A Simulation Model for Stormwater Runoff Management in Urban Blocks

A decision support tool for water sensitive urban design

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The shift towards Water Sensitive Urban Design (WSUD) has become a necessity for many cities with warm and dry climates which are still using conventional rainwater management and are adversely affected by extreme rainfall episodes or persistent heatwaves. However, WSUD still remains a complex issue for architects that requires specialized technical knowledge, relevant experience, and interdisciplinary collaboration. The paper presents initial results of an "architect friendly" computer-based model, developed by the authors, that facilitates the assessment of the efficacy of non-conventional, water-sensitive, stormwater management strategies in urban blocks, measured by the stormwater runoff mitigation. The model allows for the design and visualization of stormwater management scenarios on surfaces of selected urban blocks, as well as the quantitative comparison of their impact on runoff reduction. Users can choose from a range of different Best Management Practices (BMPs) from the BMP library of the model, create their own stormwater management scenarios, assess them, and finally choose the most appropriate one with regard to its impact on stormwater runoff. BMPs added in the library include green roofs with different substrate depths and plant types, facades, stormwater harvesting cisterns, raingardens and permeable paving. The Grasshopper programming environment has been used for the development of the model, the integration of as-built climate data and the incorporation of runoff estimation equations based on the Soil Conservation Service Curve Number (SCS-CN) method. The paper compares the results of different stormwater management scenarios that involve several BMP types and geometries, applied on an urban block in Athens, Greece. Based on this case study results, preliminary conclusions are drawn regarding the user-friendliness of the model's interface and data requirements, as well as the effectiveness of the model's visualization process.

Keywords: *Stormwater best management practices, urban blocks, runoff mitigation, decision support tool, environmental impact visualization*

INTRODUCTION

In many cities worldwide, significant changes have occurred in the natural water cycle processes. These changes are primarily driven by the rapid increase in urban density, resulting in the expansion of impervious surfaces and inadequate provision of urban green spaces. Conventional stormwater management methods in many cities prioritize swift collection and drainage, limiting opportunities for infiltration and evaporation. This is mainly caused by the rapid increase of urban density and the consequent expansion of impervious surfaces, in combination with the lack of adequate urban green areas. In many cities, conventional stormwater management methods prioritize rapid collection and drainage, limiting infiltration and evaporation opportunities. At the same time, climate change is likely to lead to an intensification of rainfall extremes (Myhre et al. 2019; Liu et al. 2019b; IPCC 2022 cited in Cristiano et al. 2022). The transition from the natural to the urban water cycle has resulted in several consequences:

- **Reduced water supply:** Decreased rates of water infiltration and groundwater recovery lead to projected drinking water scarcity by 2050 (United Nations, nd).
- **Local climate change:** The urban heat island effect exacerbates drier and warmer conditions in city centers compared to rural areas.
- **Increased pollution:** Surface water runoff carries sediments, litter, and various pollutants originating from human activities (Woods Ballard, B et al., 2015).
- **Increased flood risk:** Insufficient stormwater management amplifies flow rates and volumes in urban drainage systems, contributing to more frequent floods and water-related natural disasters**.**

In many countries worldwide, there has been a significant shift in the management of urban stormwater, aiming to mitigate the negative effects of the urban water cycle through the adoption of new approaches and strategies. Proper management of natural systems and green infrastructure plays a crucial role in enhancing city sustainability and livability (Wong T.H.F et al., 2013). Previously regarded as a problem, urban stormwater drainage is now recognized as an opportunity to improve the urban environment and climate (Ashley et al., 2013). Water Sensitive Urban Design (WSUD) is being embraced by planners, architects, and engineers to optimize stormwater supply, usage, reuse, and management. Best Management Practices (BMPs) such as green roofs, green facades, and permeable paving are employed for WSUD implementation, with the following objectives (Woods Ballard et al. 2015):

- Utilizing surface runoff as a valuable resource.
- Managing rainwater in close proximity to its source.
- Managing surface runoff.
- Allowing rainwater to infiltrate into the soil.
- Promoting evapotranspiration.
- Slowing and storing runoff to mimic natural runoff patterns.
- Reducing runoff contamination through pollution prevention and source water treatment.

