water

MDPI

Article

Enhancing the Economic Value of Large Investments in Sustainable Drainage Systems (SuDS) through Inclusion of Ecosystems Services Benefits

Santiago Urrestarazu Vincent [1,2], Mohanasundar Radhakrishnan [1], Laszlo Hayde [1] and Assela Pathirana [1,*]

[1] Water Science and Engineering Department, IHE Delft Institute for Water Education, 2611 AX Delft, The Netherlands; surresta@gmail.com (S.U.V.); m.radhakrishnan@un-ihe.org (M.R.); l.hayde@un-ihe.org (L.H.)

[2] CSI Ingenieros, Soriano 1180, 11100 Montevideo, Uruguay

* Correspondence: a.pathirana@un-ihe.org; Tel.: +31-15-215-1854

Received: 13 July 2017; Accepted: 16 October 2017; Published: 31 October 2017

Abstract: Although Sustainable Drainage Systems (SuDS) are used in cities across the world as effective flood adaptation responses, their economic viability has frequently been questioned. Inclusion of the monetary value of ecosystem services (ES) provided by SuDS can increase the rate of return on investments made. Hence, this paper aims at reviewing the enhancement of the economic value of large-scale investments in SuDS through inclusion of ecosystem services. This study focuses on the flood reduction capacity and the ES benefits of green roofs and rain barrels in the combined sewerage network of Montevideo Municipality in Uruguay. The methodology comprises a cost–benefit analysis—with and without monetised ES provided by SuDS—of two drainage network configurations comprising: (i) SuDS; and (ii) SuDS and detention storage. The optimal drainage design for both these drainage configurations have been determined using SWMM-EA, a tool which uses multi-objective optimisation based evolutionary algorithm (EA) and the storm water management model (SWMM). In both design configurations, total benefits comprising both flood reduction and ES benefits are always higher than their costs. The use of storage along with SuDS provides greater benefits with a larger reduction in flooding, and thus is more cost-effective than using SuDS alone. The results show that, for both of the drainage configurations, the larger investments are not beneficial unless ES benefits are taken into account. Hence, it can be concluded that the inclusion of ES benefits is necessary to justify large-scale investments in SuDS.

Keywords: Sustainable Drainage Systems; multi-objective optimization; multiple values

---

1. Introduction

Urban floods driven by climate variability, climate change and rapid urbanisation at various scales cause damage to lives and property [1]. The flood damages are direct economic losses (e.g., property damage) and indirect losses (e.g., health impacts and disruption of transport). A variety of flood mitigation and adaptation measures can be implemented to mitigate or adapt to urban floods [2]. Most conventional measures tend to increase the capacity of drainage infrastructure, for example by increasing conduit sizes. Other measures aim to reduce the demand for conveyance capacity by retaining or detaining stormwater at source thereby reducing the runoff before entry to the drainage system. In parallel, there is an increasing awareness of sustainable development needs [3], which necessitates the use of sustainable materials and sustainable management practices. The range of technology and techniques used to manage stormwater or surface water in a way that is more sustainable than conventional drainage techniques are known in several parts of the world as sustainable drainage systems (SuDS) [4]. For example, SuDS include rain gardens, green roofs, rainwater harvesting systems, and bio-swales.

Many SuDS are a part of Low Impact Development (LID), Water Sensitive Urban Design (WSUD), Green Infrastructure (GI), Active Beautiful and Clean Waters Design Features (ABC Waters Design Features) and Best Management Practices (BMP) [4,5]. SuDS, or their equivalent, are being used extensively in UK, USA, Canada, Australia, Netherlands, Denmark, Malaysia and Singapore [4–7]. In addition to storm water management benefits, SuDS are known to deliver other benefits such as to ecological systems, enhancement of the liveability of urban environments, reduction in ambient temperature, urban agriculture, etc. [8]. SuDS such as green roofs, swales, bio-retention systems and rain gardens may be considered as part of the natural urban ecosystem which provides ecosystem services to urban dwellers and others [4,8,9]. Ecosystem services are the goods or services provided by ecosystems to society [10,11]. The value of ecosystem services can be expressed in monetary units, so that the cost incurred and benefits accrued can be compared [8,10]. One such example is the BeST tool (Benefits of SuDS Tool) developed by CIRIA (Construction Industry Research and Information Association, London, UK), which provides a structured approach to evaluate the wide range of benefits based on overall drainage system performance and monetises many of the benefits [8].

The inclusion of SuDS in the urban environment has highlighted many of the interdependencies between the various systems in the urban environment and has also illustrated the important interactions between the stormwater management components [7]. Hence, the cost effectiveness and benefits of using SuDS needs to be assessed in the framework of these interdependencies and interactions. In places where SuDS have been implemented [4–7], they are not in isolation, but are applied to support or relieve the demand pressure on the existing traditional (grey) infrastructure. Many of the investments made in green and grey drainage infrastructure are large-scale, as these are often implemented alongside major drainage retrofitting [12]. Thus, determining the cost effectiveness of a combination of green and grey drainage infrastructure and determining the most effective mix based on the overall drainage performance are essential for making decisions for investments in stormwater drainage infrastructure. As the overall benefits of SuDS, including ecosystem services (ES), can be monetised using tools such as BeST, there is an opportunity for an increase in cost effectiveness of the large-scale investments made in green-grey drainage systems.

This paper aims at providing insights into enhancing the economic value of large-scale investments in SuDS through the inclusion of ecosystem services benefits in an urban context. The general objective is to incorporate the monetary value of SuDS ecosystem services into the decision making process for selecting storm water management (SWM) measures for an urban catchment affected by regular floods. In so doing, to optimize as far as practicable, the design of the drainage system, in order to examine whether it is possible to financially justify larger-scale investments for these types of mixed systems. SuDS are considered here in combination with underground storage to broaden the range of flood reduction measures and compare these. This study focuses on the flood reduction capacity and the ecosystem services benefits due to the incorporation of green roofs and rain barrels in the combined sewerage network of Montevideo Municipality in Uruguay. The methodology comprises a cost–benefit analysis of the two drainage network configurations, with the first configuration including SuDS and the second with SuDS and detention storage together. The analysis has been carried out using SWMM-EA [13], a tool which combines multi-objective optimisation based on the non-dominated sorting genetic algorithm II (e.g., Deb et al. [14]) with the storm water management model (SWMM) [15].

2. Methodology

The framework for this research is shown in Figure 1. This includes a first stage (I in Figure 1), which comprises the collection of climatic, physical, environmental and socio-economic data.

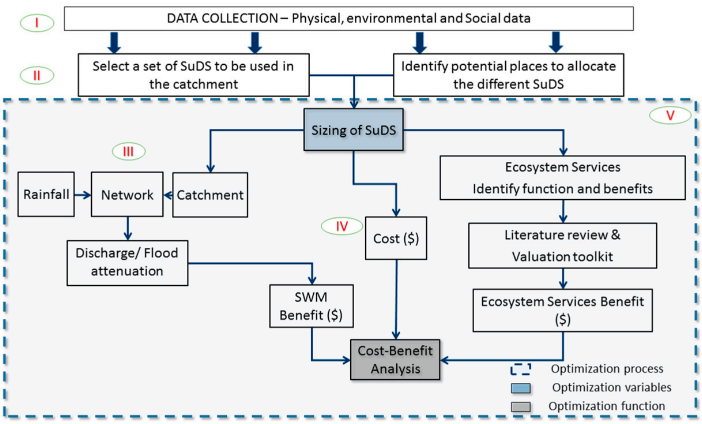

Figure 1. Research framework.

