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Analysis of the Possibilities of Rainwater Harvesting Based on the AHP Method

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1. Introduction

Poland is one of the countries with the largest water deficit in Europe. Poland's water resources per capita are 1580 $m^3 \cdot years^{-1}$ on average. It is almost three times less than the European average (Jokiel et al. 2017). The low water resources combined with the current climate change are a major challenge for polish agriculture, economy, and industry (Ptak et al. 2019, Sojka et al. 2019). Climate change causes modification of the spatial and seasonal distribution of precipitation in Poland (Szwed 2019). As a result, there is a more and more frequent occurrence of short-term, heavy rainfall and prolonged periods of drought. In the face of these changes and the threat of drought, we must think about the possibility of reducing the outflow and increasing water retention. At present, we can see a sharp increase in impermeable surfaces (such as concrete, bricks, asphalt), which is a result of the development of the urban areas. This type of surface causes that water does not reach the soil and plants but is usually discharged directly into the sewerage system. As a result, an increased amount of water flows into the sewage system, which often exceeds its designed capacity. Consequently, urban floods are increasingly frequent (Chudzicki 2018, Tokarczyk-Dorociak et al. 2017). The way to reduce the occurrence of floods in cities is rainwater harvesting (RHW). The two main objectives of rainwater harvesting are 1) to use rainwater for all general purposes and 2) to refill recharge groundwater (Haq 2017). The RHW can be used for purposes such as toilet flushing, cleaning, gardening, and vehicle washing. Accordingly, it is one of the ways to save purified, treated drinking water of high quality (Sendanayake 2016, Słyś et al. 2012). In Poland, the reuse and harvesting of rainwater is a great opportunity to reduce the water deficit problem.

Rainwater harvesting (RHW) is also one of the methods for climate change adaptation. At present, the best solution is to use blue-green infrastructure

(BGI), which mitigates the effects of floods and improves water quality. Furthermore, one of the objectives of BGI is to secure water for regional and agricultural purposes development. This infrastructure also alleviates the heat load. It is particularly effective in cooling densely built-up areas of large cities (Žuvela-Aloiseet et al. 2016). BGI reduces financial costs associated with stormwater in the long-run and creates new recreation places for people. Due to the great value-added, blue and green infrastructure must be taken into account in the spatial planning process, in particular in the formulation of regional (spatial) development strategies (Ghofrani et al. 2017). BGI includes solutions such as rain gardens, rainwater tanks, infiltration trenches and basins, ponds, bioswales, and green roofs. Apart from that infrastructure, rainwater management may also involve using drainage boxes, seepage pits, and underground storage tanks.

The right choice of the proper rainwater system is not obvious. Many factors and conditions must be taken into account during the selection. The choice of the RHW system depends on topography, land use, rainfall as well as the development of demand and economy (Martin et al. 2007). Sometimes, due to the small area of the land, we are unable to implement a new investment. In such cases, we try to adapt to already existing facilities. For example in urban areas, we can use existing ponds as rainwater receivers without compromising their other functions (Stachowski et al. 2017). Another important factor determining the choice of rainwater harvesting solution is the cost of investment. Sakson (2018) has conducted a financial assessment of rainwater collection systems for ten cities in Poland. Its results depended on the location, but in each city, the return on investment was high, especially in the case of detached houses. The cost-effectiveness of the system is extremely important for the individual user. It often happens that the decision to choose a rainwater storage system is made intuitively or is based on one criterion, which is the cost of investment. Such an approach may lead to a number of negative and long-term effects on the catchment water balance (Kordana & Słyś 2017).

This paper presents an analysis of four selected rainwater harvesting systems (RHWS): green roof, drainage boxes, underground storage tank, and infiltration basin. The analysis was conducted using the AHP (Analytic Hierarchy Process) method for two cases: a detached house in the suburbs of a large agglomeration and a block of flats in the city center.

