Developing a modeling tool to allocate Low Impact Development practices in a cost-optimized method

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ABSTRACT

Nowadays there is a need to overcome the effects caused by rapid urbanization with more innovative methods. Recently, source control approaches, known as Low Impact Development (LID), are being used by urban planners to cope with water-related problems due to their cost-effectiveness and reliability. To do this, allocation of LID techniques in most suitable locations is done by introducing a new modeling tool called LID locator to the WetSpa-Urban software package and tested in the Watermaelbeek catchment situated in the Brussels capital region. In the first step, almost half of the catchment is eliminated from the implementation of LIDs by considering only pixels with high runoff. Also, by considering the sewer network behavior, the total area of high potential pixels for implementing LID is reduced to the range of 37% and 10% of the entire area of the catchment for different scenarios. In the next step, the selected area is further eliminated by use of suitable location algorithm based on size and other installation limitation of each type of LID. Then, the results are used as an input for the newly developed cost-optimization tool. In the end, the best scenario (10-year design storm with the current state of sewer network) is selected based on their performance in surface runoff volume reduction and the total cost. As a result, maximum flow and total volume at the outlet is reduced by 21 and 8 % for the most cost-optimized scenario in January and February 2015. In addition to considering sewer network

performance, land characteristics and LID installation limits for LID implementation, producing maps indicating the most cost-efficient locations and combinations for LIDs and visualizing them through the GUI make this tool a user-friendly product. This tool was applied to this case study in Brussels however it is applicable for other urban catchments.

Keywords: Urbanization; Source control; Low Impact Development; Locator tool, Cost-optimization

1. INTRODUCTION

In recent years urbanization growth rapidly causes sealing of land surface to facilitate living for habitat. According to the UN population division (2014), more than 97% of the Belgian population live in urban areas. This alters the hydrology in cities by reducing infiltration and evapotranspiration, which leads to an increase in volume and velocity of surface runoff and may cause shorter response time of the catchment (Kaushal and Belt, 2012; Martin-Mikle et al., 2015; Rose and Peters, 2001; White and Greer, 2006).

To overcome the problems associated with sealing the natural lands as a cause of urbanization, there are two major methods: the end-of-pipe solution and the source control Green Infrastructure (GI) approach known as LID (Booth et al., 2002; County, 1999; Dorn and Ranjithan, 2003; Ellis et al., 2004; Lee et al., 2012; Martin et al., 2007; Martin-Mikle et al., 2015a; Scholz, 2006; Villarreal et al., 2004). In the last decade, LID practices have been more implemented in urban areas compared to the other conventional approaches due to their cost-effectiveness and excellent performance to mitigate water-related problems in terms of both quantity and quality and additional environmental issues (Dietz, 2007; Kuo and Sullivan,

2001; Kurtz, 2009; Montalto et al., 2007; Pyke et al., 2011; Roehr et al., 2008; Urbonas and Stahre, 1993; Van Roon, 2005). The reason for using GI is to mitigate the effects of urbanization on the hydrological cycle by increasing the infiltration rate, storage volume and also coarsening the surface (Elliott and Trowsdale, 2007; Lai et al., 2007; Wong et al., 2002). This may lead to slower runoff, more infiltration to the soil, less flooding and more evapotranspiration in urban catchments (Coffman, 2000; Doug et al., 2005; EPA, 2000; Lawson, 2010; Weinstein et al., 2006, 2009).

Over the past years, most researches have been focused on investigating the effect of experimental LID techniques, implemented at small scale (Bengtsson, 2005; Farahbakhsh et al., 2008; Gregoire and Clausen, 2011; Stovin et al., 2012; Wossink and Hunt, 2003) but only few studies examine the impact of them on a watershed scale to reach more sustainable city (Carter and Jackson, 2007; Levallius, 2005; Palla et al., 2008; Versini et al., 2015). Implementing and modeling LID on a watershed scale is different compared to the building scale. The difference is mainly due to the importance of placing each LID practices in the most suitable locations. As remotely sensed data can collect sufficient information about the terrain with the details and accuracy needed for heterogeneous urban catchments, they will be of great help in the process of finding suitable locations for different types of LIDs. To meet the main aim of urban planners, the most crucial is to identify the best places for LID techniques with the highest potential to reduce flooding in the region.

Many modeling tools are used by different researchers to answer the above questions which try to detect the best implementation of LIDs in a satisfactory way (Deletic et al., 2018; Martin-Mikle et al., 2015; Wang et al., 2010). Research is done to categorize different softwares used in this scope (Lerer et al., 2015). The division has been done based on the ability of each software packages to answer the following questions: (1) How many?, (2)

where? and (3) which type of LID?. The first term is trying to investigate the ability of the modeling tools to cover the effect of implementation of LID on water quantity, quality, economic impacts, and any other non-flow impacts. The second and third questions are also trying to categorize simulation tools based on their ability to find out the best location of LIDs and their degree of coverage in the study area, respectively. It is important to note that most of them are able to answer only one or two of the mentioned questions and just some of them are capable of covering all aspects. As an example, the EPA Storm Water Management Model (SWMM) (Rossman, 2010) can only analyze the effect of LID practices on water quantity. In addition to that, one problem associated with some of the more complete software packages is the availability of them to use freely.

