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QUANTITATIVE ASSESSMENT OF HYDROLOGICAL EFFICIENCY OF RAIN GARDEN DESIGN IN THE CONTEXT OF MANAGING THE VOLUME AND QUALITY OF STORM EFFLUENT

Marina Kravchenko[1], Tetiana Tkachenko[1], Viktor Mileikovskyi[1], Yuliia Trach[2]✉

[1] Institute of Engineering Systems and Ecology, Kyiv National University of Construction and Architecture, Kyiv, Ukraine
[2] Institute of Civil Engineering, Warsaw University of Life Sciences – SGGW, Warsaw, Poland

ABSTRACT

Rain gardens are a popular element of green infrastructure, often integrated into the sponge city concept to address stormwater management issues. Such structures perform three main functions: reducing the volume of water runoff from the catchment area, reducing peak flows in the drainage system, which is critical for preventing overloading of the sewer network, and improving water quality, which contributes to the preservation of groundwater. The design of rain gardens is based on specific requirements and characteristics that determine their construction and calculation methods to achieve optimal parameters, such as area and depth. Scientometric analysis shows that significant research contributions are made by different countries, but most existing rain garden systems are based on general recommendations, which can lead to problems in their operation. The purpose of the work is to develop a model for calculating the main parameters of rain gardens and methods for assessing their hydrological efficiency in order to improve their implementation in the urban environment. A numerical model for calculating the effective area of a rain garden is presented, which considers one rain event and excludes overflow. Methods are proposed for evaluating three key functions of rain gardens in the context of stormwater management: a method for determining runoff reduction, a method for estimating annual runoff reduction, a method for peak runoff reduction, and a method for estimating total pollutant reduction.

Keywords: rain garden, storm drains, stormwater management, modelling, rain garden parameters

INTRODUCTION

With the continuous development of global urbanisation, its impact on the climate is becoming more and more obvious. In particular, such phenomena as the urban heat island effect, extreme heat and waterlogging of cities are observed. At the same time, global climate changes affect the spatio-temporal distribution of precipitation. The higher intensity of stormwater runoff, which is currently observed in many countries, in particular in Eastern Europe (Poland, Ukraine), is a consequence of the urbanisation of catchment areas, which is accompanied by an increase in the share of impermeable surfaces. Precipitation often takes the form of torrential rains: up to 3/4 of the average monthly rainfall can fall in 30 min, indicating that rains are becoming less frequent but more intense.

Marina Kravchenko https://orcid.org/0000-0003-0428-6440; Tetiana Tkachenko https://orcid.org/0000-0003-2105-5951;
Viktor Mileikovskyi https://orcid.org/0000-0001-8543-1800; Yuliia Trach https://orcid.org/0000-0002-3217-2451
✉yuliia_trach@sggw.edu.pl

The interaction of impermeable areas with extreme and intense precipitation leads to the formation of local floods and to an increase in the speed of storm runoff of surface water (Guerreiro, Glenis, Dawson & Kilsby, 2017; Trach, 2020). To partially solve this problem, traditional drainage systems are used to divert rainwater from compacted surfaces to a centralised sewage system, treatment facilities, or the nearest water bodies.

However, the service life of such infrastructure systems has generally exceeded the planned period, and major repairs require high costs of materials and ongoing maintenance, so during heavy rainfall, these structures are usually unable to cope with large peak flows, which often leads to their overflow and flooding.

Urban areas that only have sewage systems that collect surface runoff and wastewater for discharge to sewage treatment facilities are in an even more difficult situation. Any sudden increase in surface runoff during torrential rain causes local floods and paralyses the entire system (Zhang et al., 2020b). Unfortunately, it is impossible to correct the situation in the short term, because improving the efficiency of the surface runoff system is, at best, very difficult and expensive. This is mostly due to the high density of urban buildings and the fact that sewage systems are laid deep underground.

As global warming continues, extreme weather events combined with urbanisation pose increased risks to humans and ecosystems (Giese, Rockler, Shirmohammadi & Pavao-Zuckerman, 2019). In particular, the projected changes in the duration of dry periods between precipitations have a negative impact on the quality of stormwater. Prolonged dry periods contribute to the accumulation of particulate matter and toxic pollutants on impervious urban surfaces, and heavy rainfall washes significant amounts of pollutants into water bodies through storm runoff. This increases the risk of contamination of receiving water bodies and makes it difficult to reuse stormwater without preliminary treatment (Kravchenko, Trach, Trach, Tkachenko & Mileikovskyi, 2024a).

Today, the term ‘sponge city’ is appearing more and more often in scientific literature, which indicates a growing interest in this concept. It involves the integration of natural and artificial elements to improve retention, infiltration and treatment of stormwater in the urban environment. More and more countries around the world are actively implementing the principles of the sponge city, aimed at effective management of runoff, reducing the risk of flooding, improving water quality and ensuring the resilience of urban infrastructure to climate change.

A sponge city is a concept that involves using the principles of a sponge to absorb rainwater and treat it further before returning it to the city’s drainage system. This is ensured by infiltration and purification of groundwater, which makes it possible to reduce surface runoff and prevent flooding (Fig. 1).

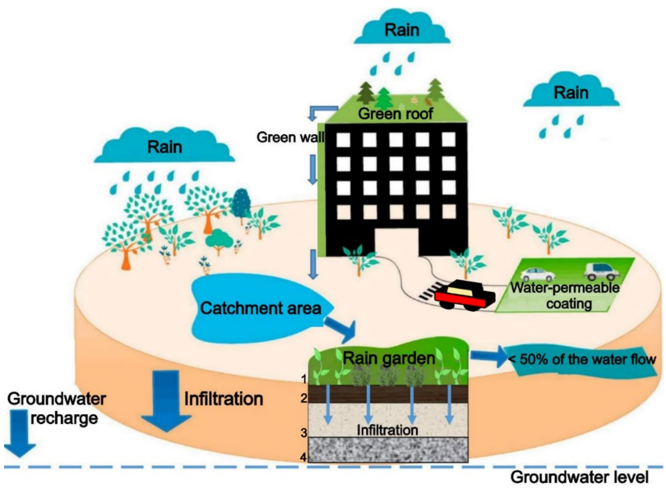

Fig. 1. Principles of stormwater management based on the sponge city concept

Source: adapted from Qi et al. (2020).