2. Materials and methods

The method of Multi-Criteria Decision Making (MCDM) facilitates the selection of the best solution in various fields of economy, environmental engineering, and business. It is used, among others, for flood risk assessment of areas (Stefanidis et al. 2013), selection of the right location for the construction of solar farms (Uyan 2013), assessment of the innovativeness of stone mining waste management technology (Kozioł et al. 2011), analysis of the possibility of using the biological early warning system in tap water (Chmist et al. 2019), choosing the best public tender (Marcarelli & Squillante 2019), assessment of the safety of the construction project (Aminbakhsh et al. 2013), and studying the factors responsible for the success of IT services (Chen & Wang 2010). It is also a tool to evaluate and select the most people-friendly design concept based on criteria and decision sub-criteria (Ariff et al. 2008) and to find the best public tender (Marcarelli & Squillante 2019). One of the MCDM is AHP (Analytic Hierarchy Process), which was used in this publication to search for the best variant of rainwater harvesting. The application of this type of method required the analysis have been divided into several steps. In the first step, a hierarchical tree was created.

The hierarchical tree presents the relationship between the factors describing the problem and its potential solutions. It consists of at least three levels. On the first level, the problem under consideration is formulated. On the next levels, there are factors that describe the analyzed problem, while the last level presents solutions. Based on the hierarchical tree, matrices are created in which the individual factors and solutions are compared using the 9-stage Saaty scale. In the scale described in the AHP method, a value of 1 means equal importance of the compared factors or solutions, while the value of 9 means a very strong difference between the pairs being compared. The results of the comparisons are entered into the matrix and the diagonals of the matrix assume values equal to one. In the next step of AHP methods, matrices are being solved and the number of calculations depends on the hierarchical tree level. On the second level, one matrix is solved. On the third level one matrics also solved, but as many times as there are factors on the second level. Then, the results are checked by determining the values of matrixes, CI consequence factor, and IR inconsistencies. The more the intrinsic value of the matrix deviates from the dimension n, the error is greater. If the CI values do not exceed 0.1 and the IR values do not exceed 0.2, then the experts' assessments are consistent (Hämmerling & Spychała 2015). The matrix solutions are local vectors. Based on their values and vectors from the higher level, global vectors are determined, which allowed to determine the best solution to the problem of rainwater harvesting in an urban area.

The problem of rainwater management is currently a very important aspect of the construction of new housing estates as well as existing urban areas. There are several reasons for this. The first reason why is the issue of increasing the intensity of weather phenomena, the second is the possibility of reusing water for irrigation of plants, the third is the changing legal regulations. Preparing the rainwater harvesting system for a given site, the characteristics of different systems were analysed. The most favourable solution was chosen on the basis of a comparative analysis of various parameters describing the different systems. Multi-Criteria Decision Making is the best for this type of analysis.

The first stage of the AHP method is the decomposition of the problem, i.e. building a hierarchical tree (Fig. 1). At the P1 level, the main goal is stated, which is described in the previous paragraph. On the P2 level, the parameters characterizing the investigated problem and its solutions are determined. During the analysis of different rainwater harvesting systems, several aspects were taken into account, including the costs of construction and exploitation of each solution. The ease of installation and construction of each solution was also taken into consideration. Another factor analysed was the influence of a system on groundwater resource changes. This aspect was both considered in terms of the change in the ordinate of groundwater level in the area and the possibility of absorbing an increased amount of water resulting from intensive rainfall. The study also took into account aspects related to the exploitation of particular elements of a rainwater management system. The convenience of performing particular exploitation and maintenance works and their frequency were analysed. A very important issue discussed in the analysis pertains to the feasibility of the systems in different conditions of land use. The paper analyses the possibilities of building systems in the area of a housing estate of detached houses in the suburbs and blocks of flats located in the city center. When comparing individual systems, the possibility of integration with both designed and the existing environment was also considered. The authors have meant here the integration of a given system into a spatial order and the existing land development. At present, the situation related to legal aspects and increasing costs has a positive impact on the need to use the harvested water again. The analyses took into account the possibility of using the harvested water for e.g. irrigation of the garden or toilet flushing.

In the article, 4 different solutions for harvesting rainwater were analysed using the AHP method. The first of them was a green roof. It is a space located on the roof of the building, covered with plants grown on the vegetation substrate. This solution is becoming increasingly popular due to the possibility of increasing the amount of greenery in intensely built-up areas without allocating additional land for it. Green roofs also create new places for people to relax on the buildings. The second solution analyzed was the drain boxes. They are placed in the soil where they support the infiltration of water coming from the roofs and paved surfaces. Thanks to the underground construction, a large area is not necessary for their installation. The third system is an underground storage tank. The water harvested in it can be reused for irrigation of the garden or flushing the toilets in houses. The last solution analysed by the authors was an infiltration basin. It is one of the elements of the blue-green infrastructure (BGI). Apart from storing rainwater, it allows the excess water to drain into the ground. Infiltration tanks with luxuriant vegetation are also a place where many plant and animal species live. Moreover, this solution creates new recreation places for the residents of the estates.