Although the physical processes in urban and natural catchments are the same, as a cause of the high complexity in urban areas due to the human-induced changes in slope, soil type and land-use classes, the use of spatially distributed simulation models is recommended (Versini et al., 2014). In this study, the recently developed rainfall-runoff model, WetSpa-Urban, is used by introducing a new module for allocation of LIDs in an optimised manner and applied to a catchment in the Brussels region.

2. MATERIALS AND METHODS

2.1 Case Study

This research tests the newly developed module on the most urbanized part of the Woluwe catchment (Watermaelbeek sub-catchment) which is located in the North West of upper Woluwe. The catchment covers an area of approximately 6.13 km^2 and it's elevation ranges from 60 m to 142 m above sea level. Urban lands cover almost 38% of the total area being the

most dominant land-use class followed by urban forest covering 36% (Figure 1). Loamy soil is the most dominant soil type in this region (Chormanski et al., 2008, Wirion et al., 2017). Based on data which has been driven from Royal Meteorological Institute at Uccel station, the average temperature for the winter and summer season are 5.0 and 14.1°C, respectively. In addition, the average yearly precipitation in Brussels capital region is around 853 *mm/yr* (Chormanski et al., 2008, Wirion et al., 2017).

Figure 1, High resolution land-use map (Wirion et al., 2017) and elevation of Watermaelbeek catchment containing hydraulic structures

As can be seen from figure 1, the study area includes the sewer network containing 32 inlet nodes (sub-catchments outlets) out of a total of 109 junctions and the reservoir with a capacity of 40,000 *m³* with a pump and a control weir.

2.2 Rainfall-Runoff model

To develop a locator tool for applications of LIDs, there is a need for rainfall-runoff simulation software which calculates above-ground processes based on remotely sensed data.

The reason why WetSpa-Urban is selected as a source tool for development of the LID locator tool is, firstly, because of the possibility to use input maps with the highest resolution for the placement of LIDs in the most suitable locations. Secondly, due to the flexibility of the model to be further developed as the software source code is open access and written modularly within the Python programming language.

The WetSpa-Urban software is generated based on the integration of two different modeling tools named WetSpa-Python (Liu and De Smedt, 2004, Salvatore, 2015) and SWMM (Rossman, 2010). This tool is very useful in urban areas as the above-ground processes are simulated by distributed geographic information system (GIS) and Remote Sensing (RS) based maps and sewer network processes are calculated by the hydraulic simulation tool. In the WetSpa-Urban 3 types of input data are needed. High-resolution input maps (Land-use, Soil, and Digital Elevation Model [DEM]) are used to derive all essential input parameters by use of pre-defined parameter tables (Salvatore, 2015). After that, meteorological input data (Precipitation and Potential Evapotranspiration time series) and the generated parameter maps are used to calculate the surface runoff by WetSpa-Python module. In the last step, the detailed information about junctions, conduits, and control structures should be provided in the form of text file called “tmp.inp” to be used SWMM section of the new modeling tool to calculate flow in a precise method.

2.3 LID Locator tool

In this research, a new module for allocation of four different types of LIDs, Porous pavements, Riparian zones, Raingardens, and Green roofs, using a cost-optimized method is developed. The main reason for selection of these four types of LID is the possibility to detect their locations by satellite imagery and implementing them above the ground. The second

reason is their high efficiency to reduce storm runoff. Finally, most of them can be implemented in public areas except green roofs. The general concept of the LID locator tool is presented in figure 2.

Figure 2, LID Locator tool main Framework

The LID locator tool is a GIS-based decision support tool that assists the user to select not only areas where LIDs could be implemented within a large catchment but also to answer what is the best spatial combination to achieve the best possible performance in a very cost-effective manner. To do this, a stepwise approach is used. As can be seen from figure 2, this tool contains three different steps: 1. Search for high potential areas to implement source control approaches; 2. Find suitable locations for different types of LIDs and 3. Find the most cost-beneficial combination using the cost-optimization tool. Subsequently, the design tool helps to define the characteristics of different types of LIDs such as soil, depth, etc.

2.3.1 High potential area search algorithm

The high potential areas for the implementation of LIDs are defined based on hydrological and hydraulic calculations. The hydrologic search algorithm is written in such a way to find the areas with a high runoff coefficient. This coefficient derives the fraction of precipitation

that turns to surface runoff. The runoff coefficient is calculated based on continuous slope described in equation one which shows a linear correlation between surface slope and near-zero runoff coefficient.

$$C = C_0 + (1 - C_0) \frac{S}{S + S_0} \quad (1)$$

Where C [-] is the runoff coefficient for a surface with a slope of S [%], C_0 [-] is the runoff coefficient for slope less than 0.5% and S_0 [%] is a slope constant. C_0 and S_0 are listed in WetSpa manual (Liu and De Smedt, 2004) for different combinations of soil type and land-use.

