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Exploring trade-offs among the multiple benefits of green-blue-grey infrastructure for urban flood mitigation

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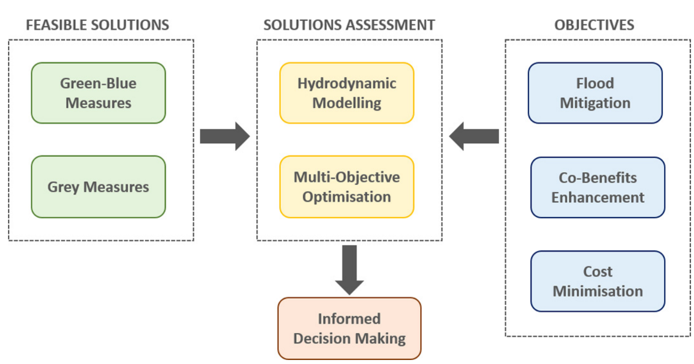
HIGHLIGHTS

- We developed a framework for green-blue-grey measures selection and comparison.
- Complex trade-offs among solutions become visible using optimisation techniques.
- Hybrid solutions are best for multiple benefits in areas with space restrictions.
- Considering co-benefits enhancement encourages the selection of green-blue measures.
- The primary benefit should not be compromised by pursuing co-benefits.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change is presenting one of the main challenges to our planet. In parallel, all regions of the world are projected to urbanise further. Consequently, sustainable development challenges will be increasingly concentrated in cities. A resulting impact is the increment of expected urban flood risk in many areas around the globe. Adaptation to climate change is an opportunity to improve urban conditions through the implementation of green-blue infrastructures, which provide multiple benefits besides flood mitigation. However, this is not an easy task since urban drainage systems are complex structures. This work focuses on a method to analyse the trade-offs when different benefits are pursued in stormwater infrastructure planning. A hydrodynamic model was coupled with an evolutionary optimisation algorithm to evaluate different green-blue-grey measures combinations. This evaluation includes flood mitigation as well as the enhancement of co-benefits. We confirmed optimisation as a helpful decision-making tool to visualise trade-offs among flood management strategies. Our results show that considering co-benefits enhancement as an objective boosts the selection of green-blue infrastructure. However, flood mitigation effectiveness can be diminished when extra benefits are pursued. Finally, we proved that combining green-blue-grey measures is particularly important in urban spaces when several benefits are considered simultaneously.

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1. Introduction

Population growth and climate change effects present a growing challenge in urban spaces (United Nations, 2014; EEA, 2016; Kabisch et al., 2017). In particular, water managers will have to deal with more frequent extreme weather events, such as higher rainfall intensities which will increase urban flooding and water pollution (IPCC, 2012; Jha et al., 2012). Additionally, other problems are expected to deepen in urban spaces around the globe due to these changes, for instance heat waves, droughts and air pollution (EEA, 2016). Consequently, the consideration of multiple benefits during urban infrastructure planning is important in order to develop sustainable solutions, which can help cities to be more resilient to worsening future conditions (Lundy and Wade, 2011; IPCC, 2012).

Adaptation to climate change can be seen as an opportunity to improve urban conditions through the implementation of green-blue infrastructures which have the capacity of providing multiple benefits (EEA, 2016; Kabisch et al., 2016). Moreover, according to Elmqvist et al., (2015) investments in enhancing green infrastructure in cities are ecologically and socially required, but also economically viable. This qualities can be assessed through the acknowledgement and quantification of the benefits provided by these infrastructures. Such information is a crucial input for decision-makers.

Urban spaces represent complex systems, since natural, social and built environments interact. Furthermore, drainage systems are also complex structures, which can integrate many different measures, imply significant investments and high uncertainties regarding future conditions (Jha et al., 2012; Simonovic, 2012). Green-blue infrastructures (GBI) offer a holistic perspective to build resilience and address complex urban challenges, in which several problems need to be addressed at the same time, with limited resources and space constraints (Vojinovic, 2015; Frantzeskaki et al., 2019).

Urban drainage terminology has expanded in the last decades, consequently similar concepts are named with different terms. For instance, BMPs (best management practices), LIDs (low impact development), WSUD (water sensitive urban design), SuDS (sustainable drainage systems), GBI (green-blue infrastructure), EbA (ecosystem-based adaptation) and NBS (nature-based solutions) are largely used (Fletcher et al., 2014). Green infrastructure is defined as a network of multifunctional green spaces which maintain and enhance ecosystem services and resilience (Tzoulas et al., 2007; Naumann et al., 2011; European Commission, 2012a). In this work, the term green-blue infrastructure is used, referring to the concept of measures or solutions based in nature or natural processes.

While traditional drainage systems depend on grey solutions, resilience against future environmental threats cannot be achieved with these approach alone (Browder et al., 2019). Besides, even though GBI has proved to be effective reducing flood risk (Kong et al., 2017; Haghighatafshar et al., 2018; Versini et al., 2018) and can contribute to multiple benefits, this might not be enough to cope with extreme future climate hazards (European Commission, 2012a; Demuzere et al., 2014; Kabisch et al., 2017). Consequently, new tendencies suggest that the combination of green-blue and grey infrastructure may offer a novel generation of solutions to enhance community's protection (Browder et al., 2019). According to Frantzeskaki et al. (2019), green infrastructures should be complemented with technology-based solutions, hence more research is needed on how to combine multiple solutions to maximize climate adaptation in cities.

Despite much research has been done showing the advantages of using GBI, traditional grey infrastructure continues to be widely preferred in urban areas throughout the world (Dhakal and Chevalier, 2017). Several barriers for GBI acceptance are identified, which comprise socio-political, institutional and technical barriers (O'Donnell et al., 2017). From a technological point of view, while traditional approaches count with enough technical support and tools for decision making, GBI for stormwater management lacks sufficient technical references, standards and guidelines (Qiao et al., 2018). In particular, this support is lacking regarding the evaluation and quantification of additional benefits (IPCC, 2012). Another commonly identified barrier is uncertainty about long-term performance and cost-effectiveness compared to conventional solutions (Davis et al., 2015). Therefore, further actions are needed to increase the acceptance of GBI over grey infrastructure for water management. To achieve this, the emphasis on the provision of multiple benefits in addition to flood protection is a key element (Kabisch et al., 2017).

Several works focus on the selection of GBI considering co-benefits and stakeholders' involvement (Alves et al., 2018b; Miller and Montalto, 2019; Santoro et al., 2019). However, more quantitative results regarding the impacts of these measures on flood mitigation and co-benefits enhancement are needed (Pagano et al., 2019). Regarding this, hydrodynamic models are widely used to select and design flood risk management strategies (Teng et al., 2017). But, the problems to be solved are usually complex and can have many possible solutions. In these cases is when optimisation evolutionary algorithms become helpful since they can be linked to hydrodynamic models to explore large solutions spaces, allowing the evaluation of many more options and trade-offs (Maier et al., 2019). Even though evolutionary optimisation processes imply high computational efforts, these algorithms offer a very useful tool for helping decision-making in complex systems, and in particular in the case of water resources management (Nicklow et al., 2010; Maier et al., 2014).

Previous research have shown that optimisation algorithms are a valuable tool to help solving stormwater management problems (Delelegn et al., 2011; Vojinovic et al., 2014; Woodward et al., 2014). Besides, some works have included green-blue infrastructure into these frameworks (Zhang et al., 2013; Alves et al., 2016; Behroozi et al., 2018). However, few works included the attainment of co-benefits from green-blue infrastructure as an extra objective when trying to solve stormwater related problems (Urrestarazu Vincent et al., 2017; Di Matteo et al., 2019). Furthermore, even though trade-offs when targeting multiple benefits have been considered in the past (Demuzere et al., 2014; Hoang et al., 2018), none of these works perform a quantitative analysis of these trade-offs. In addition, to the best of our knowledge not previous work focuses on compromises between primary and secondary benefits when comparing among green-blue and grey infrastructure application.

