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Analysis of alternative approaches to stormwater management and prospects for their implementation in Ukraine

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Abstract. Due to aging infrastructure, frequent wastewater network overflows, and potential charges for stormwater disposal, there is a need to find alternative approaches to stormwater management. Rain gardens and rainwater harvesting systems are widely used in local areas such as private homes, small businesses, and parking lots. Therefore, the aim of this study was to conduct an economic analysis of two alternative solutions – a storage tank with water reuse and a rain garden. The cost-benefit analysis was based on an evaluation of the effectiveness of each approach in reducing stormwater runoff volume and decreasing stormwater disposal fees in the wastewater network. The precipitation regime used for the calculations was selected based on data from 2014 to 2023 for the Kyiv. In the study, technical and economic aspects were considered as key factors in the decision-making process. The results of the economic sustainability analysis of both options using an example of an impermeable surface showed that both systems have an effective service life of approximately two years. The storage tank is an effective solution, reducing stormwater overflows and allowing the collected water to be reused for various purposes. However, the costs of construction and maintenance of the tank exceed the savings on stormwater disposal fees to the sewer system by almost twice, therefore the project is not economically viable in the initial period. The implementation of a rain garden design to reduce stormwater disposal fees to the wastewater network is the most cost-effective solution. Assuming that the effective use period of a rain garden design is 8-10 years, the accumulated savings on tariffs can range from €606.8 to €848.2. The introduction of financial incentives will help promote the implementation of alternative stormwater control solutions, leading to a range of environmental and economic benefits, such as reducing the impact of stormwater on the environment, protecting water resources, and potential savings in the construction and management of stormwater systems

Keywords: green infrastructure; rain garden; water storage tank; cost analysis; economic impact

Introduction

Stormwater management in the context of sustainable development is becoming a serious problem in developed cities. The modification of the Earth's surface associated with urbanisation includes the reduction of vegetation cover and

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the replacement of permeable areas with impermeable surfaces, leading to the disruption of the natural hydrological cycle of surface runoff, increases the volume of stormwater runoff, and increases the speed of peak flows. The Intergovernmental Panel on Climate Change has reported that the number of intensive precipitation events has increased significantly in many countries around the world (Climate change indicators…, 2024). As noted by K. Puczko & E. Jekatierynczuk-Rudczyk (2020), climate indicators for recent decades show a generalised statistical increase in the maximum amount of precipitation in many cities, including cities in Ukraine (Khokhlov *et al*., 2022). Traditional approaches based on the principles of "gray" infrastructure are criticised for their inefficiency, especially in cases of extreme meteorological situations, which according to X.-J. Qiao *et al.* (2018) are associated with outdated equipment and financial and budgetary constraints.

Different countries use a combination of different financing instruments. Stormwater sewer usage fees are considered to be the most effective and environmentally sustainable, as they allow for long-term planning and informed decision-making due to their high political visibility. In the USA, the Water Quality Act (1987) mandates the implementation of a comprehensive stormwater management programme through the introduction of fees. F.A. Tasca *et al*. (2018) note that other countries, such as Canada, the United Kingdom, and Australia, have similarly introduced stormwater fees. In European countries, mandatory fees for stormwater runoff into the general wastewater network have been introduced for many years for all categories of consumers. In most German cities, this payment is determined based on the area of the impermeable surface. In Hamburg, for example, the fee is calculated based on the total costs associated with impermeable areas connected to the public sewer system and amounts to €0.73/m^2 of impermeable surface, as noted by W. Dickhaut & M. Richter (2020). In Italy, there is currently no specific stormwater management fee. The cost of water services is covered by the integrated water tariff, which is paid to local organisations responsible for all types of water supply work – from water delivery to collection and purification – based on the registered volume of water consumption. In the Lithuanian city of Klaipeda, private homeowners are required to pay almost €1/m^3 of rainwater if precipitation from their property enters the general sewerage system (WaterTime, n.d.).

According to J. Boguniewicz-Zabłocka & A.G. Capodaglio (2020), the stormwater fee in Poland is included in the price of water supply services and requires payment for the discharge of rainwater or meltwater in order to encourage users to manage water resources rationally. The fee consists of a fixed and a variable component. The fixed part (subscription) is determined based on the maximum allowable discharge of rainwater, specified in the water permit. The base fee is 0.75 PLN/m^3 (approximately €0.17) per year, but can be significantly reduced if water retention systems with a capacity of more than 30% of the annual runoff are installed on the property. In areas with combined sewer systems, the fee includes the costs of wastewater collection. In areas with separate sewer systems, the fee is determined based on the volume of collected runoff or the area of the impermeable surface. In the latter case, the fee can range from 0.31 to 7.06 PLN/m^2 (approximately €0.07 to €1.63/m^2).

European integration and the implementation of priority directions of Ukraine's water protection policy require the introduction of alternative approaches to the stormwater management system as a modern mechanism for protection, rational use, and restoration of water resources under conditions of significant anthropogenic impact. The first attempts to introduce the European practice of paying for rainwater drainage to the municipal sewerage system in Ukraine were provided for in the initial version of the Order of the Ministry of Housing and Communal Services of Ukraine No. 190 "On Approval of the Rules for the Use of Centralised Communal Water Supply and Sewerage Systems in Settlements of Ukraine" (2008). As of 2024, only private entrepreneurs and legal entities pay for rainwater drainage. For instance, for the drainage of stormwater in March 2024, entrepreneurs in Kalush had to pay 98 UAH for a small store with an area of 130 m^2, 270 UAH for a shopping centre with an area of 360 m^2, and 1,600 UAH for a large warehouse with an area of 2,200 m^2 (In Kalush…, 2024).