In the second stage (II in Figure 1), the types of SuDS are determined based on the characteristics of the catchment under study (e.g., rain barrels, rain gardens and green roofs). The maximum or potential area (or number of these, depending on the SuDS element under consideration) to be treated by each SuDS element are determined based on the area of the different sub-catchments, their land use and land cover. There could be some dependence between the potential areas in some cases, hence the relation between the potential areas of the different SuDS elements has been established.

In the third stage (III in Figure 1), a one-dimensional rainfall–runoff simulation model is set up with the design rainfall, the sub-catchments and the main conduits (network), and is also calibrated. Subsequently, the general characteristics of the SuDS elements have been incorporated, keeping the area or number of these elements in the model as variables. The variable SuDS parameters are optimized later in stage five.

The fourth stage is (IV in Figure 1) the estimation of the costs and ES benefits of the SuDS, which are usually expressed in monetary terms such as US$/unit or US$/m^2. The accepted approach is to derive the flood damage by using inundation depths calculated by a two-dimensional (or 1D-2D coupled) flood model together with a depth–damage curve. Inundation models are computationally expensive to run because of the tens-of-thousands of iterations needed by optimization algorithms. Thus, an approach using correlation between flood damage and water depth simulated at two observation nodes in the one-dimensional model has been used in this study by using flood damage assessments based on flood depths for various rainfall events across the entire catchment. The resulting depth–damage correlation has then been used to estimate flood damage under different optimization-iterations. The depth–damage correlation represents the total costs for the entire area due to a single flooding event and therefore inputs to the computation of the SWM benefits for the different candidate options in the optimization process.

The fifth stage (V in Figure 1) is the implementation of a multi-objective optimization (MOO) process using an optimization tool that couples hydraulic models such as supply–demand models or rainfall–runoff models with evolutionary algorithm computations [16,17]. Within this process, a layout of the SuDS elements has been defined for each candidate option by setting the number and/or area of each of these over each of the sub-catchments. This definition is represented in the model and the reduction in flooding costs for this specific layout is computed and translated into monetary values (SWM benefit in Figure 1). At the same time, the ecosystem services provided by this option are evaluated and translated into monetary values (ecosystem services benefit in Figure 1). Finally, the costs of the SuDS have been calculated.

The iteration of this process by changing the area covered by each SuDS or the number of SuDS units over the different sub-catchments (within a predetermined range of SuDS parameters and using a MOO process) results in various cost–benefit values. The MOO is set to find solutions that minimize costs and maximize total benefits. The outputs that have a maximum benefit for a given cost will be the optimal solutions, and the rest will be non-optimal since more benefits can be derived for the same cost (by changing the SuDS layout). The "benefit vs. cost" curve formed by the optimal solutions is called the "Pareto front". This optimization process can be repeated as many times as necessary in order to assess different cases.

2.1. Storm Water Runoff Modelling

The modelling of the hydrological process and the conveyance of the storm water in the network has used version 5.0 of the Storm Water Management Model (SWMM 5.0), developed by the United States Environmental Protection Agency (US EPA). To model flooding, the roads have been included in the model, leading to a 1D-1D model, which is a simple approximation of reality. A more accurate approach would use a 1D-2D model. Several rainfall return periods have been considered and modelled to compute the flooding costs (and therefore the SWM benefits), from 2 to 50 years.

2.2. Cost and Benefits Valuation

All costs and benefits have been considered as cash flows that happen either in the present (initial costs and benefits) or in the future (future costs and benefits). To compare different options that may have different value flows during the project lifespan, the Net Present Value (NPV) is used. The NPV is the net sum of the discounted benefits (positive values) and the discounted costs (negative values). The discount rate is based on the prevailing local practices. In addition, private costs and benefits are distinguished from purely social costs and benefits. This study focuses on the benefits to the whole society, adding private to social costs and benefits whenever these apply, avoiding double counting and not considering costs and benefits that are simply money transfers from private to social, or vice versa.

2.2.1. Costs

The costs comprise initial costs and maintenance costs of SuDS during the lifespan of the project. In addition, the social costs such as environmental impacts related to the production of the materials used for the SuDS have to be considered. The costs, usually expressed as unit costs (i.e., US$/$m^2$ or US$/unit), have been computed from local prices for the case study and through literature review. The costs of conventional drainage measures have been adapted from estimates made by the local authorities in the area.

2.2.2. Benefits

The benefits derived from the SuDS can be classified into storm water management (SWM) benefits and ecosystem services (ES) benefits.

Storm Water Management Benefits

For every assessed option, storms with different return periods will produce different floods (if any) and therefore different damage costs. The differences in these damage costs are due to the difference in the number of houses affected and also due to the difference in the depth of water in the flooded houses. The depth of water in a particular house can be translated into flooding costs (for a single house) by applying a depth–damage curve. These combined effects (flooded extent and water depth in houses) have been represented by a depth–damage correlation, assuming that the damage cost for the whole area for one flooding event can be derived based on the water depth at a particular location in the network). The depth–damage curve is different from the depth–damage correlation. The former relates the damage in a single house to flood depth in the house, whereas the latter is a derived relationship between the total flood loss in the model area and the water level at a selected node in the model. Thus, the latter provides a way to estimate the loss due to flooding, which can be simulated using a 1-D model such as SWMM. This is essential to facilitate the tens of thousands of simulations that are necessary to employ the optimization algorithms.

The SWM benefit of each individual (candidate) solution is the difference between the actual damage cost due to regular floods in the area and the damage cost that is expected after the implementation of that particular solution. Expected Annual Damage (EAD), which is the integral of the damage probability function, is determined for every candidate solution [16]. A depth–damage correlation ($D\left(h_f\right)$) is determined for two control points in the network. Hedonic pricing for the loss in the market value of a property or household has been used to calculate the losses due to flooding and to derive the depth–damage correlation for control points in the network. The difference in price is assumed to represent, at least in part, the impact of flooding on the market value of a house which is regularly flooded. This difference in the price of a house implicitly includes not only the direct damage on the infrastructure, but also other factors such as distress at being flooded and all the related costs that market prices can reflect. It is not only the cost related to a single flooding event, but also the cost of recurring floods that is important, hence the analysis includes the severity and frequency of the flooding events. For example, in Quitacalzones catchment in Montevideo, it is estimated that the average decrease in price of a regularly flooded property (house) is US$ 30,000. There are 610 houses that are regularly flooded and, thus, a total loss of around US$ 18,300,000 [18,19]. Although roads cover a significant area of the catchment (26%), the damage to the roads has not been included due to a lack of reliable data.

This cost, calculated with the hedonic pricing, is comparable with the present value of all of the EADs, assuming that if the cost is calculated by any of the two methods, the final result should be the same. Based on this assumption a "damage cost vs. depth" curve has been constructed, which represents the cost per house and per flood event. The process by which the "damage cost vs. depth" curve is adjusted and therefore the depth–damage correlation is derived is presented in Figure 2.