The rain garden should be designed with following main elements: 1 – plant layer; 2 – a layer of soil mixture for planting plants, 3 – infiltration/intermediate layer; 5 – a layer of gravel.

The concept of the sponge city is aimed at restoring the urban hydrological system by integrating environmentally friendly solutions, in particular, combining different types of green infrastructure (GI) and elements of urban infrastructure to form complex infrastructure systems. This makes it possible to efficiently collect, manage and reuse urban water, contributing to the sustainable development of urban areas and improving their adaptation to climate change.

As Zaręba et al. (2022) note: 'sponge cities are used to mitigate the five main problems in the field of stormwater management in urban areas: water scarcity, waterlogging, water pollution, ecological degradation and the so-called city syndrome'.

Green infrastructure refers to methods aimed at restoring the hydrological cycle by incorporating natural components into the urban landscape that can increase rainfall interception and infiltration (Berland et al., 2017). This is a relatively new approach that has gained popularity as an effective means of reducing the destructive effects of floods and achieving a better balance between the needs of urbanisation and the needs of nature (Coleman, Hurley, Rizzo, Koliba & Zia, 2018).

In recent years, the number of studies related to the practice of GI in rainwater management has been progressively increasing. As a recent example, Ying, Zhang, Zhang and Bilan (2022) conducted a comprehensive review of the literature related to GI, examining publications published from 1995 to 2019. The analysis of the works, which were searched by the authors based on keywords, indicates that the majority of articles are focused on the study of GI in the field of stormwater management. Gao, Wang and Yang (2022) recently completed a scientific review of works related to GI published in 1999–2021, providing a lot of useful information on this topic. And within the framework of the study by Green et al. (2021), the role of GI in managing the risks of urban floods was studied. The authors analysed the specifics of using GIs to reduce urban flooding problems, exploring a number of challenges and priorities that need to be addressed in order to incorporate GIs into current stormwater management systems.

Green infrastructure includes any system that provides positive or sustainable environmental benefits, including such as permeable pavement, rainwater tanks, and solar panels, but the term 'green' directly refers to types of infrastructure where vegetation is an integral part of their design and functionality. Such systems include urban gardens, parks, forests, nature reserves, as well as systems that include engineering components, such as green walls, green coverings, rain garden structures, and wetlands (Sharma & Malaviya, 2021; Bruner, Palmer, Griffin & Naeem, 2023).

Rain gardens, often referred to as bioretention or bioinfiltration systems, have been recommended for local, near-source stormwater management due to their cost-effectiveness and positive effects on ecosystem restoration (Osheen & Singh, 2019).

These structures are usually located in lowland areas, and thanks to the infiltration and adsorption processes occurring in the system 'plants – microbial population – structural layers', effective cleaning of rainwater is achieved in a limited area. Rain gardens are mainly used to manage rainwater runoff from surfaces up to 1 ha. The main advantages of rain gardens include:

- reducing the volume of rainwater runoff from the area of the catchment basin (Shafique, 2016),
- reducing the speed of peak water flows in the sewage system, which is of particular importance for preventing hydrological overloading of the sewage network (Shuster, Darner, Schifman & Herrmann, 2017),
- water quality control, which contributes to the preservation of groundwater (Morash et al., 2019).

For example, DeBusk and Wynn (2011) evaluated the effectiveness of a rain garden, into which stormwater flows from a parking lot, and showed a 99% decrease in peak water flow rates from the parking lot. A study conducted by Rezaei et al. (2019) using the stormwater management model (SWMM) of the US Environmental Protection Agency using rain gardens indicates that even small changes in rain garden parameters such as water permeability, layer sizes and material selection, significantly affect the simulated peak flow.

The percentage reduction in the volume of stormwater diverted from the area of the catchment basin due to the use of rain gardens depends on the intensity of precipitation and its duration, as well as on the design features of the rain garden. The effectiveness of reducing the flow volume was investigated in various works (Brown & Hunt, 2011; Shafique & Kim, 2017; Zhang Ye & Shibata, 2020a).

According to Shafique and Kim (2017), the total percentage of runoff volume reduction is in the range from 50% to 98% for various studies. According to Zhang et al. (2020a), the reduction of runoff with the help of rain gardens ranges from 23% to 97%, depending on the climatic conditions in which the research was conducted. Therefore, the use of such solutions as the construction of rain gardens allows to reduce the probability of overloading of rain or combined sewage infrastructure, partially solving the problem of urban rainwater management (Wanitchayapaisit et al., 2022).

The design of rain gardens is based on the parameters and requirements associated with the specified functions. At the same time, their structure is determined in detail and the appropriate calculation method is chosen, aimed at ensuring optimal parameters, such as size and depth. One of the main methods of such calculations is numerical modelling, whose approaches remain the most widely used tool that allows you to support and improve the processes of planning, design and management in the direction of the concept of sustainable development.

Modelling is a key tool for rain garden research, as it makes it possible to predict and analyse the hydrological characteristics and water quality in systems under different operating conditions (Zhang, Lu, Ding, Peng & Yao, 2018; Wang, Zhang, Babovic & Gin, 2019). In addition, this approach allows you to develop several operational scenarios and obtain important data to improve the efficiency of rain gardens, which is not always possible to provide with experimental methods.

Calculating the optimal design area of a rain garden as part of a sponge system is critical to making effective decisions in urban stormwater management. According to the characteristics of rain gardens, the most common approach in many countries is the infiltration method based on Darcy's law, which is used to calculate the area of the garden (Li, Xiang, Che, & Ge, 2008). This method is based on an assessment of the infiltration capacity of soils but has limitations because it does not consider the influence of the structural features of the location of the rain garden and the role of plants in improving water permeability and cleaning runoff.

