Value of SuDS beyond urban flood management: The Ecosystem services value of green/blue solutions

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Abstract

We analyse the implementation of Sustainable Drainage Systems (SuDS) as a solution to better manage storm water runoffs and reduce urban flooding, and at the same time provide significant Ecosystem Services (ES). ES vary from temperature control at urban and building scale to main water savings, depending on the type of SuDS considered. The general objective is to incorporate the monetary value of SuDS' ecosystem services into the decision making process on storm water management (SWM) of an urban catchment affected by regular floods, and to optimize the design of the drainage solution, in order to justify the feasibility of larger investment on this type of systems. The case study is an urban catchment of 220 ha in the city of Montevideo, Uruguay, where approximately 600 houses are affected by pluvial floods. Rain barrels and green roofs are the two types of SuDS considered in the study. An optimization algorithm together with the hydraulic model of the drainage system is used to determine the optimum size and distribution of the drainage elements (SuDS and storages). The results show that the inclusion of ES benefits justifies significantly larger investments on SuDS. When detention storages are considered in combination with SuDS, the largest flood reductions are achieved as well as the largest total benefits.

1. Introduction

In many urbanized areas, small rivers and streams are covered by the city development, and these open streams are transformed to underground drainage systems so that the ground surface can be utilized to whatever use is given to the land (Maharjan et al., 2009). On the one hand these artificial conveyance mechanisums have a very strict limit to their hydraulic carrying capcity, which directly result from their engineering design. On the other the changing urban landuse (by the increase of impervious areas and reduction of resistance to flow,) result in increasingly larger and swifter runoff. When the flow resulting from local rainfall exceeds the carrying capacity of the drains, pluvial floods occur. Normally the first infrastructures to be flooded are the streets, and then the sidewalks, houses and other urban facilities start to be inundated as well. This results in economic losses of direct (e.g. property damage) and indirect (e.g. health impacts, disruption of transport). The water quality issues become predominant in the case of combined sewer systems, overflowing which will contribute significantly to urban pollution rain storms. Since the pluvial floods are produced by local rainfalls over the urban basin, the landuse in the basin strongly influences these events. (Dietz, 2007).

The Sustainable Drainage Systems (SuDS) constitute an increasingly practiced approach for managing the ever-increasing threat of pluvial floods. The SuDS practices are designed to retain, infiltrate and/or evapotranspirate the storm water, and therefore to reduce the amount of water that runs off the catchment in terms of volume and also in terms of maximum discharges. The British environmental regulatory agencies, for example, suggest the implementation of SuDS as a way of reducing storm water runoffs and therefore reduce floods (Ellis et al., 2012).

SuDs approach provides a host of elements and technologies: e.g. like rain barrels to collect water from roofs, swales to facilitate infiltration to manage pollution and runoff, green roofs, permeable pavements, etc., that can be adapted rto suit the specific site conditions and other factors like affordability and social acceptance. A key feature of SuDS solutions is that they attempt to move the hydrological response of the urban basin towards the pre-urbanized state. Many SuDS provide benefits other than flood and pollution control. For example some SuDS systems are strongly related with urban agriculture since they provide a place to do farming. Further they can add value to urban spaces by providing multifunctional green-blue spaces. These added benefits (sometimes termed as 'ecosystem service value') are often significant in value (Lundy and Wade, 2011), but usually ignored when drainage projects are budgeted. Considering these wide spectrum of benefits of SuDS often show that they provide significantly high value compared to just the intended objective of flood reduction (Stovin et al., 2012). In this paper, with the aid of a case study from South America, we demonstrate that the consideration of ecosystem service functions of SuDS justify the feasibility of larger investment on these systems.

A case study is presented and analysed for the Upper Quitacalzones drainage catchment located in the city of Montevideo, Uruguay. A number of different scenarios are analysed considering the implementation of SuDS as a measure to overcome the flooding events happening regularly within the catchment boundaries. The analysis of the costs and benefits of such measures is presented as a tool that later can be used by decision makers responsible of dealing with urban sewer systems.