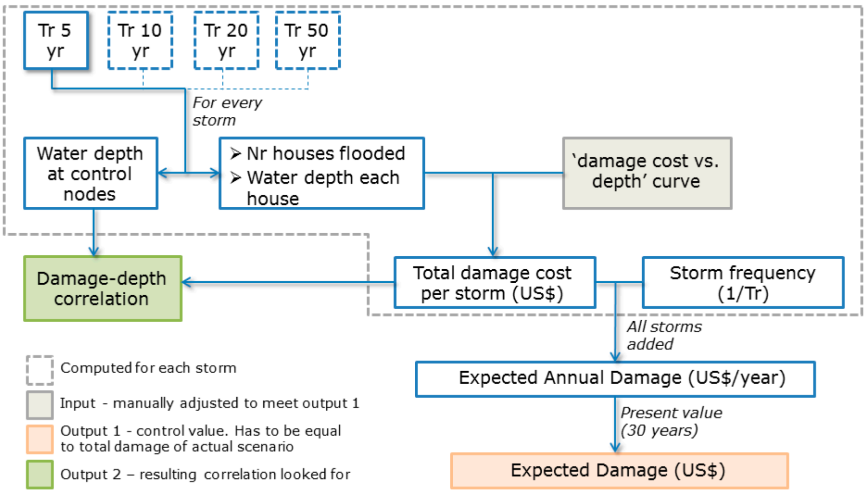

Figure 2. Process for deriving the depth–damage correlation. The depth–damage correlation links the total damage in the catchment to water level in a selected (1-D) model-node.

Ecosystem Services Benefits

The valuation of the benefits from the ecosystem services provided by a SuDS element (and for green infrastructure in general) is presented in Figure 3.

The benefits, value of benefits and the method to quantify the value of benefits have been based on literature on Ecosystem Services. Ecosystem Services Benefits of the SuDS can be computed with the help of the Green Infrastructure Valuation Toolkit Calculator [10], a valuation toolkit developed by Green Infrastructure North West, UK. However, the values can be changed with the help of literature on SuDS [20–27]. Realistic local values have been chosen whenever possible.

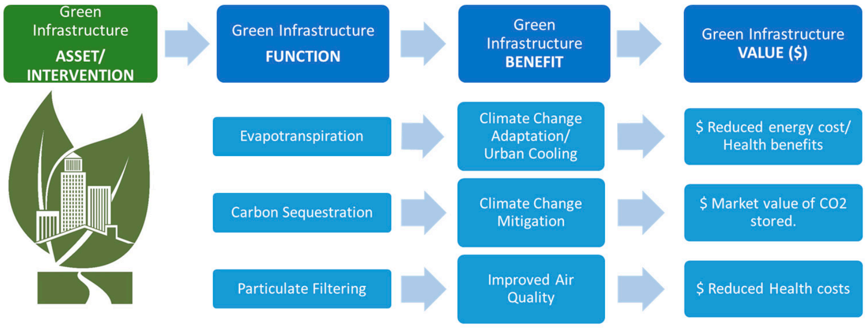

Figure 3. Translating green infrastructure intervention into monetized benefit values. After Ashton et al. 2010 [10].

2.3. Optimization Process

The optimization of the layout of the SuDS over the catchment has been set up as a Multi-Objective Optimization (MOO) problem, where the two objectives to be optimized are the total costs and the total benefits of SuDS, i.e., SWM benefits and ES benefits (Figure 4). When storage is included, the costs and benefits are also part of the objective functions.

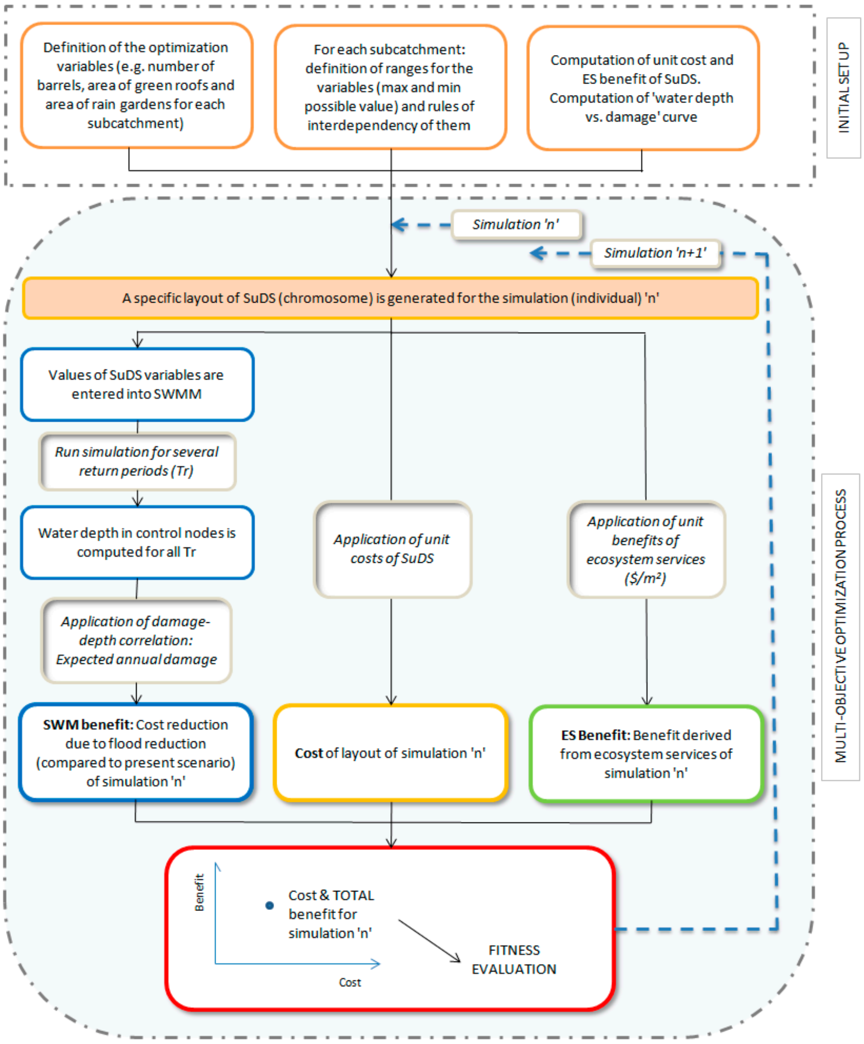

Figure 4. Optimization process framework.

The tool used for optimization was SWMM5-EA [13]. This is a software tool that applies evolutionary algorithms in urban drainage systems. This optimization tool couples the SWMM 5.0 with an evolutionary computing library. The SWMM has here been used as part of the evaluation step of the optimization process in order to assess the SWM benefits of the solutions. SWMM5-EA is a flexible tool that was originally intended for educational use and therefore provides a limited number of ways to express objective functions (e.g., cost as a sum of implementation cost and a penalty for flooding). However, the tool provides a basic Application Programming Interface (API) that facilitates implementation of arbitrary objective functions with a limited amount of coding. In this study, the API was used to implement the objective functions that were required (e.g., including ecosystem service benefits and SWM benefits).