In addition to the above-mentioned method, there are two more common approaches: the method of calculating the effective volume of the surface retention layer of rain gardens proposed by Davis and McCuen (2005), and the method of estimating proportions based on the size of the catchment area, which was described in the manual for designing structures for stormwater treatment (Auckland Regional Council, 2003).

The method of calculating the effective volume of the surface retaining layer is based on the water balance equation and uses the volume of the aquifer to reduce the runoff volume. This approach considers the effect of vegetation on water retention but ignores the infiltration capacity and retention properties of the rain garden, which are important for treating the first flush of runoff, which is about 12 mm of rainfall. The method of estimating proportions is a more simplified approach and consists of calculating the catchment area multiplied by the proportionality factor. However, the accuracy of this method is low, and its applicability is limited by the precipitation characteristics and standards for different regions.

The above methods based on Darcy's law have their advantages and limitations. The choice of the appropriate method depends on the analysis of the structural characteristics of the rain garden, its functional purpose, project standards, soil properties and other factors. The infiltration method based on Darcy's law is effective for rain gardens with sandy soil because such soil provides a high infiltration capacity. The method of calculating the effective volume of the surface retention layer is better suited for systems with clay soils and large areas, where water retention on the surface plays an important role. The proportional estimation method is usually used for calculations with known rain garden parameters and is more applicable in cases where the catchment area and other system parameters are well defined.

The universal hydrological infiltration model developed by the authors, based on Darcy's law and Bernoulli's equation, is important, as it makes it possible to describe dynamic processes in the construction of a rain garden (Kravchenko et al., 2024b). Later, this model was improved to consider the height of the water column on the surface of the structure, which made it possible to more accurately model the dynamics of storm runoff and improve the prediction of the hydrological efficiency of the system. This improvement provided a better adaptation of the model to the real conditions of rain garden operation.

In addition to the use of known models, it is important to apply methods of quantitative assessment of the hydrological efficiency of rain gardens. These methods enable the precise determination of key parameters such as water storage volume, infiltration rate, peak flow reduction and runoff retention, and pollutant reduction by the rain garden design during a rainfall event.

The purpose of this study is to model the design parameters of a rain garden and develop methods for quantifying its hydrological efficiency for stormwater management and ensuring widespread use in urban settings.

MODELLING THE RAIN GARDEN'S DESIGN PARAMETERS

The calculation of the effective area of the rain garden must consider infiltration processes, the effect of vegetation on the aquifer, the volume of the storage tank and other factors. To ensure the maximum efficiency of the water-holding capacity of the rain garden, it is assumed that the coefficient of water permeability is $K \geqq 1 \cdot 10^{-5}$ m·s^{-1}. At the same time, the rainwater flow from impermeable surfaces is directed to the rain garden, which consists of several layers: vegetation cover, a layer of soil mixture for planting plants, an infiltration (sand) layer, and a gravel layer (Fig. 1).

By the time the storm runoff exceeds the storage and infiltration capacity of the rain garden and the water begins to go beyond the calculation area (Fig. 2), a balance is established between the main hydrological elements of the system. This balance can be described using the water balance equation, which considers the volume of water inflow, storage, infiltration and outflow:

$$V + V_1 = X + Y + Z + V_2 + W_1, \tag{1}$$

where:
V – volume of rainwater collected in the construction of the rain garden during the calculation periods [m^3],
V_1 – volume of runoff accumulated by the rain garden at the beginning of the calculation periods [m^3],
X – volume of infiltrated rainwater for the calculation periods [m^3],
Y – volume of evaporation from the rain garden during the calculation periods [m^3],
Z – volume of rainwater that saturates the layer of the loose soil mixture for the calculation periods [m^3],
V_2 – volume of rainwater retained by the rain garden structure at the end of the calculation periods [m^3],
W_1 – volume of rainwater overflow during the calculation periods [m^3].

When designing the construction of a rain garden, the volume of rainwater overflow W_1 can be taken as zero. If it is assumed that there is no water in the rain garden structure at the beginning of the calculation period ($V_1 = 0$), and the volume of water from the beginning to the end of the period is V_{basin}, then, considering the equality of $V_{basin} = V_2 - V_1$, it is possible to write $V_{basin} = V_2$. Accordingly, Formula (1) takes the following form:

$$V = X + Z + V_{basin}. \tag{2}$$

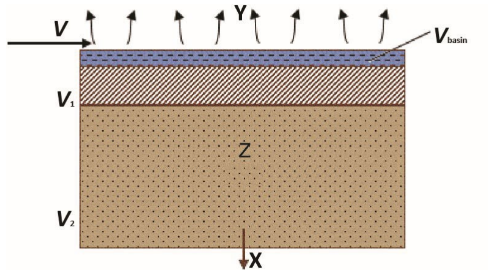

Fig. 2. Scheme used to determine the area of the rain garden structure

Source: own work.

The amount of precipitation per unit area of the rain garden R_Y [m^3·m^{-2}] during the calculation periods can be determined by considering the intensity of the precipitation $q(T)$ for the corresponding climatic region. For this, it is necessary to integrate Formula (2), which gives:

$$R_Y = \int_0^{\tau} q(T)dT, \tag{3}$$

where:
τ – calculation period [min],
T – duration of rainfall [min].

The volume of rainwater collected in the construction of the rain garden for the calculation periods is calculated according to Formula (4):

$$V = A_{\text{basin}} \cdot R_Y \cdot \varphi \cdot 10^{-4}, \tag{4}$$

where:
A_{basin} – area of the rain garden catchment basin [m^2],
φ – flow coefficient.

The calculation of the volume of infiltrated rainwater for the calculation period can be expressed using Formula (5):

$$X = \frac{K \cdot (h_{\text{sponge}} + h) \cdot A_{\text{sponge}} \cdot \tau \cdot 60}{h_{\text{sponge}}}, \tag{5}$$

where:
K – water permeability coefficient of the soil mixture layer for planting plants [m·s^{-1}],
h_{sponge} – depth of the rain garden [m],
h – submerged zone forming of the height of the water column [m],
A_{sponge} – area of the rain garden as a sponge [m^2],
τ – calculation period [min].

