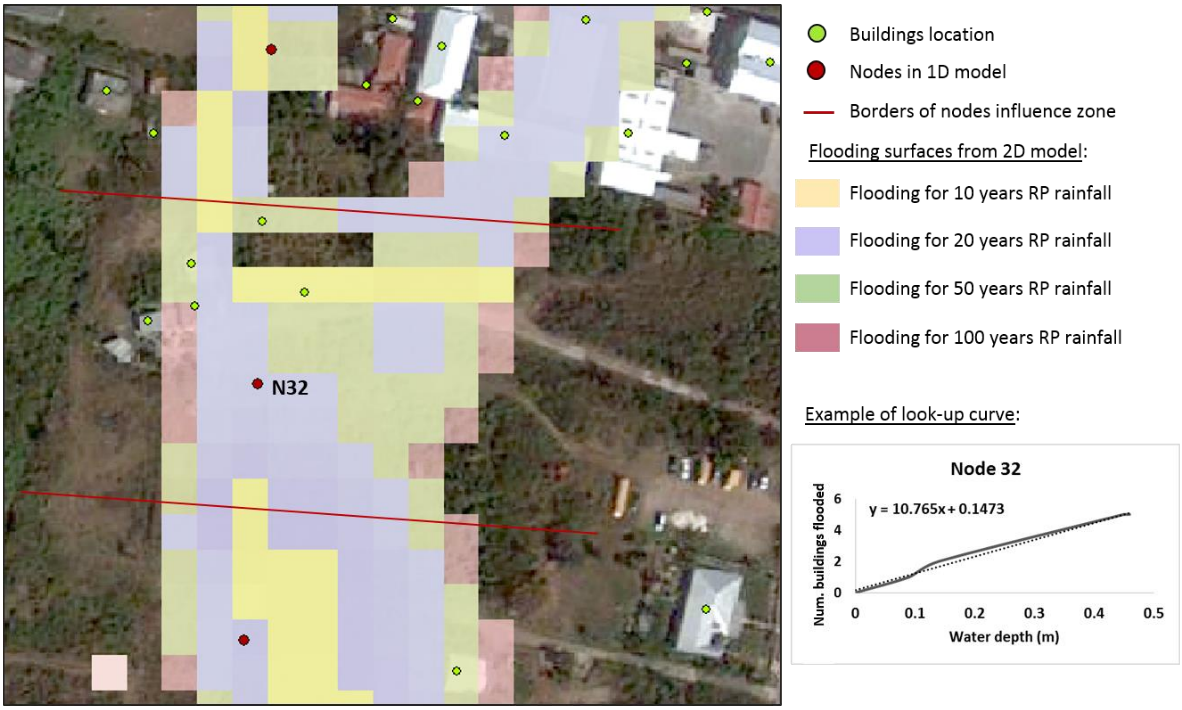

Figure 4: Example of look-up curve calculation for one node.

To estimate damages costs in buildings, Water Depth – Damages curves for residential and commercial buildings in Sint Maarten were used. These curves were obtained from Huizinga et al. (2017), which analyses different damages per continent and includes specific data for the island of Sint Maarten. Combining the results of number of buildings affected and depth-damages curves for the area, residential and commercial damages were estimated for different return period rainfall events, namely 5, 10, 20, 50 and 100 years.

Other damages considered in this study are infrastructure damages and transport damages. Again, values from Huizinga et al. (2017) were used, it gives an estimated cost per square meter of infrastructure damaged, as well as damages functions and maximum transport damage per continent. Using these values and average water depths per node from the 1D-1D model, infrastructure and transport damages per node were estimated. Table 1 shows damage values in the case of business as usual, this is without the application of flood management measures.

Finally, the value of EAD is calculated and converted to present value using NPV estimation. Table 2 shows EAD calculation and results. Notice that this value of EAD, the one corresponding to current situation, is the maximum value obtained. After applying measures, it is expected the reduction of flooding and consequently the reduction of damages.

Table 1: Calculated damages for different return period rainfalls.

Damages (1x10^6 €)	**Return period**				
	5	**10**	**20**	**50**	**100**
Residential	2.8	5.9	13.2	19.7	23.7
Commercial	0.7	0.9	1.3	1.6	1.8
Infrastructure	0.8	1.5	2.6	3.5	3.9
Transport	0.1	0.5	1.7	3.3	4.1
Total	**4.4**	**8.8**	**18.8**	**28.1**	**33.5**

Table 2: EAD calculation for current situation and NPV of EAD in a period of 30 years.

Return period	Event frequency	Damage per event (1x10^6 €)	EAD (1x10^6 €)
2	0.5	0	0.7
5	0.2	4.4	0.7
10	0.1	8.8	0.7
20	0.05	18.8	0.7
50	0.02	28.1	0.3
100	0.01	33.5	
		Total EAD	**3.0**
		EAD NPV_{30}	**46.6**

The period used for NPV calculation was 30 years with 5% discount rate (International Monetary Fund 2016). The period used is considered appropriated without replacement of measures when working with green infrastructure. For instance, different authors establish between 30 and 55 years of lifespan for green roofs (Bianchini and Hewage 2012; Claus and Rousseau 2012; Kosareo and Ries 2007; Porsche and Kohler 2003; Rowe 2011). In the case of pervious pavements, life time before clogging is estimated between 15 and 25 years (Al-rubaei et al. 2013; Pezzaniti et al. 2009; USEPA 2012; Yong et al. 2013). Regarding the discount rate, several studies on this topic were considered to validate this discount rate value. These works consider discount rates varying between 2 and 8 % when working with green measures and flood damage mitigation (Claus and Rousseau 2012; Bianchini and Hewage 2012; Carter and Keeler 2008; Jonkman et al. 2004).

3.4- Co-benefits calculation

Green Roofs

The main direct benefit obtained in this case from green roofs is energy savings due to building temperature reduction. To calculate this benefit, we applied the method presented by Center for Neighborhood Technology (2010). This method provides a simple estimation of building energy savings, seeing green roofs as an insulation and assuming that a reduction in heat flux produces direct energy savings (see Annex 1). The result for this benefit is 1.61 €/m^2/year.

