Environmental Impact Assessment and Visualization of Rain-water Best Management Practices for Urban Blocks

An "architect-friendly" simulation model

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In order to implement stormwater best management practices (BMPs) in urban blocks in Greece and other cities with warm and dry climates, such as green roofs, porous pavements etc., it is crucial that architects are able to assess their environmental impact during the design process in an efficient and simple way, without the requirement of an in depth understanding of the complex hydrological processes. To achieve the above, an "architect-friendly" computer-based model, under development by the authors, is presented. The model can be used as a decision support tool by allowing an assessment of the efficacy of non-conventional, water-sensitive, stormwater management strategies in an urban environment, measured by the stormwater runoff mitigation and temperature decrease. Wind flow simulation data from an external CFD model can be integrated into the proposed model, in order to visualize wind flow patterns in selected urban blocks. The user is able to select different stormwater BMPs from a BMP library and apply them on the 3D urban block model, in order to achieve an improved "water sensitive" state. The ENVI-MET plugin for Rhino is used for simulating temperature decrease and the SCS Curve Number method for determining stormwater runoff reduction, caused by each BMP application. The visualization of the results in the graphical interface of the Grasshopper programming environment facilitates the study of the environmental impact of stormwater BMPs in urban blocks and the comparison of different stormwater management scenarios. Several urban blocks in Athens will be used as case studies to test the proposed model and assess the efficiency of the visualization process.

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

INTRODUCTION

In many cities around the world the processes of the natural water cycle have changed significantly. Common features of such cities include the following: high density construction, lack of adequate urban green areas, relatively uniform height of structures, and building surfaces made of building materials with high thermal mass, mainly concrete. Such features impacted greatly the natural water cycle, which has been replaced by the urban water cycle. The latter is characterized by rapid collection and drainage of rainwater, as well as minimal infiltration and evaporation, which, combined with the negative effects of climate change, has contributed to the deterioration of the urban environment microclimate and living conditions in many cities across the world characterized by warm and dry climates.

In order to prevent an aggravation of the problem of the current hydrological urban cycle and to remedy the environmental imbalance caused by conventional water management models, a philosophical change is required in the way urban areas are planned and designed (Wong et al., 2000). This change is based on the principles of Water Sensitive Urban Design (WSUD). WSUD uses better urban planning and design to reuse stormwater, stopping it from reaching our waterways by mimicking the natural water cycle as closely as possible (Melbourne Water, 2017). For the implementation of WSUD, stormwater Best Management Practices (BMPs) are used on a city, urban block or building scale. Stormwater BMPs increase sustainability by using porous pavement, bioretention, green roofs, rainwater harvesting and other strategies.

However, the integration of WSUD and specifically sustainable rainwater management into the design and planning process has not yet been accomplished, as it still remains a complex issue for architects and urban planners that requires specialized technical knowledge, relevant experience, and interdisciplinary collaboration.

In the case of Greece, despite the efforts made by individual researchers, Water Sensitive Urban Design has not yet been developed and set as a priority in the design process. Due to their characteristics, Greek urban blocks could become good examples of stormwater BMP retrofit: they could benefit from the runoff mitigation that BMPs offer, as well as from the evaporative cooling during summer periods. The typical Greek urban block consists of several attached multi-storey apartment buildings in its periphery and an inner block void which is underused or even abandoned. The majority of the buildings consist of usually 3 to 5 floors, with a typical floor height of 3 meters. Buildings have balconies, an essential feature of all residential buildings in Greece, and flat roofs that are rarely used.

In order to implement stormwater BMPs retrofit in such urban blocks it is crucial for architects and landscape designers to have a greater understanding of the environmental impact of stormwater management scenarios that will inform their design process. Currently, there are only few "architect-friendly" models in the market for stormwater runoff calculation that can support architectural and landscape design. Rainwater+, the Urban Biophysical Environments and Technologies Simulator (Urban BEATS) and Autodesk ®Green Stormwater Infrastructure Extension for InfraWorks® 360 (GSI) are three planning-support models for exploring design and placement of WSUD infrastructure. However, all three models are designed for specific national requirements and regulations (Urban BEATS follows Australian regulations and Rainwater+ and GSI US ones) and are not suitable for Greek urban blocks.