3. Case Study: Montevideo, Uruguay

The case study area is a part of the dense urban area of Montevideo, capital city of Uruguay. Mean annual precipitation in Montevideo is 1100 mm/year. The annual distribution of the rainfall is relatively homogenous, with a minimum of 81 mm/month in June and a maximum of 108 mm/month in October [28]. This study covers 220 ha of the upper part of an urban catchment called "Quitacalzones". The whole Quitacalzones catchment has an area of 600 ha and drains towards the Montevideo bay located to the West. The catchment is entirely urbanized, with dense residential land use. However, buildings with more than three storeys are rarely found. Green spaces, as well as free public areas are very few. From the analysis of aerial imagery it can be said that roughly 26% of the area corresponds to roads and pathways, 64% corresponds to buildings and the rest (10%) to private gardens [29].

The area is served by a combined sewer system, which was constructed between 1920 and 1950, using design criteria that were internationally used at that time [18]. Interceptors, which are located along the coast of the city, collect sewage from most of the catchments of Montevideo, including Quitacalzones. During dry periods, sewage collected from the catchment is brought to Punta Carretas pre-treatment plant through an intermediate pumping station and is pumped out to the sea after treatment. However, these interceptors do not have sufficient capacity to convey storm water flows, except smaller events (i.e., storms of less than one month return period). This causes frequent overflows of combined sewage and storm water to the sea. In Quitacalzones, these overflows are discharged into the bay.

The Municipality of Montevideo (MM) estimates that approximately 610 houses are regularly flooded. For storms of three-year return period, the drainage system's capacity is surpassed and polluted storm water starts to flow into the streets and accumulates in low lying areas for typically less than 3 h. 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, the ponded surface water is drained from the catchment by the drainage system.

Flood water depths can reach more than 1 m in the worst cases and water enters the houses, causing economic and health damage. The flood extents for storms of 5-, 10- and 20-year return periods are shown in Figure 5. Montevideo Municipality has started making adaptation and mitigation plans to overcome flooding problems. Three off-line underground storage tanks, Conservación, Quijote and Liceo, are planned to be implemented as flood detention measures [19]. These storage areas (Figure 5) are designed to avoid flooding during a storm with one in ten-year frequency. Characteristics and costs of these underground storage tanks are presented in Table S1 (Supplementary Materials).

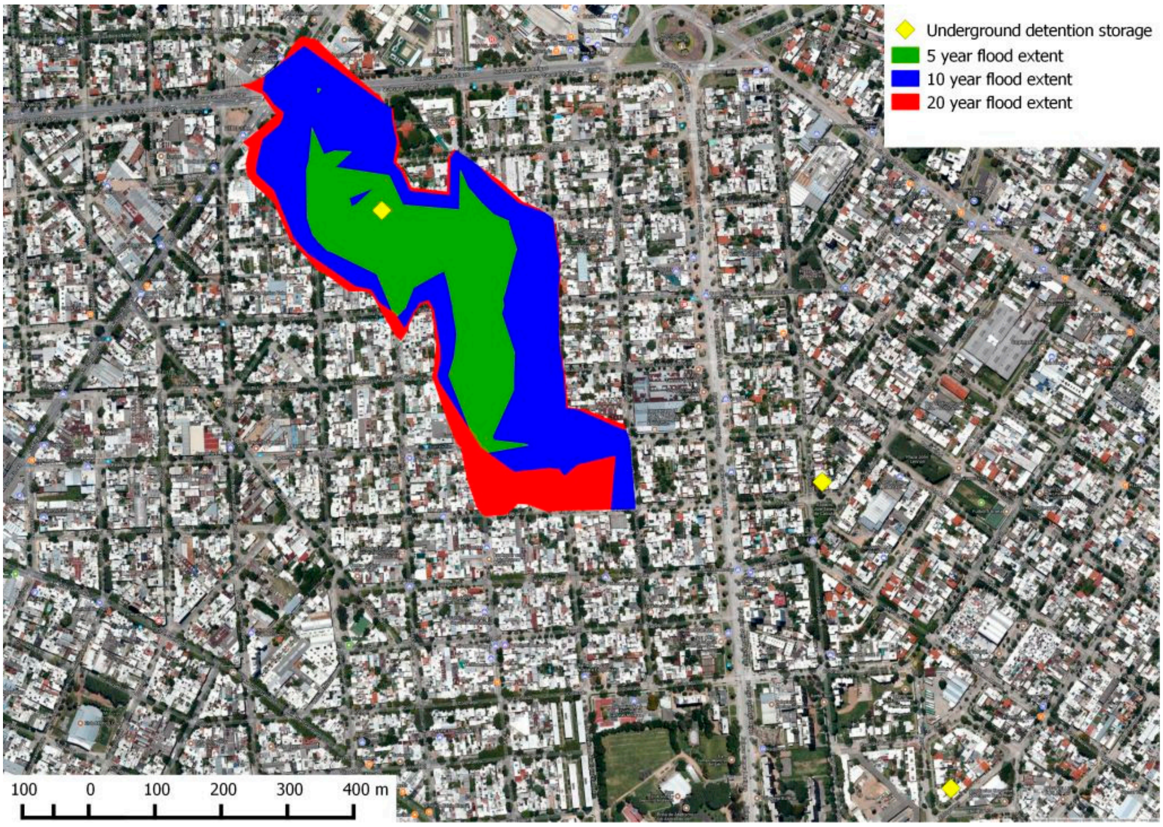

Figure 5. Location of proposed underground detention storage tanks and flooded extents for 5-, 10- and 20-year storm events in Quitacalzones catchment.

4. Application of SWMM-EA in Montevideo

4.1. Set Up of Storm Water Runoff Model

Montevideo Municipality has constructed a SWMM model of the study area, which is already calibrated, where the main network has been defined and the sub-catchments delineated. A number of streets are also included, represented as rectangular channels of 17 m width, to model their conveyance of surface storm water (which cannot be conveyed by the drainage network). This is a simplification, since it considers neither the real cross sections formed by the pavement, or the pathways and the houses, nor the elements that might affect the flow pattern, such as trees. Moreover, the entry of stormwater into the houses is also not considered in detail. However, the hydrology is not modelled in the SWMM model provided by the municipality and has therefore been included in the model as inflows into the different network calculation nodes. Since SuDS are part of the hydrologic components of the SWMM model (i.e., sub-catchments), sub-catchments elements have been incorporated into the model replacing the original inflow hydrographs. A part of the SWMM model of the catchment with sub-catchments is shown in Figure 6.

Extensive green roofs were considered in the selection of the SuDS. Extensive green roofs are shallow, lighter and therefore can be implemented on roofs (even on sloped roofs) that are not originally designed to support green roofs [30]. There is usually no need for additional structural reinforcement. These extensive green roof modules are made of several layers. The bottom layer is a plastic support, which prevents the soil to be in contact with the roof and provides space, which acts as the under-drain for the green roof. Above this support, there is a geotextile layer that prevents the soil being washed out, but allows water to drain. The growing media, with a depth of 90 mm, is on top of the geotextile.

A photograph of green roof modules installed in Montevideo by a local manufacturer (Verde facil, Montevideo, Uruguay) is shown in Figure 7.