Two indirect benefits are attained from energy savings when, as in this case, energy is obtained from fossil fuel power plants. These benefits are the reduccion of carbon dioxide emissions and the improvement of air quality. Regarding air quality improvement, two pollutants were considered in this work, nitrogen dioxide (NO_2) and sulphur dioxide (SO_2). Again, we used the methods presented by Center for Neighborhood Technology (2010) to calculate the quantities of pollutants avoided and their economic values. Results show that savings due to energy related air quality improvement are 0.08 €/m^2/year; while savings due to reduction of carbon emissions are estimated as 0.17 €/m^2/year.

The installation of green roofs also has a direct impact on air quality improvement. As a consequence, the reduction of four pollutants was considered in this work: nitrogen dioxide (NO_2), sulphur dioxide (SO_2), ozone (O_3) and particulate matter (PM). The benefit obtained in this case is 0.5 €/m^2/year.

Another direct impact of green roofs implementation is carbon dioxide sequestration. Although there are other types of greenhouse gases contributing to climate change, the focus here was on carbon dioxide since is the one most directly affected by green infrastructure (Center for Neighborhood Technology 2010). The direct benefit due to carbon sequestration is 0.03 €/m^2/year.

Finally, an increase on roof longevity is experienced due to the implementation of green roofs. The soil layer of green roofs protects the membrane from weather conditions, incrementing its longevity

(Kosareo and Ries 2007). In this work, an average value of 108 €/m^2 applied every 20 years was considered as the investment avoided for roof retrofitting.

More details about these calculations are presented in Annex 1. The accumulation of direct and indirect co-benefits related to green roofs gives a value of 2.91 €/m^2/y. With an interest rate of 5%, the net present value of benefits over 30 years due to green roofs installation is 447823 €/Ha.

Rainwater barrels

The main co-benefit obtained from applying rain barrels is water savings. In this case, because water is obtained from seawater desalination, the reduction of water production implies energy savings. Moreover, since energy production is oil based, energy savings cause a reduction on carbon emissions and air pollution. Another benefit from using rainwater barrels is freedom from water restrictions, this is the economic value of avoiding drought related impacts, such as loss of amenity and other lifestyle benefits (CRC for Water Sensitive Cities 2016). Figure 5 summarises all the processes considered to calculate these benefits, while in Annex 1 more details regarding these calculations are presented.

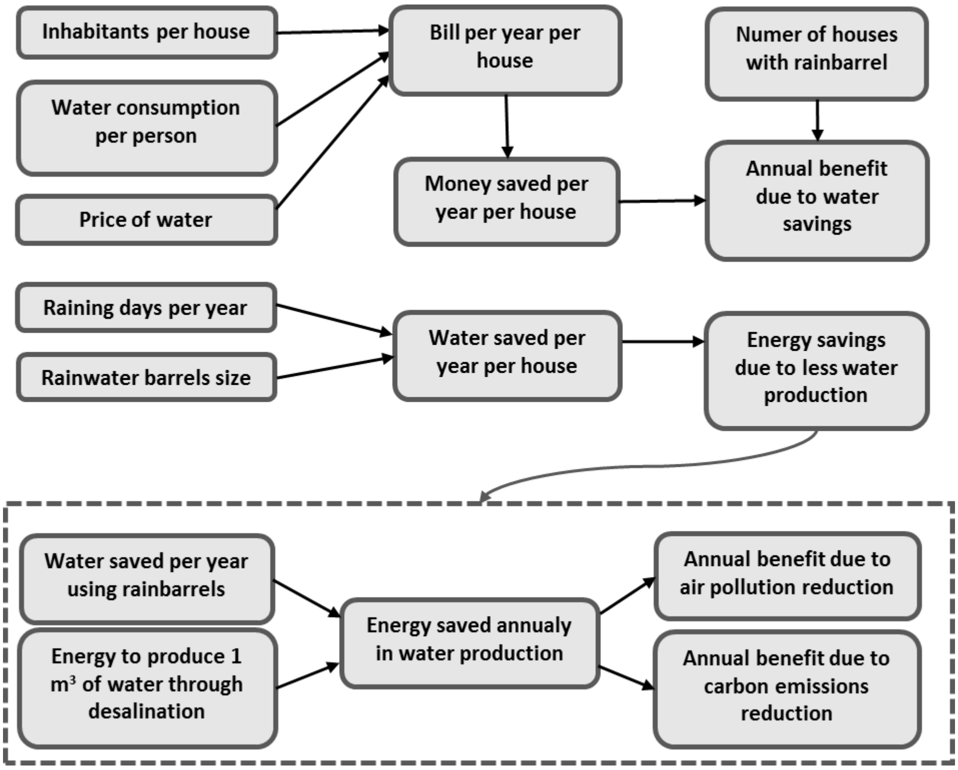

Figure 5: Benefits calculation due to rainwater barrels installation.

The total benefit due to rainwater barrels installation is 2.82€/m^2 of roof connected to a rainwater barrel. With an interest rate of 5%, the net present value of benefits over 30 years due to rainwater barrels installation is 433621 €/Ha.

Pervious pavements

The main benefit considered here due to pervious pavements installation is heat stress reduction. Cooler pavements reduce outdoor temperatures, decreasing the use of air conditioning, hence reducing energy consumption and the emission of CO$_2$ and air pollutants. As stated by Santamouris (2014), cooling energy consumption is increasing de to urban heat insland effect. Moreover, according to Akbari et al. (2001), the demand of electricity in cities is increased by 2 to 4% per each °C of outdoor temperature. The installation of pervious pavements can reduce surface temperatures up to 4°C, due to lower reflection and evaporation when the pavement is wet (Foster et al. 2011). Furthermore, since pervious pavements are more effective on reducing outdoor temperatures when are wet, better results are obtained in warm and humid climates (Santamouris 2013). The results obtained show a reduction of energy consumption in impacted houses of 12%. This number is in agreement with Santamouris (2014), who estimates an energy consumption increment of 13% due to urban heat island effect.

Finally, the benefit of having cooled suburbs in summer was considered (CRC for Water Sensitive Cities 2016). Details about the calculation of these benefits are presented in Annex 1. The total benefit due to pervious pavements installation is 2.87€/m^2 of pavement per year. Considering an interest rate of 5%, the net present value of benefits over 30 years due to pervious pavements installation is 440700 €/Ha.