The research presented in this paper is part of a research program which aims to develop an "architect-friendly" computer-based model to facilitate retrofitting of Greek urban blocks using stormwater BMPs. The model is expected to function as a decision making-support tool for architects and landscape designers that will provide simulation of stormwater BMPs have been applied. Visualization of the results in the in Grasshopper will facilitate the assessment of the environmental impact of stormwater BMPs retrofit of Greek urban blocks and the comparison of different stormwater management scenarios.

MODEL DESCRIPTION

The objective of this model is to allow for:

- Integration of climate data (precipitation, temperature, etc.) either from an external model (Energy Plus) or a built-in database (precipitation database)
- Integration of wind flow simulation data from an external CFD model applied on the designed urban block

- Development of an interoperable model: the model is able to co-operate with other models and run simulations through them
- Creation of a user-friendly interface: the model interface is not complex or difficult to navigate, but it is rather straightforward, providing quick access to common features or commands. It is well-organized and intuitive, making it easy to locate different tools and options. Model processes and built-in databases are not visible to the user. The model requires limited data entries requirements by the user (see figure 1):

- Selection of geometries and surface areas from the as-built Rhino 3D drawing of the urban block
- Selection of materials for each surface and geometry of the as built from a drop down list
- Selection of plant types for existing plants in the urban block
- Entry of start day, start time and duration of simulation
- Design of surface area for each BMP in Rhino 3D
- Selection of BMP for each surface from drop-down list

- Development of an accurate model that simulates complex processes: it uses simplified but widely accepted concepts to represent complex natural processes.
- Scenario-building of stormwater Best Management Practices: users are free to choose from a range of different BMPs, create their own stormwater management scenarios, assess them, and finally choose the most appropriate one with regard to its impact on the microclimate.
- Development of a flexible model: it can be used for different types of Greek urban blocks. By making the required alterations in the climate database and the built-in BMPs library, the model can be implemented in different cities around the world with similar climate types for radiation analysis and evaporative cooling simulation, runoff calculation, CFD simulation and results visualization.
- Design and visualization of stormwater management scenarios on surfaces of the selected urban block by selecting Best Management Practices (BMPs) from the BMP Library of the model.
- Quantitative comparison of the impact of stormwater management scenarios on:

1. Runoff volume in sewers
2. Temperature reduction during summer months due to evaporative cooling effected by the stormwater management BMPs

The model is developed in Rhino Grasshoper. and is linked with ENVI-met, a software that simulates the climatological interactions between surfaces, plants, and the atmosphere and allows the architect to specify surface types and building materials, as well as vegetation on walls and roofs. In order to link Grasshoper with ENVI-met the "ENVI-MET plugin for Rhino Grasshopper" is used. The plugin enables users to convert Rhinoceros 3D designs to ENVI-met model areas and run ENVI-met simulations without directly opening the ENVI-met software.

The model workflow is divided into three phases (see figure 2):