In this calculation, the only input is the runoff coefficient limit, between 0 and 1, which is defined by user selection. It is important to note that, the algorithm uses the available runoff coefficient map generated based on 3 given input maps (land-use, soil and DEM) to the WetSpa-Urban during preprocessing of the surface runoff calculation. The output of the hydrological calculation is a map showing areas prone to high runoff in ASCII format.

Moreover, the hydraulic search algorithm combs any sub-catchments in the region that cause a pressure higher than the user-specified value (logically between 0.5 and 1) in the sewer network by analyzing “maximum over full flow” in every single conduit. The “maximum over full flow” information is generated by the SWMM (Rossman, 2010) section of the rainfall-runoff model in the form of a text file called report.rpt.

The final step in this section is overlaying the outputs of these two algorithms. In this way, the high potential area for implementation of LIDs is defined through the elimination of unsuitable regions containing sub-catchments which do not add any pressure to the sewer network and also elimination of pixels with a low runoff rate. This approach is novel since, in

addition to considering the characteristics of the surface, the sewer network function plays a vital role in the selection of high potential areas to implement LIDs. Is it also important to note that, the module gives users the option to simultaneously select the hydrology or hydraulic conditions or both, based on their main focus or data availability.

2.3.2 Suitable location search algorithm

The most suitable locations for four types of LIDs in a high potential area are detected by running different algorithms. This search algorithm works as an additional filter to omit more areas by considering the installation criteria of the four LID types. Porous pavements, Riparian zones, Raingardens, and Green roofs are the four main types of LIDs executed in the tool.

To find the most suitable location for porous pavement, the software uses a detailed land-use map containing a road class together with two different parameters: depth to groundwater table and the suitable soil classes. According to McDonald (2011) depth to groundwater table should be at least 60cm for higher infiltration to the soil and to avoid fast ponding. In addition, soil classes with high infiltration rates (ranging from silty loam to sand) are considered as suitable (Jerjen et al., 2015; Poulikakos et al., 2013), since a permeable soil is needed to ensure infiltration of the captured water. The search algorithm then starts to calculate road pixels with the depth to groundwater table greater than the user-specified value by using a digital elevation map in combination with the use of the soil map in order to find the perfect match between current soil conditions with user preferences.

The second algorithm tries to calculate areas suitable for implementation of the riparian zone. Riparian zones are areas close to all types of water bodies. In other words, floodplains or other adjacent buffer zones are riparian zones. The main important element used in this

algorithm is the available land-use map to find water pixels. Additionally, urban and built up pixels such as buildings, roads, etc. together with regions with improper soil class are eliminated from the riparian zone with the specified width defined by the user.

In the next step, areas appropriate for allocation of rain gardens are calculated by the third search algorithm. To do this, the user should specify the minimum area for implementation of a single rain garden. After that, the algorithm searches for suitable pixels that are connected which are then taken as a unit with appropriate soil, land-use classes and an area more than the user-defined value.

Last but not least, suitable flat roofs need to be identified for installation of green roofs. In reality this is complex and depends on many factors such as building ownership, physical characteristics of the foundation, slope of the roofs, etc. Since finding these types of information is difficult, this process is simplified by using an algorithm that only uses the available high resolution (2m) elevation map for finding flat roofs. Availability of higher resolution of DEM leads to a more accurate finding of protrusions which should be eliminated from flat roof area over the roofs. The calculation is done by comparing the elevation of each roof pixel with eight surrounding pixels. If the difference is less than the user-specified value (e.g. 10cm), then the algorithm considers the specific pixel as a horizontal pixel. Then, this process continues for all roof pixels. The connected horizontal pixels are then merged together. By calculating the area of each merged flat pixel and comparing this with a user-defined parameter called *minimum suitable area for implementation of a green roof*, the appropriate areas of green roofs are identified.

Since the outputs of the above algorithms are generated based on size and installation limitations, there is a need to overlay each by the result of the high potential search algorithm to avoid installation of LIDs at unsuitable locations. Following this, each of these four maps

area overlaid together to form one new land-use map, final output, with the highest possible coverage in the most suitable places for the four types of LIDs in the ASCII format. The creation of the final map considers the prioritization of the different types of LIDs based on user preferences and/or their performance of volume reduction versus cost.

2.3.3 Cost-optimization

In the last step, a Multi-Criteria Evaluation (MCE) (Carver, 1991) approach is used where various measures need to be analyzed to reach a specific objective. In this case, reducing urban surface flow with the lowest cost is the primary objective.