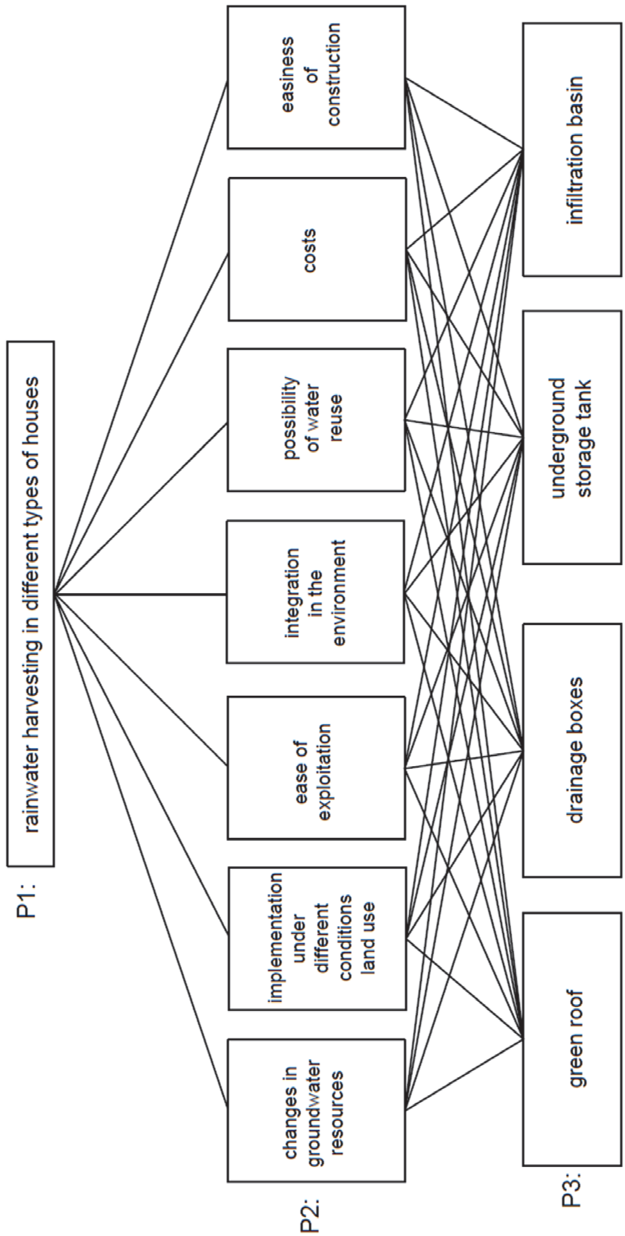

Fig. 1. The hierarchical tree used in the analyses

3. Results and discussion

The calculations using the Multi-Criteria Decision Making (MCDM) methods were performed for two different scenarios (a detached house in the suburbs of a large agglomeration and a block of flats in the city). Fig. 2 shows the global vector values for level 2 of the hierarchical tree. The highest values for both scenarios were obtained by a factor related to the possibility of rainwater reuse (for a detached house 0.35 and a block of flats 0.28). For a detached house, ease of exploitation (0.20) and costs (0.19) were the next most important factors, which had the greatest impact on the choice of rainwater harvesting method. For a block of flats, the second and third most important factors were costs (0.24) and operation and construction ability (0.12). The least important aspect for both scenarios is an adaptation to the environment (0.04 and 0.06). Analysing the results of the second level global vector, it can be concluded that the hierarchy of factors for the two scenarios is similar, and the differences can be explained by the specificity of each scenario. The possibility of reusing rainwater is an extremely important aspect from the point of view of the environment and small water resources as well as from the perspective of the user. For this reason, a slightly higher value of the vector (0.35) has been noted in the case of a detached house, where the reuse of water (for watering the garden or flushing the toilets) allows to significantly reduce the costs of living the household by decreasing the amount of tap water used. In the case of a detached house, the ease of exploitation of the system is also considerable, which has a direct impact on the costs incurred. In the case of a block of flats, ease of exploitation is less important than in the case of a detached house, due to the fact that it is not the responsibility of a single user. The analysis showed that the least significant aspect is the adaptation of the system into the environment. The vector value, in this case, is higher for a block of flats in the city center. This is due to the fact that in a strongly urbanised area, each of the solutions will have a huge impact on the reduction of the negative environmental impact of the buildings (in the suburbs this impact will be smaller). It is worth noting that some of the analysed solutions will contribute not only to the increase of water resources but also to the extension of biologically active areas, which is extremely important in the context of the adaptation of cities to climate change.