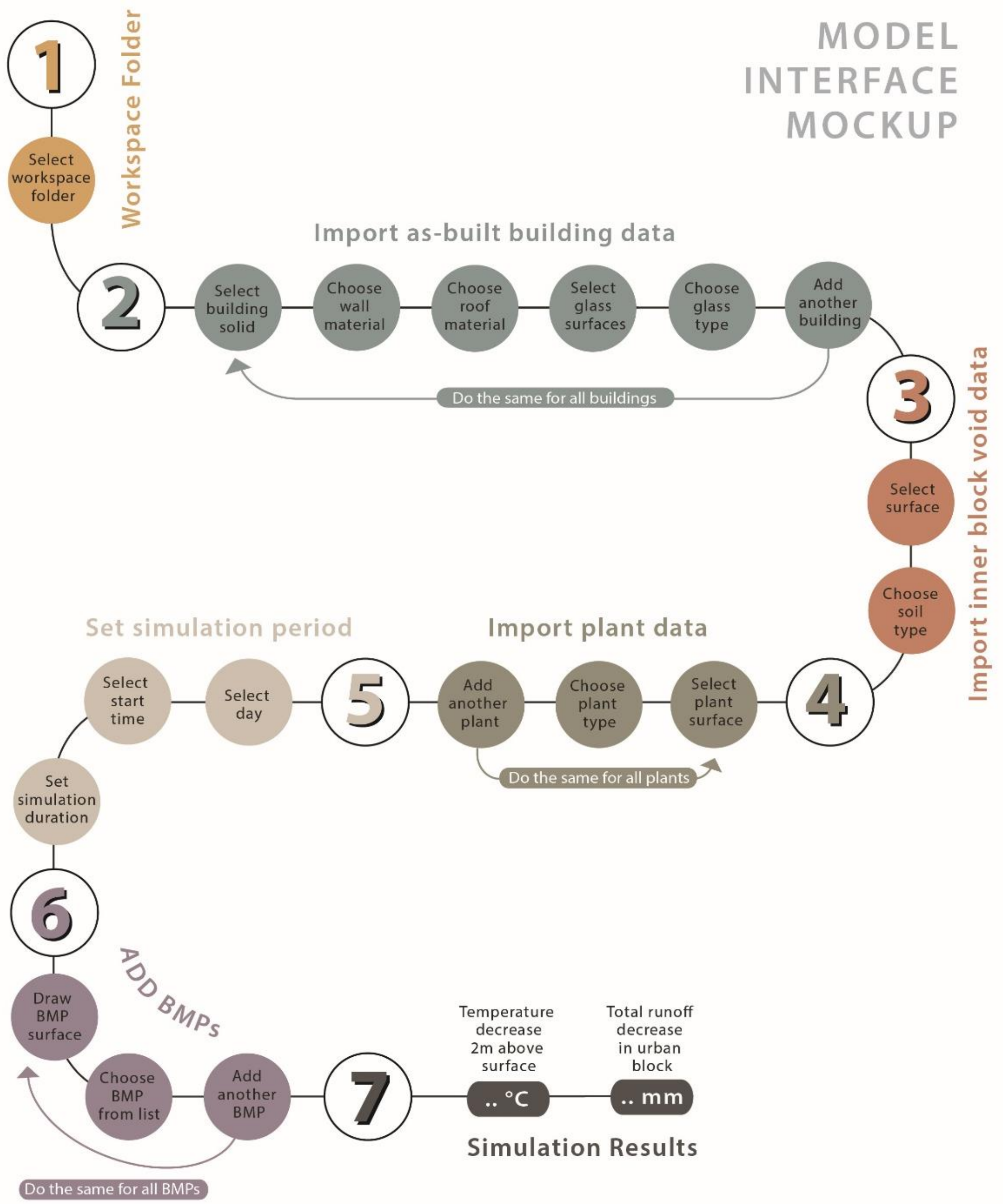
1. Data preparation
2. As-built simulation
3. BMP simulation

Moreover, it is comprised of 7 main process components:

1. Climate database
2. Geometry input
3. Built-in BMPs Library
4. Radiation Analysis and evaporative cooling simulation
5. Runoff Calculation
6. CFD simulation
7. Results visualization