3.5- Costs calculations

Regarding costs calculation, cost values were taken from local or regional data, combined with inputs from literature review. Several factors were taken into account, for instance that pervious pavements have higher cost than conventional pavements. To estimate this cost, a layer of permeable asphalt or concrete was considered above a highly permeable layer of gravel. Also, a perforated underdrain pipe was included. The construction cost includes excavation, layers and underdrain development and contingencies. Maintenance is mainly cleaning since this measure is susceptible to clogging (Narayanan and Pitt 2006).

Regarding the cost of rain barrels, we considered the cost of 600lts barrels and the pumping system. The operation cost is in this case the enery needed for pumping. The cost presented in Table 3 is per square meter of roof apporting to the barrel. In the case of green roofs, materials and installation of extensive green roof were considered for investment cost calculation, while maintenace includes mainly inspection, vegetation care and roof reparations (Narayanan and Pitt 2006). To estimate the capital costs of earthen open detention basins, regression equations calculated by Narayanan and Pitt (2006) were used. This calculation considers soil movement and compactation assuming that the soil needed is available, and there is not rock excavation nor groundwater problems.

Finally, to calculate the cost of pipes, lookup tables for reinforced concrete pipes (Narayanan and Pitt 2006) were considered together with excavation, bedding and backfill costs. To estimate operation and maintenance costs an annual value of 3% of capital cost was included.

Table 3 summarizes the costs of the structures previously described: open detention basins, pipes and green measures: green roofs, rainwater barrels and pervious pavements. The costs are in euros, actualized according to consumer price index (see Eq. 2) and presented as net present value over a period of 30 years with a disount rate of 5%.

Table 3: Total costs presented as net present value over 30 years

Green-Blue infrastructure	**Total Present Value$_{30}$ (€/m^2)**
Pervious pavements	161
Rain barrels	20
Green roofs	278
Open detention basin	349
Grey infrastructure (pipes diameter)	**Total Present Value$_{30}$ (€/m)**
800 mm	719

1000 mm	894
1500 mm	1534
2000 mm	2947
2500 mm	3615

3.6- Strategies development and results comparison

The evaluation of measures efficiency is performed for different alternatives, considering each measure applied separately and combinations of them. The description of each measure is presented in Table 4. The areas presented for each infrastructure are the maximum possible application for each case. In the case of pervious pavements, it was assumed that these pavements can be installed on 50% of roads in zones of low slope. As a result, this measure covers a maximum of about 5% of the total area. In the case of green roofs and rainwater harvesting, it was assumed that these two measures cover the total area of roofs which represents about 15% of the total area.

Table 4: Total costs, damages reduction and total benefits for green measures (green roofs: GR, pervious pavements: PP, rainwater harvesting: RH) presented as net present values over 30 years

Strategy	Strategy description	Area PP (Ha)	Area GR (Ha)	Area to RH (Ha)	Volume of ODB (m^3)	Pipes Diameter (mm)
PP	Pervious pavements	23.8	0	0	0	0
GR	Green roofs	0	35.7	0	0	0
RH	Rainwater harvesting	0	0	35.7	0	0
ODB	Open detention basins	0	0	0	90750	0
Pi	Pipes	0	0	0	0	2500
PP+GR	Pervious pavements and green roofs	23.8	35.7	0	0	0
PP+RH	Pervious pavements and rainwater harvesting	23.8	0	35.7	0	0
GR+RH	Green roofs and rainwater harvesting	0	35.7	35.7	0	0
PP+GR+RH	Pervious pavements, green roofs, rainwater harvesting	23.8	35.7	35.7	0	0
ODB+Pi	Open detention basins and pipes	0	0	0	90750	2500
ODB+RH	Open detention basins and rainwater harvesting	0	0	35.7	90750	0
Pi+RH	Pipes and rainwater harvesting	0	0	35.7	0	2500
ODB+Pi+RH	Open detention basins, pipes and rainwater harvesting	0	0	35.7	90750	2500

If the ratio between primary benefit and total cost is plotted for each strategy (in blue in Figure 6), we observe that the application of pipes (Pi) appears as the best strategy. This option offers benefits more than two times higher than costs. However, when primary benefits and co-benefits are presented together as total benefits, and the ratio of this value vs. cost is analysed (in red in Figure 6), other strategies appear as good options too. In this case, the options of rainwater harvesting (RH) and its combinations with open detention basins and pipes (ODB+RH, Pi+RH, ODB+Pi+RH), also offer benefits higher than costs. In particular, pipes (Pi), rainwater harvesting (RH), and the combination of both (Pi+RH) appear as the most promising strategies from this analysis.