2. Area of study

2.1 General description of the area of study

The Upper Quitacalzones has an area of 220 ha, and is part of the Quitacalzones catchment, located in the city of Montevideo, Uruguay. The area of the whole catchment is 600 ha and drains towards the Montevideo bay located at the West. The location is illustrated in Figure 1.

Figure 1. Location of Upper Quitacalzones catchment (Google Maps)

The catchment area is entirely urbanized, with a prevailing dense residential land use. Green spaces and free public areas are very few. The land use distribution of the catchment is 26% of roads and pathways, 64% of buildings and the rest corresponds to private gardens.

2.2 Urban drainage system

The combined sewer system that serves the area was constructed between 1920 and 1950. The sewerage collected from the catchment is conveyed to Punta Carretas pre-treatment plant, though an intermediate pumping station. The effluent is released to the sea.

The basin under analysis is composed by four main subcatchments: More, Cufr, Enri and Requ. (Figure 2) Requ, while is considred in runoff computation is not retrofitted with SuDS. This area is already considered by the Municipality of Montevideo (MM) for the implementation of a large detention storage structure.

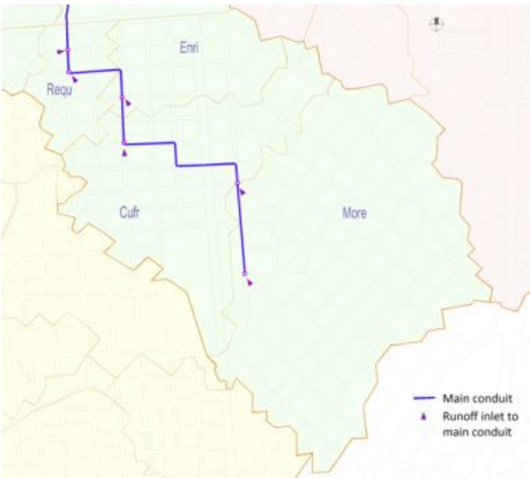


Figure 2. Three main subcatchments of the study area

2.3 Flooding problem in the area

According to the MM, approximately 610 houses are regularly flooded in rainy season. Some events of 3 year-return-period cause saturation and overflow of the drainage system in certain parts of it, and polluted storm water starts to flow over the streets until a depressed area of the catchment where it is accumulated for a period of time. This flooded area is located in the most downstream part of the 220 ha study area. Once the inflows to the drainage system start to decrease after the peak of a rainstorm, this water is drained out from the catchment by the drainage system.

Water depth can reach levels of more than 1 m in the worst cases and water gets into the houses causing direct financial damages and health problems (latter due to combined sewer surcharge). As the flooding events are recurrent, the people living in the area have attempted to reduce the property damage by ad-hoc solutions , like removable gates at the front door.

3. Methodology

in the analytical approach is illustrated in Figure 3.