In response to these limitations, this work focuses on a method to quantitatively analyse the trade-offs when different benefits are pursued in stormwater infrastructure planning. First, different green, blue and grey measures and their combinations are considered in the evaluation of their performance to achieve flood risk reduction. Second, we include into the performance analysis the achievement of other benefits. Then, we investigate how the effectiveness of solutions regarding the primary function of flood risk reduction varies when the extra benefits are added. Finally, the changes in the composition of optimal solutions when the pursued objective is switched are analysed. In other words, we analyse how green, blue and grey measures are selected in different cases.

2. Methodological approach

2.1. Strategies selection, cost and co-benefits calculation

The optimisation of urban drainage strategies is a complex and time-consuming analysis. Therefore, the reduction of alternatives to be analysed is an important step. A pre-processing method is applied to choose among drainage measures (see Fig. 1a). Through this step, the number of options is reduced before starting the optimisation process. In this case we use a multi-criteria analysis in which local characteristics and needs are considered. This method is based on questions answered by local stakeholders (see Supplementary Material). The questions are about flood characteristics and local physical conditions, which are inputs for measures screening. In addition, the stakeholder selects weights establishing which are the preferred co-benefits in the area. The final step consists on defining the order of importance among flood mitigation, costs minimisation and co-benefits enhancement. Then, the answers are processed following the multi-criteria procedure. The result is a ranking of applicable measures for the area, more details can be found in Alves et al. (2018a).

An important aspect pursued with the use of this multi-criteria selection method is to improve the stakeholders' acceptance of the measures selected. By taking into account local preferences and necessities when choosing among options, and considering the opinion of local stakeholders from the very beginning, it is expected that the final solution will be better accepted for implementation (Kabisch et al., 2017; Bissonnette et al., 2018). Moreover, this multi-criteria method can be used with diverse stakeholders, allowing to take into account their different objectives.

The next step after the identification of applicable measures is the development of possible combinations of green-blue and grey measures. These combinations are called here strategies and are selected after performing a spatial analysis of the study case. For instance, open detention basins are chosen if there is availability of open public spaces where to locate them, and green roofs are chosen if there exist adequate roofs where to build them. Afterwards, these strategies are evaluated quantitatively considering its flood risk reduction performance, co-benefits enhancement capacity and life cycle costs. To evaluate the selected strategies regarding co-benefits, we need first to identify direct and indirect co-benefits provided by each measure.

Several previous studies help us to recognise the multiple benefits delivered by GBI, see for example Woods-Ballard et al. (2007), Center for Neighborhood Technology (2010) and Horton et al. (2016). These works also offer quantitative data about the benefits, which allow us to calculate the annual values of those co-benefits which can be directly monetised (Alves et al., 2019). For example, water saving from rainwater barrels installation provides the co-benefit value of reducing the water bill accumulated along the year. The present value of these co-benefits is then calculated defining the measure's lifetime and a discount rate. These values will be given per unit of measure and will be an input into the optimisation process.

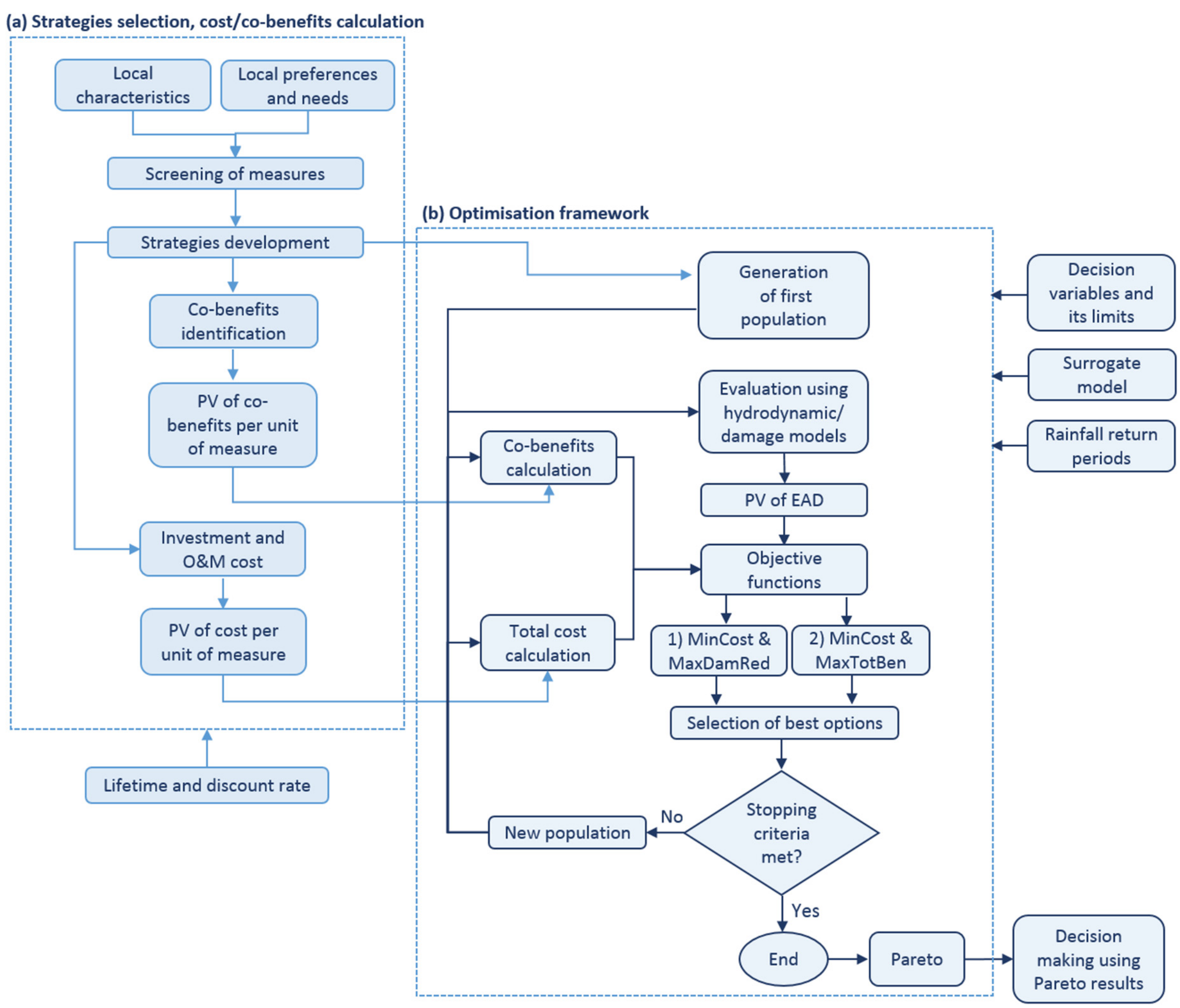

Fig.1. Methodological approach (a) Strategies selection and cost-benefits calculation, (b) Optimisation process; with PV: present value, O&M: operation and maintenance, EAD: expected annual damage, MinCost: minimum cost, MaxDamRed: maximum damage reduction, MaxTotBen: maximum total benefits.

The aim of this study is to compare among green-blue, grey and hybrid strategies for flood mitigation from an economic point of view, and show how this comparison changes when co-benefits are considered. There are several co-benefits not easily quantifiable in economic terms, such as aesthetic value and biodiversity enhancement. Even though these co-benefits could be an important driver for decision making, they are not considered here because are not representable in a cost-benefits analysis.

Finally, to calculate the total cost for each measure local prices and literature review data are used (e.i. Narayanan and Pitt, 2006). Investment and annual operation and maintenance costs are considered through the lifespan period of each infrastructure. Then the values are converted to the same year valuation using the consumer price index. Once more present values of these costs per unit of measure are calculated and will be an input to the optimisation process. More details about costs calculation are given in Alves et al. (2019).

2.2. Optimisation framework

According to Maier et al. (2019), in a traditional or informal process the selection of solutions is based on experience or intuition. In the case of flood management this would represent the type of measures, its size and where to locate them. Then, the performance of selected solutions is evaluated using for instance a hydrodynamic model. Afterwards, other options would be evaluated with the aim of improving performance. However, when many decision variables exist it is unlikely to find even a near optimal solution. The authors argue that is in these cases that formal optimisation helps to identify optimal solutions in an efficient manner.