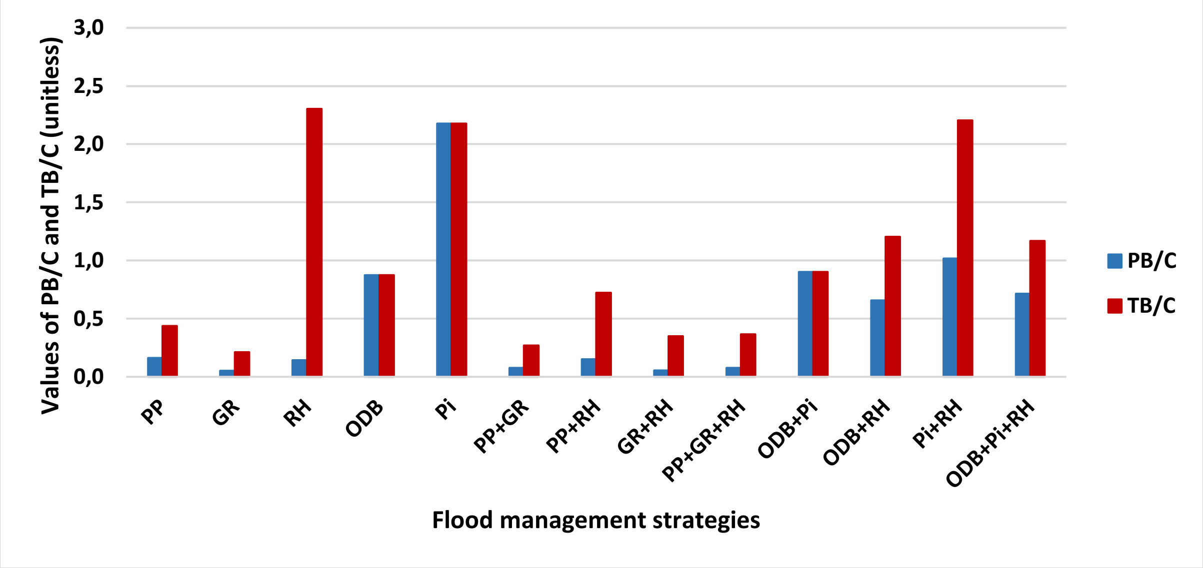

Figure 6: Primary benefit vs. cost (PB/C) and total benefits vs. costs (TB/C) for each strategy.

With the objective of analysing further the options which present total benefits higher than costs, total cost, damages reduction, total benefits and residual damages are plotted in Figure 7. Here we can see that the option of RH, which presented the best ratio between benefits and costs in the previous analysis, does not perform well for the primary benefit, since it presents high residual damages. The strategy with lowest residual damages is the combination of ODB, Pi and RH, but these options presents high costs. An alternative, with higher residual damages but lower costs is the combination of Pi and RH.

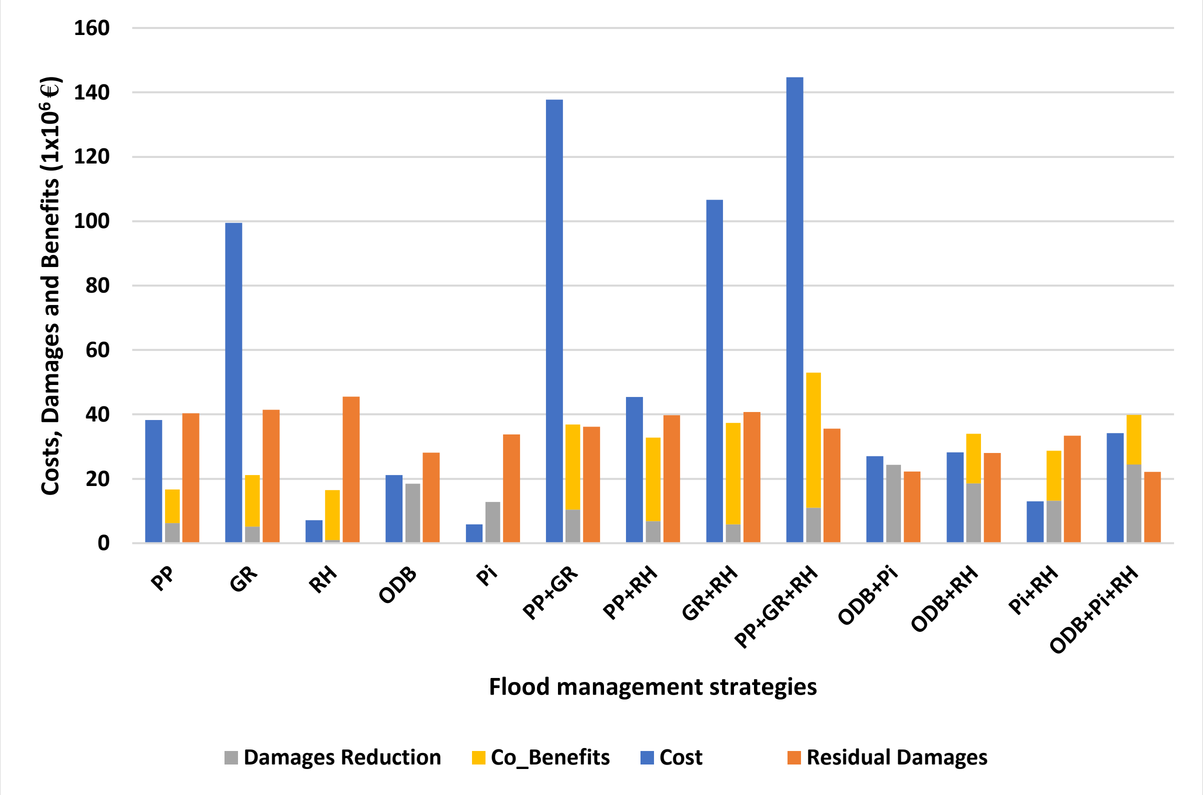

Figure 7: Total costs, total benefits (damages reduction + co-benefits) and residual damages for each strategy.

Klijn et al. (2015) studied how decision-making changes when different criteria are considered. Following a similar analysis, three different rankings were developed (Table 3). The first ranking represents the minimisation of societal cost, calculated as the addition of cost (implementation plus maintenance) and residual damage. The second ranking maximises the ratio between primary benefit and cost, this criterion represents the traditional approach, in which the only benefit taken into account is damages reduction. The third ranking maximises the ration between total benefits and cost, with total benefits being the sum of damages reduction plus co-benefits. If only the first and second rankings are considered (traditional approach), it is clear that pipes is the strategy to apply in this case. However, if the first and third rankings are considered, also RH appears as a good option. In this case the combination of pipes and RH, which is the second option in both cases, seems to be the strategy to choose. Moreover, looking at the third and fourth positions in these rankings, ODB should be included in further analysis as well. This is, combinations of green, blue and grey measures should be evaluated in this case.

Table 5: Rankings according to: societal costs, PB/C (primary benefit/cost), TB/C (total benefit/cost)

Strategy	Societal Cost	PB/C	TB/C
PP	8	7	9
GR	10	13	13
RH	5	9	**1**
ODB	4	4	7
Pi	**1**	**1**	**3**
PP+GR	12	11	12
PP+RH	9	8	8
GR+RH	11	12	11
PP+GR+RH	13	10	10
ODB+Pi	**3**	**3**	6
ODB+RH	6	6	4
Pi+RH	**2**	**2**	**2**
ODB+Pi+RH	7	5	5

In this work only material damages are considered, including buildings, transport and infrastructure. However, if other material damages not considered here, or non-material damages (such as physiological trauma or risk of life) are considered, the importance of reducing residual damages turns crucial. Besides, open detention basins can offer co-benefits such as recreational spaces, which are not considered in this work. For these reasons the option that combines ODB, Pi and RH seems to be the most suitable for the case under study here, even though it does not offer the lowest societal cost, neither the best ratios PB/C or TB/C.