Implementing Water Sensitive Urban Design (WSUD) strategies in the design process can be a complex task for architects and urban planners, requiring specialized technical knowledge, experience, and interdisciplinary collaboration. In the context of Greece, retrofitting existing urban blocks with Best Management Practices (BMPs) can be an effective approach for stormwater management and improving the urban microclimate. Specifically, flat roofs, facades, and inner block voids are potential surfaces for BMP retrofitting to enhance stormwater management. However, architects and landscape designers need the ability to construct and compare stormwater management scenarios to inform their design process and assess environmental impacts.

The work described in this paper is part of a research program that aims to develop an "architect-friendly" computer-based model facilitating the retrofitting of urban blocks using stormwater BMPs. The model is expected to serve as a decision-making support tool for architects and landscape designers, providing simulations of stormwater BMP scenarios. Specifically, it will enable quantitative comparisons of the impact of stormwater management scenarios on the following factors:

1. Runoff volume in sewers
2. Temperature reduction during summer months due to evaporative cooling

The paper presents the first part of the model, which calculates the surface runoff volume for an as-built urban block and a "water-sensitive" retrofit of the same block by incorporating green roofs and rainwater harvesting cisterns on the buildings' roofs. Visualization of the results on a 3D drawing of the urban block in Rhino, using Grasshopper, facilitates the assessment of the impact of stormwater BMPs on retrofitting urban blocks and allows for the comparison of different stormwater management scenarios. The initial results of the model are presented using a case study of an urban block in central Athens, Greece.

MODEL OVERVIEW

The development of a user-friendly, accurate, and flexible stormwater BMP model for architects and urban planners is crucial for effective stormwater management in Greece and beyond. The model under development possesses the following key features:

- **Simplified processes:** The model employs widely accepted concepts to represent complex natural processes in a simplified manner. This allows architects and urban planners without in-depth knowledge of hydrology to use the model effectively.
- **Light data entry:** The model has relatively minimal data entry requirements, making it easy and quick to use. This enables users to assess different stormwater scenarios rapidly and easily.
- **Accurate simulation:** Despite its simplified approach, the model strives to simulate complex processes with sufficient accuracy. This ensures reliable and valuable results for decision-making.
- **Flexibility:** The model is flexible and can be applied to different types of urban blocks in Greece. By adjusting the climate data and BMP library, users can also apply the model in cities of other countries.
- **User-friendly interface:** The model features a well-organized and intuitive user interface, making it easy for architects and urban planners to locate various tools, options, and quickly access the desired features.

The model is developed in the visual programming language Grasshopper, which enables the creation of complex algorithms and models using a visual interface. The 3D drawing of the urban block is created by the user in Rhino. architects and urban planners to locate different tools and options, and quickly access the features they need.

MODEL COMPONENTS

To simulate the runoff volume for different stormwater scenarios in an urban block, the user begins by simulating the runoff volume from each building's roof within the block. The model includes several interconnected components, as depicted in Figure 1:

1. **Time Period Precipitation Calculator**: This component utilizes hourly precipitation data from the National Observatory of Athens between 2004 and 2021 to create a Typical Meteorological Year file. By specifying the start and end dates, the calculator generates a data

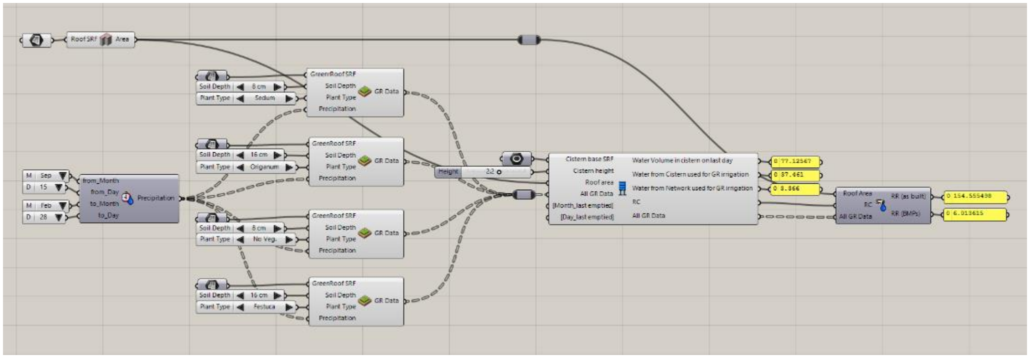

Figure 1
Grasshoper model interface

tree that includes the days of the year (DOYs), total precipitation for each specific day, and the sum of the prior five days' precipitation, which is required for runoff volume calculation.