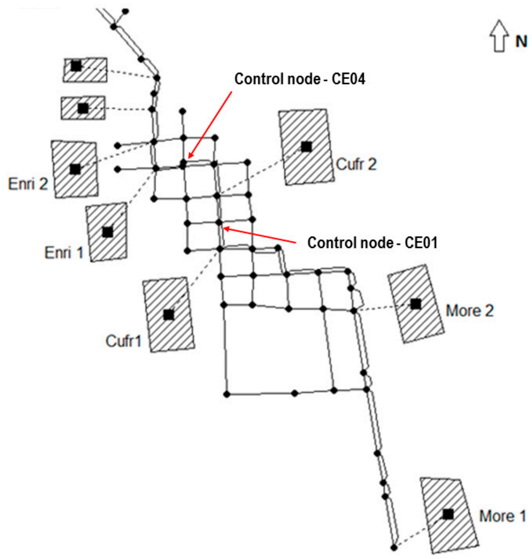

Figure 6. Representation of sub-catchments in Storm Water Management Model (SWMM).

Figure 7. Green roof modules in Montevideo [31].

Rain barrels are storage devices that collect storm water from roof downspouts. In this study, only individual household barrels have been considered. Larger cisterns that collect water from two or more houses were not considered, even though they are cost-effective in some cases [32]. There are cases in which rain barrels of 208 and 284 L (relatively small) are successfully implemented at parcel level in a small sub-urban watershed, e.g., in Cincinnati, OH, USA [33]. Here, the selected rain barrel has a volume of 600 L.

The extensive green roofs and rain barrels were incorporated into the SWMM model that was used for generating the Pareto-optimal front solutions. In the SWMM model, the height and area of the rain barrels, the total impervious area served by the barrels and the initial level of saturation of the impervious area had to be specified. The initial water level was set as 30% of the barrel (rather than assuming them to be completely empty, as they will be used for other purposes such as watering plants), and the impervious area connected by each barrel was set as 40 m^2. The SWMM modelling parameters were set according to the approximate characteristics of the selected green roof. However, some of the parameters, such as the hydraulic conductivity of the soil, are difficult to estimate and influence the storm water runoff performance of the green roof, which is also sensitive to the surface storage depth or the under-drain's drain coefficient. A value of 38 mm/h was considered as the hydraulic conductivity, which is based on a similar study done by Tang et al. [34]. The initial saturation of the soil was set as 14%, which corresponds to the midpoint between field capacity and wilting point. This is a simplification and it is possible for the soil moisture to be much closer to field capacity if a rainstorm occurs preceded by a rain event (e.g., 2–3 days or less antecedent dry weather period).

The SWMM model was coupled with a multiple objective optimisation evolutionary algorithm, set up in such a way that it received the SuDS/LID input parameters from the EA module. The inputs to the model that vary from one option to the another during the optimization process were:

- Percentage area covered by each SuDS control and the percentage of water treated from the impervious area;
- Width of the sub-catchment: the width of the non-SuDS portion of the sub-catchment, where, if the area occupied by the SuDS changed, the width should also be changed;
- Percentage of impervious area in the sub-catchment: the percentage of impervious area over the non-SuDS portion of the sub-catchment; if the area occupied by the SuDS changed, the impervious area should be changed; and
- Per cent routed: the percentage of the non-SuDS portion of the routed subarea (in this case, the impervious area was routed through the pervious area) that is routed through the corresponding routing subarea.

4.2. Cost and Benefit Valuation

Costs are those related to investment and maintenance of the systems while benefits were the ecosystem services benefits plus the storm water management benefits (flood reduction benefits in this case). A discount rate of 5% was used to calculate the present value of costs and benefits [35]. The lifespan of green roofs was taken as 40 years [21,23] and could be extended up to 55 years [36]. Rain barrels had a lifespan of 50 years [32,37]. A life span of 30 years was considered for both the SuDS options considered in this study. All the costs and benefits were based on the market rates of suppliers of green roofs (e.g., Verdefacil and Maria Pietranera), rain barrels and services associated with these in Montevideo and Buenos Aires.

4.2.1. Costs

The costs of the SuDS corresponded to local prices at the case study location. However, values from literature were also considered—in some cases to compare with the local prices, and in others to complement these. Private and social costs were added to obtain the total costs related to green roof implementation. The net present value (NPV) of the cost of the green roofs was 142 US$/$m^2$ and the NPV of the cost of a rainwater barrel was 300 US$/barrel. The unit cost of the detention storage to be used during the optimization process was obtained from the engineering and planning documents of municipality of Montevideo [18,19]. A detailed cost breakdown of the green roofs and rain barrels is provided in Tables S2 and S3.

4.2.2. Benefits

Storm Water Management Benefits

On average, the price of the houses that flood regularly decreases by about US$30,000 and, with 610 houses in the study area, the total loss is about US$18,300,000 [18,19]. The total damage in the entire area was correlated to the water depths at two control nodes CE01 and CE04 and a depth–damage correlation curve obtained (Figure 6). This is a major simplification in the study. Flood depths are typically non-linear functions of runoff and therefore can be difficult to accurately estimate using a relationship with stage at a limited number of locations within a catchment. However, due to the computational burden of a 2D model, it was decided to make this assumption, as optimization typically demands thousands of model runs. The depth–damage curve (Figure 8), which represents the cost per house and per flooding event based on the maximum depth of water, was used to generate the depth–damage correlation (Figure 9). A trend line is also shown for each curve with the respective correlation, which has been used subsequently to compute the flood related costs when assessing the candidate solutions during the optimization process.

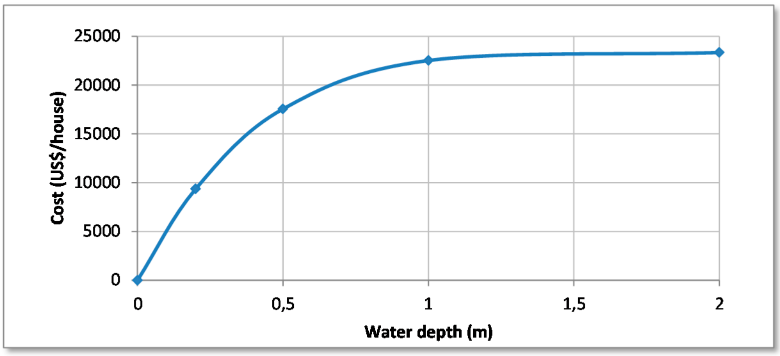

Figure 8. Damage cost per house and per flooding vs. water depth at the house—Quitacalzones.

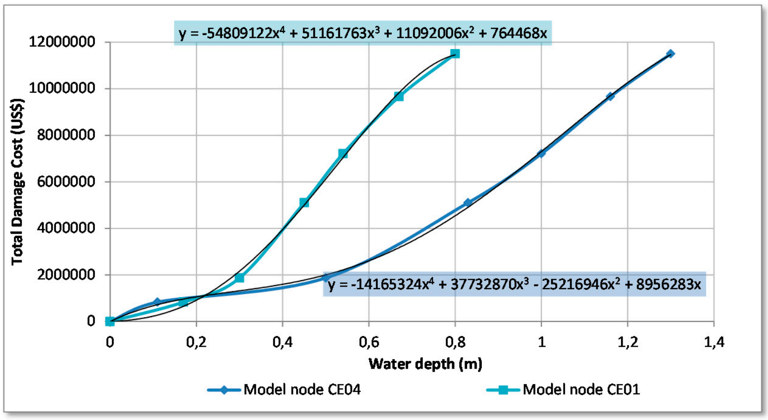

Figure 9. Depth–damage correlation: Damage cost per flooding event for the whole area vs. water depth at the control node. The total damage depends on water level in each house that is flooded. As the depth of water in the control nodes increases, both the flooded area (hence the number of houses flooded) and the depth of flooding in each house increases. Therefore, the shape of the depth–damage correlation function is different to that of the depth–damage curve (Figure 8) for a single house. The depth–damage correlation is contextual as it depends on many factors such as topography, spatial distribution of houses, etc.