4- Discussion

The main goal of this work was to see how economic viability of different flood management strategies changes when co-benefits are included into the analysis. To achieve this, we presented monetary values of flood damages reduction, co-benefits and costs for different combinations of green-blue-grey infrastructures when several rainfall intensities are considered. The analysis of results shows how the selection of strategies changes when co-benefits are considered. Only grey measures appear as feasible if co-benefits are not considered. However, when these secondary benefits are included, combinations of green-grey measures and green-blue-grey measures appear as economically viable and, at the same time, good to ensure the primary benefit of flood risk reduction. Similar results have been obtained previously by Ossa-Moreno et al. (2017) and Engström et al. (2018).

Our analysis is based on literature review and local and regional data for the case studied here. The numerical results obtained, and rankings of measures developed are valid under the assumptions made for this case. This study does not attempt to provide precise cost and benefits data. Rather, the objective of this work was to show how a holistic approach can help to choose sustainable solutions for urban flood mitigation. Moreover, the analysis presents uncertainties and constraints based on data availability and particularities about local data and local issues.

Despite these uncertainties and constraints, similar values of costs and co-benefits have been found in other works. Comparable values of costs and lifespans for green roofs and pervious pavements have been presented by Engström et al. (2018) and Foster et al. (2011). Regarding co-benefits, Foster et al. (2011) mention values between 25 to 50% of reduction in water consumption due to water barrels installation, we obtained 23% of water savings in this case. The same work presents examples with values between 15 and 45% of annual energy savings due to green roofs installation, while they obtained 4% of energy reduction because of lower cooling costs. In this work we obtained annual energy savings of 12% due to green roofs installation. Finally, we assumed 4°C of surface temperature reduction due to pervious pavements application and their impact on heat stress mitigation, again, a similar value than the one obtained by Foster et al. (2011). We obtained 12% of energy savings in houses located close to pervious pavements, a similar result was obtained by Santamouris (2014).

In this work, only case relevant and easily quantifiable co-benefits were considered. As a result, the values of co-benefits obtained were relatively low. These values can be enlarged if other benefits are considered, such as enhancement of biodiversity, health, water quality, property value, etc. Future work should include a broader range of co-benefits.

Concerning runoff reduction, the results obtained indicate low values of damages reduction when only green measures were applied. This result is adequate considering that five return period rainfalls were considered, including extreme events with 50 and 100 years of return period. Other authors have found green and blue-green measures effective on providing flood reduction benefits (Haghighatafshar et al. 2018; Kong et al. 2017), but the reduction of this effectiveness under strong rainfall events has been argued as well (Versini et al. 2018; Zölch et al. 2017).

For the case studied here, rainwater harvesting appears as an efficient measure if co-benefits are taken into account. However, this measure is not effective for flood management. This remarks the importance of keeping the focus on the primary function for which the measures are applied. If the focus is shifted to co-benefits maximisation, there is the risk of not achieving the flood mitigation pursued. The option with best performance regarding flood damages reduction is the combination of the three measures: rainwater harvesting, open detention basins and pipes. While the second highest value of flood damages reduction is obtained combining open detention basins and rainwater harvesting.

Following a traditional approach, the pipes system appears as the only measure which achieves benefits higher than costs and effective flood damages reduction. However, through this work we proved that net benefits can be much enlarged if pipes are combined with rainwater harvesting. As a result, the combination of these two measures is the best option if the objective is to maximise benefits in the case here studied. But, if the main objective is to minimise flood damages and maximise positive net benefits, the best option will be a combination of pipes with rainwater harvesting and open detention basins.

Future work is needed to further understand how the flood mitigation and co-benefits can be maximised while costs are minimised. Urban drainage systems are complex systems and the combination of different strategies to achieve several different benefits makes the problem even more complex. Additional work should focus on understanding how different combinations of measures can be better designed to improve efficiency.

5- Conclusions

In this work we present a method to introduce the monetary analysis of co-benefits into a cost-benefits analysis of flood risk mitigation measures. Traditionally, the benefits of green infrastructure other than flood risk reduction were not taken into account in decision making processes. Several such co-benefits were considered in this work: water savings, energy savings due to less cooling usage, air quality improvement and carbon sequestration. The above approach was then applied to a case study, comparing costs and benefits with and without co-benefits. Different intervention strategies were considered, using green, blue and grey measures.

The results obtained illustrate in quantitative terms how the viability of green and blue infrastructure for flood mitigation can be improved substantially when co-benefits are considered. In the case analysed here, costs outweigh benefits for all the green strategies if co-benefits are not included. This means that the traditional grey option appears as the only economically viable strategy if co-benefits are not considered. Thus, it is important to assess co-benefits when identifying best adaptation strategies to improve urban flood risk management, otherwise green infrastructure is likely to appear inferior than more conventional grey infrastructure.

When co-benefits are considered for the same case, the option of rainwater harvesting offers benefits higher than costs. However, this alternative has bad performance achieving the primary benefit (flood damages reduction). This issue can be solved, and net benefits maximised, if rainwater harvesting is combined with pipes, i.e. if green-grey strategy is used. Moreover, the reduction of flood damages is maximum, maintaining positive net benefits, if these two measures are mixed with open detention basins (green-blue-grey strategy). Consequently, a mix of green, blue and grey infrastructures is likely to result in the best adaptation strategy as these three tend to complement each other. Grey (and blue) infrastructure excels at reducing the risk of flooding whilst green infrastructure brings in multiple additional benefits that grey infrastructure cannot deliver.

Acknowledgment

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under Grant agreement n° 603663 for the research project PEARL (Preparing for Extreme And Rare events in coastaL regions), and from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 776866 for the research project RECONECT. The study reflects only the authors' views and the European Union is not liable for any use that may be made of the information contained herein.