The multi-objective optimisation process followed in this work is presented in Fig. 1b. The first step is problem formulation, this includes the establishment of decision variables, its search boundary values, and objective functions for the problem under analysis. In this case, the decision variables are the areas covered by the different drainage measures applied. The optimisation process will evaluate different options, each one with different measure's application areas. The definition of the minimum and maximum value of the areas is based on land use analysis. This is done measuring the surface covered by roofs, pavements, and open spaces with the use of aerial images and GIS analysis. Using this analysis we can define maximum values for each variable. For instance, a maximum of 50% of pavements with less than 5% slope covered by pervious pavements, or a maximum of 75% of roofs connected to rainwater barrels.

Concerning objective functions, we defined three objectives: total cost minimization, maximization of flood damage risk reduction, and maximization of total benefits:

$$O_1 = Min\left\{\sum_{x=1}^{N}\left[\left(C_{Inv\_x} + \sum\nolimits_{y=1}^{LT}\frac{C_{O\&M\_x}}{(1+i/100)^y}\right) * \sum\nolimits_{j=1}^{SC} S_{xj}\right]\right\} \tag{1}$$

where C_{Inv-x} is the investment cost for the measure ×, $C_{O\&M-x}$ is the operation and maintenance cost of the measure ×, LT is the lifetime considered for the measures, i is the discount rate, and S_{xj} is the application size of the measure × in the sub catchment j.

$$O_{2.1} = \mathrm{Max}\left\{\mathrm{EAD_{Max}} - \sum_{y=1}^{LT}\left[\sum_j\left(\left(\frac{\mathrm{TD_{RPj+1}} + \mathrm{TD_{RPj}}}{2}\right) * \left(\frac{1}{\mathrm{RP_j}} - \frac{1}{\mathrm{RP_{j+1}}}\right)\right)/\left(1+\frac{i}{100}\right)^y\right]\right\} \tag{2}$$

where EAD_{Max} is the expected annual damage for the current situation which represents the maximum damage (before measures are applied), TD is total damage obtained from the model once the measures have been applied (includes residential, commercial, infrastructural and transport damage), RP is the rainfall return period, i is the discount rate, and LT is the lifetime considered for the measures.

$$O_{2.2} = \mathrm{Max}\left\{\mathrm{EAD_{Max}} - \sum_{y=1}^{LT}\left[\sum_j\left(\left(\frac{\mathrm{TD_{RPj+1}} + \mathrm{TD_{RPj}}}{2}\right) * \left(\frac{1}{\mathrm{RP_j}} - \frac{1}{\mathrm{RP_{j+1}}}\right)\right)/\left(1+\frac{i}{100}\right)^y\right] + \sum_{x=1}^{N}\left[\left(\sum_{y=1}^{LT}\frac{\mathrm{AnnualCo - Ben_x}}{(1+i/100)^y}\right) * \sum\nolimits_{j=1}^{SC} S_{xj}\right]\right\} \tag{3}$$

where EAD_{Max} is the expected annual damage for the current situation which represents the maximum damage (before measures are applied), TD is total damage obtained from the model once the measures have been applied (includes residential, commercial, infrastructural and transport damage), RP is the rainfall return period, i is the discount rate, and LT is the lifetime considered for the measures, Annual Co-Ben_x are the co-benefits obtained in one year from the measure ×, and S_{xj} is the application size of the measure × in the sub catchment j.

Since all costs, co-benefits and flood damage are in monetary units, we could solve a single objective problem by maximizing net benefits (total benefits – costs). A single objective problem is much easier to solve than multiple objective ones, nevertheless in this work we optimize for two objectives separately. Even though computationally more demanding, this approach gives a detailed trade-offs picture between the objectives which would otherwise not be possible. This, in turn, helps decision makers to make better informed decisions at the end.

Concerning the experimental setup, the objective functions are used for options evaluation in two different cases, in which two objectives are pursued. First, the optimisation problem is formulated with minimisation of total costs and maximisation of flood damage reduction (O_1 and $O_{2.1}$) as objectives. The second optimisation problem is reformulated from the first one by changing the second objective to maximisation of total benefits (i.e. using O_1 and $O_{2.2}$ as objective functions). In the first objective function (O_1), the value to be minimised is total cost, which comprises investment and maintenance costs for the different drainage measures considered. The total cost is calculated multiplying the present value of cost per unit of measure, estimated in the past step, times the size of measures defined for each option during the optimisation process (see Eq. (1)).

The evaluation of options regarding flood damage reduction is performed using the hydrodynamic model EPA SWMM (Rossman, 2010). Using a 1D-1D model we estimate flood water depths at several locations in the area under different rainfalls. In this 1D-1D model, two parallel conduits connected among them are defined, one representing the drainage system and the other one representing the streets. Flooding occurs when water is accumulated in the conduit representing the streets. Then a surrogate model is used to estimate damages. The surrogate model links the 1D-1D model results with pre-calculated results from a 1D-2D model to estimate water depths and corresponding flooding damage values (see Fig. 2), more details can be found in Alves et al. (2019). Through this method the total flooding damage can be calculated and it is possible to calculate the reduction of damage, which will be our primary benefit. Residential, commercial, infrastructure and transport damage are considered here. These damage values are used to calculate the risk of flooding as the expected annual damage (EAD) for different rainfall events (Delelegn et al., 2011). Then, we maximise the flood risk reduction (O_2) which is the difference between maximum EAD (without measures application) and the EAD obtained applying measures (Eq. (2)). This value is also used in the third objective function (O_3), in which total benefits are maximised. To achieve this we add co-benefits to the equation, which are the result of

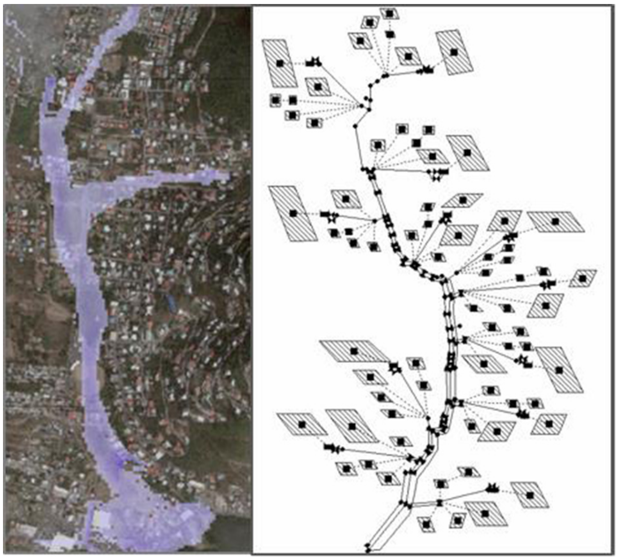

Fig. 2. 1D-2D flood modelling result (left) and 1D-1D model representation (right).

multiplying the present value of co-benefits per unit of measures, times the size of measures defined for each option during the optimisation process (Eq. (3)).

Once decision variables and objectives are established, the optimisation process follows the steps of the genetic algorithm NSGA-II applied in this work (Deb et al., 2002). The decision variables in this case are coded as GA chromosomes using integer values, these values represent the areas covered by the applied measures. In the first step, the optimisation process evaluates an initial random generation using the objective functions. Then the best options are selected and a new population is created applying concepts of crossover and mutation. This new population is then evaluated and the same process is repeated in a loop until the stopping criteria is met. The stopping criteria in this case is the number of generations to be analysed. There are other parameters which are also inputs for the optimisation process besides objectives and variables: population size, number of generations, crossover and mutation rates. These values were defined through a sensitivity analysis. Finally, when the stopping criteria is met, several "best options" are presented in a Pareto plot. The present optimisation framework builds upon and connects to previous work (Vojinovic et al., 2006; Vojinovic and Sanchez, 2008; Barreto et al., 2010).