Ecosystem Services Benefits

The private benefits from green roofs considered in this study are the reduction in energy consumption for cooling and heating, increase in value of private property, food production and increase in roof longevity. Other benefits such as avoided infrastructure costs for drainage installations are not considered because these green roofs will be installed on to existing buildings. The social benefits from green roofs considered are the avoided carbon emissions from energy savings, energy and carbon emission savings from reduced storm water volumes entering into the combined sewers, avoided costs for air pollution control measures and increased aesthetic value. Other benefits such as CSO (combined sewer overflow) control, habitat creation and job generation are not considered due to lack of reliable local data. Even though it is expected that jobs will increase in relation to maintenance of green roofs, it is also likely that this will lead to a reduction in other jobs such as maintenance of traditional roofs [24]. The total benefit presented in US$/m^2 is the net present value (NPV) of the benefits during the lifespan of the green roof (assumed as 30 years). The total ES benefits were calculated with the help of the GIVTC toolkit [38]. The values were adjusted to the local context as much as possible with local data. The total ES benefits (net present value of benefits during the life time) from green roofs is 132 US$/m^2. Detailed calculations of benefits are presented in the supplement with costs in Tables S4 and S5.

The private benefits from rain barrels considered in this study are the water savings due to the use of rainwater [39] and the reduction on sanitation fees due to the lower water consumption even though this may not lead to changes in sanitary waste discharges. In Uruguay, for every dollar charged in water fee, another 0.6 dollars are charged as sanitation fees [40]. However, sanitation fees are just a transfer of sanitation costs to the final users, the households. Other benefits such as reduction in detergent use due to the reduced hardness of rainwater were not considered. Social benefits of rain barrels include savings on energy and carbon emissions due to the reduction of storm water entering the sewers. Other benefits such as reduction in CSO discharges and employment generation are not considered for the same reasons as already stated for green roofs. The total ES benefits from rain barrels is 125 US$/barrel. Detailed calculation of benefits can be found in the Supplementary Materials.

4.3. Set up of Multi-Objective Optimization Model

Two different drainage configurations are optimized. The first one is a drainage system where only SuDS (green roofs and rain barrels) can be installed within the sub-catchment. In this configuration, the optimization variables are the number of modelling units of the two different SuDS groups in each sub-catchment. In the second configuration, storage tanks are also considered, where the area of each of the three tanks, as well as orifices and pipes dimensions are considered as optimization variables. Further, each of these two configurations has been optimized for two different cases: when computing the ecosystem services benefits of using SuDS and when not considering these. Thus in total, four different cases have been assessed, as presented in Table 1.

Table 1. Combination of drainage configurations with and without ES benefits for optimization.

Configuration	With ES	Without ES
SuDS	Case 1	Case 2
SuDS and storage tanks	Case 3	Case 4

Optimisation based on the population of 40 individuals across 70 generations yielded consistent results. The optimisation runs were performed by restricting the algorithm to find solutions based on total costs. The maximum total cost for the solution was fixed at US$35,000,000, approximately twice the flooding cost. The individuals whose total cost was above this set cost were penalized so that they are less likely to be passed on to the next generation.

5. Results and Discussion

The output of the optimization process for Case 1 is shown in Figure 10. Every assessed option is represented by a point with the total costs and the total benefits as axes. The upper envelope is the Pareto front, formed by the optimal solutions. In the 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 options. The net benefits increase with the costs; however, the benefit–cost ratio remains approximately constant for the solutions below US$10 million cost and then decreases for higher investment costs.

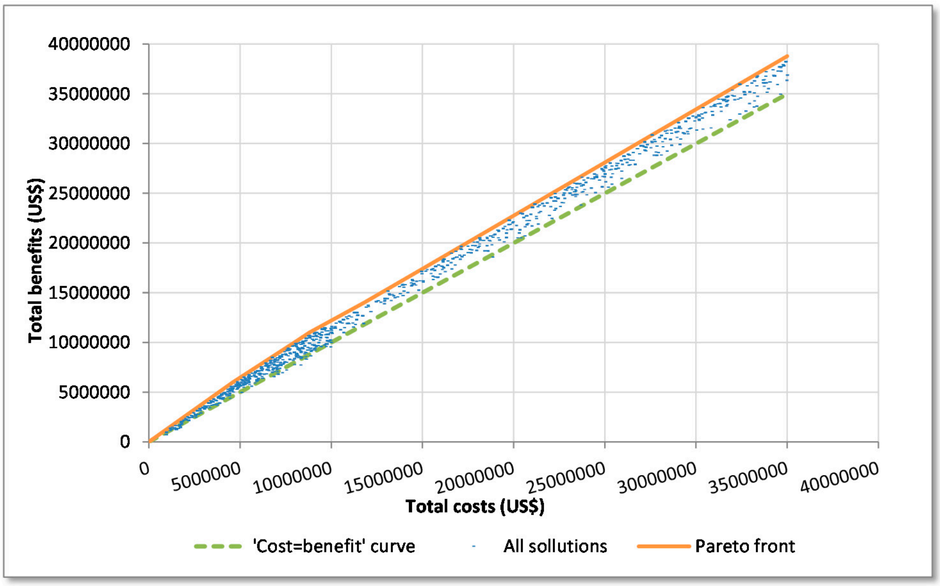

Figure 10. The Pareto-front relating total cost and total benefits for Case 1 (SuDS without underground storage; benefits including ES). The dots represent sub-optimal solutions, which are not a part of the final optimal results.

Each point in Figure 10 is a drainage network configuration comprising rain barrels and green roofs without added storage, each of which has distinct costs and benefits.

The results of the optimization process for the four assessed cases are shown in Figure 11. In Figure 11, we can see that storage tanks combined with SuDS give a cost-effective solution, regardless of the consideration of ES benefits. However, when ES benefits of SuDS are considered, it is possible to justify larger investments as they yield positive net benefits. Conversely, for SuDS only without storage tanks, the inclusion of ES benefits results in a positive benefit–cost ratio. The economic indicators for the assessed cases are presented in Table 2. Only the case with SuDS without ES benefits (case 2) results in negative net benefits for any total cost. Case 3 is the one with higher net benefits, while the one with higher total benefit–cost ratio is Case 4, which is similar to Case 3.

Larger flood reductions are achieved when the system is optimized with the combination of SuDS and storage tanks, and especially when ES benefits are not considered. The results are similar when only SuDS are considered. The SWM benefits of optimal solutions are higher for the case in which ES benefits are not taken into account. This suggests that when considering the ES benefits, the solutions that optimize the total benefits are not those that optimize the SWM benefits. Thus, if the drainage system were to be optimized for maximum SWM benefits instead of maximum total benefits, the results would have been different [41].