Figure 1

Model interface mockup



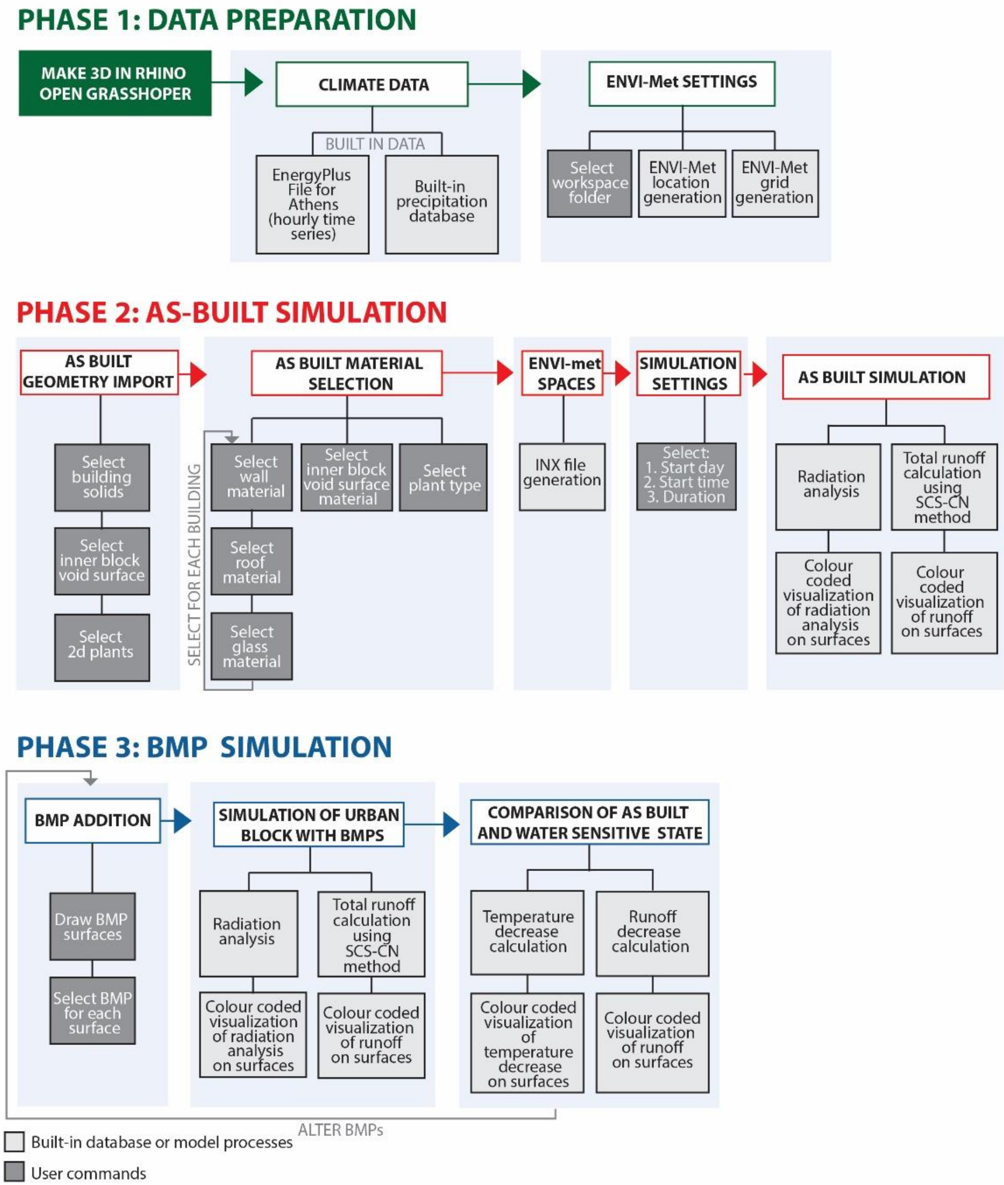


Figure 2

Model diagram: built-in databases, model processes and data requirements commands for model users

CLIMATE DATABASE

The climate database of the model has been created from two climate data sources:

1. **Energy plus weather (EPW) file:** It is a TMY (Typical Meteorological Year) file downloaded from onebuilding.org generated from data collected between 2004 and 2015. It is a collation of selected weather data for Athens, listing hourly values of solar radiation and meteorological elements for a one-year period. Specifically, it lists hourly data for dry bulb temperature, dew point temperature, relative humidity, wind speed, wind direction, direct normal radiation, diffuse horizontal radiation, global horizontal radiation, horizontal infrared radiation, direct normal illuminance, diffuse horizontal illuminance, global horizontal illuminance, total sky cover, barometric pressure. The EPW file is imported into Grasshoper using Ladybag.
2. **Precipitation database:** a TMY file was created using hourly precipitation data of years between 2004 and 2021 provided by the National Observatory of Athens.

GEOMETRY INPUT

A 3D drawing of the urban block using the Rhino 3D modeler is created by the user. The user imports the geometric data from Rhino to Grasshoper by placing them in one of the following groups: 1. Buildings; 2. Plants; 3. Inner block void surface.