3. Results

3.1. Study area description

The study area is the catchment Cul De Sac, one of the most vulnerable areas to flooding in the Dutch side of Sint Maarten Island,

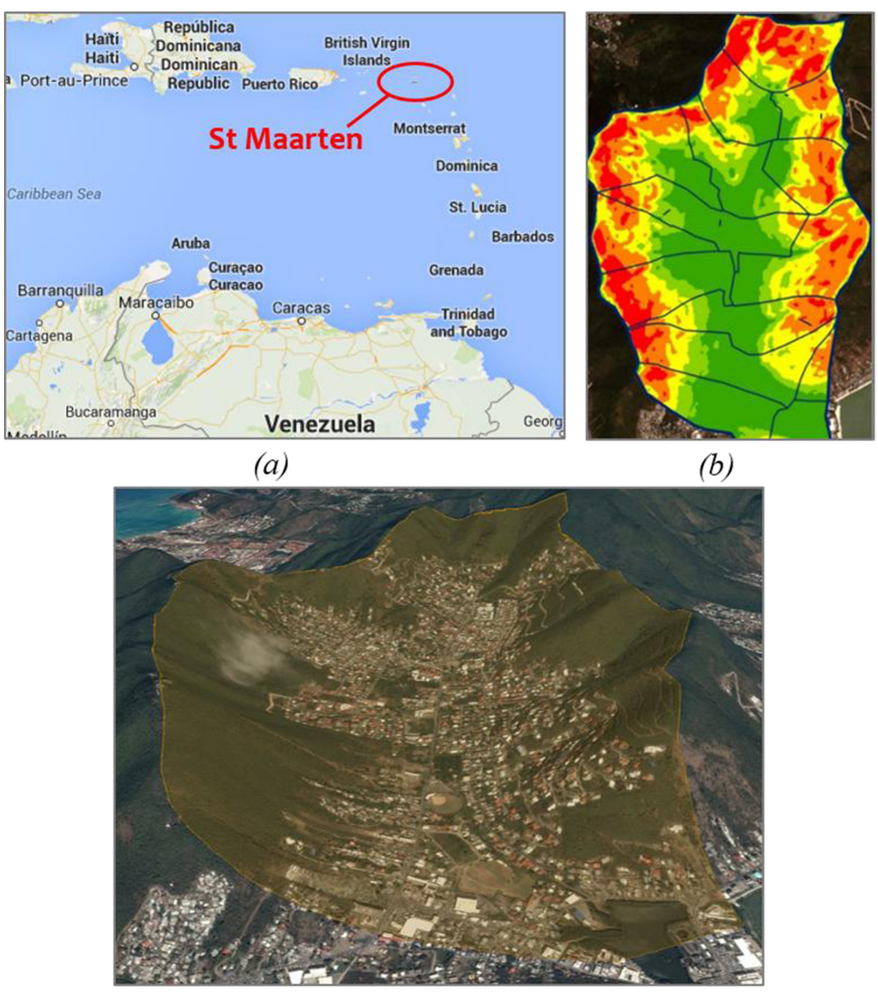

Fig. 3. (a) Sint Maarten location, (b) Catchment topography and sub-catchments division, (c) Cul De Sac aerial visualisation.

located in the Caribbean region (see Fig. 3a). This catchment has an area of 509Ha and the land use is predominantly residential, with some dispersed commercial areas in the lower part. Elevation ranges from near sea level to hilly areas with until 380 m altitude at the northern borderline and the catchment is divided in 12 sub-catchments (see Fig. 3b).

The catchment has several characteristics contributing to flood risk. For instance, urban areas are situated on low-lying zones (see Fig. 3c). Besides, the existing drainage system which is composed by channels, has not enough capacity to avoid flooding (UNDP, 2012). In addition, most of the streets are narrow limiting the enlargement of these drainage channels (Vojinovic and van Teeffelen 2007). Recurrent inconveniences such as transport disruptions occur during small rainfall events. Whereas heavy rainfall causes large-scale flooding with damage to residential and commercial buildings (UNDP, 2012).

3.2. Screening of measures and cost-benefits calculation

A questionnaire was filled by technical and political decision makers related to water management in the island. The questions were about flood type, physical site conditions, drainage system characteristics, land use and preferred co-benefits for the area under study (see Supplementary Material). The answers where used to apply the multi-criteria analysis described in Section 2.1 and illustrated in Fig. 1a.

Regarding local characteristics, this analysis allowed us to conclude that the main flooding problem in the area is pluvial flooding. Furthermore, the soil has medium permeability with deep water table and bedrock. The surface's slope is larger than 5%, the sewer system is separate but there is also illegal combined sewer system. The main land use is residential with medium to low density. The availability of public spaces is less than 25% and there is low space availability along roads and sidewalks. Finally, combined sewer overflows were identified as a problem in the area. Regarding local preferences and needs, several co-benefits were identified. The most important co-benefits identified for this area were liveability improvement (heat stress reduction and aesthetics enhancement), socio-cultural benefits (community engagement, recreation and educational spaces), water quality enhancement (runoff pollutants removal) and environmental benefits (groundwater recharge and water reuse, and species habitat creation). Besides, decision makers identified flood problems affecting buildings and generating significant damage in the area as occurring every two years. Furthermore, they recognised budget restrictions when investing on infrastructure for flood management. Lastly, they described the achievement of co-benefits as a medium to low importance objective.

Using this information and through the screening of measures we identified preferred infrastructures to be applied in the area. Details about the method to select these measures can be found in Alves et al. (2018a). This screening process established daylighting water courses and open water channels as preferred options for this case. This is in accordance with the practice of maintaining and enlarging (when possible) the existent channels system, already recommended by the study performed by UNDP (2012). Besides, the analysis detected pipes as a preferred option. This measure can be applied to enhance conveyance capacity of the existing channels, since there is limited space to enlarge them. Another selected measure was open detention basins. This result confirmed previous outcomes from a study performed in this catchment in which open detention ponds were identified as an effective flood management alternative (UNDP, 2012). Additionally, the multi-criteria analysis identified rainwater disconnection as another option for runoff management. Several measures could be applied to achieve this, but rainwater barrels was a preferred alternative in this case since it allows the reuse of water, an expensive and scarce resource in the island. Finally, measures that allow the infiltration of runoff were recommended. Due to the low availability of public spaces, the infiltration option chosen for this case was pervious pavements, to be applied in low slope and low traffic roads. In summary, the measures selected in this study for further analysis are: closed pipes (Pi), open detention basins (ODB), rainwater barrels (RB) and pervious pavements (PP). These options, and its combinations, were further evaluated using hydrodynamic modelling. The assessment was performed considering the existing channels system working at its current capacity.

Six strategies, or measures combinations, were chosen for further analysis using the optimisation framework. The objective is the comparison among green-blue and grey measures and its combinations. These six strategies are: rainwater barrels with pervious pavements (RB + PP), the same two measures combined with open detention basins and combined with pipes (RB + PP + ODB and RB + PP + Pi), the four measures combined (RB + PP + ODB + Pi), open detention basins alone (ODB) and combined with pipes (ODB + Pi). The selection of these combinations was based on the intention of comparing green-blue and traditional (or grey) measures. RB and PP are green-blue measures providing co-benefits, while ODB and Pi are traditional measures which do not provide co-benefits. The selected combinations represent then examples of only green-blue measures (RB + PP), different combinations of green-blue and traditional measures (RB + PP + ODB, RB + PP + Pi and RB + PP + ODB + Pi), and alternatives with only traditional measures which do not provide co-benefits (ODB and ODB + Pi).

The next step was to identify the relevant co-benefits provided by the selected measures and their importance for the case here studied. Rainwater harvesting barrels allow the reduction of drinking water consumption. This benefit is important in this case because drinking water in the island is produced using reverse osmosis, an expensive and high energy consumption technology (Elimelech and Phillip, 2011). In addition, water production and its cost have risen notoriously in the last 10 years in the area (Centrale Bank Curaçao en Sint Maarten, 2017) and the area goes through water shortages during high consumption hours (European Commission, 2012b). Pervious pavements allow urban cooling by means of lower reflection and higher evaporation (Foster et al., 2011). The benefits obtained are energy savings and carbon dioxide and air pollutants reduction (USEPA, 2012). Temperature reduction is especially important in areas with tropical weather, where energy consumption can increase between 2 and 4% per each extra Celsius degree (Akbari et al., 2001; Santamouris, 2014). Other benefits obtained from pervious pavements installation are water quality enhancement due to runoff filtration and groundwater recharge, which were also considered here. Even though recreation and liveability enhancement can be considered as co-benefits for open detention basins, these are not easily converted into monetary values and hence were not considered in the present study.