2. **As-Built Roof Geometry Selector**: The user selects the total roof surface of a specific building from the Rhino 3D model.
3. **Add Green Roof**: This component represents one of the Best Management Practices (BMPs) available in the model's BMP library. By incorporating this component, the user can add a green roof to the as-built roof. Four types of green roofs are included in the BMPs: no vegetation, succulent plants (Sedum sediforme (Lacq.) Pau), xerophytic plants (Origanum onites L.), and turf grasses (Festuca arundinacea Shreb). The green roofs have substrate depths of 8 cm and 16 cm, based on the research by Soulis et al. (2017) regarding the impact of shallow green roof systems on stormwater runoff and their Curve Number (CN) values in the Greek urban microclimate. The user inputs for this component include:

- The geometry of the green roof (surface or a closed line curve),
- The soil substrate depth (0 = 8 cm / 1 = 16 cm)
- The plant type (0 = No Vegetation / 1 = Origanum / 2 = Sedum / 3 = Festuca).

The outputs of this component include the area of the green roof, the runoff for the specified period, and the total precipitation received on the green roof. The user can add multiple types of green roofs on the upper surface of the building's roof.

4. **Add Rainwater Harvesting Cistern**: This component allows for the addition of a rainwater harvesting cistern, which collects and stores rainwater runoff from the rooftops, including the green roofs. The collected water can be used for irrigating the green roofs as needed. Additionally, any remaining water can be utilized for irrigating plants within the inner block void of the urban block. Rainwater harvesting cisterns serve as a valuable resource for urban irrigation. The user inputs for this component include:

- The geometry of the cistern (area of cistern base and cistern height)
- The date when the cistern is empty of water. The default assumption for this date is October 1st, as it marks the end of the hot summer days in Greece and is considered the beginning of the typical hydrological year. Cisterns are usually nearly empty by this date due to high water demand during the summer season. Rainy days following this date help replenish the water supplies.

The outputs of this component include

- The water volume in the cistern on the last day of the analysis period,
- The total volume of water extracted from the cistern for green roof irrigation, and
- The overflow runoff from the cistern.

5. **Green Roof Irrigation Requirements Calculator**: This module calculates the irrigation requirements of the green roof for the selected analysis period. It uses the Penman-Monteith equation, which is widely used for estimating reference evapotranspiration, which is the evapotranspiration from a well-watered grass surface ((Koutsoyiannis, D., Xanthopoulos, 2016)

$$E = \frac{\Delta}{\Delta + \gamma'} \frac{R_n}{\lambda} + \frac{\gamma}{\Delta + \gamma'} F(u) D \quad \text{kg/(m}^2\text{d)} \qquad (1)$$

In which:

- E= rate of evapotranspiration, kg/(m2d)
- Δ= slope of the saturation vapor pressure-temperature curve, hPa/°C
- γ= psychrometric constant, hPa/° C
- γ′= modified psychrometric constant, hPa/° C
- Rn= net radiation at the crop surface, kJ/(m2d)
- λ= latent heat of evaporation, kJ/kg
- F(u)= wind function, kg/(hPam2 d)
- D= vapor pressure deficit, hPa

The Penman-Monteith equation requires daily air temperature data, wind speed, saturated vapor pressure, and other factors. To obtain this data, an EnergyPlus weather (EPW) file is imported into Grasshopper using the Ladybug plugin. The equation operates based on the following assumptions:

- **Steady-State Conditions**: The equation assumes that atmospheric conditions and plant physiological factors remain constant throughout the calculation period.
- **Well-Mixed Atmosphere**: It assumes a uniform distribution of temperature and humidity within the air layer in contact with the surface.
- **Homogeneous Surface**: The equation assumes that the land surface is homogeneous regarding vegetation cover, soil type, and other relevant properties.
- **Unlimited Water Supply**: It assumes an abundant water supply without any limitations for evapotranspiration.
- **Idealized Plant Behavior**: The equation assumes idealized plant behavior, where plants have unrestricted access to water and can transpire at their maximum potential rate without experiencing water stress.