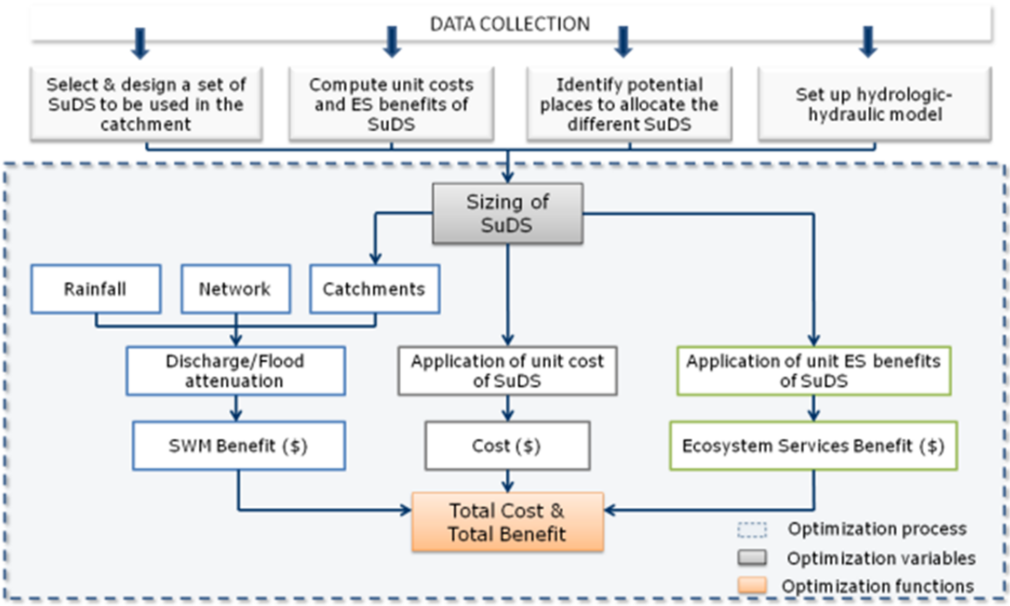


Figure 3. Methodological framework

First stage. The collection of climatic, physical, environmental and socio-economic data.

Second stage. Consists on the selection of SuDS to be implemented. Two SuDS elements are considered: green roofs and rain barrels. The selection of them takes into account the characteristics of the case study catchment, mainly land use and land cover, and priority was given to those elements that are more related to urban agriculture, such as green roofs and rain barrels (to collect water and irrigate later on). For this selection it was checked the available options for modelling this kind of drainage elements in the selected model.

Third stage. A rainfall-runoff simulation model is set up with the design rainfalls, the subcatchments and the main conduits (network), and it is calibrated. The modelling of the hydrological process and the conveyance of the storm water in the network was done with the Storm Water Management Model version 5.0 (SWMM 5.0) developed by the United States Environmental Protection Agency (US EPA)(USEPA, 2010).

A design rainfall for every considered return period is formulated with the rainfall data collected for the location of the catchment, based on the information provided by the MM. Several return periods are considered and modelled to compute the flooding costs, from 2 years up to 50 years.

The base model of the study area with the main network was provided by the MM, already calibrated. The hydrology is modelled using the model called PlutonM and the runoff is generated by the convolution of a unit triangular hydrograph which was calibrated in the 90's for the urban areas of Montevideo. SuDS are considered as part of the hydrologic components of the SWMM model and are later e incorporated in the model replacing the inflow hydrographs already mentioned.

After that, the general characteristics of the SuDS elements are incorporated, remaining undefined the area or number of these elements in the model; these are the parameters that are optimized later on.

Fourth stage. The estimation of the costs and ES benefits of the SuDS which are expressed in terms of US$/unit or US$/m2. The flooding costs are also estimated through the deduction of a damage-depth correlation, which represents the total costs on the whole area due to a single flooding event and therefore allows the computation of the SWM benefits for the different candidate solutions during the optimization process.

All costs and benefits are considered as cash flows that happen either in the present (initial costs and benefits) or in the future (future costs and benefits). The total lifespan of the project in order to compute the future cash flows is 30 years.

The valuation of the benefits from the ecosystem services provided by a SuDS element (and for a green infrastructure in general) is schematized in Figure 4.

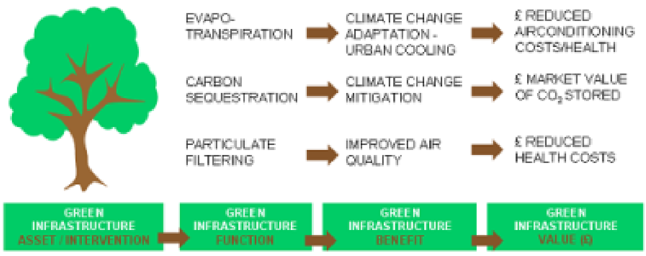


Figure 4. Translating green infrastructure intervention into monetized benefit values. Source: (Ashton et al., 2010)