At level 3, seven matrixes were calculated. Fig. 3 presents the results of the calculations of local vectors for a detached house. For the factor of groundwater resources change, the infiltration basin (0.45), and drainage boxes (0.43) were most affected. The highest values for the factor associated with the possibility of implementation in various land use conditions were obtained for the underground storage tank (0.36) and drainage boxes (0.34), as these are the solutions that can be applied regardless of the existing land use. On the other hand, the implementation of the infiltration basin requires a large area, which can be used e.g. to create a resting area, car park, or garage. The easiest to exploit are drainage boxes (0.32) and an underground storage tank (0.32) because, unlike a green roof or an infiltration tanks, they do not require a lot of time and work for their maintenance. In terms of integration into the environment, the best solution is to use the infiltration basin (0.43) and green roofs (0.39). The development of the roof of a detached house increases its market value and makes it more attractive. The green roof also creates additional space for the recreation of purposes. The infiltration reservoir located on the plot can not only serve as a retention function but it can affect the aesthetics of the garden. The biggest possibility of water reuse as grey water is created by an underground storage tank with no outlet (0.56), in which we can accumulate all the precipitation in contrast to other solutions in which water is taken by plants, soaked in the ground or is evaporated and infiltrated. In terms of the cost, the cheapest were the drain boxes (0.38) and the underground storage tank (0.37). Due to constructional requirements, green roofs proved to be a very expensive solution for a detached house. The easiest system to implement is an underground storage tank (0.38) and drain boxes (0.34). A more demanding investment is the system of green roofs due to the construction and the need to perform work at height.