Since MCE is a time-consuming approach, a unique procedure is added to the optimization tool by taking three options with different aims into consideration before calculating the size and location of each LID. The main reason to do this is related to limiting the number of scenarios by satisfying the objective of implementing LIDs as a source control approach. In other words, instead of selecting a random location with different size and combination of LIDs, the newly developed cost-optimization tool tries to focus on reduction of the flood by implementing LIDs based on their performance in most remote areas.

In the first option, the main idea is to reduce flooding outlets only through the implementation of LIDs in the responsible source sub-catchments. Source sub-catchments are the sub-catchments that provide more water to the sewer network compared to the volume available in their inlet manholes. To do this, the cost-optimization tool uses the data available in the “Node Inflow Summary” section in “report.rpt”, an outcome of the rainfall-runoff model. If the following condition is met then the sub-catchment is considered as a source:

$$\frac{\text{Lateral inflow volume } [10^6 l]}{\text{Total inflow volume } [10^6 l]} > s [-] \quad (2)$$

Where S is the parameter specified by the user as a limit for defining the source sub-catchment. Next, the tool looks into the section "Node Flooding Summary" in the "report.rpt" file to check whether any of the flooding nodes are a source or not. By knowing the total flood volume of the desired source sub-catchment, the coverage and order of precedence of the LIDs are defined. This can be done by asking the user the volume reduction and the cost of each LID per pixel. In this research the volume reduction for each type of LID is calculated using the conceptual mathematical equation (equation 3) provided by (CNT, 2010).

$$\text{Runoff reduction [liter]} = \text{Average daily precipitation [mm]} * \text{Area [m}^2\text{]} * \text{Retention [\%]} \quad (3)$$

As the average yearly rainfall depth over the Watermaelbeek catchment is nearly 780 mm, the retention rate for each type of LID per pixel is 0.6, 0.7, 0.6 and 0.8 for green roofs, porous pavement, riparian zones and rain gardens respectively (CNT, 2010). At the end of this stage, a new land-use map is generated based on the final output of the previous section showing the most suitable location for LID implementation.

In contrast to the first option, the second option checks how flooding is reduced by introducing LID techniques in the closest responsible sub-catchments whether they are sources or not. This means that the total flood volume of any sub-catchment available in the section "Node Flooding Summary" in "report.rpt" is used with the same procedure as option one to make a new land-use map consisting of LID measures.

Compared to the first option, source sub-catchment for each flooding outlet is not restricted to only one sub-catchment. The algorithm is written in a way to find as many source sub-catchments as possible which can be responsible for flooding in different manholes, not only inlet nodes. Then the LID practices are placed into the responsible source sub-catchments for each manhole by filling, first the closest and then the others based on their distance from the flooded manhole. As the sewer network has the shape of tree or diagram, the LID location for

the third option is calculated using a programming technique called Breadth-first search (BFS) algorithm (Zuse, 1972). The schematic behavior of BFS is presented in figure 3.

Figure 3, The schematic behavior of Breadth-first search (BFS) algorithm

As can be seen, the search algorithm start at the root of the diagram (source node) in layer zero. This is a node which receives flooding in reality. If this flooding manhole is an inlet node and its source, the connected sub-catchment starts filling by LID practices. If not, the algorithm moves to layer one to find a source inlet manhole. In case of having more than one source inlet manhole in this layer, it starts filling with the sub-catchment which has more space for implementation of LID and then goes horizontally to the next one. This procedure continues till the time when the flooding in “Node Flooding Summary” table disappears. The prioritization, volume reduction and price of each LID practice are the same as previous options.

By following the above steps, four new land-use maps with different LID coverage and order of precedence are generated. To avoid low accuracy when selecting the best scenario out of only four scenarios, it is advisable to do this procedure for rainfall with different return periods. In this context, the composite design storm of 20, 10, 5, 2 and one years with the duration of three hours and an interval of 10 minutes derived from IDF relationship (Intensity/Duration/Frequency-relationships) for Uccel station (Delbeke, 2001) is used. In

addition to considering the current situation of the sewer network, a hypothetical sewer network without any hydraulic structures is generated to use in the model to check to what extent the source control approach can handle flooding in urban land by removing the end of pipe solution. Following this procedure the number of scenarios is increased to the maximum of 40 options in order to facilitate selection of the most cost-optimized scenario. Figure 4 demonstrates the general scheme to generate the maximum possible 40 options that can be used in the selection of the best scenario.

Figure 4, General scheme for generation of the maximum possible 40 scenarios

2.3.4 LID implementation

After deriving new land-use maps containing different LID practices, new soil and elevation maps need to be generated by adding proper soil classes for each type of LID and digging area of rain gardens, respectively. In this study, the resulting land-use maps include only three types of LIDs, rain gardens, green roof, and porous pavement. For this reason, the soil characteristics of these three practices will be discussed in this paper.