Due to the lack of distinction between drinking and domestic water in the Ukrainian water supply system, this leads to the inefficient use of drinking water. The implementation of alternative approaches to stormwater management has an indirect economic impact on water conservation scenarios. According to the principles of "green" infrastructure and similar practices, rainwater should be retained as much as possible at or near the place of precipitation. As I. Nowogoński (2021) argues, this can be achieved through surface or underground retention, as well as infiltration processes into the soil. This article considered two simulation studies on stormwater management in the context of sustainable development: rainwater harvesting in on-site tanks with subsequent reuse; the implementation of rain garden designs to reduce stormwater volume. The aim of the study was to analyse these two approaches and evaluate their effectiveness based on two factors: reducing stormwater runoff volume and reducing sewage discharge fees into the wastewater network.

Materials and Methods

To study the precipitation pattern in a specific area, it is necessary to have up-to-date data on their amount for at least the last 10 years. Studying the precipitation regime is a key factor in confirming that a water collection system can be an alternative method of improving stormwater management. Thus, the average monthly precipitation data in Kyiv for the period from 2014 to 2023 were obtained from the Borys Sreznevsky Central Geophysical Observatory (Table 1).

Table 1. Average monthly precipitation in Kyiv from January 2014 to December 2023

Characteristics	Period	Months												Year
		1	2	3	4	5	6	7	8	9	10	11	12	
Average monthly precipitation, mm	2014-2023	37	40	43	47	65	77	68	56	59	45	46	47	**630**

Source: created by the authors based on Climate data for Kyiv (2024)

Analysis of precipitation data for the past 10 years in Kyiv (Fig. 1) shows that most of the precipitation occurs from May to September, with a total of 325 mm. The peak precipitation occurs in June when the average amount is 77 mm, and the least precipitation is observed in January, with a monthly indicator of 37 mm. From October to April, approximately 305 mm of precipitation falls. The total annual average precipitation is about 630 mm. The design of a soil retention system is based on an assessment of the volume of rainwater and meltwater that is generated on the site. For small solutions (e.g., single-family homes, commercial construction, small businesses), as in the case of the examples considered in this work, complex dynamic flow calculations are not required, unlike situations involving large-area watersheds (Liu *et al.*, 2020). The potential volume of stormwater runoff is estimated based on the total catchment area, the average annual precipitation, and the runoff coefficient and can be determined using the equation:

$$Q = P \times A \times \psi, \quad (1)$$

where Q is the annual volume of stormwater runoff, m^3; P is the average annual precipitation, mm/year; A is the area of the watershed surface (roof, parking lot), m^2; ψ is the runoff coefficient (dimensionless). The ψ values used in this study are 0.8 for a tiled roof and 0.85 for an asphalt concrete parking lot. Average values of ψ for other roof materials and surface types can be found in Table 2.

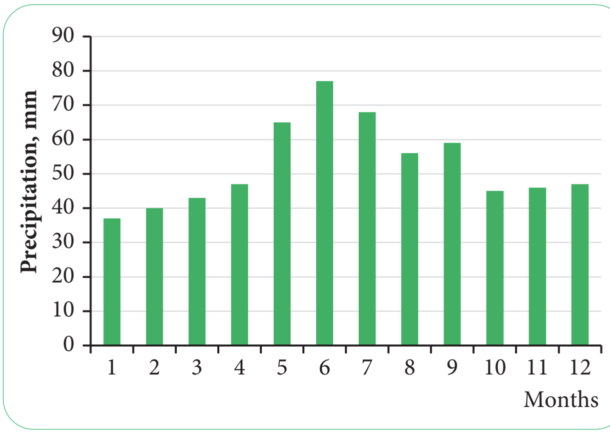

Figure 1. 10-year average monthly precipitation in Kyiv

Source: created by the authors based on Climate data for Kyiv (2024)

Table 2. Average values of the ψ for different coatings

Surface type	ψ
Roof covering:	
◉ galvanised iron	> 0.9
◉ tiles	0.6-0.9
◉ asbestos	0.8-0.9
◉ organic materials	0.2
Asphalt concrete road surfaces	0.85
Paving	0.60
Cobblestone paving	0.45
Macadam pavement not treated with binders	0.40
City blocks without pavement, small squares, boulevards	0.2-0.3
Lawns	0.10
Blocks with modern buildings	0.4-0.5
Midsized cities	0.4-0.5
Small towns and villages	0.3-0.4

Source: created by the authors based on DSTU 8691:2016 (2016), K.K. Kuok & P.C. Chiu (2020)

In most cases, to determine the size of a rainwater harvesting tank, an approach based on consumer demand for alternative water supply is used (Abdulla, 2020). This method depends on the water demand for a specific building object. The tank volume is determined as the total water demand for this object over a certain period of time (for example, during the dry season). The study discusses the volume of stormwater discharged into the wastewater network with corresponding payment rates. Therefore, to determine the size of the rainwater harvesting tank, it is advisable to take into account the maximum intensity of the precipitation event in recent years, which is repeated with a certain periodicity. The maximum precipitation rate can be calculated using the following formula for 15-minute events and areas with annual precipitation $P < 800$ mm (Boguniewicz-Zabłocka & Capodaglio, 2020):

$$q = \left(6{,}631 \times \sqrt[3]{P^2 \times C}\right)/t^{2/3}, \quad (2)$$

where C is the recurrence interval of the rain event lasting for duration t and intensity q, years; P is the average annual precipitation, mm. The volume of the storage tank is calculated by the formula:

$$VR = 0.06 \times (q_{max}(t) - q_{out}) \times t_d \times f_a \times f_z \times F_{zr}, \quad (3)$$

where VR is the volume of the storage tank, m^3; $q_{max}(t)$ is the maximum precipitation intensity, dm^3/ha, for a certain duration t_d, min; q_{out} is the amount of water that can leave the tank when overflowing, dm^3/ha; f_a is reduction coefficient, typically equal to or less than 1, and depends on the time it takes for water to pass through the system and the frequency of precipitation; f_z is a coefficient that takes into account the possibility of exceeding the water storage volume (1.1-1.2); F_{zr} is the area from which water enters the collection system, ha. The amount of the fee for centralised wastewater disposal within the discharge requirements (P_{vc}) is calculated using the formula:

$$P_{vc} = T \times Q_d, \quad (4)$$

where T is the tariff established for providing centralised wastewater disposal services to consumers within the respective category, UAH/m^{-3}; Q_d is the volume of wastewater discharged by the consumer within the limits specified by the contract, m^{-3}. To calculate and select the optimal dimensions for the rain garden design, a universal hydrological model developed by M. Kravchenko *et al.* (2024a) was used. This model is based on Darcy's law, which allows describing dynamic processes within the system at a specific moment in time using equation:

$$y_i(\tau) = \frac{A_{bassin}}{A_{sponge}} \times \left(\int_0^\tau v_r \times d\tau\right) - \\ - \frac{\sum_{j=1}^{m-1}(w_{sat,j} \times \delta_j)}{w_{sat,m}} + \sum_{i=1}^{m-1}\delta_j, \quad (5)$$

where $y_i(\tau)$ is the level of rainwater infiltration and saturation of the rain garden design at the current time step τ; A_{bassin} is the area of the watershed basin, m^2; A_{sponge} is the area of the rain garden, as a sponge tool, m^2; v_r is the average rate of rainfall onto the surface of the rain garden design, m/s, over time $d\tau$; w_{sat} is the water holding capacity of the rain garden soil media, m^3/m^3; δ_j is the thickness of the rain garden soil layers, m; i, j, m are the layers of the rain garden design, starting from the first ($j = 1$) and ending with the layer ($m - 1$), in which saturation occurs at a specific moment in time. The number of these layers can vary from 1 to i. The developed hydrological model was implemented in the Scilab software.

Results and Discussion

Many systems for rainwater harvesting have been proposed over the past few decades. In most cases, the main task of the design solution is to evaluate the tank capacity in accordance with the required level of system performance. There is a considerable amount of scientific research dedicated to the methodology for evaluating the effectiveness and determining the size of rainwater harvesting systems. According to M.G. Di Chiano *et al.* (2023), the capacity of the tanks cannot be standardised, since it significantly depends on various variables characteristic of a particular geographic region, such as local rainfall, the area of the catchment basin (roof, parking lot, etc.), drinking water needs, and the number of people in the household.

Example 1. Collecting rainwater in a storage tank and then reusing it. For the first considered case, it should be assumed that the total area of impermeable surfaces on the property of a private house or enterprise is 700 m^2, of which the roof area is 400 m^2 and the parking lot area is 300 m^2. Next, it should be assumed that initially stormwater from the site was discharged directly into the wastewater network. In addition to environmental considerations, one of the main factors that motivates the search for alternative stormwater management solutions is the fee for their discharge. Therefore, it must be assumed that during the redevelopment of the territory, the drainage system was redesigned with the introduction of a storage tank to reduce the amount of stormwater entering the sewer system from the property.

According to V. Ovcharuk *et al.* (2020), climate change has led to an increase in the frequency and duration of droughts, as well as a change in the pattern and intensity of precipitation over the past few decades in Ukraine. This highlights the importance of local rainwater storage as a key element in stormwater management. The total average runoff of 201.6 and 160.6 m^3/year, thus, were calculated using equation (1) for the roof and parking area, respectively. Equation (1) correlates with the widely used Polish standard (complies with European standards) PN-EN 75, which suggests a similar formula for calculating the runoff rate for surfaces < 10,000 m^2 (Boguniewicz-Zabłocka & Capodaglio, 2020). Researchers K.K. Kuok & P.C. Chiu (2020) propose using the value of the daily precipitation amount (mm) in the equation. The authors also suggest not collecting the first flush in the tank, which contains dust, bird and animal droppings, leaves and other debris from adjacent areas that have accumulated on the roof surface. Based on the maximum intensity value of 2.8 mm calculated for a 15-minute event using formula (2), the volume of the storage tank was calculated using formula (3). The volume of the storage tank for collecting stormwater from a roof with an area of 400 m^2 was calculated as 24.2 m^3. The volume of the tank for the parking area of 300 m^2 is 19.3 m^3. Excess stormwater during more intense events will be discharged to the sewer system.

Thus, stormwater management can be organised as follows: direct the runoff from the roof to a storage tank with a volume of 24.2 m³, and runoff from the parking area is directed to a tank with a volume of 19.3 m³. According to Ukrainian legislation, when discharging water that flows from the parking area into the sewer system, it is necessary to ensure that the content of petroleum hydrocarbons does not exceed 10 mg/dm³ (Order of the Ministry of Regional Development, Construction, Housing and Communal Services of Ukraine No. 316, 2017). In view of this, a cleaning system can be provided at the inlet to the tank to help reduce the content of harmful substances. One solution could be to install an oil separator, which effectively separates petroleum hydrocarbons from water or to use a sorption filter with activated carbon or other absorbing materials capable of capturing petroleum hydrocarbons. The results of the calculated economic effect of stormwater management in Example 1 are presented in Table 3. The tariff for discharging stormwater into the wastewater network was calculated for the Kyiv using formula (4).

Table 3. The economic impact of stormwater management in Example 1

Costs	Without a drainage system		With a drainage retention system	
	Roof	Parking area	Roof	Parking area
Water reuse from collected wastewater (approximate average), m³/year	0	0	201.6	160.6
Costs of tank construction, €	0	0	3,191	3,191
Maintenance and operation costs, €/year	20		75	
Tariff for wastewater disposal in Kyiv (0.34 €)/m³ × (201.6 + 160.6) m³, €/year	68.5	54.6	0	0
Payment for discharge to the wastewater network, €/year	68.5	54.6	0	0
Total annual costs, €/year	**143.1**		**75**	

Note: *1 € = 42.3 UAH (average as of May 1, 2024); this exchange rate will be used for all subsequent cost indicators presented in the article
Source: created by the authors

Considering that the projected lifespan of a rainwater harvesting tank is 20 years, the savings on water bills in the 20th year will be about €1,362, assuming no tariff fluctuations. Given that the construction costs of the tank exceed the savings on the fee for stormwater discharge into the sewer system by almost half, the project is not economically viable in the initial period. The advantages of such a system are the possibility of using stormwater accumulated in the tank for local non-potable reuse and meeting domestic needs, such as watering green spaces, washing surfaces or cars, flushing toilets, cleaning premises, etc. In addition, the volume of the tank may be sufficient for the irrigation of a green area of about 1,000 m², especially during dry seasons.