6. **Roof Runoff Calculator**: This component calculates the total roof runoff for the analysis period, both for the as-built condition and after incorporating the Best Management Practices (BMPs). To predict the runoff depth from rainfall, the model includes a module based on the Soil Conservation Service Curve Number (SCS-CN) method. The SCS-CN method was originally developed by the U.S. Department of Agriculture, Soil Conservation Service (now known as Natural Resources Conservation Service—NRCS) for predicting direct runoff volumes in agricultural watersheds and evaluating storm runoff. It is an empirical formula that quantifies the rainfall-runoff relationship, making it suitable for designing water resources infrastructure. The SCS-CN method simplifies the factors influencing runoff generation by incorporating them into a single parameter, the curve number (CN). The CNs for the green roofs in the model's BMP library are derived from the research conducted by Soulis et al. in 2017. The runoff equation is as follows:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad (2)$$

Where:

- Q is runoff (in mm)
- P is rainfall (in mm)
- S is the potential maximum soil moisture retention after runoff begins (mm)

The runoff curve number, CN, is related to S via equation (3):

$$S = \frac{1000}{CN} - 10 \tag{3}$$

The NRCS has categorized soils into three soil moisture groups based on the cumulative rainfall in the five days leading up to the rainfall event. The previous soil moisture is calculated in the "Time Period Precipitation Calculator" and imported into the "Roof Runoff Calculator." The soil moisture groups are as follows:

- ACSI: Dry conditions (rainfall depth less than 13 mm, or less than 35 mm for vegetation in growing conditions).
- ACSII: Moist conditions (rainfall depth between 13 mm and 38 mm, or between 35 mm and 53 mm for vegetation in growing conditions).
- ACSIII: Wet conditions (rainfall depth over 38 mm, or over 53 mm for vegetation in growing conditions) (Pontikos S., 2014).

The Soil Conservation Service Curve Number (SCS-CN) method, used to estimate direct runoff from rainfall events, operates under the following assumptions:

- **Homogeneous Land Use:** Assumes uniform soil properties, land cover, and hydrological response throughout the study area.
- **Constant Antecedent Soil Moisture:** Considers a constant soil moisture condition across the entire study area.
- **Uniform Rainfall Distribution:** Assumes rainfall is evenly distributed across the study area, ignoring spatial variability.
- **Constant Curve Numbers:** Assumes Curve Number values assigned to land cover and soil types remain constant over time, regardless of changes in conditions.
- **Steady-State Conditions:** Assumes a constant hydrological response during the rainfall event, without accounting for dynamic changes.

7. **Roof Runoff Visualization:** this component allows for a color-coded visualization of runoff volumes on the green roofs of the urban blocks. A gradient color scheme based on the color red is used to identify the runoff volume. (darker red indicates increased runoff volume).

CASE STUDY

To test the model, an urban block located in central Athens was chosen as a case study (refer to Figure 2 and Figure 3). Athens experiences a Mediterranean climate characterized by mild, wet winters and hot, dry summers. The urban block comprises buildings with 5 to 7 floors, all featuring flat roofs covered with impermeable materials. Most of these roofs have semi-permanent structures installed, such as solar panels and solar water heaters. However, the remaining space on the roofs can be utilized for implementing green roofs and rainwater harvesting cisterns. For testing purposes, three water management scenarios were considered:

1. As-built scenario (see Figure 4).
2. Implementation of different types of green roofs on all buildings (see Figure 5).
3. Implementation of different types of green roofs on all buildings in combination with rainwater harvesting cisterns on each roof (see Figure 6).

The analysis period was set for three winter months, from December 1st to February 28th, as this period represents the time with the highest likelihood of rainfall in Greece.

To simulate the scenarios, green roofs of various types and substrate depths were randomly placed on the roof surfaces, considering the presence of

Figure 2
Selected urban block in Athens

Figure 3
Photograph of one of the buildings of the selected urban block. It is a block of flats designed by the Greek architect Nikos Valsamakis, built in 1955. View from Vasilissis Sofias street.

semi-permanent structures on the as-built roofs. In Scenario 1, green roofs with different plant types and substrates were added. In Scenario 2, cisterns with a circular base of 1 meter radius and a height of 2 meters were installed on each roof to collect water for irrigation purposes.