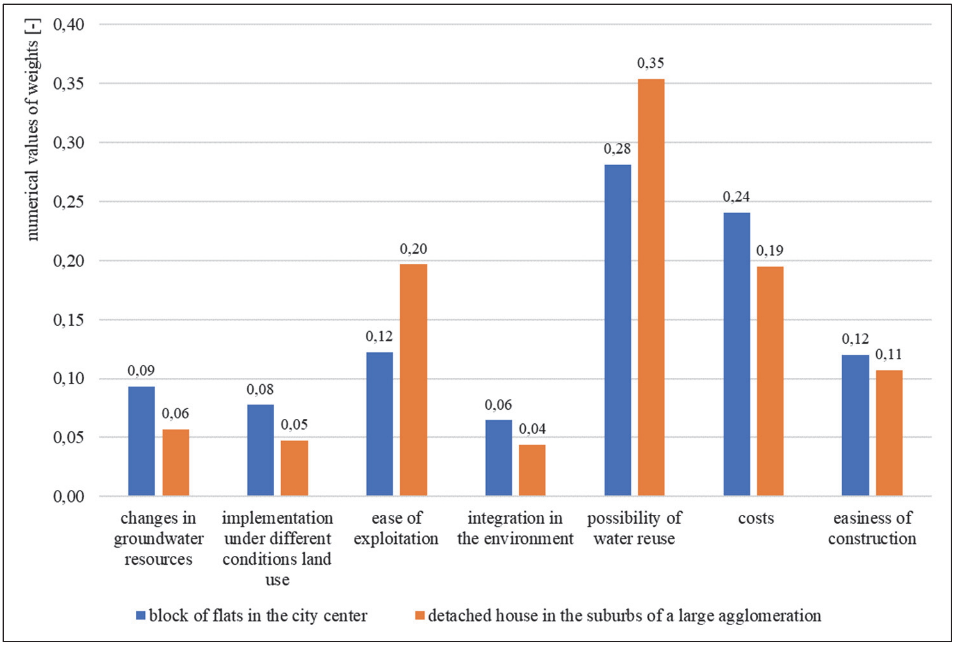

Fig. 2. Results for vectors in level 2

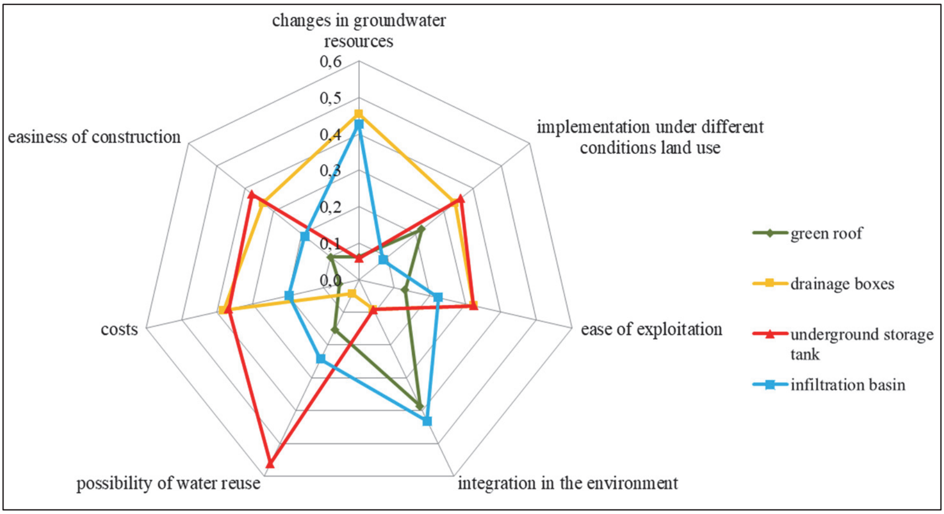

Fig. 3. Results for vectors from level 3 for a detached house located in the suburbs of a large agglomeration

Figure 4 shows the values of local vectors for level 3 in the case of a block of flats located in the city center. In terms of influence on changes in groundwater resources, the most advantageous solutions are the drainage boxes (vector value 0.45) and the infiltration basin (0.43). The result obtained for the underground storage tank is low (0.06) due to the fact that it is an airtight reservoir and the water cannot infiltrate the ground. The vector value for the green roof was also low (0.06). This is determined by the fact that most of the water in the case of this solution will be stored on the roof and will not affect the increase of groundwater resources. When considering the solutions in the context of land use, the best solution will be an underground storage tank (0.35) or drainage boxes (0.31) whose installation do not require a large area. This is extremely important in the case of a block of flats located in the city center. Construction of the infiltration basin (0.08) requires a large area, so this solution cannot always be realized. According to the analysis carried out in view of ease of exploitation for the block of flats, the best system will be an underground storage tank (vector value 0.35). It does not require frequent maintenance or treatments to maintain the functionality of the solution such as green roof (0.12) or infiltration basin (0.22). In the case of both of these systems, users must take into account, among other things, the need for continuous monitoring of the development of vegetation and the use of care treatments. In the case of the system integration with the environment, the greatest benefit for the block of flats will be the installation of a green roof (0.40) or construction of the infiltration basin (0.40). Both of these solutions will significantly increase the biologically active area and reduce the urban heat island effect. They also perfectly fit into the adaptation plans of cities and the latest trends in increasing the participation of green and blue infrastructure in urban areas. The biggest possibility of reusing water in the case of the block of flats is the underground storage tank (local vector value 0.56). It allows to keep a large amount of water and use it at any time for sanitary purposes of the block inhabitants The drainage boxes are the least favorable solution due to their permeable nature (0.04). The cost analysis showed that the optimal solution will be the drain boxes (0.37). The cost of their installation is much lower than in the case of a green roof (0.05). The construction of the infiltration basin is also associated with high costs (excavation, vegetation) so that the local vector was only 0.20. The ease of construction is also directly related to the cost aspect. The simplest solution will be to install an underground storage tank (0.39) or drainage boxes (0.32), which do not require a lot of work in comparison to the construction of the infiltration tank, which requires a lot of groundwork, which is the reason why the vector reached the lowest value of 0.11. The local vector for green roofs was at the level of 0.18. The ease of construction is related to the type of existing roof in a block of flats. Depending on the case, the adaptation of the structure will require respectively more or less work.