According to the design features of the rain garden and various physical and chemical properties of the soil environment, the value of K entered in Formula (5) can be described based on the following three conditions:

1. Provided that the design of the rain garden includes a layer of an impermeable geotextile membrane or the permeability coefficient of the infiltration layer K_2 is significantly less than the water permeability coefficient of the soil mixture for planting plants K_1, i.e. $K^2 << K_1$ (under other conditions, preferably, $K_2 > K_1$), K_2 can be considered a limiting factor and the volume of infiltrated rainwater X can be neglected, i.e. $X = 0$.
2. Provided that the design of the rain garden includes a drainage system for collecting and draining rainwater or $K_2 >> K_1$, it can be assumed that $K = K_1$. Provided that $K_2 < K_1$, it can be assumed that $K = K_2$.
3. If the volume of runoff in a rain garden structure exceeds the volume of infiltrated water absorbed by the layers of the structure during the same period, excess stormwater inevitably remains in the system. Suppose that the height of the vegetation cover exceeds the height of the layer forming the water column; in this case, the calculation of the actual volume V_{basin} is determined using Formula (6):

$$V_{basin} = A_{sponge} \cdot h_{max} \cdot (1 - f_v) \cdot 10^{-3}, \tag{6}$$

where:
h_{max} – maximum depth of the immersion zone for the structure of the water column,
f_v – percentage of the cross-sectional area of the vegetation cover from the surface area of the layer for the structure of the water column, which is usually equal to 20%.

The volume of rainwater that saturates the depth of the soil mixture for the calculation periods is determined as:

$$Z = n \cdot A_{sponge} \cdot h_{sponge}, \tag{7}$$

where:
n – average porosity of the layer of the soil mixture for planting plants and the infiltration layer, which is taken for calculation as 0.3.

Considering the above formulas, the calculation of the area of the rain garden as an element of the spongy system can be expressed using Formula (8):

$$A_{sponge} = \frac{A_{basin} \cdot R_Y \cdot \varphi \cdot h_{sponge}}{60 \cdot K \cdot \tau (h_{sponge} + h) + h_{max} \cdot (1 - f_v) \cdot h_{sponge} + n \cdot h_{sponge}^2}. \tag{8}$$

Under the condition that $X = 0$, i.e. $K = 0$, Formula (8) can be changed to:

$$A_{sponge} = \frac{A_{basin} \cdot R_Y \cdot \varphi}{h_{max} \cdot (1 - f_v) + n \cdot h_{sponge}}. \tag{9}$$

The proposed method for calculating the area of a rain garden structure is designed to analyse a single rain event under the condition that there is no overflow or water leakage from the structure. The method is also recommended for calculating the effective area of a rain garden in situations where treated rainwater is stored in a tank for reuse. It is important to note that rain gardens are designed for regular rainfall and not for individual extreme events, so the average local rainfall characteristics should be considered when determining the effective area.

Calculating the effective area of a rain garden design is critical for the optimal functioning of such systems in stormwater management, as Figure 3 clearly illustrates.

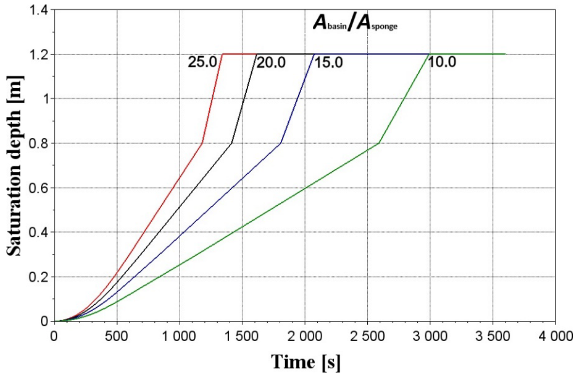

Fig. 3. Curves of the efficiency of the rain garden design without considering the height of the water column depending on its area

Source: own work.

As shown in Figure 3, the maximum efficiency of the rain garden is achieved when the area ratio (A_{basin}/A_{sponge}) = 10. This means that for a 100 m² catchment area, a 10 m² rain garden will be completely filled with water within 50 min of a rain event. As the area of the rain garden decreases, the hydrological efficiency of the structure decreases. For example, in the case of an area ratio equal to 25, that is, with a rain garden area of 4 m², the system is filled in 26 min.

When modelling rain gardens, it is necessary to consider the parameter of the height of the water column, since it significantly affects the dynamics of hydrological processes in the system. Models that consider the height of the water column on the surface of the rain garden are designed mainly to predict the behaviour of the system under conditions of high rainfall intensity (from 25 mm·h^{-1} and more).

Modelling of hydrological processes in rain gardens with the same design parameters and conditions, but with and without the height of the water column, shows a significant difference in results. The addition of this parameter significantly improves the accuracy of predicting and describing the behaviour of the system during storm events, which is clearly illustrated by the results shown in Figure 4.

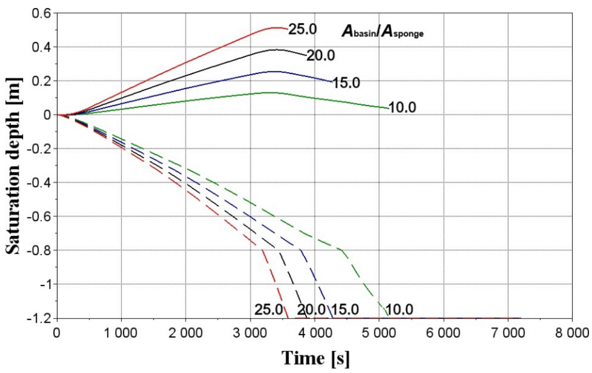

Fig. 4. Efficiency curves of the rain garden design considering the height of the water column depending on its area

Source: own work.