Overall, such a stormwater harvesting system is capable of: reducing and delaying runoff into the sewer system, retaining rainwater on-site, ensuring water infiltration into the soil, increasing evaporation from biologically active surfaces, reusing residual water for local needs, and lowering water bills. It can also optimise the operation of stormwater sewers, reducing the risk of flooding of neighbouring areas and pollution of receiving waters. The disadvantages of such a system, in addition to the high cost, include the need for periodic cleaning of the tanks from debris. It is recommended to use the water accumulated in the tank within a month to avoid microbiological contamination and reduce the risk of the proliferation of bacteria, fungi, and other microorganisms that can occur during long-term storage of water without proper treatment or circulation.

Example 2. Rain garden design. A rain garden is a type of "green" structure that is installed along the roadway, near residential buildings, gas stations, parking areas and is designed for infiltration of runoff, temporary retention, and preliminary purification of rainwater. They consist of perennial plants that accumulate and return rainwater to the ecosystem thanks to a special drainage system (Kravchenko *et al.*, 2024b). A rain garden is created in a shallow depression in the terrain, where it receives rainwater, for example, from the roof using gutters and downspouts. Immediately after precipitation, water can temporarily flood the surface of the garden, but for most of the year, it remains dry and functions as an ordinary garden without additional irrigation. The design of a rain garden consists of several layers, using soil materials with high hydraulic permeability and porosity. These materials ensure rapid water penetration into the recessed drainage pipes, which can be connected to the stormwater sewer system or the underlying aquifer. This helps to effectively manage stormwater, reducing the risk of flooding and promoting natural water infiltration into the ground. The design of a rain garden consists of three main layers: a soil layer for planting vegetation; a transition layer or infiltration layer; a gravel layer for temporary water retention (Kravchenko *et al.*, 2024b). The correct choice of soil and vegetation can perform not only water storage functions but also pollutant removal functions. A rain garden is specially designed to collect wastewater from roofs and asphalt surfaces, temporarily store it, and infiltrate it into underground drainage pipes.

The construction of a rain garden begins with digging a trench 1.3 m deep, the bottom of which is filled with a 30 cm layer of gravel (fraction 2-8 mm). A perforated drainage pipe (90 mm in diameter) wrapped in geotextile is laid on this layer. A vertical overflow pipe (also 90 mm in diameter), connected to the drainage system, protrudes about 10 cm above the decorative surface of the garden, ensuring rapid infiltration in case of high-intensity rainfall events. The space above the drainage gravel layer is filled with a medium-grained sand mixture, which serves as the basis for the intermediate infiltration layer. According to the results of further modelling, the depth of the infiltration layer is 60 cm. The top layer for planting plants, 40 cm thick, consists of a fertile soil mixture, which is selected according to the physicochemical composition of the corresponding type of vegetation. The drainage pipe is connected to the general stormwater sewer system to avoid overflow and local flooding in case of extreme events. Plants for the construction of rain gardens are selected depending on their functional purpose. For example, as R. Dudrick *et al.* (2024) state, shrubs, bushes and trees contribute to the improvement of the hydrological process through transpiration and improve the ability of the soil to accumulate water, especially in combination with herbaceous plant species.

The optimal area of a rain garden design is considered to be 4-7% of the area from which runoff will be collected (watershed area) (Rinchumphu *et al.*, 2023). Similar recommendations are proposed in Rain garden (n.d.), according to which the rain garden structure should be from 5 to 10% of the watershed area. The initial simulation data on the area of the watershed surface and the amount of precipitation remain the same as in Example 1. The recommendations indicate that the corresponding required area of the garden should be at least 4% of the effective watershed area. The total watershed area is 700 m^2, of which the roof area is 400 m^2 and the parking area is 300 m^2. Based on the characteristics of the site, the total calculated area should be at least 16 m^2 for the roof and 12 m^2 for the parking area. Rain garden designs, each with an area of 8 m^2, can be placed on opposite corners of the building so that each of them receives runoff from different parts of the roof according to the slope.

To calculate the depth of the layers (top soil, intermediate sandy, and lower gravel) of rain garden designs, using a developed simplified mathematical model taking into account Darcy's law, which allows for analysing the dynamic processes of water passage and saturation of the layers of the rain garden design at a specific moment in time (Kravchenko *et al.*, 2024a; 2024b). The authors implemented the model in the Scilab software based on the simulation of a real rainfall event, during which a record amount of precipitation of 36 mm/h or 36 dm^3/m^2×h was recorded in Kyiv on July 22, 2023, the highest in the last 10 years. Using the developed model and Scilab software with the given values of the water retention capacities of the soil layers of the rain garden (0.33/0.33/0.1 m^3/m^3), the hydrological efficiency of the design was calculated, depending on the change in the ratio of areas (ratio of the watershed area to the area of the rain garden), at which the rain garden design allows for the complete retention of water runoff at a given precipitation intensity (Fig. 2).