Afterwards, implementation and operation and maintenance costs were calculated. Details about how these costs and benefits values were calculated are presented in Alves et al. (2019). Table 1 presents the results of costs and co-benefits for each one of the four measures selected. In the case of Pi, the cost results are presented in €/m and for each diameter to be considered in the optimisation process. The cost of ODB is given in €/m^2, considering an average depth of 1.5 m in order to reduce the variables in the hydrodynamic model. The values corresponding to RB and PP are presented as €/m^3 and €/m^2, respectively. Regarding co-benefits, only these two measures provide them and PP presents a higher value than RB.

The values of costs and benefits showed in Table 1 are present values over a lifetime of 30 years with a discount rate of 5% rate

Table 1
Cost and co-benefits values for each selected measure (RB: Rainwater Barrel, PP: Pervious Pavement, ODB: Open Detention Basin, Pi: Pipes).

Measure		Cost		Annual co-benefit	
RB		1040	€/m^3	30	€/m^3
PP		160	€/m^2	86	€/m^2
ODB		350	€/m^2	0	€/m^2
Pi (mm)	800	720	€/m	0	€/m
	1000	895	€/m	0	€/m
	1500	1530	€/m	0	€/m
	2000	2950	€/m	0	€/m
	2500	3615	€/m	0	€/m

(International Monetary Fund, 2016). The period of 30 years is considered as maximum before the necessity of replacement for green infrastructure (Pezzaniti et al., 2009; USEPA, 2012; Al-rubaei et al., 2013; Yong et al., 2013).

3.3. Optimisation results

The decision variables used in the optimisation process were the size of application of each measure. In the cases of RB, PP and ODB, these are the measures' application areas in each one of the 12 sub-catchments included in the hydrodynamic model. The ranges in which the area of each measure varies for each sub-catchment were defined through a land use analysis performed using aerial images (see Table 2). In the case of pipes, a single pipe was chosen to follow the main channel path from the mid area of the catchment until its discharge. The variables are the diameters of the four segments which cover the pipe's extension. Depending on the strategy and the number of measures combined, the optimisation framework has different numbers of variables (see Table 3).

Different parameters can be chosen when applying the NSGA-II algorithm, such as population size, number of generations, and mutation and crossover operators. Several runs of the framework were performed to assess convergence and to choose the values of these parameters. Three indicators were used for Pareto fronts evaluation: the number of non-dominated solutions obtained in the final Pareto compared to the given number of initial population, the extent or spread of Pareto fronts with respect to the objectives, and the average space among solutions. We analysed the sensitivity of optimisation results to the parameters. Since the theoretical value of mutation is the inverse of decision variables (Mala-Jetmarova et al., 2015), this analysis was applied for the cases of maximum and minimum number of variables. Changing values of population (between 80 and 400), generations (between 20 and 80), crossover (between 0.2 and 0.9) and mutation (between 0.01 and 0.08), the values of number of non-dominated solutions, extend of Pareto curve and average space among solutions were evaluated. As a result, values of 350 individuals for population, 70 generations, 0.9 for crossover and 0.021 for mutation were selected to apply the optimisation framework.

Table 3
Number of decision variables for each strategy.

Strategy	Decision variables
RB + PP	24
RB + PP + ODB	36
RB + PP + Pi	28
RB + PP + ODB + Pi	40
ODB + Pi	16
ODB	12

The optimisation framework was applied twice for each one of these six strategies. Firstly, the framework was applied using the objective functions of cost minimisation (Eq. (4)) and flood risk reduction maximisation. Secondly, the objective functions of cost minimisation and total benefits maximisation were used. Rainfalls with return periods of 5, 10, 20, 50 and 100 years and 2 h duration (UNDP, 2012) were considered to calculate EAD in objective functions $O_{2.1}$ and $O_{2.2}$.

For this case the first objective function is

$$O_1 = Min\left\{C_{RB} * \sum_{i=1}^{12} A_{RB} + C_{PP} * \sum_{i=1}^{12} A_{PP} + C_{ODB} * \sum_{i=1}^{12} A_{ODB} + C_{Pi} * \sum_{i=1}^{4} L_{Pi}\right\} \quad (4)$$

where C_{RB}, C_{PP}, C_{ODB} and C_{Pi} are the present values over 30 years of total costs of rainwater barrels, pervious pavements, open detention basins and pipes, respectively. A_{RB}, A_{PP} and A_{ODB} are the areas of measures for each one of the 12 sub catchments, and L_{Pi} is the length of each one of the 4 pipes proposed for this case.

Fig. 4 (a) and (b) show the obtained Pareto results. ODB combined with Pi (green) and the combination of all the measures (yellow) are the best performing strategies for flood risk reduction (Fig. 4.a). However, costs exceed benefits when the cost is higher

Table 2
Value ranges of decision variables: area of roof connected to rain barrels (roof to RB), area of pervious pavement (PP), area of open detention basin (ODB), and pipe's diameter (Pi_Diam).

Sub-catchment	roof to RB (ha)		PP (ha)		ODB (m^2)		Pipe	Pi_Diam (mm)	
	Min	Max	Min	Max	Min	Max		Min	Max
1	0	3.4	0	1.5	0	3000	1	500	2500
2	0	1.9	0	0.8	0	4000	2	500	2500
3	0	3.0	0	1.3	0	3500	3	500	2500
4	0	6.1	0	2.7	0	4000	4	500	2500
5	0	2.4	0	1.1	0	6000			
6	0	4.8	0	2.1	0	4000			
7	0	7.8	0	3.5	0	5000			
8	0	2.6	0	1.2	0	8000			
9	0	4.9	0	2.2	0	5000			
10	0	3.2	0	1.4	0	7000			
11	0	6.1	0	2.7	0	5000			
12	0	7.5	0	3.3	0	6000			

than 24 million € (Pareto fronts under grey line in the plot, where the grey line represents cost equal benefits) and hence these strategies are not cost efficient. The only benefit in this case is the reduction of flood damage and has a maximum of around 24 million € before the strategies are no longer efficient. The maximum present value of expected annual damage over 30 years in