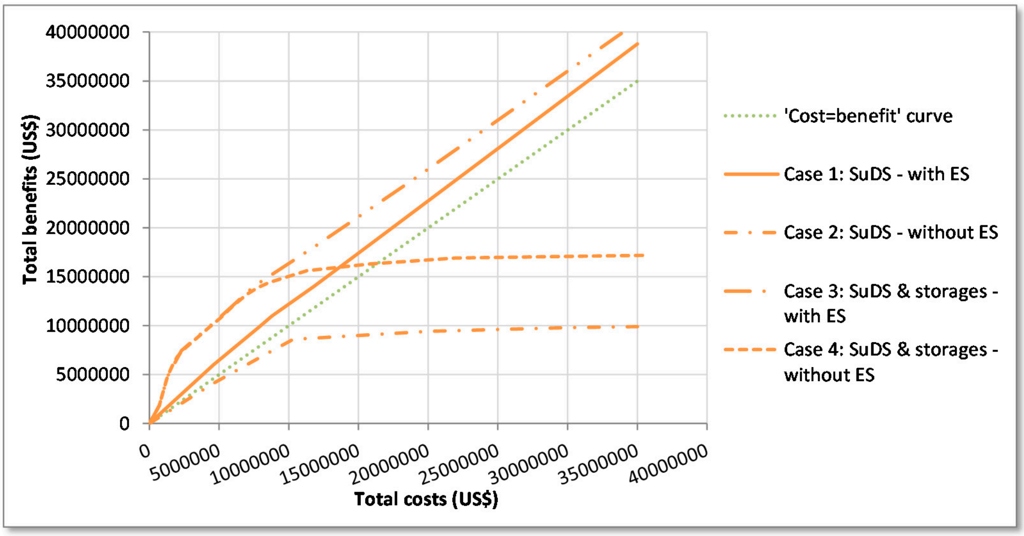

Figure 11. Pareto fronts for the four assessed cases/options.

Table 2. Maximum net benefits and benefit–cost ratios for the assessed cases.

Item	Case 1 (SuDS/with ES)	Case 2 (SuDS/without ES)	Case 3 (SuDS & Storage Tanks/with ES)	Case 4 (SuDS & Storage Tanks/without ES)
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

Note: [a] for an investment of approximately US$75 million.

An important consideration when estimating the costs and benefits is the level of uncertainty of the input parameters. The magnitude of the differences between cost and benefits can vary due to the uncertainty of the underlying information. Although it is possible to systematically treat (known) uncertainties in optimization, by approaches such as robust-optimization, it was beyond the scope of this study. The objective of the current study was to demonstrate that it is possible to better justify investments in SuDS when ES benefits are considered alongside SWM benefits.

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 utilise the results from this type of study, for instance, if the budget for solving flooding problems is relatively low, results have shown that storage tanks are the best option and therefore it would not be necessary to analyse the willingness of homeowners to install these SuDS or to consider the legal and other implications of installing SuDS.

6. Conclusions

This paper aimed at enhancing understanding of the economic value of large investments in SuDS through inclusion of ecosystem services valuation. The study has focused on the flood risk reduction capacity and the ES benefits of green roofs and rain barrels in the combined sewerage network of Montevideo Municipality in Uruguay. The cost and benefits of two drainage network configurations were analysed: (i) comprising SuDS; and (ii) comprising SuDS and detention storage in underground detention tanks. Optimal design configurations of SuDS, based on their costs and benefits, with and without ecosystem service benefits were determined for a wide range of costs and benefits. This provided a Pareto-optimal front of design configurations. In both of the design configurations, total benefits comprising both flood reduction and ES benefits are always higher than their costs. However, the exclusion of ES benefits when using SuDS alone was not found to deliver a positive BCR. Where the drainage configuration utilised both SuDS and storage tanks, declining BCRs subsequently leading to sub-zero values were found when the investments were increased without considering ES benefits. Hence, it can be concluded that larger investments can provide a positive return only when the ES benefits of SuDS are included.

Although none of the solutions eliminated flooding completely, the use of storage tanks resulted in the greatest reduction in flooding and, together with ES benefits, was found to be more cost-effective than when only using SuDS. Rain barrels were found to be more effective than green roofs in reducing storm water runoff and thus more effective in reducing flooding. When ES benefits were ignored, rain barrels were more cost effective when compared with green roofs, due to the higher investment costs for green roof compared with rain barrels for the same roof area.

Supplementary Materials: The following are available online at www.mdpi.com/2073-4441/9/11/841/s1.

Author Contributions: This paper is based on a master's thesis research of S.U.V., L.H. and A.P. together with Charlotte de Fraiture (who is acknowledged) supervised the thesis work. A.P. provided guidance on SWMM5EA tool. M.R., L.H., S.U.V. and A.P. wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Organisation for Economic Co-Operation and Development (OECD). Financial Management of Flood Risks. In *OECD Report Series*; Organisation for Economic Co-Operation and Development (OECD): Paris, France, 2016.
2. Radhakrishnan, M.; Pathirana, A.; Ashley, R.; Zevenbergen, C. Structuring climate adaptation through multiple perspectives: Framework and case study on flood risk management. *Water* **2017**, *9*, 129. [CrossRef]
3. United Nations. *Transforming Our World: The 2030 Agenda for Sustainable Development*; United Nations, Ed.; United Nations: New York, NY, USA, 2005.
4. Fletcher, T.D.; Shuster, W.; Hunt, W.F.; Ashley, R.; Butler, D.; Arthur, S.; Trowsdale, S.; Barraud, S.; Semadeni-Davies, A.; Bertrand-Krajewski, J.-L.; et al. Suds, Lid, Bmps, Wsud and More-The Evolution and Application of Terminology Surrounding Urban Drainage. *Urban Water J.* **2015**, *12*, 525–542. [CrossRef]
5. PUB Singapore's National Water Agency. *Active, Beautiful, Clean Waters Design Guidelines*; P.S.S.N.W. Agency, Ed.; PUB Singapore's National Water Agency: Singapore, 2014.
6. Charlesworth, S.M.; Mezue, M. Sustainable Drainage Out of the Temperate Zone: The Humid Tropics. In *Sustainable Surface Water Management: A Handbook for SUDS*; Wiley-Blackwell: Hoboken, NJ, US, 2016; p. 301.
7. Hoang, L.; Fenner, R.A. System interactions of stormwater management using sustainable urban drainage systems and green infrastructure. *Urban Water J.* **2016**, *13*, 739–758. [CrossRef]
8. Horton, B.; Digman, C.J.; Ashley, R.M.; Gill, E. *BeST (Benefits of SuDS Tool) W045c BeST-Technical Guidance*; Release Version 3; CIRIA: London, UK, 2016.
9. Ashley, R.; Walker, L.; D'Arcy, B.; Wilson, S.; Illman, S.; Shaffer, P.; Woods-Ballard, B.; Chatfield, P. UK sustainable drainage systems: Past, present and future. *Civ. Eng.* **2015**, *168*, 125–130. [CrossRef]
10. Ashton, R.; Baker, R.; Dean, J.; Golshetti, G.; Jaluzot, A.; Jones, N.; Moss, M.; Steele, M.; Williams, W.; Wilmers, P. *Building Natural Value for Sustainable Economic Development: The Green Infrastructure Valuation Toolkit User Guide*; Green Infrastructure Valuation Network: London, UK, 2011.
11. Costanza, R.; d'Arge, R.; De Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; O'Neill, R.V.; Paruelo, J. The value of the world's ecosystem services and natural capital. *Nature* **1997**, *387*, 253–260. [CrossRef]
12. European Environment Agency. *Urban Adaptation to Climate Change in Europe: Transforming Cities in a Changing Climate*; European Environment Agency: Copenhagen, Denmark, 2016; p. 135.
13. Pathirana, A. SWMM5-EA-A Tool for Learning Optimization of Urban Drainage and Sewerage Systems with Genetic Algorithms. In *International Conference on Hydroinformatics*; CUNY Academic Works: New York, NY, USA, 2014.