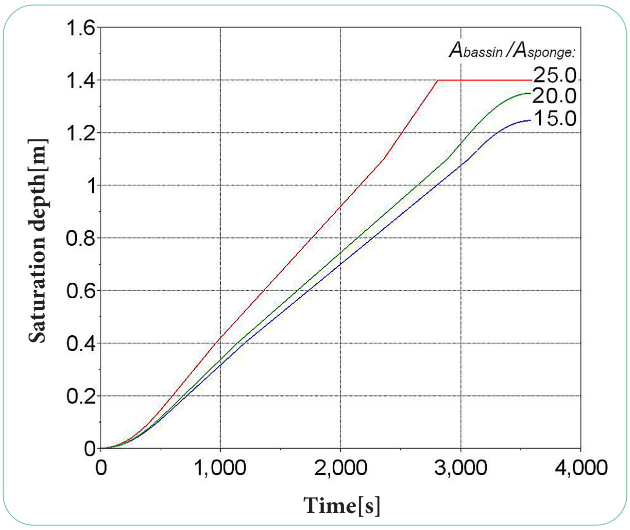

Figure 2. Curves of changes in the depth of saturation of the layers of the rain garden design in time depending on the ratio of A_{bassin}/A_{sponge}

Source: created by the authors

The modelling results showed that with the depth of the layers (0.4/0.6/0.3 m), the full saturation of the rain garden design begins with a threshold value corresponding to an area ratio of 25 for the time $\tau = 2{,}296.16$ s. In other words, if a rain garden design with an area of 16 m^2 and a depth of 1.3 m is arranged at a roof area of 400 m^2, it will allow to retain rainfall of critical intensity (36 mm/h or 576 m^3) avoiding overflow of the design in 38 minutes (2,296.16/60). As can be seen from Figure 2, the rain garden design is fully capable of retaining rainfall with an area ratio of 15 and 20, i.e., with an area of the rain garden of 26 and 20 m^2, respectively, for the roof. For the parking area, which has an area of 300 m^2, the rain garden designs will fully retain rainfall with an area of 20 and 15 m^2, respectively. Since the total average runoff, as in Example 1, is 201.6 and 160.6 m^3/year for the roof and parking area, respectively, the calculated dimensions of the rain garden design for the critical rainfall intensity will allow all rain events throughout the year to be retained without overflow. Before the construction of the rain garden, the cost of discharging stormwater into the sewer system involved a fee of €123.1 per year. According to the data of the authors J. Boguniewicz-Zabłocka & A.G. Capodaglio (2020), the average construction cost of a rain garden is €12.3/m^2 (excluding vegetation). Based on research conducted during the first year of operation, the annual maintenance and operation costs are estimated at approximately €0.5/m^2 per year (Boguniewicz-Zabłocka & Capodaglio, 2020). The economic effect of stormwater management in Example 2 is presented in Table 4.

Table 4. The economic impact of stormwater management in Example 2

Costs	Without a rain garden		With a rain garden	
	Roof	Parking area	Roof	Parking area
Costs for the construction of a rain garden design, €	0	0	196.8	147.6
Maintenance and operation costs, €/year	0		8	6
Payment for discharge to the wastewater network, €/year	68.5	54.6	0	0
Total annual costs, €/year	**123.1**		**14.0**	

Source: created by the authors

The results presented in Table 4 are based on the calculated maximum precipitation volumes and the hydrological efficiency of the rain garden design. Similarly to Example 1, it can be noted that all investments in the construction of a rain garden will be paid off within three years. If assumed that the effective period of use of the project will be 8-10 years (after which some intervention may be needed to restore soil permeability), the accumulated savings on tariffs would be from €606.8 to €848.2. In both presented simulation studies, the advantages of the alternative approach to stormwater management are due to two factors: a reduction in the volume of stormwater runoff and a reduction in discharge fees due to the implementation of mitigation measures. In addition to economic benefits, the implementation of such solutions brings such environmental benefits as the possibility of using water for irrigation (Example 1), which allows for improving the care of green spaces even during prolonged periods of drought. The use of a tank to reduce the load on the storm sewer during heavy rainfall can prevent network overload and local flooding. Stormwater harvesting is a profitable solution despite its high cost. However, as the calculation results show, the rain garden design is more economically viable and effective in stormwater management (Table 5).

Table 5. Comparison of the economic effect of using a rainwater harvesting tank and a rain garden design for the entire area of the impermeable site (roof + parking area)

Costs	With a drainage retention system	With a rain garden design
Water reuse from collected wastewater (approximate average), m³/year	362.2	0
Construction costs, €	3,191	344.4
Maintenance and operation costs, €/year	75	14
Payment for discharge to the wastewater network, €/year	0	0
Total costs, €	**3,266**	**358.4**

Source: created by the authors

According to the analysed results, the implementation of a rain garden design to reduce stormwater discharge fees into the wastewater network is the most acceptable solution in terms of cost. However, when implementing this system in field conditions, it is necessary to take into account the soil conditions on the site, which should be favourable for rapid infiltration. In addition, this solution excludes any further local use of water, unlike the solution with a stormwater harvesting tank. The impact of alternative stormwater management practices cannot be underestimated, even in areas that are traditionally subject to significant rainfall. These practices successfully detain and filter a significant portion of stormwater runoff, reducing pressure on existing sewer systems and mitigating the adverse effects of runoff, such as erosion and pollutant loading. Urbanised areas of Athens, Greece, according to the results of I.M. Kourtis *et al.* (2018) demonstrate a potential reduction in peak flow in the range of 13.4-28.2% and total runoff volume in the range of 24.5-29% after the implementation of "green" infrastructure practices. A modelling study conducted by J. Leimgruber *et al.* (2019) in Graz, Austria, showed that the application of cost-effective stormwater management practices has great potential for reducing and controlling runoff, considering all aspects of the water balance and life cycle costs, including land costs. An analysis of the costs and benefits of stormwater management practices in an urban watershed in Norway conducted by C.-Y. Xu & H. Li (2020) showed that these methods reduce combined sewer overflow, and optimised solutions can be identified using hydrological modelling to maximise efficiency at minimal cost. Although neither of the cited studies conducted a quantitative assessment of the overall impact of alternative practices on stormwater sewer size requirements in urban settings, it can be assumed that their widespread implementation may have long-term benefits in terms of infrastructure design and investment costs.