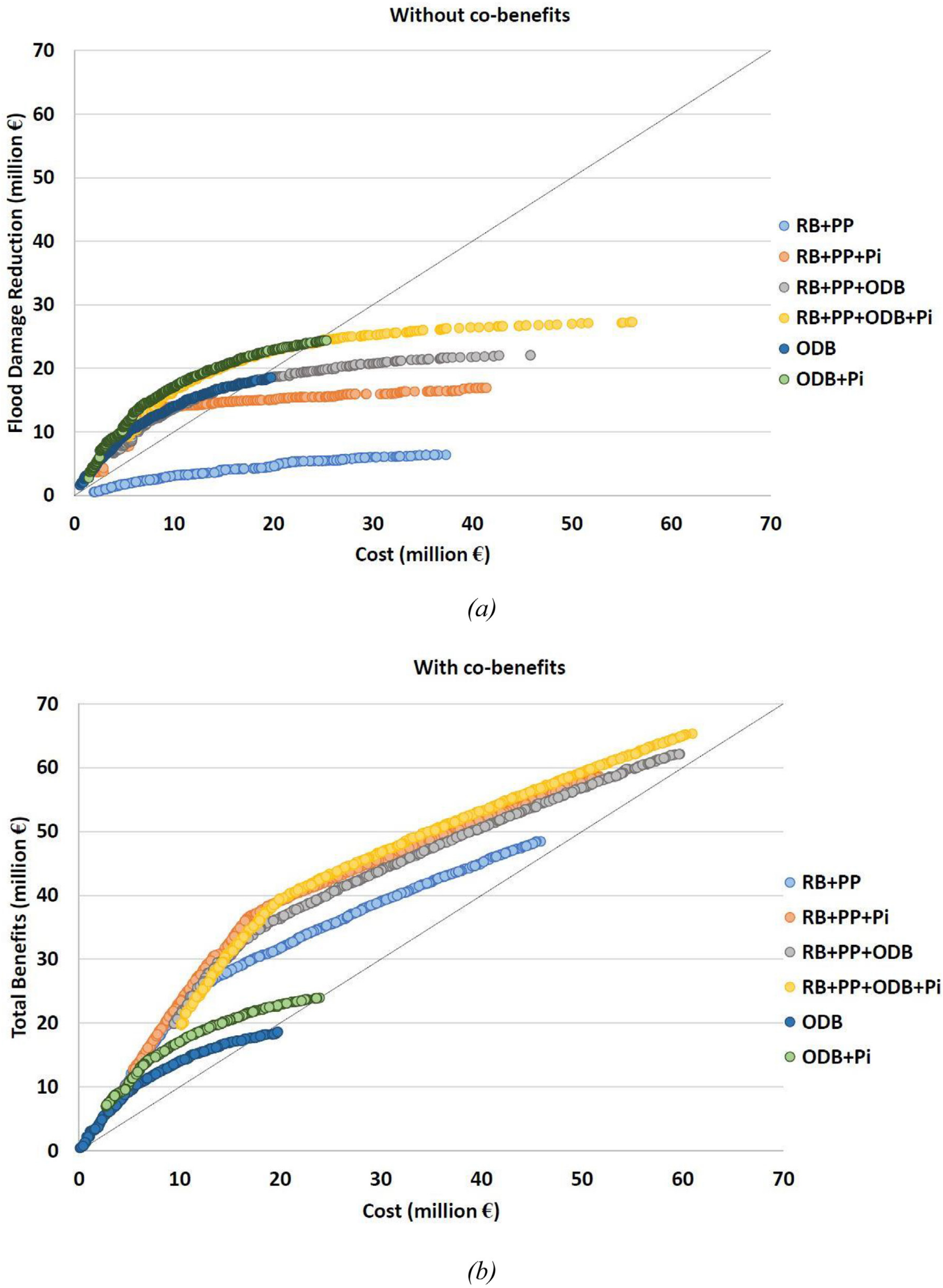

Fig. 4. Pareto fronts obtained for the six strategies selected with (a) cost minimisation and flood risk reduction maximisation as objectives (b) cost minimisation and total benefits maximisation as objectives (grey line: costs = benefits).

the current situation (without measures) is 47.5 million €. Therefore, the maximum damage reduction achieved applying these strategies is about 50% of that value.

All strategies achieve benefits higher than costs if we analyse the results obtained from total benefits maximisation (Fig. 4.b). Even the combination of RB and PP (light blue) shows efficient results in this case, in contrast with the case of damage reduction maximisation. The best strategy in this case is the combination of RB, PP and Pi (orange) when the cost is lower than 19 million €. For higher costs the strategy achieving best results is the combination of the four measures (RB + PP + ODB + Pi). However, from the results obtained in the case of damage reduction, we observe that after 8 million € of cost the strategy RB + PP + ODB + Pi performs much better than RB + PP + Pi on flood risk reduction. As a result, even if slightly higher total benefits are obtained in the case of RB + PP + Pi for costs lower than 19 million €, the decrease on flood risk reduction seems not worth. Consequently, the combination of the four measures appears to be the best option. The Pareto curve for this strategy presents a slope change around the cost of 20 million €, suggesting that a solution around this cost will be the best option in view of the benefits obtained from the investment. In that case, damage reduction will be around 23 million € (48% of the maximum damage) and total benefit around 40 million € (twice the cost).

Although the strategies including RB and PP deliver other benefits besides flood damage reduction (e.g. water and energy savings), these co-benefits cannot be appreciated in the results presented in Fig. 4a. To visualise this, we added the value of these co-benefits to the Pareto fronts obtained in the case of only flood damage reduction as second objective. The original optimal values are represented by DR and the results including co-benefits by DR + Co_Ben in Fig. 5. Moreover, the results presented in Fig. 4b do not allow us to see the performance of the strategies on flood mitigation. To appreciate this, we subtracted the co-benefits from the Pareto fronts obtained in the case of maximising total benefits as second objective. The Pareto fronts are represented by TB and the results without co-benefits by TB-Co_Ben in Fig. 5. This is presented only for the four strategies providing co-benefits: RB + PP (Fig. 5a), RB + PP + ODB (Fig. 5b), RB + PP + PI (Fig. 5c) and RB + PP + ODB + Pi (Fig. 5d).

Analysing these results, we observe a considerable difference between total benefits when it is an optimisation objective (yellow circles) and when the objective is only to reduce flood risk (blue circles). However, the differences between damage reduction when it is the only optimisation objective (blue triangles) and when the objective is to maximise total benefits (yellow triangles) is not that significant. Nevertheless, it is important to pay attention to the impact of focusing on maximising total benefits on the reduction of flood damage. In some cases, the reduction of flood damage can be substantially diminished when we change the objective from flood risk reduction to total benefits maximisation. This can be observed, for instance, in the cases of RB + PP + ODB (strategy 2, Fig. 5b) and RB + PP + ODB + Pi (strategy 4, Fig. 5d) for costs lower than 20 million €. Furthermore, this tendency can be much enlarged if more co-benefits are considered.