Appendix

Green roofs co-benefits calculation:

Equation 1.1 presents the calculation of energy savins due to green roofs implementation:

$$Annual\ energy\ savings\ (kWh/m^2) = C\ \times \left[\left(\frac{1}{R_{conv\,roof}}\right) - \left(\frac{1}{R_{green\,roof}}\right)\right] \times \frac{24hrs}{day} \times 0.00315 \qquad (3)$$

where C = annual number of cooling degree days (°F*days); $R_{conv\ roof}$ = thermal resistance for conventional roofs (11.34 SF*°F*hrs/BTU); $R_{green\ roof}$ = thermal resistance for green roofs (23.4 SF*°F*hrs/BTU); 0.00315 is factor to convert from BTU/SF to kWh/m^2; BTU = Brithish termal units.

Annual cooling degree days is an estimation of how hot the climate is and is used to calculate the energy needed to keep buildings cool. This value is calculated as the difference between a balance temperature and the mean daily temperature, and adding only positive values over an entire year. In this case the estimation of annual cooling savings was done considering four months of 27 celsius degrees as an average (Meteorological Department St. Maarten 2018), with 20 celsius degrees as balance temperature.

Table 1.1 shows savings and prices for all the benefits obtained from green roofs installation. For instance, values of energy saved and price (National Renewable Energy Laboratory 2015) due to building insulation are presented. Concerning the calculation of carbon dioxide reduction due to energy savings, emissions due to oil based electricity production were estimated as 1.616 lb CO_2/kWh (WNA 2011). An average carbon price of 0.02 €/lb CO_2 was assumed (Center for Neighborhood Technology 2010).

Regarding direct air quality improvement, the quantities of air pollutants directly removed per square meter of green roof and per year, as well as the economic value of these pollutants, are average values provided by Center for Neighborhood Technology (2010). In the case of direct carbon sequestration, the annual amount of carbon sequestered is calculated as the total area of green roofs times the average annual amount of carbon sequestered per unit area of green roof. The range of carbon sequestered per area of green roof considered is 162 to 168 g C/m^2 (Getter et al. 2009).

About the calculation of savings due to the increment of roof longevity, a conventional roof has a lifespan of between 10 and 20 years (Claus and Rousseau 2012; Kosareo and Ries 2007). While the lifespan of green roofs is expected to be between 40 and 55 years (Bianchini and Hewage 2012; Carter and Keeler 2008; Claus and Rousseau 2012; Rowe 2011). Finally, values of re-roofing are established between 92 and 160 USD/m^2 (Bianchini and Hewage 2012; Montalto et al. 2007).

Table 1.1: Calculation of green roofs annual benefits

Building temperature: energy savings (direct)			
Cooling savings (KWh/m^2)	5.38	Energy price (€/KWh)	0.3
Air quality due to energy savings (indirect)			
Electricity production by fossil fuel produces the emission of NO_2 and SO_2			
NO_2 avoided (g/KWh)	0.88	NO_2 value (€/g)	0.0063
SO_2 avoided (g/KWh)	2.39	SO_2 value (€/g)	0.0039
Carbon reduced due to energy savings (indirect)			
Electricity production by fossil fuel produces the emission of CO_2			
CO_2 avoided (g/KWh)	733.02	CO_2 value (€/g CO_2)	0.00004
Air quality: pollutants removal (direct)			
NO_2 removal (g/m^2/y)	2.33	NO_2 value (€/g)	0.0063
SO_2 removal (g/m^2/y)	1.98	SO_2 value (€/g)	0.0039
O_3 removal (g/m^2/y)	4.49	O_3 value (€/g)	0.0063
PM removal (g/m^2/y)	0.65	PM value (€/g)	0.0054
Carbon sequestration (direct)			

C sequestred (g C/m^2/y)	165	C value (€/g CO$_2$)	0.00004
C to CO$_2$ (g CO$_2$/g C)	3.67		
Increment of roof longevity **(direct)**			
		Investment avoided (€/20y/roof)	108
		Total Benefit Green Roof (€/m^2/year)	**2.91**

Rainwater barrels co-benefits calculation:

Considering a population of 40009 inhabitants and annual water production of 4836x10^3 m^3 (Central Bureau of Statistics 2009), the average consumption of water is 10m^3 per month. Assuming three people per house (Department of Statistics 2011) and an average water price of 3€/m^3, the cost of water per house and per month is 89€. If a barrel of 600 liters is installed, and considering that in average it rains 12 days per month (Meteorological Department St. Maarten 2018), about 7.25m^3 are saved per house per month. It means that 22 €/house/year are saved.

Drinkable water is obtained in the island through seawater desalination, in this process energy is consumed and CO$_2$ released. Therefore, savings on water consumption are indirect savings of energy and less CO$_2$ released. Energy consumption due to seawater desalination is estimated as 3 to 4 kWh/m^3 of water produced (Elimelech and Phillip 2011). Considering the same energy price than in the case of green roofs, 6.5€ are saved per house and per month. Also, like in the case of green roofs, oil based energy production releases air pollutants, following a similar calculation than for the case of green roofs, the benefit in this case is 3.9€/house/year. Regarding the decrease of CO$_2$ released, it is estimated that 1.4 to 1.8 Kg of CO$_2$ are released by each m^3 of desalinated water (Elimelech and Phillip 2011). Again, following a similar calculation than in the case of green roofs, the benefits due to carbon emissions reduction is 5.3 €/house/year.

Finally, for each house free of water restrictions, the benefit is equivalent to the willigness to pay for the impact of droughts avoided, estimated as 74 to 137 €/house/year (CRC for Water Sensitive Cities 2016). In this work the benefit considered is 74 €/house/year. The average roofs size is assumed as 150m^2.

Pervious pavements co-benefits calculation:

In this work, energy savings due to pervious pavements installation were calculated considering that the impact of outdoors temperature reduction reachs the houses located directly in front of these pavements. Therefore, to estimate the number of houses impacted, the length of pervious pavements installed was taken into account as well as an area covering about 50m each side of the pavement. A 3% of energy reduction per each °C of temperature decreased was assumed. The temperature reduction achieved was assumed as 4°C per each raining day, with a total of 145 raining days per year (Meteorological Department St. Maarten 2018).