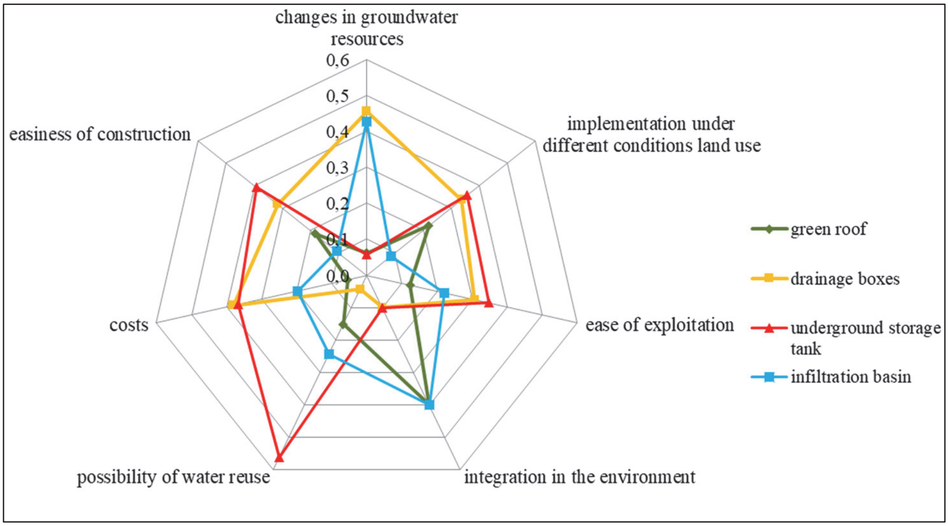

Fig. 4. Results for vectors from level 3 for the block of flats located in the city center

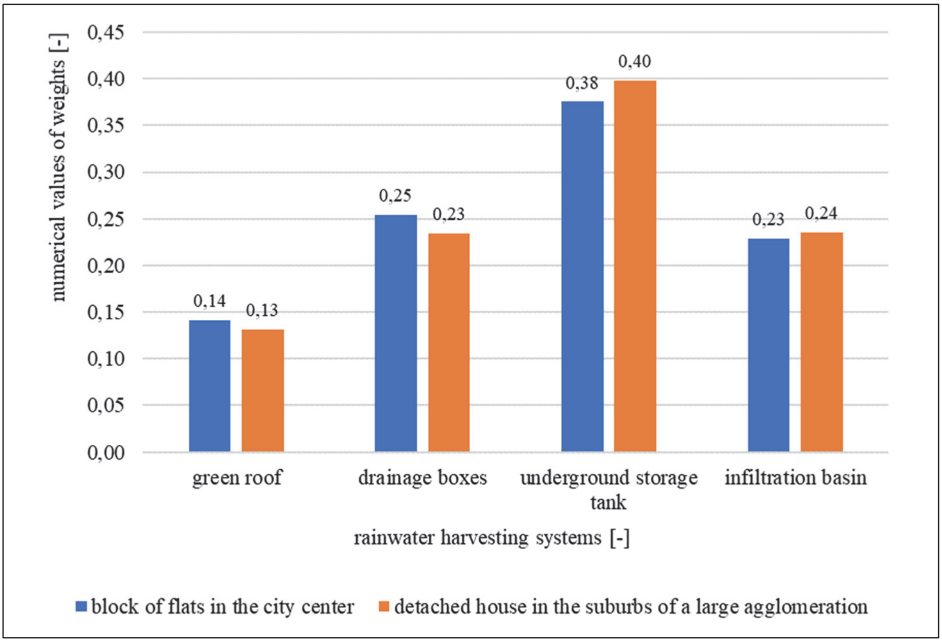

Fig. 5. The results of the global vector solving the problem of rainwater harvesting

Figure 5 shows the results (global vectors) obtained from the solution of all matrices describing the hierarchical tree for the two scenarios. The analysis carried out using the AHP method showed that for a detached house and a block of flats the most beneficial solution for rainwater harvesting is to use an underground storage tank (0.40 and 0.38). For a detached house located in the suburbs of a large agglomeration, the infiltration basin (0.24) was the second in the hierarchy of choice. In the third place were classified drainage boxes (0.23) and on the last place the green roof (0.13). A similar hierarchy of choice of solutions was characterized by the second scenario, for which the second most advantageous option was the use of drainage boxes (0.25), and the third was the construction of the infiltration basin (0.23). According to the analysis conducted using the AHP method, the green roof proved to be the least profitable rainwater harvesting system for the block located in the city center. It should be remembered that the results only represent the factors selected by the experts, which were considered in the AHP analysis. The use of the Multi-Criteria Decision Making (MCDM) method is connected with assigning particular factors and solutions to the weights and it is the experts who decide on the selection of criteria to be considered and their importance in resolution of a given problem.