In contrast to the results that do not consider the height of the water column, simulations with an area ratio of $(A_{basin}/A_{sponge}) = 10$ show that a 10 m² rain garden will completely fill with water in 1 h and 25 min during a rain event, creating a water column of 0.15 m. With an area ratio of 25, that is, for a rain garden with an area of 4 m², the system will fill in 1 h, and the height of the water column on the surface will reach 0.5 m.

The rain garden design serves three key functions in stormwater management – reducing in stormwater runoff volume, reducing peak runoff velocity, and reducing in total water pollutants – therefore, a quantitative assessment method for these functions was proposed.

Method of assessing the reduction of the volume of storm runoff by the construction of a rain garden

Let us assume that the estimated recurrence period of a certain rain event is N_1, and the corresponding amount of precipitation is R [mm]. The recurrence period N_1 is the time interval, expressed in years, during which a certain rainfall event is expected to recur with the same amount of precipitation or an excess of precipitation intensity compared to the previous event.

The curve showing the change in the intensity of rain runoff depending on the flow of rainwater Q [m³·s⁻¹] and the duration of precipitation T [min] is presented in Figure 5.

Taking the corresponding area of the rain garden as $A_{sponge1}$ and the volume of water retained by the rain garden as U_1, according to formula (1), the water balance equation can be written as $U_1 = X + V_{basin} + Z$. The value of X can be neglected if a layer of waterproof membrane is placed on the bottom of the rain garden structure or provided that $K_2 << K_1$.

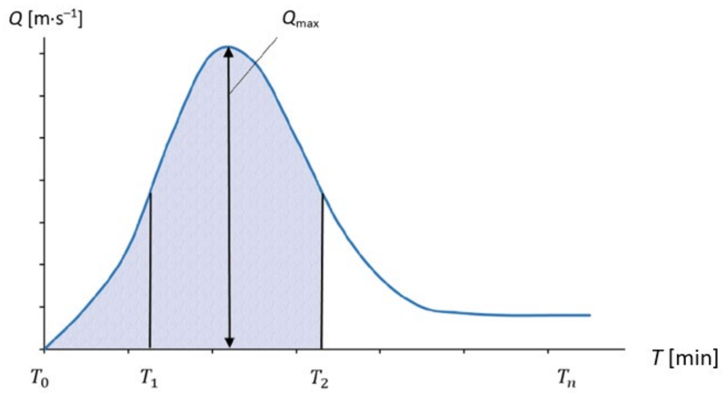

Fig. 5. Curve of changes in the intensity of storm runoff

Source: own work.

Under the condition that the period of repetition of the rain event is $N \geq N_1$, it can be assumed that $U' = U_1$. Otherwise, under the condition that the repetition period is $N \leq N_1$, it can be assumed that $U' = U$. The coefficient of reduction of the volume of storm runoff can also be written as a ratio:

$$\eta = \frac{U'}{U} \cdot 100\%. \quad (10)$$

where:
U' – volume of runoff retained by the structure of the rain garden [m³],
U – output flow volume [m³].

Method of estimating the reduction of the annual flow volume

This method is based on the calculation of the daily amount of precipitation. Let us assume that the calculated amount of precipitation is R [mm]. According to the data of climate observations and long-term precipitation statistics, the following parameters can be determined: the amount of precipitation n per year; the amount of precipitation exceeding or equal to R was a; the amount of precipitation less than R was b, then $n = a + b$, and the corresponding amount of precipitation for each rain event is R_i ($i = 1, 2, ... , n$).

If there is no data on the amount of precipitation in a certain climatic area, this information can be obtained from the data on the daily amount of precipitation, which, for example in Ukraine, is updated on the Boris Sresnevsky Central Geophysical Observatory website. Then, the annual flow reduction volume and the annual flow reduction coefficient are represented in Formulas (11) and (12) as:

$$U'' = a \cdot \varphi \cdot R \cdot A_{\text{basin}} + \Sigma_{i=1}^{b} \varphi \cdot R_i \cdot A_{\text{basin}}, \tag{11}$$

$$\eta' = \frac{U''}{\Sigma_{i=1}^{n} \varphi \cdot R_i \cdot A_{\text{basin}}} \cdot 100\% = \frac{a \cdot R + \Sigma_{i=1}^{b} R_i}{\Sigma_{i=1}^{n} R_i} \cdot 100\%, \tag{12}$$

where:
U'' – annual volume of storm runoff reduction [m^3],
η' – coefficient of annual flow reduction.

Method of estimating the reduction of peak runoff volume by the construction of a rain garden

Considering the volume of water retained by the rain garden and the volume of peak runoff, the curve that describes the process of reducing the peak water runoff during a rain event is presented in Figure 6.

The volume of water retained by the rain garden U_1 can be written as:

$$U_1 = \varphi \cdot A_{\text{basin}} \cdot \int_{T_0}^{T_n} q(T)dT, \tag{13}$$

where:
T_0 – start time of storm runoff formation [min],
T_n – flow duration [min].

The runoff volume, which depends on the volume of water retained by the rain garden structure, corresponds to the size of the shaded area as shown in Figure 4. Then the peak runoff volume corresponding to time T_2 and the corresponding peak runoff reduction factor are described by Formulas (14) and (15):

$$Q' = Q_{\max} - U_1. \tag{14}$$

$$\theta = \frac{Q_{\max} - Q}{Q_{\max}}, \tag{15}$$

where:
Q' – volume of retained peak flow [m^3],
$Q_{\max}$ – maximum peak flow volume [m^3],
U_1 – volume of water retained by the rain garden [m^3],
θ – reduction factor of the peak flow level.