The average domestic electricity bill in Sint Maarten is 172€ per month and per house (Radjouki and Hooft Graafland 2014). Therefore, the benefit due to energy savings is around 98€ per impacted house and per year. Regarding the indirect benefits of energy savings, the benefit due to air pollutants reduction is 12.8 €/house/year, while the benefit due to carbon emissions reduction is 22.6 € per year and per impacted house. Regarding the benefit of having cooled suburbs in summer, the value of this benefit is sustained in the willingess to pay for improvements in human thermal comfort and avoided halth care costs. This value is established between 30 and 51€/year per house which experiments a reduction of peak summer temperature of 2°C (CRC for Water Sensitive Cities 2016). In this work an average value of 40€/year per impacted house is considered.

References

Akbari, H., Pomerantz, M., and Taha, H. (2001). “COOL SURFACES AND SHADE TREES TO REDUCE ENERGY USE AND IMPROVE AIR QUALITY IN URBAN AREAS.” *Solar Energy*, 70(3), 295–310.

Al-rubaei, A. M., Stenglein, A. L., Viklander, M., and Blecken, G. (2013). “Long-Term Hydraulic Performance of Porous Asphalt Pavements in Northern Sweden.” *J. Irrig. Drain Eng. (ASCE)*, 139(6), 499–505.

Alves, A., Gersonius, B., Sanchez, A., Vojinovic, Z., and Kapelan, Z. (2018). “Multi-criteria Approach for Selection of Green and Grey Infrastructure to Reduce Flood Risk and Increase CO-benefits.” *Water Resources Management*, Water Resources Management, 32(7), 2505–2522.

Bianchini, F., and Hewage, K. (2012). “Probabilistic social cost-bene fi t analysis for green roofs : A lifecycle approach.” *Building and Environment*, Elsevier Ltd, 58, 152–162.

Carter, T., and Keeler, A. (2008). “Life-cycle cost – benefit analysis of extensive vegetated roof systems.” *Journal of Environmental Management*, 87, 350–363.

Center for Neighborhood Technology. (2010). *The Value of Green Infrastructure: A Guide to Recognizing Its Economic, Environmental and Social Benefits*.

Central Bureau of Statistics. (2009). *Statistical Yearbook of the Netherlands Antilles 2009 (http://digitallibrary.cbs.cw/CBS0000005/00053)*.

CENTRALE BANK CURAÇAO EN SINT MAARTEN. (2017). *The Economy of Curaçao and Sint Maarten in Data and Charts*.

Charlesworth, S. M. (2010). “A review of the adaptation and mitigation of global climate change using sustainable drainage in cities.” *Journal of Water and Climate Change*, 1(3), 165–180.

Chenoweth, J., Anderson, A. R., Kumar, P., Hunt, W. F., Chimbwandira, S. J., and Moore, T. L. C. (2018). “The interrelationship of green infrastructure and natural capital.” *Land Use Policy*, 75, 137-144.

Claus, K., and Rousseau, S. (2012). “Urban Forestry & Urban Greening Public versus private incentives to invest in green roofs : A cost benefit analysis for Flanders.” *Urban Forestry & Urban Greening*, Elsevier GmbH., 11(4), 417–425.

CRC for Water Sensitive Cities. (2016). *Enhancing the economic evaluation of WSUD. CRC for Water Sensitive Cities*, Cooperative Research Centre for Water Sensitive Cities, Melbourne, Australia.

Defra. (2007). *An introductory guide to valuing ecosystem services*. London, UK.

Delelegn, S. W., Pathirana, A., Gersonius, B., Adeogun, A. G., and Vairavamoorthy, K. (2011). “Multi-Objective Optimization of Cost-Benefit of Urban Flood Management using a 1D2D Coupled Model.” *Water Science and Technology*, 63(5), 1054.

Department of Statistics. (2011). “Department of Statistics - Sint Maarten.” *Census 2011 (http://www.stat.gov.sx/)*.

Elimelech, M., and Phillip, W. A. (2011). “The Future of Seawater Desalination: Energy, Technology, and the Environment.” *SCIENCE*, 333(August), 712–718.

Engström, R., Howells, M., Mörtberg, U., and Destouni, G. (2018). “Multi-functionality of nature-based and other urban sustainability solutions: New York City study.” *Land Degradation and Development*, (June), 3653–3662.

European Commission. (2012a). *The Multifunctionality of Green Infrastructure*. *Science for Environment Policy*, Bristol, England.

European Commission. (2012b). “INTERNATIONAL COOPERATION AND DEVELOPMENTBuilding partnerships for change in developing countries.” *Single Programming of Curacao, Sint Maarten,Bonaire, Sint Eustatius and Saba under 10th EDF*, <https://ec.europa.eu/europeaid/sites/devco/files/spd-10th-EDF-Curacao-Sint Maarten-Bonaire-Sint Eustatius-Saba-20120629_EN.pdf> (Dec. 28, 2017).

Foster, J., Lowe, A., and Winkelman, S. (2011). “The Value of Green Infrastructure for Urban Climate Adaptation.” *The Centre For Clean Air Policy*, (February), 52.

Getter K., Rowe D. B., Robertson G. P., Cregg B. M., A. J. A. (2009). “Carbon Sequestration Potential of Extensive Green Roofs.” *Environ. Sci. Technol.*, 43(19), 7564–7570.

Haghighatafshar, S., Nordlöf, B., Roldin, M., Gustafsson, L. G., la Cour Jansen, J., and Jönsson, K. (2018). “Efficiency of blue-green stormwater retrofits for flood mitigation – Conclusions drawn from a case study in Malmö, Sweden.” *Journal of Environmental Management*, 207, 60-69.

Horton, B., Digman, C. J., Ashley, R. M., and Gill, E. (2016). *BeST (Benefits of SuDS Tool) W045c BeST - Technical Guidance Release version 2*.

International Monetary Fund. (2016). *KINGDOM OF THE NETHERLANDS — CURACAO AND SINT MAARTEN*. Washington, D.C.

IPCC. (2012). *Managing the Risks of Extreme Events and Disasters To Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*. (and P. M. M. C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, ed.), Cambridge University Pres, Cambridge and New York.