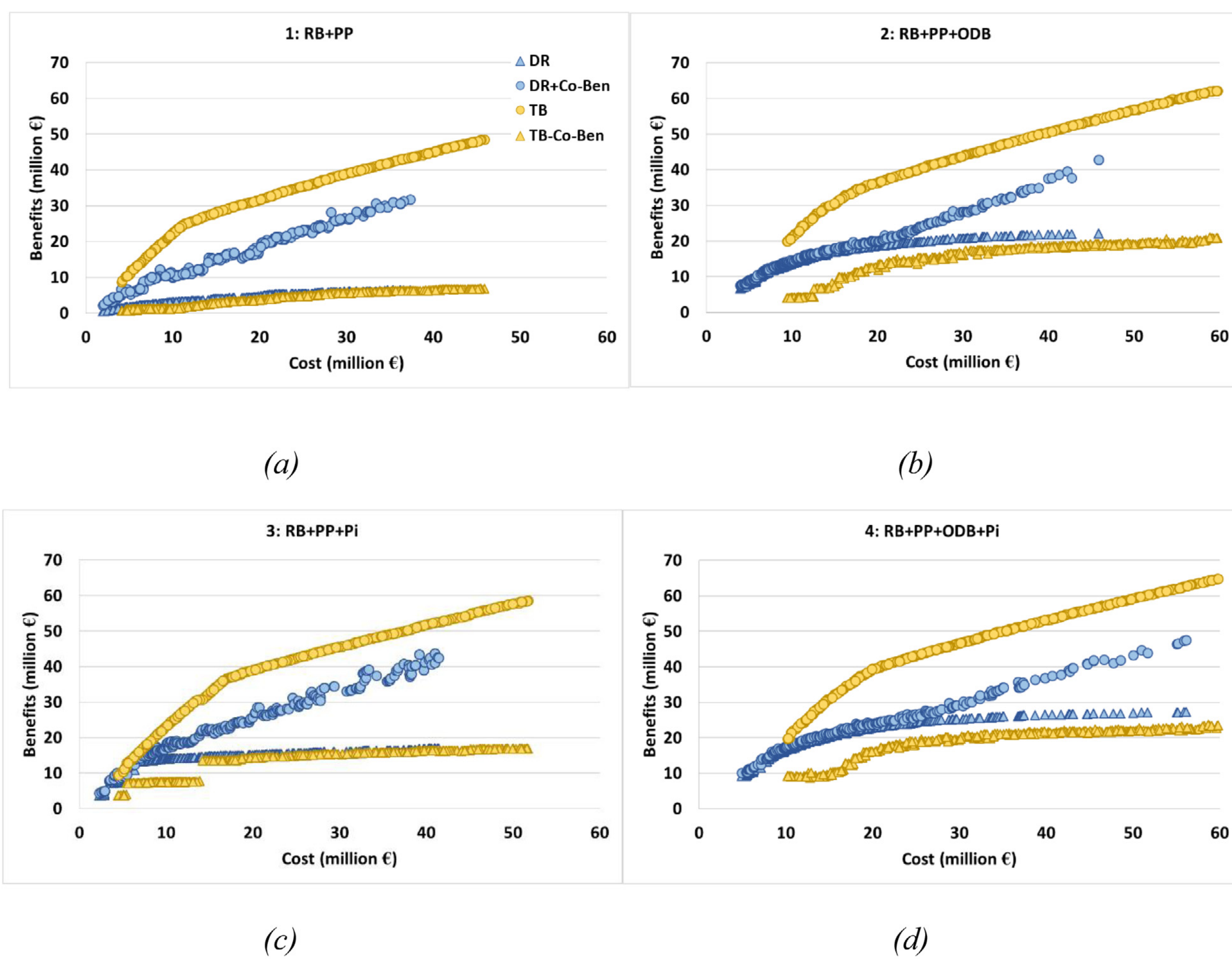

Fig. 5. Pareto fronts obtained for damage minimisation (DR) and the result adding co-benefits (DR + Co_Ben), and total benefits maximisation (TB) and the result removing co-benefits (TB-Co_Ben).

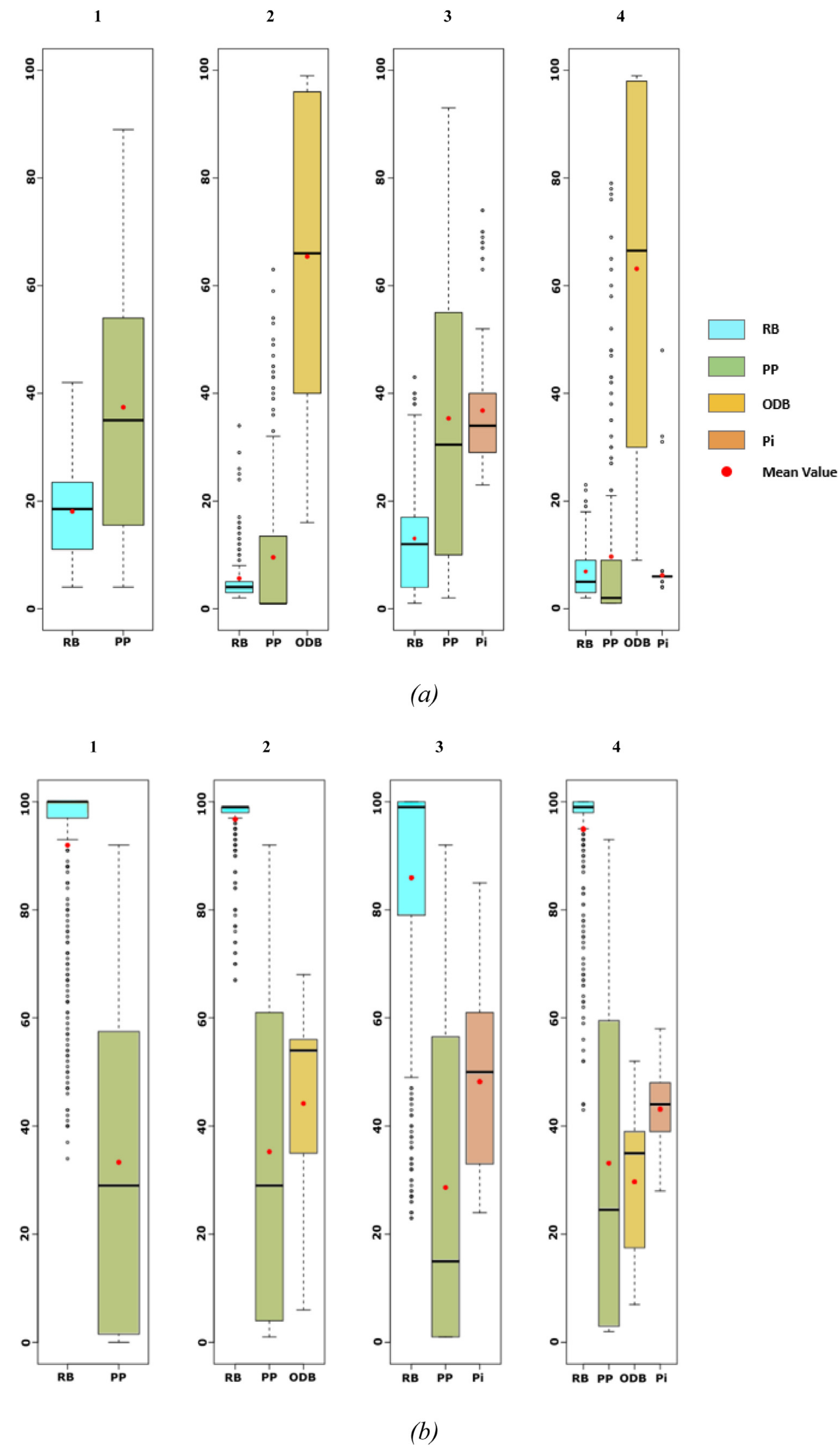

Fig. 6. Measures selection analysis for four strategies, with the objectives of cost minimisation and (a) flood risk reduction, (b) total benefits maximisation. With RB: rain barrels, PP: pervious pavements, ODB: open detention basins, Pi: pipes.

The explanation of these differences can be found on the different performances of green-blue and grey measures regarding the objectives of reducing flood risk and increasing co-benefits. It is expected that the optimisation algorithm will choose differently among the measures, according to the pursued objective. To better understand this, an analysis of the measures selected for optimal solutions in each case was performed. The analysis shows the application value selected for each measure as a percentage of the maximum measure's area that can be applied in each case (presented in Table 2). The results are shown in Fig. 6, with damage reduction as objective in Fig. 6a, and with total benefit maximisation as objective in Fig. 6b.

Based on this analysis we can observe that RB and PP (blue and green in Fig. 6a) are not preferred when the pursued benefit is to reduce flood risk. In this case, ODB (yellow) is the most applied option. However, when the sought benefit shifts to total benefits maximisation (Fig. 6b), the application of RB increases sharply from a mean value below 20% to approximately 90% in all cases. Unlike ODB, RB is not a very effective measure for coping with runoff excess (i.e. reducing flood damage) but it is a low cost measure which provides substantial water and energy savings (main co-benefits in this case). Note that the usage of PP also increases when the second objective is to maximise total benefits, although to a lesser extent. This is because of PP is more expensive than RB and some of the co-benefits it provides are not so profitable, namely groundwater recharge and water quality enhancement.

Regarding the use of ODB (yellow), we can observe an important application decrease for strategies 2 and 4 when the objective is switched to total benefits maximisation (Fig. 6b). This is expected because, despite being an effective flood reduction measure, we have not considered co-benefits for this measure which makes it less attractive to the optimisation algorithm. In addition, note that the application of Pi (red) increases for all strategies in the case of total benefits maximisation (Fig. 6b) relative to the case of flood risk reduction maximisation (Fig. 6a). The explanation of this can be linked to the lower application of PP (green) in case of strategy 3 and ODB (yellow) in case of strategy 4, which implies less runoff reduction. As a result, optimal solutions focus on the improvement of system's conveyance to keep flood damage low.

Finally, major differences can be observed in terms of optimal strategy 4 composition when the second objective is changed. The application of GBI increases considerably, with mean values increasing from approximately 10% to 95% and 35% for RB and PP respectively. Besides, the mean application of ODB reduces substantially, from above 60% to 35%, and the mean use of pipes increases from approximately 10% to more than 40%. These changes imply the achievement of higher co-benefits, but also a decrease in the efficiency of flood risk reduction. This is the result already observed for strategy 4 (Fig. 5d), in which a significant growth of total benefits is observed, but also a decrease of efficiency regarding flood mitigation. These changes suggest that special attention should be paid to the selection of second optimisation objective when multi functionality of measures is pursued. Local priorities should be considered closely with stakeholders in order to define the importance of each objective. These needs can then be represented in the optimisation process, for example incorporating a suitable weight for each objective, or with a careful post-process to analyse these trade-offs and make a decision accordingly.