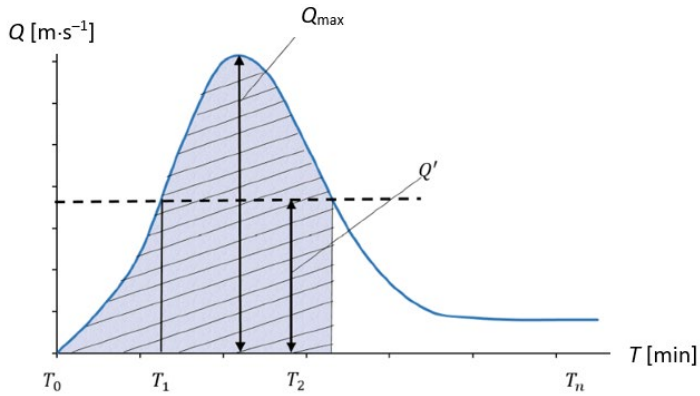

Fig. 6. Curve of reduction of peak water flow during a rain event

Source: own work.

Method of assessing the reduction of the total amount of pollutants by the construction of a rain garden

Let us denote the change in the intensity and concentration of stormwater pollutants over time through the parameters $q(T)$ and $C(T)$, and the concentration decreases with the increasing time. Depending on the structure and design features of the rain garden, the overall reduction of pollutants can be considered in two cases.

Method for assessing pollutant reduction by rain garden construction during a single rain event

First case. If the rain garden design includes a drainage system of impervious and non-perforated collector pipes that are installed in a layer of gravel, this means that the runoff that enters the rain garden is collected inside the structure. In this case, it can be assumed that the pollutants are fully removed by the rain garden structure in full, which can be described as:

$$m = M - U' \cdot C_r, \tag{16}$$

$$\varepsilon = \frac{m}{M} \cdot 100\%, \tag{17}$$

where:

m – total amount of pollutants removed by the rain garden construction [mg],
M – total amount of pollutants entering the rain garden structure [mg],
U' – volume of water retained by the rain garden [m^3],
C_r – average concentration of pollutants in the water of one rain event [mg·dm^{-3}],
ε – overall coefficient of reduction of pollutants in stormwater runoff.

The average concentration of pollutants in the water of one rain event can be calculated based on Equation (18):

$$C_r = \frac{M}{U} = \frac{\int_{T_0}^{T_n} C(T) \cdot q(T) dT}{q(T) dT} = \frac{\Sigma\, C(T) \cdot q(T) \Delta T}{\Sigma\, q(T) \Delta T}, \tag{18}$$

where:
U – total volume of initial rain runoff [m^3],
T_0 – start time of flow formation [min],
T_n – flow duration [min],
ΔT – sampling interval time (time between successive measurements or sampling) [min].

Then, considering Formula (13), the total amount of pollutants removed by the construction of the rain garden can be determined:

$$m = \varphi \cdot A_{\text{basin}} \cdot C_r \cdot \int_{T_0}^{T_n} q(T)dT. \tag{19}$$

Second case. If the rain garden design includes a permeable layer and a drainage system of perforated pipes in the bottom layer of gravel is present, then it can be assumed that the pollutants are partially removed by the rain garden design.

Then:

$$M = m - U' \cdot C_r, \tag{20}$$

$$\varepsilon = \frac{m}{M} \cdot 100\%, \tag{21}$$

where:
C – average concentration of pollutants in the effluent at the exit from the rain garden structure [mg·dm^{-3}].

Method of assessing the annual reduction of pollutants by the construction of a rain garden

For the first case, the total annual amount of pollutants removed and the coefficient of reduction of their total amount are shown in the form of Formulas (22) and (23):

$$M' = \left(a \cdot \varphi \cdot R \cdot A_{\text{basin}} + \Sigma_{i=1}^{b} \varphi \cdot R_i \cdot A_{\text{basin}}\right) \cdot C_1, \tag{22}$$

$$\varepsilon' = \frac{M'}{\Sigma_{i=1}^{n} \varphi \cdot R_i \cdot A_{\text{basin}} \cdot C_1} \cdot 100\% = \frac{a \cdot R + \Sigma_{i=1}^{b} R_i}{\Sigma_{i=1}^{n} R_i} \cdot 100\%, \tag{23}$$

where:
M' – total annual amount of pollutants removed [mg],
C_1 – average concentration of pollutants in the runoff for n cases of rain events [mg·dm^{-3}],
ε' – coefficient of reduction of the total amount of pollutants.

For the second case, the total annual amount of pollutants removed and the coefficient of reduction of their total amount are shown in the form of Formulas (24) and (25):

$$M'' = \left(a \cdot \varphi \cdot R \cdot A_{\text{basin}} + \Sigma_{i=1}^{b} \varphi \cdot R_i \cdot A_{\text{basin}}\right) \cdot \left(C_1 - C'\right), \tag{24}$$

$$\varepsilon' = \frac{M''}{\Sigma_{i=1}^{n} \varphi \cdot R_i \cdot A_{\text{basin}} \cdot C_1} \cdot 100\% = \frac{\left(a \cdot R + \Sigma_{i=1}^{b} R_i\right) \cdot \left(C_1 - C'\right)}{\Sigma_{i=1}^{n} R_i \cdot C_1} \cdot 100\%, \tag{25}$$

where:
C' – average concentration of pollutants in the runoff for *n* cases of rain events [mg·dm^{-3}].

CONCLUSIONS

Rain gardens are widely used for stormwater management in small catchment areas, playing a key role in reducing peak runoff rates, wastewater volume and overall pollution, and protecting water resources. Although there are many models in the scientific literature describing the hydrological parameters of rain gardens, an important aspect that remains understudied is the detailed consideration of the main hydrological elements of the water balance. A numerical model has been developed that makes it possible to calculate of the effective area of a rain garden structure for a single rainfall event, provided that the structure does not overflow or leak. Methods of assessing three key functions of rain gardens in the field of stormwater management are proposed: a method of assessing the reduction of the volume of stormwater runoff; a method of estimating the reduction of the annual flow volume; a method of estimating the reduction of the peak flow volume; and a method of assessing the reduction of the total amount of pollutants.

These numerical models can be a useful tool in the planning and implementation stages of rain garden investments, especially in urban areas, enabling more efficient stormwater management. In further studies, it is planned to validate the developed methodology by comparing the simulation results with the data of field observations and experimental measurements. This will allow us to assess the accuracy and reliability of the calculation methods, and to clarify and improve the existing models considering the real conditions of operation of rain gardens. This validation will include an analysis of different scenarios of rain events and types of rain gardens, which will allow more accurate prediction of their hydrological performance and optimisation of their design and implementation in the urban environment.