The identification and valuation of benefits a toolkit was chosen complementing the process of translating the SuDS ES benefits into monetary terms. These benefits are calculated on an area or unit basis (i.e. US$/m2 or US$/unit). For a particular solution, the total present value of the ES benefits is computed as follows:

$$\mathrm{TESB} = \sum_{i=1}^{n} \mathrm{Nr_i} \times \mathrm{ESB_i} \qquad \text{(Equation 1)}$$

Where, TESB is the total ES benefits of SuDS (US$), n is the number of types of SuDS elements considered, $\mathrm{Nr_i}$ is the number of units (or square meters) of the $\mathrm{i^{th}}$ SuDS element, $\mathrm{ESB_i}$ is the unit Ecosystem Services' benefits (US$/m2 or US$/unit) of the $\mathrm{i^{th}}$ SuDS element. Note that this is already the PV of all initial and future benefits.

Fifth stage. Is the implementation of a multi-objective optimization (MOO) process by the use of an optimization tool that couples the rainfall-runoff model with evolutionary algorithm computations. Within this process, for each candidate solution a layout of the SuDS elements is defined by setting the number and/or area of each of them over each of the subcatchments. This definition is represented in the model and the reduction on flooding costs for this specific layout is computed and translated into monetary values. At the same time the ecosystem services of this specific layout are evaluated and also translated into monetary values. Finally the costs of these SuDS elements are calculated. With all these three values the fitness of the candidate solution can be assessed and can be plotted in a graph where the costs are represented in the “x” axis and the total benefits in the “y” axis.

Two different drainage schemes are optimized. The first one is a drainage system where only SuDS (green roofs and rain barrels) can be installed within the subcatchments, while in the second scheme storages are also considered as an option. On the other hand, each of these two systems is optimized for two different cases: when computing the ecosystem services' benefits of SuDS and when not computing them. In total, four different scenarios are assessed, as presented in Table 1.

Table 1: Assessed scenarios for optimization

	With ES	Without ES
SuDS	Scenario 1	Scenario 2
SuDS & storages	Scenario 3	Scenario 4

If this process is repeated several times, but every time changing the area covered by each SuDS or the number of them over the different subcatchments (under certain limits, and under a MOO process), other points of cost-benefit can be plotted. The MOO is set to find solutions that minimize costs and maximize total benefits. A MOO is preferred to a Single-objective optimization (SOO) due to the availability of information and flexibility to manage decisions that the former provides (Delelegn et al., 2011).

4. Results and discussion

The output of the optimization process is shown in Figure 5. Every assessed solution is represented by a point having the total costs and the total benefits as coordinates. The upper envelope is the Pareto front, formed by the optimal solutions. In that figure it can be seen that the benefits are higher than the costs, for the optimal solutions. The Pareto front has a steeper slope for the low-cost solutions than for the more costly ones. One remarkable aspect is that net benefits increase with the costs; however, the benefit-cost ratio remains approximately constant for the solutions below 10 million US$ cost and then decreases for higher investment costs.

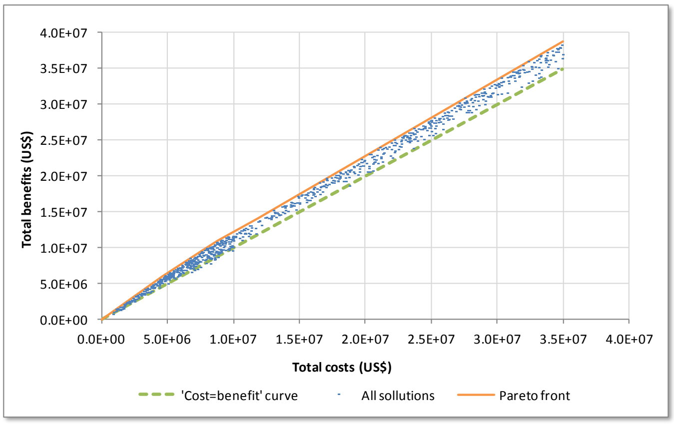


Figure 5: Cost and benefits of all assessed solutions and Pareto front

If we segregate the costs and benefits from the SuDS layouts and select a set of representative solutions of the Pareto front, a detailed analysis can be performed. For each solution, costs of SuDS are computed differentiating between rain barrels and green roofs. Also benefits are disaggregated in ES benefits and SWM benefits. The outcome is presented in Figure 6, where is clearly shown that the inclusion of ES benefits generates positive net benefits. If only the benefits of SWM are considered, the investment would not be feasible in economic terms and therefore difficult to justify, because they are always below the curve of total costs.