A key factor in choosing the appropriate alternative stormwater management practice for a specific case is understanding the characteristics and specifics of hydrological conditions, landscape, infrastructure, and the needs of the local population. For example, rain garden design is an ideal solution for small developments (as in Example 2 of the presented research), but not for sites with large drainage areas. The results obtained within the framework of the presented study are consistent with the research conducted by L. Bortolini & G. Zanin (2018). Testing the functionality of rain gardens with three different area ratio values (10, 15, and 20), located on the campus of the University of Padua, Italy, they demonstrated that even in a small rain garden, almost all runoff volumes from the watershed area infiltrate vertically into the soil. Other authors, E. Burszta-Adamiak *et al.* (2023), showed that rain gardens can support the operation of inadequate sewer infrastructure, especially during moderately intense rainfall events.

In terms of rainwater harvesting systems, the most popular option for homeowners is the so-called "rain barrel" (or a small tank with a volume of up to 1 m^3), which does not always provide sufficient water volume, even for small irrigation needs during dry periods, and often overflows during intense rainfall events. Research shows that rain barrels, while having a certain function of demonstration and awareness raising, have little impact on runoff reduction, except in specific cases. Only larger rainwater harvesting systems (tanks), similar to the one described in Example 1 of the presented study, can significantly affect runoff reduction and replace typical household irrigation needs, as confirmed by F. Abdulla (2020). Peak flow volume and rate are important factors that influence flood risk. The use of water harvesting tanks can reduce the peak flow rate during many rainfall events, depending on the tank volume and rainfall characteristics. Case studies conducted in Italy by G. Freni & L. Liuzzo (2019) showed that runoff volume and rate were reduced by 9% to 57.7% due to the use of harvesting tanks with volumes ranging from 139 to 2,040 m^3 for rainfall of 50 mm in one rainfall event. Other authors, M.J. Deitch & S.T. Feirer (2019), found that runoff volume in Florida was reduced by more than 20% due to the installation of an 11.3 m^3 rooftop tank on a residential building.

In some developing countries with high water tariffs, rainwater harvesting systems are considered an inexpensive system that only involves installation and maintenance costs (Pala *et al.*, 2021). In addition, according to the authors J.A. Gleason Espíndola *et al.* (2018), such systems contribute to reducing dependence on the traditional sewer system and reduce water bills by up to 50% per month. An advantage of using rainwater harvesting systems is the possibility of reusing the accumulated water. Studies show that in most developed countries, such systems are implemented primarily for non-potable use. In developing countries, they are also used for potable use, often as a source of drinking water. This difference in use may be related to easy access to traditional water sources, higher average consumer income, and affordable water tariffs in developed countries. Overall, according to D. Słyś & A. Stec (2020), harvested rainwater from tanks can meet most non-potable water needs, such as toilet flushing (approximately 70% to 90%), laundry (50% to 90%), and garden watering (57%). Several studies, including S. Ali *et al.* (2020), have concluded that the cost-effectiveness of rainwater harvesting methods is closely related to local water prices and that such systems are desirable to be installed at the level of new construction districts to be economically efficient. Climatic conditions in Ukraine generally Favor the effective functioning of alternative approaches, as confirmed by the results of simulation studies.

In order for the implementation of such systems to become more relevant and widespread in the future, it is necessary to develop and implement a comprehensive programme that should include a system of measures. Among the mandatory aspects of such a programme are: the development of legislative policy (regulations, codes and standards), regulatory policy (state regulation in the field of stormwater management), incentive policy (creation of research funds, launch of financing schemes), policy of assistance at the state and regional levels (creation of associations, organisations and institutions for the study of alternative systems, provision of professional training, promotion of public awareness) and information policy (providing a platform for knowledge exchange, organising conferences of various levels, seminars, competitions, etc.). The formation of general public opinion through the use of the media, conducting surveys and excursions to study the latest alternative approaches, practices and methods are also of great importance.

Conclusions

As of 2024, the scale of implementation of alternative approaches in Ukraine is quite small, which makes the issue of sustainable stormwater management extremely relevant. One of the popular, effective and relatively simple solutions is the use of small retention or infiltration structures for individual building sites, which contributes to the increase in the use and infiltration of rainwater. As shown in this research, the implementation of such alternative approaches into practice can have significant environmental and financial benefits for property owners and local water supply and sanitation organisations. The effectiveness of such measures is largely dependent on whether there are tariff incentives. However, such solutions as rainwater harvesting tanks with the possibility of reuse can reduce costs for owners of private residential houses, small businesses and other individual water users for water purchase, as well as contribute to the conservation of water resources.

Alternative stormwater management methods are aimed at reducing the load or partially replacing traditional sewer systems. For example, rain garden designs represent an economically efficient and sustainable approach that has advantages within the framework of the sustainable development concept. However, their financial viability is limited by the lack of water reuse opportunities, as rainwater infiltrates into the drainage system without being stored. Storing (harvesting) rainwater on-site for later use can save on water supply costs, making such solutions attractive to individual users even in the short term. According to the results of the economic analysis, the implementation of rain garden designs to reduce the fee for discharging stormwater into the wastewater network is the most economically beneficial solution. According to the calculations, the total construction cost of a reservoir is €3,191, and a rain garden is €344.4. The savings on water bills over 20 years of operation of a rainwater harvesting tank will be around €1,362, assuming stable tariffs. The implementation of a rain garden design will allow savings from €606.8 to €848.2 in just 8-10 years of operation. For further research, it is important to evaluate and address additional aspects of the implementation of rainwater harvesting systems and rain garden designs that will contribute to the sustainability of water supply and wastewater disposal. In particular, it is necessary to investigate the duration of stormwater flow in distribution systems and possible water quality problems that may arise as a result.