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Authors' contributions

Conceptualisation: M.K., T.T. and V.M.; methodology: M.K., Y.T. and V.M.; software: V.M.; validation: T.T. and V.M.; formal analysis: Y.T.; investigation: M.K., T.T. and V.M.; resources: Y.T.; data curation: M.K., T.T. and V.M.; writing – original draft preparation: M.K., and Y.T.; writing – review and editing: Y.T.; visualisation: M.K., T.T. and V.M.; supervision: Y.T.; project administration: M.K., and Y.T.; funding acquisition: M.K., and Y.T.

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REFERENCES

Auckland Regional Council (2003). *TP10 Stormwater management devices: Design guideline manual* (2nd ed.). Auckland. Retrieved from: http://www.aucklandcity.govt.nz/council/documents/technicalpublications/TP10%20Stormwater%20management%20devices%20design%20guideline%20manual%202003.pdf [accessed: 17.03.2024].

Berland, A., Shiflett, S. A., Shuster, W. D., Garmestani, A. S., Goddard, H. C., Herrmann, D. L. & Hopton, M. E. (2017). The role of trees in urban stormwater management. *Landscape and Urban Planning*, *162*, 167–177. https://doi.org/10.1016/j.landurbplan.2017.02.017

Brown, R. A. & Hunt, W. F. (2011). Underdrain Configuration to Enhance Bioretention Exfiltration to Reduce Pollutant Loads. *Journal of Environmental Engineering*, *137* (11), 1082–1091. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000437

Bruner, S. G., Palmer, M. I., Griffin, K. L. & Naeem, S. (2023). Planting design influences green infrastructure performance: Plant species identity and complementarity in rain gardens. *Ecological Applications*, *33* (7), e2902. https://doi.org/10.1002/eap.2902

Coleman, S., Hurley, S., Rizzo, D., Koliba, C. & Zia, A. (2018). From the household to watershed: A cross-scale analysis of residential intention to adopt green stormwater infrastructure. *Landscape and Urban Planning*, *180*, 195–206. https://doi.org/10.1016/j.landurbplan.2018.09.005

Davis, A. P. & McCuen, R. H. (2005). *Stormwater Management for Smart Growth*. Springer. https://doi.org/10.1007/0-387-27593-2

DeBusk, K. M. & Wynn, T. M. (2011). Storm-Water Bioretention for Runoff Quality and Quantity Mitigation. *Journal of Environmental Engineering*, *137* (9), 800–808. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000388

Gao, M., Wang, Z. & Yang, H. (2022). Review of Urban Flood Resilience: Insights from Scientometric and Systematic Analysis. *International Journal of Environmental Research and Public Health*, *19* (14), 8837. https://doi.org/10.3390/ijerph19148837

Giese, E., Rockler, A., Shirmohammadi, A. & Pavao-Zuckerman, M. A. (2019). Assessing Watershed-Scale Stormwater Green Infrastructure Response to Climate Change in Clarksburg, Maryland. *Journal of Water Resources Planning and Management*, *145* (10), 05019015. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001099

Green, D., O'Donnell, E., Johnson, M., Slater, L., Thorne, C., Zheng, S., Stirling, R., Chan, F. K. S., Li, L. & Boothroyd, R. J. (2021). Green infrastructure: The future of urban flood risk management? *WIREs Water*, *8* (6), e1560. https://doi.org/10.1002/wat2.1560

Guerreiro, S., Glenis, V., Dawson, R. & Kilsby, C. (2017). Pluvial Flooding in European Cities – A Continental Approach to Urban Flood Modelling. *Water*, *9* (4), 296. https://doi.org/10.3390/w9040296

Kravchenko, M., Trach, Y., Trach, R., Tkachenko, T. & Mileikovskyi, V. (2024a). Behaviour and Peculiarities of Oil Hydrocarbon Removal from Rain Garden Structures. *Water*, *16* (13), 1802. https://doi.org/10.3390/w16131802

Kravchenko, M., Trach, Y., Trach, R., Tkachenko, T. & Mileikovskyi, V. (2024b). Improving the Efficiency and Environmental Friendliness of Urban Stormwater Management by Enhancing the Water Filtration Model in Rain Gardens. *Water*, *16* (10), 1316. https://doi.org/10.3390/w16101316

Li, J. Q., Xiang, L. L., Che, W. & Ge, R. L. (2008). Design and Hydrologic Estimation Method of Multi-Purpose Rain Garden: Beijing Case Study. *In Low Impact Development for Urban Ecosystem and Habitat Protection* (pp. 1–10). https://doi.org/10.1061/41009(333)67

Morash, J., Wright, A., LeBleu, C., Meder, A., Kessler, R., Brantley, E. & Howe, J. (2019). Increasing Sustainability of Residential Areas Using Rain Gardens to Improve Pollutant Capture, Biodiversity and Ecosystem Resilience. *Sustainability*, *11* (12), 3269. https://doi.org/10.3390/su11123269

Osheen & Singh, K. K. (2019). Rain Garden – A Solution to Urban Flooding: A Review. In A. K. Agnihotri, K. Reddy & A. Bansal (Eds), *Sustainable Engineering* (Vol. 30, pp. 27–35). Singapore: Springer. https://doi.org/10.1007/978-981-13-6717-5_4

Qi, Y., Chan, F. K. S., Thorne, C., O'Donnell, E., Quagliolo, C., Comino, E., Pezzoli, A., Li, L., Griffiths, J., Sang, Y. & Feng, M. (2020). Addressing Challenges of Urban Water Management in Chinese Sponge Cities via Nature-Based Solutions. *Water*, *12* (10), 2788. https://doi.org/10.3390/w12102788