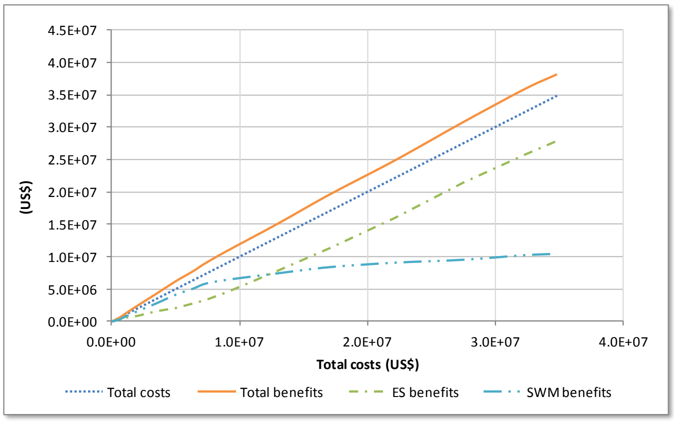
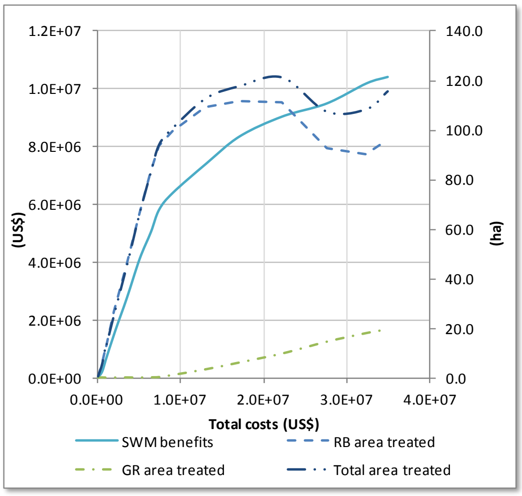


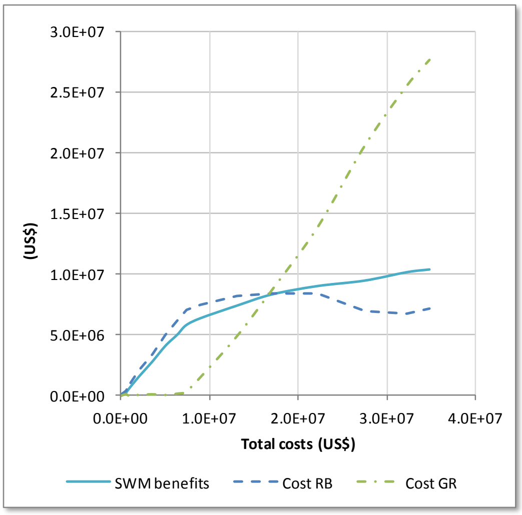
Figure 6: Cost and benefit decomposition of Pareto front

The impact of the implementation of SuDS on SWM benefits is more effective for the first 10 million US$ of investment, where for every dollar invested about 0.75 dollars are reduced in terms of flood damage costs. Beyond that point, this coefficient decreases up to values of 0.3. The opposite effect is observable with ES benefits; this has to do with the distribution of rain barrels and green roofs over the area.

The decrease of slope for the SWM benefits for investments beyond 8 million US$ (see Figure 6) can be better understood with the Figure 7. Although rain barrels are relatively cheap devices and more cost efficient in terms of providing SWM benefits (flood reduction), provide less ES benefits compared to green roofs. For the low investment's range rain barrels perform better, and are preferred over the green roofs. However, there is a point in which these SWM benefits provided by the rain barrels start to lose importance compared to the ES benefits that green roofs can provide with the same amount of money invested. Since the objective function is the maximization of the total benefits and not the SWM benefits, green roofs start to be more cost efficient than rain barrels.



a.



b.