In terms of visualization, a color-coding system was employed in the model to distinguish between different plant types of green roofs (indicated by varying shades of green) and rainwater harvesting cisterns (indicated by blue). The reduction in runoff resulting from the implementation of best management practices (BMPs) was represente dusing a gradient format of red. Darker shades of red indicated a larger percentage of runoff reduction compared to the as-built state, while lighter shades of red indicated a smaller reduction.. In order to test the model, 3 water management scenarios are considered: 1. as-built (see figure 4); 2. different types of green roofs on all buildings (see figure 5); 3. different types of green roofs on all buildings in combination with rainwater harvesting cisterns on all roofs (see figure 6).

The analysis period was set for three winter months, from 01 December to 28 February, when it is most likely to rain in Greece.

From the color coding in both scenarios one can easily understand that a significant runoff reduction is achieved due to the BMPs added. The data output of the model indicates that in scenario 1, where only green roofs are added, runoff reduction from the roofs of the urban block is 19,3% (Table 1) of the initial runoff from the as-built roofs; whereas, in Scenario 2 the runoff reduction is 39,6% (Table 2). The data calculated from the model also inform on the exact area of each of the green roofs on the block and the runoff reduction attributed to each one of them.

CONCLUSIONS

At its current stage of development, the model can simulate runoff from green roofs and scenarios involving the combination of green roofs and cisterns on the roofs of an urban block. The simulation of cistern overflow, estimation of total water extraction from the supply network, and irrigation water requirements for green roofs are components that are nearing completion.

Initial results obtained from applying the model to an urban block in Greece have demonstrated the potential benefits of implementing common BMPs such as green roofs and rainwater harvesting cisterns in urban areas. The significant reduction in runoff achieved through these water management strategies highlights their effectiveness in mitigating the negative impacts of stormwater runoff in urban environments.

In Scenario 1, where only green roofs were added to the buildings, a runoff reduction of 19.3% was observed. This indicates that green roofs, with their vegetation and substrate layers, effectively absorb and retain rainfall, thereby reducing the amount of water that becomes runoff.

In Scenario 2, where green In Scenario 2, where green roofs were combined with rainwater harvesting cisterns, the runoff reduction further increased to 39.6%. The additional inclusion of cisterns allowed for the collection and storage of rainwater for future uses, such as irrigation of green roofs and inner-block void vegetation, or evaporative cooling of building facades. This dual approach not only mitigates runoff but also promotes water conservation and sustainable water management practices.

The findings from this simulation model can inform current and future water management plans

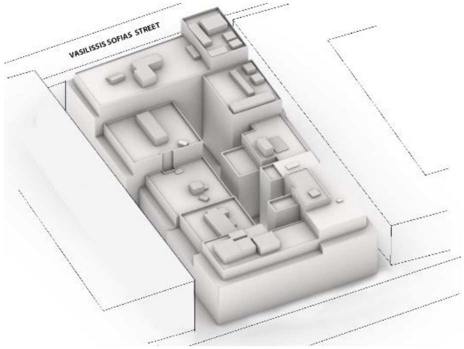

Figure 4
Scenario 0: As built geometry of case study urban block

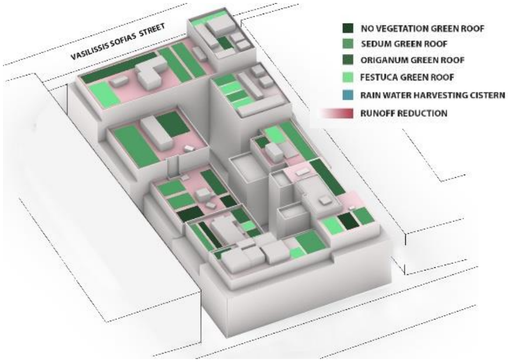

Figure 5
Stormwater Management Scenario 1: Addition of green roofs with different plant types and substrates and runoff mitigation visualization

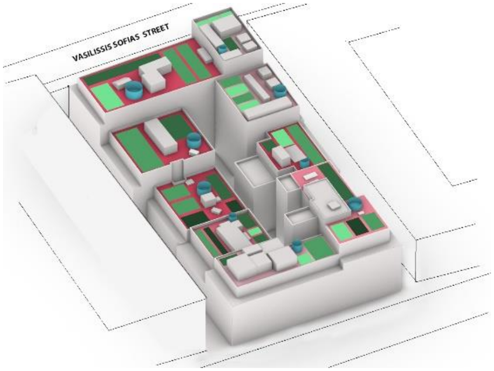

Figure 6
Stormwater Management Scenario 2: Addition of green roofs with different plant types and substrates and rainwater harvesting cisterns. Runoff mitigation visualization demonstrates the increase of runoff mitigation in this scenario.