To simulate the surface runoff by the WetSpa-Urban model, the WetSpa (Salvadore, 2015) modeling tool is used. As elevation, soil and land-use maps are the base input maps for this

tool; it is essential to modify the soil classes with proper characteristics for each type of LID. Twelve parameters such as hydraulic conductivity, root depth, porosity, etc. need to be added to the parameter tables for each LID practice. Based on works done by (Asleson et al., 2009; Berretta et al., 2014; Bosley and Kern, 2008; Carpenter and Hallam, 2009; De-Ville et al., 2017; Jerjen et al., 2015; Marchioni and Becciu, 2015; Poulikakos et al., 2013; Soulis et al., 2017) the value for each parameter is listed in table 1.

Table 1, LID parameter value for WetSpa-Urban modeling tool

Land-use class	n $[m^{-1/3} s]$	PI [-]	PS $[\frac{m^3}{m^3}]$	RM $[\frac{m^3}{m^3}]$	RD [m]	C [-]	WP $[\frac{m^3}{m^3}]$	Kc $[\frac{mm}{hr}]$	DP [mm]	FC $[\frac{m^3}{m^3}]$
Raingarden	0.8	3.39	0.476	0.0203	2	0.03	0.024	208.8	8	0.242
Porous pavement	0.1	3.39	0.39	0.012	0.5	0.25	0.024	75	1.88	0.22
Green roof	0.35	3.39	0.399	0.0205	0.15	0.1	0.021	0	5	0.263

As can be seen from table one, the parameters of extensive types of green roofs are provided. Due to the fact that the characteristics of this type of roof are similar to grassland, the root depth is specified as 0.15 m (Soulis et al., 2017). It is important to note that by using root barrier and waterproofing membrane underneath the green roof, 0 mm/hr is selected for the hydraulic conductivity as a cause of not having any deep percolation and interflow originating from this type of green roof (Berretta et al., 2014; De-Ville et al., 2017). In contrast to the green roof, 1 m is selected as the root depth for the rain garden. The maximum depth of rain gardens is defined as 2 m with a slope of 10%. These changes in the

elevation map cause smoothening in the region where rain gardens are implemented. The engineered shape of rain gardens helps the user to model rain gardens closer to reality and avoid digging rain gardens like a swimming pool.

By converting roads and parking lots to porous pavement covered with loamy sand underneath the front layer (Jerjen et al., 2015; Poulikakos et al., 2013) the runoff coefficient is set to 0.25 for almost flat areas (Marchioni and Becciu, 2015).

3. RESULTS AND DESCUSION

It is clear that analyzing the effect of implementing a different combination of LID practices on flood and volume reduction needs a precise storm runoff modeling tool suitable for urban areas. Thus, the calibrated WetSpa-Urban model for the Watermaelbeek catchment was used. It is good to note that the calibration of the flow was not the aim of this research. This is why the calibrated model with the Nash–Sutcliffe efficiency of 88% was being used for further investigation of the effect of the best combination and most cost-optimized LID scenario on water quantity.

As explained, five composite design storms with different return periods (20, 10, 5, 2 and 1 year) were generated based on the IDF relationship of Uccle station. Each design storm has a total duration of 3 hours with an interval of 10 minutes. These design storms were then used as an input of the rainfall-runoff model. By running the model with the same input maps (current land-use, soil, and elevation), existing sewer network and meteorological data (rainfall) with generated return periods, five different "report.rpt" files were created as an output of the model containing flooding depth in each node, pressure of the pipes, hydraulic structures function and flow at the outlet. Additionally, five more report.rpt files were

generated by using the mentioned input maps and rainfall data with a different sewer network. In this hypothesis, all the end of pipe solutions such as reservoirs, weirs, and pumps were removed to check to what extent the LID practices can tackle the problems associated with the sewer network if the source control approach is replaced by the end of pipe solutions.

3.1 High potential areas

After running the model for different return periods with two specified hypotheses (with and without control structures), the LID locator tool starts calculating the high potential area maps. First of all, pixels with a runoff coefficient of less than 0.7 were eliminated from the study area. The runoff coefficient threshold was defined by considering the average value of the study area. As a result of the calculation of the high potential map based on hydrology algorithms, almost 51% (3.1Km^2) of the catchment was eliminated from implementing any type of LID. The pixels with high potential to generate runoff are represented in red in figure 5.A.