4. Discussion

While the application of optimisation techniques in water resources enables the assessment of multiple options, it is often a time consuming task (Maier et al., 2014). The application of some form of pre-processing can shorten this time by reducing the number of optimisation options. This is even more important in cases with a bigger computational burden than the one here studied, for instance in cases with more extensive or complex drainage systems. However, the reduction of options needs to be done carefully not to lose useful information in the process and end up with suboptimal solutions. In this work a systematic multi-criteria analysis was applied which allowed to shortlist measures and to interact with stakeholders, without losing information. The combination of this multi-criteria pre-process with a more quantitative post-process, which allows to compare strategies according to costs and benefits in the long term, is seen as novel in this research.

Besides, we have confirmed the usefulness of optimisation as a decision-making support tool in the context of stormwater management with green, blue and grey measures considered. The optimisation approach allows decision makers to identify the most effective solutions covering a wide range of costs and benefits. Moreover, they can visualise the effectiveness achieved for each level of investment, recognising which investment level gives them the highest return. The usefulness of optimisation methods for urban stormwater problems has been previously established, but co-benefits have been included into the analysis in few cases only (Urrestarazu Vincent et al., 2017; Di Matteo et al., 2019).

Since the simultaneous delivery of social, economic and environmental benefits by GBI increases the willingness to accept these solutions, awareness about these co-benefits is crucial to convince decision-makers about GBI implementation (EEA, 2012; Liu and Jensen, 2018; Qiao et al., 2018). Moreover, the economic analysis of these co-benefits can have a significant impact on decision-making by establishing evidence-based decisions and allowing its financial consequences to be visualised (EEA, 2016). The study presented in this work shows how the inclusion of co-benefits can encourage the selection of GBI for urban flood mitigation. Although the analysis presents constraints due to data availability and local characteristics, similar results concerning the effectiveness of this approach have been found in previous research (Elmqvist et al., 2015; Ossa-Moreno et al., 2017; Engström et al., 2018).

The inclusion of co-benefits in this analysis has been greatly limited due to the consideration of only those co-benefits easily represented in economic terms. Moreover, we chose only the most important co-benefits for this case, the ones having more economic relevance. Still, the results show how the inclusion of co-benefits analysis, even if limited, has an important impact encouraging the selection of GBI. A post analysis could be added to this framework to include a qualitative analysis of not monetisable co-benefits. Through this step, decision making could be further imporved considering the complete range of benefits achievable applying GBI and stimulating even more the selection of holistic and adaptive solutions.

Our results also highlight that combinations of green-blue-grey measures can be the best option for climate change adaptation, this result is compatible with other recent studies (WWAP/UN-Water, 2018; Browder et al., 2019). We proved that this is particularly important when several benefits are considered simultaneously. In urban spaces, where space is limited, the combination of green, blue and grey measures allows to maximise the efficiency with some measures performing best at flood risk reduction (open detention basins and pipes in this case) and other at co-benefits provision (rain barrels and pervious pavements in this case). Our results also state the importance of considering the achievement of co-benefits as a relevant objective from the beginning, when selecting and comparing among stormwater management options. When the focus is only on flood risk reduction, even if GBI is used, the co-benefits will be achieved as a side effect which can decrease largely its value.

The importance of considering trade-offs among objectives is also stressed in this work. This is particularly significant when adding new benefits while maintaining stormwater management as primary functions. Blue-green infrastructure can have low effectiveness decreasing flood damage in the case of high return period rainfalls (Zölch et al., 2017; Mei et al., 2018). Therefore, even if a strategy achieves the highest total benefit, attention has to be paid to the resulted compromise on flood damage reduction. A possible solution to this is to determine the importance of each benefit and add weights into the measures assessment framework. These weights will represent the level of trade-offs accepted and should be jointly defined with local stakeholders.

Finally, this work presents an analysis of which are the application values of measures selected in optimal solutions when the objective is switched from the traditional approach of flood mitigation to total benefits maximisation. This analysis allows a clear visualisation of which measures are best in each situation, showing that optimal solutions will prefer grey infrastructure when the objective is only to mitigate floods, but will prefer GBI if the objective of maximising co-benefits is added.

Further work is needed on methods for economic valuation of co-benefits such as liveability and aesthetics enhancement, biodiversity improvements and recreation. This is important considering that economic calculations are nowadays insufficient to fully represent the co-benefits related to green infrastructure in cities, since many important co-benefits are difficult to assess economically (Elmqvist et al., 2015). An improvement on economic representation of these benefits will help to encourage further application of GBI in urban spaces. Besides, this work, and most of the publications examined, which study the multiple benefits provided by GBI, focus on its positive aspects. However, these measures can also have negative impacts, also called dis-benefits or co-costs (Demuzere et al., 2014; Calliari et al., 2019), which should be quantified and considered in the analysis when assessing and comparing different alternatives. This will allow more realistic results and avoid future negative impacts, which can damage even more the acceptance of this approach. Lastly, the results obtained in this work were not discussed with the involved stakeholders. This is an important step to be performed in the future in order to validate the model outputs. Validation is particularly important for the multi-criteria analysis results, since this step determines which measures are selected to be further analysed. The not corroboration of this result can lead to the selection of measures which, for instance, have not local acceptance or which are not applicable due to particular circumstances not considered in the analysis.

5. Conclusions

A method to assess the performance of different green, blue and grey measures and their combinations in the achievement of flood risk reduction and the improvement of other benefits has been described and applied in this study. To achieve this, a hydrodynamic model was coupled with an evolutionary optimisation algorithm to evaluate and optimise preselected green-blue-grey measures. We also analysed how the effectiveness of optimal solutions regarding the primary function of flood risk reduction varies when the objectives are changed. This was performed applying the optimisation framework twice. First it was applied with the objectives of cost minimisation and flood risk reduction maximisation. Secondly the objectives were costs minimisation and total benefits maximisation. This allowed us to evaluate in a quantitative way the trade-offs when different benefits are pursued in stormwater infrastructure planning. Finally, we analysed how the composition of optimal solutions changes when the pursued objective is switched. In other words, how green, blue and grey measures are selected in different cases. It allows to understand which measures are best for each objective.

The results obtained can be summarised as:

- We confirmed optimisation as a helpful decision-making tool for stormwater management when several strategies are considered. More specifically, it allows to compare among optimal combinations of green, blue and grey measures for a wide range of costs. Using this approach, the decision maker can visualise complex trade-off between cost, flood damage reduction and co-benefits enhancement. Hence, the effectiveness of solutions for different levels of investment can be assessed.
- The combination of green, blue and grey measures is the best strategy in this case. This is particularly important when several benefits are considered simultaneously in urban spaces, where there are space limitations. The combination of measures allows to maximise the efficiency, with some measures performing best at flood risk reduction (grey) and other at co-benefits provision (green-blue).
- From the analysis of results with primary benefits as objective versus total benefits as objective, we conclude that there are inevitable trade-offs among different benefits obtained from different green-blue-grey measures. Our results stress the importance of considering the co-benefits as a central objective when selecting flood mitigation options. When only flood risk reduction is considered, even if green-blue infrastructure is applied, the achievement of co-benefits would be much lower. However, the effectiveness on flood mitigation could be severely diminished when we add the improvement of co-benefits as an objective. In order to manage these trade-offs, the establishment of priorities among benefits, or the relative importance between flood management and co-benefits, should be further studied to include objective weights within the framework.

Even though the quantitative results in this work are indicative and uncertainty should be further assessed, we recommend the application of this type of multifunctional and multisystem assessment to support urban sustainability planning. It allows a broad and reliable comparison of diverse green-blue-grey solutions and its multiple benefits.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.134980.

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