SCENARIO 1: ADDITION OF GREEN ROOFS										
AS-BUILT ROOF		NO VEGETATION GREEN ROOF		ORIGANUM GREEN ROOF		FESTUCA GREEN ROOF		SEDUM GREEN ROOF		RUNOFF MITIGATIO N
BUILD ING No	**TOTAL ROOF AREA (m^2)**	**TOTAL AREA (m^2)**	**ROOF RUNOFF DECREA SE (%)**	**TOTAL AREA (m^2)**	**ROOF RUNOFF DECREASE (%)**	**TOTAL AREA (m^2)**	**ROOF RUNOFF DECREA SE (%)**	**TOTAL AREA(m^2)**	**ROOF RUNOFF DECREASE (%)**	**TOTAL REDUCTIO N OF ROOF RUNOFF (%)**
1	152	0	0	11	4,8	16	6,2	0	0	11
2	410	0	0	54	9	37	5,5	72	10,1	24,6
3	292	0	0	43	10	0	0	76	15	25
4	246	33	6,7	25	6,9	0	0	45	10,4	24
5	202	18	4,5	27	9,1	5	1,6	18	5,2	20,4
6	246	0	0	11	2,6	9	2,2	33	7,7	12,5
7	290	18	3	37	8,7	18	3,7	18	3,5	18,9
8	159	0	0	9	4	18	5,8	40	14,3	24,1
9	205	0	0	0	0	24	7,2	24	6,2	13,4
URBAN BLOCK RUNOFF REDUCTION %										**19,3%**

Table 1. Roof runoff simulation for scenario 1 for case study urban block for an analysis period of 3 months in winter.

SCENARIO 2: ADDITION OF GREEN ROOFS AND RAINWATER HARVESTING CISTERNS											
AS-BUILT ROOF		NO VEGETATION GREEN ROOF		ORIGANUM GREEN ROOF		FESTUCA GREEN ROOF		SEDUM GREEN ROOF		RAINWATER HARVESTING CISTERN	RUNOFF MITIGATIO N
BUILD ING No	**TOTAL ROOF AREA(m^2)**	**TOTAL AREA (m^2)**	**ROOF RUNOFF DECREA SE (%)**	**TOTAL AREA (m^2)**	**ROOF RUNOFF DECREASE (%)**	**TOTAL AREA (m^2)**	**ROOF RUNOFF DECREA SE (%)**	**TOTAL AREA (m^2)**	**ROOF RUNOFF DECREA SE (%)**	**ROOF RUNOFF DECREASE (%)**	**TOTAL REDUCTIO N OF ROOF RUNOFF (%)**
1	152	0	0	11	4,8	16	6,2	0	0	10,9	11
2	410	0	0	54	9	37	5,5	72	10,1	24,9	24,6
3	292	0	0	43	10	0	0	76	15	25,4	25
4	246	33	6,7	25	6,9	0	0	45	10,4	26	24
5	202	18	4,5	27	9,1	5	1,6	18	5,2	21,5	20,4
6	246	0	0	11	2,6	9	2,2	33	7,7	13,5	12,5
7	290	18	3	37	8,7	18	3,7	18	3,5	19,2	18,9
8	159	0	0	9	4	18	5,8	40	14,3	26,3	24,1
9	205	0	0	0	0	24	7,2	24	6,2	14,5	13,4
URBAN BLOCK RUNOFF REDUCTION %											**39,6%**

Table 2. Roof runoff simulation for Scenario 2 for case study urban block for an analysis period of 3 months in winter.

in Greece and other urban areas. By highlighting the effectiveness of green roofs and rainwater harvesting systems, decision-makers can consider integrating these strategies into urban planning and development guidelines.

Regarding the model's user friendliness, it is important that it requires limited data from the user. The interface, which will be further developed and improved, aims to make it easy for the architect to navigate and use it for assessing different stormwater management scenarios. Visualization with color coding on the roofs and runoff mitigation given as a percentage % of the initial stormwater runoff makes it easy for the assessments of the scenarios and choose the most suitable one.

The model, which is still under development, will include more BMPs for the facades of the buildings of the urban block and the inner block void, in order to provide a wider choice of BMPs that can be applied in urban blocks in Greece or elsewhere.

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