Figure 5, Outputs of the high potential algorithm for 20 year return period storm and sewer with no control structure: A) Based on Hydrology algorithm, B) Based on the Hydraulic algorithm, C) Overlay of hydrology and hydraulic

On the other hand, the high potential area was calculated based on the pressure in the sewer network. In this step, the ten generated "report.rpt" files were used to find the responsible sub-catchments for high pressure in the pipes. It is evident that pipes go under more pressure for storms with higher return periods. Also, more pressure is expected in a system which has no control structure in contrast to the current sewer system. To find pipes with high pressure, the “maximum over full flow” threshold was set to 0.75 (three-quarters full at maximum discharge). This criterion is defined by sewer design manuals to ensure unaccounted flows are considered as a result of further development in urban lands in the future (San Diego Public Utilities Department, 2015). Then the hydraulic algorithm finds responsible sub-catchments for pressurized pipes based on their distance and surface runoff volume. Figure 5.B shows the responsible locations for high pressure in pipes as a result of a 20-year design storm. As shown in the following figure, most of the pressurized pipes are in the lower branch and the pipes with a high diameter that convey flow from two upper branches. This leads to a selection of a larger number of high potential sub-catchments in the southern half of the catchment area.

In general, the area of high potential sub-catchments which cause further pressure to the system compared to the user-specified value varies between 3.7 and 0.9 Km^2 (60% and 15% of total catchment area) for different scenarios. As an example, the hydraulic algorithm concluded that 16 sub-catchments with the entire area of 3.7 Km^2 were responsible for approximately 34 pressurized pipes out of the total 109 available for the scenario with a 20 year return period design storm and no control structures.

At the end of this stage, more pixels were eliminated from the result of the hydraulic algorithm for each scenario by overlaying this with the result of the hydrology algorithm. By combining these two, the total area of high potential pixels for implementing LID was reduced to the range of 2.25 and 0.64 Km^2 (37% and 10% of the entire area of the catchment) for different scenarios. The final outcome of high potential area generated by overlaying the results of hydrology and hydraulic algorithms for the scenario with no control structure and 20 year design storm is presented in figure 5.C.

3.2 Suitable locations

The generated maps from the high potential algorithm for different scenarios were used as an input of the algorithm to find the most suitable place for a combination of LID practices. The appropriate locations for implementing porous pavement was defined by specifying two thresholds. First, the depth to groundwater table was selected as 5 meters, and secondly, sandy loam, silt loam, and silty clay were chosen as suitable soil types for this implementation. This results in 16% to 52% of the total pavement area (1 Km^2) ideal for implementing porous

pavement for different scenarios. This was continued by defining all appropriate locations adjacent to the water bodies with a buffer width of 30m as a riparian zone class.

In addition to the suitable soil classes and depth to groundwater defined in the previous step, the minimum acceptable area for each single rain garden needed to be specified. In this research, all rain gardens with an area less than $500m^2$ were eliminated from implementation.

This criterion was defined mainly to give priority to big rain gardens, generally, owned by public sectors due to their higher efficiency. As a result, 155 rain gardens with an area greater than the user-specified threshold was detected. This algorithm found an area of $1.9Km^2$ in the southwest of the catchment as the largest suitable location for conversion to a rain garden. At the end of this stage, this map was overlaid by the high potential map for the ten different scenarios to implement rain gardens with higher efficiency.

In the last step, suitable locations for installing the green roofs over the flat roofs was detected by considering the minimum possible area of $30m^2$. As can be seen from figure 6, the newly developed method for finding the flat roofs over the catchment area with the least input data (only need a map showing the location of each tent called parcel map) is very precise.

Figure 6, Demonstration of LID implementation for a flat roof. (A) Real flat roof Vs. (B) generated green roof

The high precision of the LID locator tool to find flat roofs can easily be seen by comparing the orthophoto provided by Esri_BeLux_Content (figure 6.A) and the map generated by the software (figure 6.B). Although the model eliminates any protrusions over the roofs (appeared here as rounded glass protrusions), it can identify as many green roofs as possible with an area higher than the user-specified threshold over a single roof with different elevation. As can be seen in the above figure, almost eight green roofs could be implemented over the single roof surrounded by a red line.

3.3 Most cost-efficient locations and combinations for LIDs

As mentioned before the results from the suitable location algorithm were overlaid with the high potential map for the ten intermediate scenarios. These maps are new land-use maps containing distinguished porous pavement, riparian zone, rain garden, and green roof classes together with original land-use classes for unsuitable and low potential pixels. Table 2, shows the extent of these four types of LID in all scenarios.

Table 2, Area covered by LID practices for ten different scenarios

Return period [yr]	1	2	5	10	20	1	2	5	10	20
	Sewer with no control structures					Current sewer network				
Total LID coverage [%]	11	11	22	29	47	10	11	22	26	44
Raingarden [Km ²]	0.5	0.5	1	1.3	2.3	0.46	0.5	1	1.2	2.1
Porous Pavement [Km ²]	0.17	0.17	0.3	0.4	0.4	0.15	0.17	0.3	0.35	0.47
Riparian Zone [Km ²]	0	0	0	0	0	0	0	0	0	0
Green Roof [Km ²]	0.03	0.03	0.05	0.06	0.09	0.03	0.03	0.05	0.06	0.08

As expected, the sewer network is under more pressure for design storms with higher return periods. This leads to approximately two times more LID coverage area for the scenario with the 20 years return period storm compared to the storm of 5 year return period. As can be seen from table 2, although in general the maximum suitable location for LID implementation is slightly higher for the scenario with no control structures in comparison with the current state of the sewer network, the rate is almost steady for scenarios with return periods less than five years. It is worth mentioning that the most dominant LID selected for implementation in this catchment are rain gardens followed by porous pavement. Green roofs are the third LID class concerning their coverage. This is mainly because the Brussels region is mostly covered by sloped roofs and the tool further eliminated the remaining flat roofs with an area less than $30m^2$. , the riparian zone can only comprise a small proportion of catchment area (near zero).