Rezaei, A. R., Ismail, Z., Niksokhan, M. H., Dayarian, M. A., Ramli, A. H. & Shirazi, S. M. (2019). A Quantity–Quality Model to Assess the Effects of Source Control Stormwater Management on Hydrology and Water Quality at the Catchment Scale. *Water*, *11* (7), 1415. https://doi.org/10.3390/w11071415

Shafique, M. (2016). A review of the bioretention system for sustainable storm water management in urban areas. *Materials and Geoenvironment*, *63* (4), 227–236. https://doi.org/10.1515/rmzmag-2016-0020

Shafique, M. & Kim, R. (2017). Retrofitting the Low Impact Development Practices into Developed Urban areas Including Barriers and Potential Solution. *Open Geosciences*, *9* (1). https://doi.org/10.1515/geo-2017-0020

Sharma, R. & Malaviya, P. (2021). Management of stormwater pollution using green infrastructure: The role of rain gardens. *WIREs Water*, *8* (2), e1507. https://doi.org/10.1002/wat2.1507

Shuster, W., Darner, R., Schifman, L. & Herrmann, D. (2017). Factors Contributing to the Hydrologic Effectiveness of a Rain Garden Network (Cincinnati OH USA). *Infrastructures*, *2*(3), 11. https://doi.org/10.3390/infrastructures2030011

Trach, Y. (2020). Perspective method for removing heavy metals from underground waters of Western Ukraine. *Acta Scientiarum Polonorum. Architectura*, *19* (1), 85–92.

Tsentralna Heofizychna Observatoriya Imeni Borysa Sreznevskoho [Boris Sresnevsky Central Geophysical Observatory] website (2024). Available at http://cgo-sreznevskyi.kyiv.ua/uk

Wang, X., Zhang, J., Babovic, V. & Gin, K. Y. H. (2019). A comprehensive integrated catchment-scale monitoring and modelling approach for facilitating management of water quality. *Environmental Modelling & Software*, *120*, 104489. https://doi.org/10.1016/j.envsoft.2019.07.014

Wanitchayapaisit, C., Suppakittpaisarn, P., Charoenlertthanakit, N., Surinseng, V., Yaipimol, E. & Rinchumphu, D. (2022). Rain garden design for stormwater management in Chiang Mai, Thailand: A Research-through-Design Study. *Nakhara: Journal of Environmental Design and Planning*, *21* (3), 222. https://doi.org/10.54028/NJ202221222

Ying, J., Zhang, X., Zhang, Y. & Bilan, S. (2022). Green infrastructure: Systematic literature review. *Economic Research – Ekonomska Istraživanja*, *35* (1), 343–366. https://doi.org/10.1080/1331677X.2021.1893202

Zaręba, A., Krzemińska, A., Adynkiewicz-Piragas, M., Widawski, K., Van Der Horst, D., Grijalva, F. & Monreal, R. (2022). Water Oriented City – A '5 Scales' System of Blue and Green Infrastructure in Sponge Cities Supporting the Retention of the Urban Fabric. *Water*, *14* (24), 4070. https://doi.org/10.3390/w14244070

Zhang, L., Lu, Q., Ding, Y., Peng, P. & Yao, Y. (2018). Design and Performance Simulation of Road Bioretention Media for Sponge Cities. *Journal of Performance of Constructed Facilities*, *32* (5), 04018061. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001209

Zhang, L., Ye, Z. & Shibata, S. (2020a). Assessment of Rain Garden Effects for the Management of Urban Storm Runoff in Japan. *Sustainability*, *12* (23), 9982. https://doi.org/10.3390/su12239982

Zhang, Y., Zhao, W., Chen, X., Jun, C., Hao, J., Tang, X. & Zhai, J. (2020b). Assessment on the Effectiveness of Urban Stormwater Management. *Water*, *13* (1), 4. https://doi.org/10.3390/w13010004

ILOŚCIOWA OCENA EFEKTYWNOŚCI HYDROLOGICZNEJ PROJEKTU OGRODU DESZCZOWEGO W KONTEKŚCIE ZARZĄDZANIA OBJĘTOŚCIĄ I JAKOŚCIĄ ŚCIEKÓW DESZCZOWYCH

STRESZCZENIE

Ogrody deszczowe są popularnym elementem zielonej infrastruktury, często integrowanym z koncepcją miasta-gąbki w celu rozwiązania problemów związanych z zarządzaniem wodami opadowymi. Takie konstrukcje spełniają trzy główne funkcje: zmniejszają objętość spływu wody z obszaru zlewni, zmniejszają przepływy szczytowe w systemie odwodnienia (co jest krytyczne dla zapobiegania przeciążeniu sieci kanalizacyjnej) oraz poprawiają jakość wody (co przyczynia się do zachowania wód gruntowych). Projektowanie ogrodów deszczowych polega na spełnieniu konkretnych wymaganiach i uwzględnieniu cech, które determinują ich konstrukcję i metody obliczeniowe w celu uzyskania optymalnych parametrów takich jak powierzchnia i głębokość. Analiza scjentometryczna pokazuje, że znaczący wkład badawczy wnoszą różne kraje, ale większość istniejących systemów ogrodów deszczowych polega na ogólnych zaleceniach, co może prowadzić do problemów w działaniu. Celem pracy jest opracowanie modelu obliczania głównych parametrów ogrodów deszczowych i metod oceny ich wydajności hydrologicznej w celu poprawy wdrażania tych systemów w środowisku miejskim. Przedstawiono model numeryczny do obliczania efektywnej powierzchni ogrodu deszczowego, który uwzględnia jedno zdarzenie deszczowe i wyklucza przelew. Zaproponowano metody oceny trzech kluczowych funkcji ogrodów deszczowych w kontekście zarządzania wodami opadowymi: metodę określania redukcji odpływu powierzchniowego, metodę szacowania rocznej redukcji odpływu powierzchniowego, metodę redukcji szczytowego odpływu powierzchniowego oraz metodę szacowania całkowitej redukcji zanieczyszczeń.

Słowa kluczowe: ogród deszczowy, odwodnienia burzowe, zarządzanie wodami opadowymi, modelowanie, parametry ogrodu deszczowego