Jonkman, S. N., Brinkhuis-Jak, M., and Kok, M. (2004). “Cost benefit analysis and flood damage mitigation in the Netherlands.” *Heron*, 49(1), 95–111.

Klijn, F., Mens, M. J. P., and Asselman, N. E. M. (2015). “Flood risk management for an uncertain future: economic efficiency and system robustness perspectives compared for the Meuse River (Netherlands).” *Mitigation and Adaptation Strategies for Global Change*, 20(6), 1011–1026.

Kong, F., Ban, Y., Yin, H., James, P., and Dronova, I. (2017). “Modeling stormwater management at the city district level in response to changes in land use and low impact development.” *Environmental Modelling and Software*, 95, 132–142.

Kosareo, L., and Ries, R. (2007). “Comparative environmental life cycle assessment of green roofs.” *Building and Environment*, 42, 2606–2613.

Meteorological Department St. Maarten. (2018). “Climatological Summary 2017.” (http://www.meteosxm.com/)

Montalto, F., Behr, C., Alfredo, K., Wolf, M., Arye, M., and Walsh, M. (2007). “Rapid assessment of the cost-effectiveness of low impact development for CSO control." *Landscape and Urban Planning*, 82(3), 117–131.

Narayanan, A., and Pitt, R. (2006). "*Costs of Urban Stormwater Control Practices*. *Department of Civil and Environmental Engineering", The University of Alabama*, Tuscaloosa.

National Renewable Energy Laboratory. (2015). "Energy Snapshot Saint-Martin/Sint Maarten." *Energy Transition Initiative - Islands*, <https://www.nrel.gov/docs/fy15osti/64122.pdf> (Aug. 29, 2017).

NYC Environmental Protection. (2013). "NYC Green Infrastructure Co-Benefits Calculator." *NYC Green Infrastructure Co-Benefits Calculator*.

Ossa-moreno, J., Smith, K. M., and Mijic, A. (2017). "Economic analysis of wider benefits to facilitate SuDS uptake in London , UK." *Sustainable Cities and Society*, Elsevier B.V., 28, 411–419.

Pezzaniti, D., Beechman, S., and Kandassamy, J. (2009). "Influence of clogging on the effective life of permeable pavements." *Proceedings of Institution of Civil Engineering - Water Management*, 162(3), 211–220.

Porsche, U., and Kohler, M. (2003). "LIFE CYCLE COSTS OF GREEN ROOFS - A Comparison of Germany, USA, and Brazil - Ulrich." *RIO 3 - World Climate & Energy Event*, Rio de Janeiro, 461–467.

Radjouki, E., and Hooft Graafland, C. (2014). *National Energy Policy for Country Sint Maarten Towards a sustainable development*.

Rossman, L. A. (2010). *Storm water management model. User's manual.* USEPA, Cincinnati, OH.

Rowe, D. B. (2011). "Green roofs as a means of pollution abatement." *Environmental Pollution*, Elsevier Ltd, 159(8–9), 2100–2110.

Saarikoski, H., Mustajoki, J., Barton, D. N., Geneletti, D., Langemeyer, J., Gomez-Baggethun, E., Marttunen, M., Antunes, P., Keune, H., and Santos, R. (2016). "Multi-Criteria Decision Analysis and Cost-Benefit Analysis: Comparing alternative frameworks for integrated valuation of ecosystem services." *Ecosystem Services*, Elsevier, 22(November), 238–249.

Santamouris, M. (2013). "Using cool pavements as a mitigation strategy to fight urban heat island — A review of the actual developments." *Renewable and Sustainable Energy Reviews*, Elsevier, 26, 224–240.

Santamouris, M. (2014). "On the energy impact of urban heat island and global warming on buildings." *Energy & Buildings*, Elsevier B.V., 82, 100–113.

Udoh, E., and Wang, F. Z. (2009). *Handbook of Research on Grid Technologies and Utility Computing: Concepts for Managing Large-Scale Applications*. IGI Global.

UNDP. (2012). *Flood Risk Reduction : Innovation and technology in risk mitigation and development planning in Small Island Developing States : towards floor risk reduction in Sint Maarten*. United Nations Development Programme (UNDP).

United Nations. (2014). "World Urbanization Prospects." <http://esa.un.org/unpd/wup/Highlights/WUP2014-Highlights.pdf> (Oct. 6, 2015).

Urrestarazu Vincent, S., Radhakrishnan, M., Hayde, L., and Pathirana, A. (2017). “Enhancing the Economic Value of Large Investments in Sustainable Drainage Systems (SuDS) through Inclusion of Ecosystems Services Benefits.” *Water*, 9, 841.

USEPA. (2012). *Reducing Urban Heat Islands : Compendium of Strategies - Cool Pavements*.

Versini, P. A., Kotelnikova, N., Poulhes, A., Tchiguirinskaia, I., Schertzer, D., and Leurent, F. (2018). “A distributed modelling approach to assess the use of Blue and Green Infrastructures to fulfil stormwater management requirements.” *Landscape and Urban Planning*, 173(February), 60–63.

Vojinovic, Z. (2015). *Floor Risk: The Holistic Perspective*. IWA Publishing.

Vojinovic, Z., and van Teeffelen, J. (2007). “An Integrated Stormwater Management Approach for Small Islands in Tropical Climates.” *Urban Water Journal*, 4(3), 211 – 231.

Wild, T. C., Henneberry, J., and Gill, L. (2017). “Comprehending the multiple ‘ values ’ of green infrastructure – Valuing nature-based solutions for urban water management from multiple perspectives.” *Environmental Research*, Elsevier Inc., 158(July), 179–187.

WNA. (2011). *Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources*. London.

Yong, C. F., Mccarthy, D. T., and Deletic, A. (2013). “Predicting physical clogging of porous and permeable pavements.” *Journal of Hydrology*, 481, 48–55.

Zölch, T., Henze, L., Keilholz, P., and Pauleit, S. (2017). “Regulating urban surface runo ff through nature-based solutions – An assessment at the micro-scale.” *Environmental Research*, Elsevier Inc., 157(May), 135–144.