The ten generated new land-use maps containing the maximum suitable location for LID were used as an input to the cost-optimization tool. Although, until now, between 53 and 90% of the area are eliminated from LID implementation, the cost-optimization tries to check whether any other cost-optimized solution is available or not. As an example, the results of the cost-optimization tool for the scenario with a 20 year return period design storm and sewer with no control structures is represented in figure 7.A.

Figure 7, The newly generated land-use map containing LID practices for sewer without control structures and rainfall with 20 years return period: A) the maximum suitable location for LID implementation; B) The output of the second scenario in the cost-optimization tool; C) The output of the third scenario from cost-optimization tool

For this scenario, nine manholes and two inlet nodes were flooded. On one hand, as the lateral inflow volume over the total volume inflow for these two inlet nodes was less than $S=0.7$ (the user-specified threshold for defining source sub-catchments), the first scenario could not produce any more optimized options. On the other hand, the second scenario tried only to reduce flooding from inlet nodes by their connected sub-catchments, whether they were sources or not, as shown in figure 7.B. To check the extent of LIDs needed to overcome flooding, the desired sub-catchments first were filled by the rain gardens followed by porous

459 pavements, and green roofs, respectively. The order of their priorities was defined by
460 considering their performance in runoff volume reduction calculated by equation 2. In other
461 words, the rain garden was the first priority due to runoff reduction rate of 7litre per day per
462 square meter and green roof and riparian zone classes are the least priority as each square
463 meter could reduce runoff by 5litre per day. By calculating the number of needed pixels to
464 overcome flooding in these two sub-catchments, their number was compared with the
465 maximum number of pixels identified in the previous step. In this case, the total flooding of
466 0.062 and 0.081 $\times 10^6$ litre are removed by implementing rain gardens over 2215 and 2893

467 pixels in sub-catchments 21 and 6, respectively. This means, as this coverage of rain gardens
468 fulfills the aim to stop the flooding there was no need to implement other types of LID. For
469 the last scenario, the objective was to reduce flooding in all connecting manholes and inlet
470 nodes. As a result, three source sub-catchments (shown in Figure 7.C with full transparency)
471 were selected for implementing LIDs with the total area of 0.85 Km^2 dominated by rain

472 gardens. This process is repeated for the other nine scenarios.

473 Finally, 17 land-use maps contain LID practices with different combinations, and areal
474 distribution are generated. The reason why only 17 out of 40 land-use maps with LID are
475 generated is that for some of the scenarios there were no more cost-optimized scenarios
476 available. As an example, for scenarios with one and two-year design storms with and without
477 control structures, the maximum suitable location maps are the most cost-optimized. Based on
478 these maps and the two specified thresholds (slope and the maximum depth of rain garden)
479 new elevation and soil maps were provided by the LID locator tool. These three maps are
480 necessary to run the WetSpa-Urban modeling tool in order to calculate flow for each
481 scenarios containing LIDs. Then, total inflow reduction to the sewer network was compared

to the original state for different design storm. The results of flow reduction versus cost are presented in figure 8.

Figure 8, Two criterias evaluation: Volume reduction Vs. Cost

The flow volume reduced in the range of 0.015 and 15 $\times 10^6$ liters for different scenarios and the total cost for the LID implementation varied between 0.04 and almost 22 million euros. The best scenario was selected based on considering only two criteria: flow reduction and cost. As can be seen from the above graph a polynomial trend line was fitted to the data with the R-Squared value around 0.99. Also, by calculating the derivatives of the data in the chart and checking their slopes, the best scenario (with the highest slope) is represented by the red arrow. This results in best performance of maximum possible location for LID implementation calculated by 10-year design storm with current sewer network. Last but not least, the performance of the most cost-optimized scenario is evaluated by comparing “maximum over full depth” of pipes, flood reduction, inflow and outflow volume reduction with no LID scenario to check how far the changes increase the sewer network efficiency. The results showed a total inflow volume to the sewer network reduced by approximately 15%. Besides, the total amount of flow at the outlet declined by 12%.