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Conflict of Interest

None.

References

[1] Abdulla, F. (2020). Rainwater harvesting in Jordan: Potential water saving, optimal tank sizing and economic analysis. *Urban Water Journal*, 17(5), 446-456. doi: 10.1080/1573062X.2019.1648530.

[2] Ali, S., Zhang, S., & Yue, T. (2020). Environmental and economic assessment of rainwater harvesting systems under five climatic conditions of Pakistan. *Journal of Cleaner Production*, 259, article number 120829. doi: 10.1016/j.jclepro.2020.120829.

[3] Boguniewicz-Zabłocka, J., & Capodaglio, A.G. (2020). Analysis of alternatives for sustainable stormwater management in small developments of Polish urban catchments. *Sustainability*, 12(23), article number 10189. doi: 10.3390/su122310189.

[4] Bortolini, L., & Zanin, G. (2018). Hydrological behaviour of rain gardens and plant suitability: A study in the Veneto plain (north-eastern Italy) conditions. *Urban Forestry & Urban Greening*, 34, 121-133. doi: 10.1016/j.ufug.2018.06.007.

[5] Burszta-Adamiak, E., Biniak-Pieróg, M., Dąbek, P.B., & Sternik, A. (2023). Rain garden hydrological performance – responses to real rainfall events. *Science of The Total Environment*, 887, article number 164153. doi: 10.1016/j.scitotenv.2023.164153.

[6] Climate change indicators reached record levels in 2023: WMO. (2024). Retrieved from https://wmo.int/media/news/climate-change-indicators-reached-record-levels-2023-wmo.

[7] Climate data for Kyiv. (2024). Retrieved from http://cgo-sreznevskyi.kyiv.ua/uk/diialnist/klimatolohichna/klimatychni-dani-po-kyievu.

[8] Deitch, M.J., & Feirer, S.T. (2019). Cumulative impacts of residential rainwater harvesting on stormwater discharge through a peri-urban drainage network. *Journal of Environmental Management*, 243, 127-136. doi: 10.1016/j.jenvman.2019.05.018.

[9] Di Chiano, M.G., Marchioni, M., Raimondi, A., Sanfilippo, U., & Becciu, G. (2023). Probabilistic approach to tank design in rainwater harvesting systems. *Hydrology*, 10(3), article number 59. doi: 10.3390/hydrology10030059.

[10] Dickhaut, W., & Richter, M. (2020). Decentralized stormwater management: Experiences with various measures in Germany. In F. Wang & M. Prominski (Eds.), *Water-related urbanization and locality* (pp. 167-179). Singapore: Springer. doi: 10.1007/978-981-15-3507-9_9.

[11] DSTU 8691:2016. (2016). *Wastewater. Guidelines for the establishment of technological standards for the discharge of rainwater into water bodies*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=67545.

[12] Dudrick, R., Hoffman, M., Antoine, J., Austin, K., Bedoya, L., Clark, S., Dean, H., Medina, A., & Gotsch, S.G. (2024). Do plants matter? Determining what drives variation in urban rain garden performance. *Ecological Engineering*, 201, article number 107208. doi: 10.1016/j.ecoleng.2024.107208.

[13] Freni, G., & Liuzzo, L. (2019). Effectiveness of rainwater harvesting systems for flood reduction in residential urban areas. *Water*, 11(7), article number 1389. doi: 10.3390/w11071389.

[14] Gleason Espíndola, J.A., Cordova, F., & Casiano Flores, C. (2018). The importance of urban rainwater harvesting in circular economy: The case of Guadalajara City. *Management Research Review*, 41(5), 533-553. doi: 10.1108/MRR-02-2018-0064.

[15] In Kalush, they demand not to approve the "rain fee". (2024). Retrieved from https://vikna.if.ua/news/category/articles/2024/04/04/152301/view.

[16] Khokhlov, V.M., & Zamfirova, M.S. (2022). Precipitation regime projections for the territory of Ukraine in the next thirty years. *Hydrology, Hydrochemistry and Hydroecology*, 1(63), 54-60. doi: 10.17721/2306-5680.2022.1.5.

[17] Kourtis, I.M., Tsihrintzis, V.A., & Baltas, E. (2018). Simulation of low impact development (LID) practices and comparison with conventional drainage solutions. *Proceedings*, 2(11), article number 640. doi: 10.3390/proceedings2110640.