Building surfaces are then categorized into 3 different types: walls, roofs and glazing. The user can choose the suitable material for each surface from the material library of ENVI-met plugin which is linked to Grasshoper. The materials of the as-built surfaces are chosen by the user, the Grasshoper geometries are then converted into ENVI-met spaces (grid-based surfaces) which is an essential process in order to run simulations with the ENVI-met plugin in the Grasshoper environment.

BUILT-IN BMP LIBRARY

To achieve a more "water sensitive" state, the user will then be able to select BMPs from the built-in BMP library and set the exact geometry on the 3D drawing for each BMP chosen. ENVI-met "Database manager" has been used by the authors to create the new built -in materials, soils and plants that are added to the BMP Library. For the creation of a BMP scenario, appropriate values must be assigned to a number of parameters all the elements it consists of. These parameters are divided into three groups:

Materials: thickness, absorption, transmission, reflection, emissivity, specific heat, thermal conductivity and density.

Soils: water content at saturation, water content at field capacity, water content at wilting point, matrix potential, hydraulic conductivity, volumentric heat capacity, Clapp Constant and heat conductivity.

Plants: CO2 Fixation Type, leaf type, albedo, transmittance, plant height, root zone depth, leaf area (LAD) profile, root area (RAD) profile, season profile.

For this study, the BMPs created correspond to the needs of the microclimate in urban blocks in Athens and are based on previous studies. The library will contain BMPs for three different types of surfaces: roofs, walls and the inner block void. BMPs in this model are:

Green roofs: designed to intercept and retain rainwater, reducing the volume of runoff and attenuating peak flows. The selection of the types of green roofs will be based on the research of Soulis K. et al. (2017), an on-going experimental program on shallow green roof systems in the Greek urban microclimate, their impact on stormwater runoff and the estimation of their CN values. Therefore, four types of vegetation, each one with two different substrate depths (8 cm or 16 cm) will be created for the BMP library:

1. No vegetation
2. Succulent plants (Sedum sediforme (Lacq.) Pau),
3. Xerophytic plants (Origanum onites L.)
4. Turf grasses (Festuca arundinacea Shreb)

Green facades: vertical structures that have different types of plants or other greenery attached to them contributing to the evapotranspiration of water. The user will have the choice to choose between different types of greening of the façade. All plant types selected are resistant to the hot weather of Athens during summer periods.

Porous pavement: permeable pavement surface with an underlying reservoir that temporarily stores surface runoff in order to slowly infiltrate through the surface into underlying layers. Water can be temporarily stored before infiltration to the ground, reused, or discharged to a watercourse or other drainage system. This porous surface replaces traditional pavement, allowing runoff to infiltrate directly into the soil, which acts as a natural water filter and improves its quality (Pond W., 1997).

Three porous pavement types will be used as BMPs in this model: 1. porous asphalt; 2. pervious concrete; 3. grass pavers.

Raingardens: relatively small depressions in the ground that can act as infiltration and treatment points for roof water and other 'clean' surface water (susdrain.org).

RADIATION ANALYSIS AND EVAPORATIVE COOLING SIMULATION

The module Solar Access of ENVI-met is linked to the model in order to conduct a quick but comprehensive analysis of solar radiation on all building surfaces, taking into account environmental factors such as vegetation. Temperature decrease on building surfaces and also on the air environment due to plant shading, but also due to evaporative cooling from plants and permeable paving are also simulated through ENVI-met. Radiation analysis and evaporative cooling simulation are performed for the as-built urban block as well as the "water sensitive" scenarios that the user will create by choosing BMPs from the built-in BMP library.