Moreover, 63% reduction in total flood volume observed. In other words, the overall flood volume decreased around 1.262×10^6 liter by implementing LIDs in 29% of the catchment area. It is worth mentioning, “maximum over full depth” in one-quarter of pressurized pipes reach to the value less than the specified threshold (0.75) after these changes.

Figure 9, Comparison of flow at the outlet for current state and LID implemented based on best scenario for real-time series

The design storms were used for evaluation of scenarios to make the selection of best option out of MCE faster. Therefore, checking the response of sewer network to implementing LIDs in the most cost-optimized method was essential by running the rainfall-runoff model for real-time series. To do this, the newly generated land-use, elevation and soil maps for the best scenario were used as inputs for the WetSpa-Urban together with rainfall and evaporation data with 10-minute intervals for January and February in 2015. The comparison of flow at the outlet for maps driven in 2015 and LID implemented scenario for a short period in January is represented in figure 9. It is clear that the flow at the outlet decreased by introducing LIDs to the catchment area. As can be seen from figure 8, the flow reduction after LID implementation followed the same pattern. The first peak after a long dry period reduced by

around 30% compared to the current state. This is different for the consecutive rainfall events. As an example, the two most significant rainfall events that came immediately after smaller events experienced approximately 10% reduction in comparison to the original state. This is because LIDs are not capable of handling big rainfall events. In addition to that, the storage capacity of LIDs became almost full by the first rainfall event, and they could not function well for consecutive rainfall events. Lastly, it is worth mentioning that the maximum flow decreased from 6.452 to 5.764 CMS at the outlet which showed a 21% reduction.

4. CONCLUSION

In this research, the new stepwise methodology to generate suitability maps for implementing four types of LID (rain garden, green roof, porous pavement, and riparian zone) introduced in a module called LID locator tool was evaluated. The tool tried to eliminate unnecessary locations for LID implementation through high potential calculation followed by the suitable location algorithm. The high potential algorithm was further divided into two sections: hydrology and hydraulic. By specifying the catchments average runoff coefficient as a threshold for the hydrology algorithm, nearly 49% of the catchment area was identified as high potential. Besides, by checking the pressure in conduits, the determined high potential area varied between 3.7 and 0.9 Km^2 for different scenarios. Overlaying of these two algorithms led to a final combined high potential map for different scenarios.

The generated map was further used as an input for the suitable location algorithm to place different types of LID over the selected regions. In this step, further elimination was done by installation and construction limitation such as size, depth to ground water, soil type, etc. As a result, between 10 and 47% of the Watermaelbeek catchment was considered as the maximum

suitable location for implementing LID for different scenarios. Then, these maps were used as an input for the cost-optimization tool to check whether any more optimized solutions were available or not. By comparing the flow reduction versus investment cost for resulting scenarios, the maximum suitable areas spatially distributed for LIDs generated by considering a 10-year design storm with the current state of sewer network was selected as the best scenario.

Compared to the original land-use state, implementing LID following the order of the best scenario for a 10-year design storm led to a 15% reduction in surface runoff. This means 12 and 63 % reduction in flow volume at the catchment outlet and total flood volume reduction, respectively. The effect of implementing LID was not only limited to the mentioned aspects. Therefore, the reservoir is evaluated to get a better overview of the functioning of the whole system. The results show approximately 30% reduction in the average volume of water stored in the reservoir during the rainfall event. In addition, less than half of the reservoir capacity becomes full. This shows 11% decline compared to the original land-use state without any source control approaches. Finally, the results from real-time series (January and February) shows the same pattern in flow volume reduction compared to the current state. After implementing LID only 10% of reservoir capacity become full, this causes 30% reduction in power usage of the pump. Although the maximum flow at the outlet reduced by 21% after LID implementation based on best scenario, the total volume reduced by approximately 8%.

The LID locator tool is developed in a way to be applicable for any other case study and for different target users by having a minimum data requirement of the 3 input maps (land-use, soil and DEM) at any resolution. Having more information regarding the groundwater table, parcel maps, etc. together with higher resolution data enable users to select more algorithms and thus obtain a more precise location for LID practices.

It is worth adding that, in addition to the high precision of the LID locator tool in finding the most suitable location for four specified LIDs using an optimized method, having a GUI (graphical user interface) makes the software user-friendly. This allows users to select the appropriate algorithms for specific types of LIDs based on the availability of input data and parameters (such as runoff coefficient and size limit) and user experience. Moreover the tool produces user-friendly maps indicating the best and most cost-efficient locations and combinations for LIDs and visualizing them through the GUI. This will help urban planners and decision-makers to implement sustainable water management with more ease. All mentioned features makes the software applicable for a wide range of users from scientists to stakeholders. The other advantage is considering sewer network performance in selection of suitable sites for implementing LIDs together with land characteristics and LID installation limits. Finally, developing a module to assess the ecosystem services such as air quality, amenity, air temperature, carbon sequestration, etc. would be a great help to avoid selection of best scenario by considering only flow volume reduction and cost.

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