[18] Kravchenko, M., Trach, Y., Trach, R., Tkachenko, T., & Mileikovskyi, V. (2024a). Improving the efficiency and environmental friendliness of urban stormwater management by enhancing the water filtration model in rain gardens. *Water*, 16(10), article number 1316. doi: 10.3390/w16101316.
[19] Kravchenko, M.V., Tkachenko, T.M., & Mileikovskyi, V.O. (2024b). Study of the influence of the main parameters of the rain garden on its hydrological parameters by modeling. *Collection of Scientific Papers of Admiral Makarov National University of Shipbuilding*, 1(494), 166-176. doi: 10.15589/znp2024.1(494).23.
[20] Kuok, K.K., & Chiu, P.C. (2020). Optimal rainwater harvesting tank sizing for different types of residential houses: Pilot study in Kuching, Sarawak. *Journal of Engineering Science and Technology*, 15(1), 541-554.
[21] Leimgruber, J., Krebs, G., Camhy, D., & Muschalla, D. (2019). Model-based selection of cost-effective low impact development strategies to control water balance. *Sustainability*, 11(8), article number 2440. doi: 10.3390/su11082440.
[22] Liu, W., Feng, Q., Deo, R.C., Yao, L., & Wei, W. (2020). Experimental study on the rainfall-runoff responses of typical urban surfaces and two green infrastructures using scale-based models. *Environmental Management*, 66, 683-693. doi: 10.1007/s00267-020-01339-9.
[23] Nowogoński, I. (2021). Runoff volume reduction using green infrastructure. *Land*, 10(3), article number 297. doi: 10.3390/land10030297.
[24] Order of the Ministry of Housing and Communal Services of Ukraine No. 190 "On Approval of the Rules for the Use of Centralised Communal Water Supply and Sewerage Systems in Settlements of Ukraine". (2008, June). Retrieved from https://zakon.rada.gov.ua/laws/show/z0936-08#Text.
[25] Order of the Ministry of Regional Development, Construction, Housing and Communal Services of Ukraine No. 316 "On Approval of the Rules for Acceptance of Wastewater to Centralised Sewage Systems and the Procedure for Determining the Amount of Fee Charged for Excessive Wastewater Discharges to Centralised Sewage Systems". (2017, December). Retrieved from https://zakon.rada.gov.ua/laws/show/z0056-18#Text.
[26] Ovcharuk, V., Gopchenko, E., Kichuk, N., Shakirzanova, Z., Kushchenko, L., & Myroschnichenko, M. (2020). Extreme hydrological phenomena in the forest steppe and steppe zones of Ukraine under the climate change. *Proceedings of the International Association of Hydrological Sciences*, 383, 229-235. doi: 10.5194/piahs-383-229-2020.
[27] Pala, G.K., Pathivada, A.P., Velugoti, S.J.H., Yerramsetti, C., & Veeranki, S. (2021). Rainwater harvesting – a review on conservation, creation & cost-effectiveness. *Materials Today: Proceedings*, 45(7), 6567-6571. doi: 10.1016/j.matpr.2020.11.593.
[28] Puczko, K., & Jekatierynczuk-Rudczyk, E. (2020). Extreme hydro-meteorological events influence to water quality of small rivers in urban area: A case study in northeast Poland. *Scientific Reports*, 10, article number 10255. doi: 10.1038/s41598-020-67190-4.
[29] Qiao, X.-J., Kristoffersson, A., & Randrup, T.B. (2018). Challenges to implementing urban sustainable stormwater management from a governance perspective: A literature review. *Journal of Cleaner Production*, 196, 943-952. doi: 10.1016/j.jclepro.2018.06.049.
[30] Rain gardens. (n.d.). Retrieved from https://www.susdrain.org/delivering-suds/using-suds/suds-components/infiltration/rain-gardens.html.
[31] Rinchumphu, D., Suriyanon, N., Phichetkunbodee, N., Munlikawong, S., Wanitchayapaisit, C., & Sitthikankun, S. (2023). Economics and cost effectiveness of a rain garden for flood-resistant urban design. *Global Journal of Environmental Science and Management*, 10(1), 1-12. doi: 10.22034/gjesm.2024.01.01.
[32] Słyś, D., & Stec, A. (2020). Centralized or decentralized rainwater harvesting systems: A case study. *Resources*, 9(1), article number 5. doi: 10.3390/resources9010005.
[33] Tasca, F.A., Assunção, L.B., & Finotti, A.R. (2018). International experiences in stormwater fee. *Water Science and Technology*, 2017(1), 287-299. doi: 10.2166/wst.2018.112.
[34] Water Quality Act. (1987, April). Retrieved from https://www.congress.gov/bill/100th-congress/house-bill/1/text.
[35] WaterTime. (n.d.). Retrieved from https://blogs.gre.ac.uk/psiru/watertime/.
[36] Xu, C.-Y., & Li, H. (2020). Cost and benefit analysis of low impact development (LID) for stormwater management in an urban catchment in Norway. *EGU General Assembly*, 2020, article number EGU2020-21881. doi: 10.5194/egusphere-egu2020-21881.

Аналіз альтернативних підходів до управління зливовими водами та перспективи їх впровадження в Україні

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Анотація. У зв’язку зі застарілою інфраструктурою, частими переливами каналізаційної мережі та можливою платою за скидання дощових вод, існує потреба в пошуку альтернативних підходів до управління зливовими водами. Конструкції дощових садів та системи збору дощової води широко використовуються на таких локальних територіях, як приватні будинки, невеликі підприємства та парковки. Тому метою цієї роботи було провести економічний аналіз двох альтернативних рішень – накопичувального резервуара з повторним використанням води та конструкції дощового саду. Аналіз витрат та переваг проводився на основі оцінки ефективності кожного підходу щодо зменшення об’єму зливового стоку та зменшення плати за скидання стоків у каналізаційну мережу. Режим опадів, використаний для розрахунків, було вибрано на основі даних за період із 2014 по 2023 рік для міста Києва. Технічні та економічні аспекти в дослідженні розглядалися як ключові фактори під час прийняття рішення про вибір підходу. Результати аналізу економічної стійкості обох варіантів на прикладі імітованої водонепроникної поверхні показали, що обидві системи мають ефективний термін експлуатації приблизно два роки. Накопичувальний резервуар є ефективним рішенням, що зменшує переливи дощових вод і дозволяє повторно використовувати накопичену воду для різних потреб. Проте витрати на будівництво та обслуговування резервуара перевищують економію на оплату за скид зливових вод у каналізаційну систему майже вдвічі, тому проєкт не є економічно вигідним у початковий період. Впровадження конструкції дощового саду для зниження плати за скид зливових вод в каналізаційну мережу є найбільш прийнятним рішенням із точки зору вартості. Якщо припустити, що термін ефективного використання конструкції дощового саду становитиме 8-10 років, накопичена економія тарифів може становити від 606,8 до 848,2 євро. Впровадження фінансових стимулів сприятиме реалізації альтернативних рішень із контролю зливових вод, що призведе до ряду таких екологічних та економічних переваг, як зменшення впливу зливових вод на навколишнє середовище, захист водних ресурсів та можлива економія при будівництві й управлінні зливовими системами

Ключові слова: зелена інфраструктура; дощовий сад; резервуар для збирання води; аналіз витрат; економічний ефект