14. Deb, K.; Pratap, A.; Agarwal, S.; Meyarivan, T. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Trans. Evolut. Comput.* **2002**, *6*, 182–197. [CrossRef]
15. James, W.; Huber, W.; Pitt, R.; Dickinson, R.; Rosener, L.; Aldrich, J.; James, W. *SWMM4 User's Manual (User's Guide to the EPA Stormwater Management Model and to PCSWMM)*; University of Guelph and CHAI: Guelph, ON, Canada, 2002.
16. Delelegn, S.; Pathirana, A.; Gersonius, B.; Adeogun, A.; Vairavamoorthy, K. Multi-objective optimisation of cost-benefit of urban flood management using a 1D2D coupled model. *Water Sci. Technol.* **2011**, *63*, 1054. [CrossRef] [PubMed]
17. Radhakrishnan, M.; Pathirana, A.; Ghebremichael, K.; Amy, G. Modelling formation of disinfection by-products in water distribution: Optimisation using a multi-objective evolutionary algorithm. *J. Water Supply Res. Technol. AQUA* **2012**, *61*, 176–188. [CrossRef]
18. CSI Ingenieros S.A. *Estudio de Alternativas y Proyecto Ejecutivo de las Obras de Drenaje Pluvial en las Cuencas de los Arroyos seco y Quitacalzones—Memoria Descriptiva y Justificativa*; Municipality of Montevideo: Montevideo, Uruguay, 2012. (In Spanish)
19. CSI Ingenieros S.A. *Estudio de Alternativas y Proyecto Ejecutivo de las Obras de Drenaje Pluvial en las Cuencas de los Arroyos seco y Quitacalzones—Evaluación SocioeconóMica de Priorización de Inversiones*; Municipality of Montevideo: Montevideo, Uruguay, 2011. (In Spanish)
20. Bianchini, F.; Hewage, K. How "green" are the green roofs? Lifecycle analysis of green roof materials. *Build. Environ.* **2012**, *48*, 57–65. [CrossRef]
21. Carter, T.; Keeler, A. Life-cycle cost–benefit analysis of extensive vegetated roof systems. *J. Environ. Manag.* **2008**, *87*, 350–363. [CrossRef] [PubMed]
22. Lee, A.; Sailor, D.; Larson, T.; Ogle, R. Developing a web-based tool for assessing green roofs. In *Greening Rooftops for Sustainable Communities, Minneapolis*; Green Roofs for Healthy Cities: Toronto, ON, Canada, 2007.
23. Clark, C.; Adriaens, P.; Talbot, F.B. Green roof valuation: A probabilistic economic analysis of environmental benefits. *Environ. Sci. Technol.* **2008**, *42*, 2155–2161. [CrossRef] [PubMed]
24. Doug, B.; Hitesh, D.; James, L.; Paul, M. *Report on the Environmental Benefits and Costs of Green Roof Technology for the City of Toronto*; Ryerson University: Toronto, ON, Canada, 2005.
25. Kosareo, L.; Ries, R. Comparative environmental life cycle assessment of green roofs. *Build. Environ.* **2007**, *42*, 2606–2613. [CrossRef]
26. Rosenzweig, C.; Gaffin, S.; Parshall, L. *Green Roofs in the New York Metropolitan Region: Research Report*; Columbia University Center for Climate Systems Research and NASA Goddard Institute for Space Studies: New York, NY, USA, 2006; pp. 1–59.
27. Smit, J.; Nasr, J.; Ratta, A. *Urban Agriculture: Food, Jobs and Sustainable Cities*; Urban Agriculture Network, Inc.: New York, NY, USA, 1996; pp. 35–37.
28. Dirección Nacional de Meteorología. Rainfall Data. Available online: http://meteorologia.gub.uy/index.php/estadisticasclimaticas (accessed on 12 January 2011).
29. Googlemaps. Satellite imagery of Montevideo. Available online: http://bit.ly/2qnmyws (accessed on 26 May 2017).
30. Getter, K.L.; Rowe, D.B. The role of extensive green roofs in sustainable development. *HortScience* **2006**, *41*, 1276–1285.
31. Verde Facil. Green Roofs. Available online: www.verdefacil.com (accessed on 23 May 2017).
32. Morales-Pinzón, T.; Lurueña, R.; Rieradevall, J.; Gasol, C.M.; Gabarrell, X. Financial feasibility and environmental analysis of potential rainwater harvesting systems: A case study in Spain. *Resour. Conserv. Recycl.* **2012**, *69*, 130–140. [CrossRef]
33. Thurston, H.W.; Taylor, M.A.; Shuster, W.D.; Roy, A.H.; Morrison, M.A. Using a reverse auction to promote household level stormwater control. *Environ. Sci. Policy* **2010**, *13*, 405–414. [CrossRef]
34. Tang, Y. *Exploring the Response of Urban Storm Sewer System to the Implementation of Green Roofs, in Civil & Environmental Eng*; University of Illinois at Urbana-Champaign: Champaign, IL, USA, 2012.
35. Oficina de Planeamiento y Presupuesto. *Metodología General de Formulación y Evaluación Social de Proyectos de Inversión PúBlica*; Oficina de Planeamiento y Presupuesto, Uruguay: Montevideo, Uruguay, 2012.
36. Bianchini, F.; Hewage, K. Probabilistic social cost-benefit analysis for green roofs: A lifecycle approach. *Build. Environ.* **2012**, *58*, 152–162. [CrossRef]

37. Anand, C.; Apul, D. Economic and environmental analysis of standard, high efficiency, rainwater flushed, and composting toilets. *J. Environ. Manag.* **2011**, *92*, 419–428. [CrossRef] [PubMed]
38. Ashton, R.; Baker, R.; Dean, J.; Golshetti, G.; Jaluzot, A.; Jones, N.; Moss, M.; Steele, M.; Williams, W.; Wilmers, P. *Building Natural Value for Sustainable Economic Development: Green Infrastructure Valuation Toolkit*; Colling, R., Ed.; Genecon LLP: Leeds, UK, 2010.
39. Kuhn, K.; Serrat-Capdevila, A.; Curley, E.F.; Hayde, L.G. Alternative water sources towards increased resilience in the Tucson region: Could we do more? In *Water Bankruptcy in the Land of Plenty*; Poupeau, F., Ed.; CRC Press/Taylor and Francis Group Boca Raton: London, UK; New York, NY, USA; Leiden, The Netherlands, 2016; pp. 337–362.
40. Presidencia. Decretos de Setiembre de 2012. Available online: https://www.presidencia.gub.uy/normativa/2010-2015/decretos/decretos-09-2012 (accessed on 23 May 2017).
41. Ashley, R.M.; Digman, C.J.; Horton, B.; Gersonius, B.; Smith, B.; Shaffer, P.; Baylis, A. Evaluating the Longer Term Benefits of Sustainable Drainage. Available online: https://doi.org/10.1680/jwama.16.00118 (accessed on 17 October 2017).