RUNOFF CALCULATION

A module to predict runoff depth from rainfall depth has been incorporated into the model. It is based on the Soil Conservation Service Curve Number (SCS-CN) method. This method was originally developed by the U.S. Department of Agriculture, Soil Conservation Service (now known as Natural Resources Conservation Service—NRCS) to predict direct runoff volumes for given rainfall events and mainly for the evaluation of storm runoff in small agricultural watersheds (Soulis K., 2021).–It is an empirical formula which quantifies the rainfall-runoff relationship of small watersheds for the design of water resources infrastructure (Schwartz S.S., 2010). Its success lies in the fact that it is a very simple but well-established method: it features easy to obtain and well-documented environmental inputs and it accounts for many of the factors affecting runoff generation, incorporating them in a single parameter, the curve number (CN) (Ponce, V.M. et. 1996, cited by Soulis K., 2021). The runoff curve number is based on the area's hydrologic soil group, land use, treatment and hydrologic condition

CFD SIMULATION

As wind flow and wind direction play an important role in the evaporative cooling process, wind patterns inside the urban block be modeled in the as-built state by using CFD plugins in Grasshoper. This will contribute to the decision-making process when the architect is asked to select the surfaces where the BMPs are to be applied.

RESULTS VISUALIZATION

The visualization of the simulation results on the 3D model in Rhino is a key feature of the model as it renders the environmental parameters comprehensible and accessible to the architect, without requiring specialized technical knowledge on environmental design or hydrologic expertise. To this end, color-coded visualization data tools of

Grasshoper are used. Simulation results are visualized in the following phases of the simulation:

1. **As-built state simulation results:** radiation analysis and evaporative cooling analysis of the as-built state are visualized by indicating the temperature of the air over the surfaces. Rainwater runoff capacity of surfaces will also be indicated using color-coded visualization on the 3d-model.
2. **Optimal surfaces for BMP application:** combining wind flow analysis results in the urban block, solar radiation analysis and stormwater storage capacity of each surface, the model will suggest optimal surfaces for BMP application for evaporative cooling and runoff mitigation.
3. **'Water sensitive' state simulation:** the simulation results, after a BMP application, will be similarly visualized on the 3D model, highlighting temperature decrease in summer periods due to evaporative cooling and runoff mitigation during rainfall events.

CONCLUSION

The "architect-friendly" model, which is currently developed by the authors, aims to investigate the environmental impact of stormwater BMPs applied on selected building surfaces and the inner voids in urban blocks in Greece or other countries with similar climate. It will thus contribute to the decision-making process of architects from an early stage of the design process. The visualization of the simulation results plays a key role in making the model "architect-friendly". The first testing and validation of the model will take place on several urban blocks in Athens that will be used as case studies, in order to assess and improve the model.

The model has the potential to increase awareness of the benefits of WSUD for Greek and other cities with similar climate and characteristics and trigger a discourse within the scientific community on ways of implementing stormwater BMPs in these cities. The model could also be used for educational purposes in architectural institutions: it will allow students to integrate purely environmental parameters (stormwater runoff, evaporative cooling, etc.) into the design criteria and methodology for their current and future projects.

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REFERENCES

Ponce, V.M.; Hawkins, R.H. Runoff Curve Number: Has It Reached Maturity? J. Hydrol. Eng. 1996, 1, 11–19.

Pond, W. (1997). 'Stormwater Management Fact Sheet: Porous Pavement'. pp.1–8.

Schwartz, S. S. (2010). 'Effective Curve Number and Hydrologic Design of Pervious Concrete Storm-Water Systems'. *Journal of Hydrologic Engineering,* 15(6), 465–474. https://doi.org/10.1061/(asce)he.1943-5584.0000140

Soulis, K. X., Ntoulas, N., Nektarios, P. A., & Kargas, G. (2017). Runoff reduction from extensive green roofs having different substrate depth and plant cover. Ecological Engineering, 102, 80–89. https://doi.org/10.1016/j.ecoleng.2017.01.031

Soulis, K. X. (2021). 'Soil conservation service curve number (SCS-CN) method: Current applications, remaining challenges, and future perspectives.' *Water* (Switzerland), 13(2). https://doi.org/10.3390/w13020192

Wong, T. and Eadie, M. (2000). 'Water Sensitive Urban Design - a Paradigm Shift in Urban Design', 10th World Water Congress, (May), p. 8.

[1] https://www.melbournewater.com.au/planning-and-building/stormwater-management/introduction-wsud
[2] https://www.susdrain.org/delivering-suds/using-suds/suds-components/infiltration/rain-gardens.html