Figure 7. SuDS coverage, costs and SWM benefits

The results of the optimization process for the four assessed scenarios are summarized in Figure 8. In the figure, we can see that storages combined with SuDS is a cost-effective solution, regardless if ES benefits are considered or not. However, when ES benefits of SuDS are considered, larger investments are possible while still having positive net benefits. On the other hand, when storages are not included and only SuDS are used, the inclusion of ES benefits turns the solutions from unprofitable to profitable.

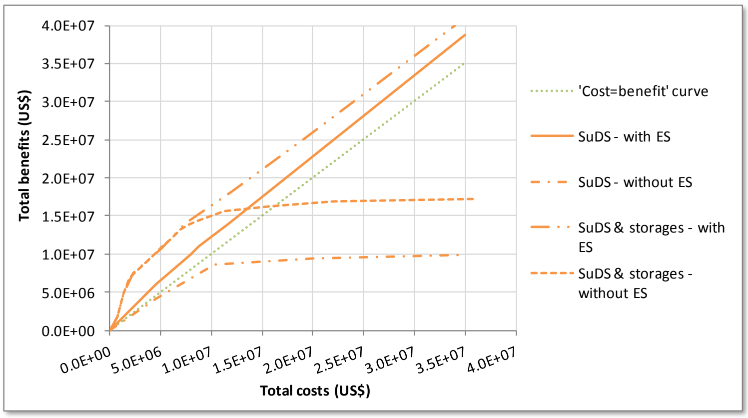


Figure 8. Pareto fronts for the assessed scenarios

Also, the main economic indicators can be obtained for the assessed scenarios, as shown in Table 2. Only the scenario with SuDS but without considering their ES benefits (scenario 2) gives negative net benefits for any total cost. Scenario 3 is the one with higher net benefits while the one with higher total benefit-cost ratio is scenario 4, but very close to scenario 3.

Table 2. Maximum net benefits and benefit-cost ratios for the assessed scenarios

	Scenario			
	1	2	3	4
Max net benefit (million US$)	4.5(a)	-	6.3	6
Max total B/C ratio	1.25	0.85	3.3	3.5
Max profitable investment (million US$)	>120	-	>120	16.3

(a) for an investment of 75 million US$ approximately

5. Conclusions

In this paper SuDS were analysed as potential solution for urban floods, and the impact of their ecosystem services' benefits were assessed. For every assessed solution, the expected benefits from flood reduction, the ecosystem services' benefits and their costs were computed.

Four different scenarios were assessed and their design optimized. Figure 8 summarizes the overall results of the paper. For the scenarios in which only SuDS are considered, the inclusion of ES benefits proved to justify investments that would not otherwise be profitable.

Larger investments are possible when ES benefits of SuDS are considered while still being profitable. The use of storages demonstrated to be more cost-effective than only using SuDS, providing larger total benefits, and the solutions with storages resulted to have the largest reductions in SWM benefits, or in other words, the largest reductions in flooding. However, in none of the scenarios the flooding is totally eliminated (non-zero flooding cost), at least for the range of costs analysed.

Rain barrels resulted as more cost-effective solutions than green roofs for reducing storm water runoff and therefore floods. This is mainly due to higher cost per area of green roofs when compared to rain barrels.

The analysis presented in this paper does not provide a complete picture of all the measures required when decisions have to be made. Social, legal, institutional and political implications related to the installation of SuDS are beyond the scope of this paper; however, these results can give an important input to the decision making process. Moreover, legal and social analyses can also take advantage of this study; for instance, if the budget for solving these problems is relatively low, results have shown that storages are the best option and therefore it would not be needed to analyse the willingness of homeowners to install these SuDS or to the legal implications of installing them.

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