4. Conclusions

The paper presents an analysis of the possibilities of rainwater harvesting for two different land-use scenarios using the multi-criteria AHP decision making method. In both cases, it can be concluded that the use of an underground storage tank is the best solution. This is mainly due to low construction costs, ease of exploitation and the possibility of reusing the accumulated water. According to the analysis, the systems which, should be used less frequently are the drainage boxes and the infiltration basin. Each of these solutions has its advantages but also disadvantages. Drainage boxes can be installed in different land-use conditions, their operation is not a problem and the cost of construction is not too high. The infiltration basin is characterized by an easy adaptation to the environment but more demanding construction. On the other hand, green roof proved to be the least advantageous solution mainly due to high construction costs and relatively high workload associated with exploitation. The analyses considered two different variants in terms of the land use: a detached house situated in the suburbs of a large agglomeration and a block of flats located in the city center. According to the analysis and the identified factors, in both cases, the best solution was to use an underground storage tank. This system proved to be the most advantageous due to the possibility of water reuse, low construction costs and ease of exploitation.

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Abstract

In the face of the current climate change, the increasing incidence of extreme weather events, prolonged periods of drought and water scarcity, attention should be paid to rational water management with particular emphasis on rainwater. Excessive development and sealing of urban catchments result in a faster outflow of water to the sewage system, which prevents it from reaching the soil and plants. This situation intensifies the drought effect and contributes to the occurrence of urban floods. In order to mitigate the negative impact of this process, solutions allowing for rainwater harvesting should be implemented. A wide variety of systems are currently available on the market to harvest and reuse rainwater. In the publication, the authors analysed four solutions: a green roof, drainage boxes, an underground storage tank, and an infiltration basin. The AHP (Analytic Hierarchy Process) method was used to select the best rainwater harvesting system, which is one of the methods of Multi-Criteria Decision Making. The analyses considered two different variants in terms of land use: a detached house located in the suburbs of a large agglomeration and a block of flats placed in the city center. According to the analysis and the assumed factors, in both cases, the best solution was to use an underground storage tank. This system proved to be the most advantageous due to the possibility of reuse of water, low construction costs, and ease of exploitation.

Keywords:
rainwater harvesting, Multi-Criteria Decision Making, AHP, green roof, drainage boxes, underground storage tank, infiltration basin

Analiza możliwości zagospodarowania wody opadowej z wykorzystaniem metody AHP

Streszczenie

W obliczu zachodzących obecnie zmian klimatycznych, występowania coraz częstszych ekstremalnych zjawisk pogodowych, długotrwałych okresów suszy oraz deficytu wody należy nacisk zwrócić uwagę na prowadzenie racjonalnej gospodarki wodnej ze szczególnym uwzględnieniem wód opadowych. Nadmierna zabudowa i uszczelnienie zlewni miejskich powoduje szybszy odpływu wody do kanalizacji, przez co nie trafia ona do gleby i roślin. Sytuacja ta potęguje zjawisko suszy, a także przyczynia się do występowania miejskich powodzi. Aby złagodzić negatywny wpływ tego procesu, należy wdrażać rozwiązania pozwalające na zagospodarowania wód opadowych. Obecnie na rynku dostępnych jest wiele różnorodnych systemów umożliwiających gromadzenie deszczówki oraz jej ponowne wykorzystanie. W publikacji autorzy przeanalizowali cztery rozwiązania: zielony dach, skrzynki rozsączające, podziemny zbiornik bezodpływowy oraz zbiornik infiltracyjny. Do wyboru najlepszego wariantu zagospodarowania wody deszczowej zastosowano metodę AHP (Analytic Hierarchy Process), która jest jedną z metod wielkokryterialnego wspomagania decyzji. W analizach rozważono dwa różne warianty pod względem zagospodarowania terenu: dom jednorodzinny znajdujący się na przedmieściach dużej aglomeracji oraz blok zlokalizowany w centrum miasta. Według przeprowadzonej analizy oraz założonych czynników, w obu przypadkach najlepszym według rozwiązaniem było zastosowanie podziemnego zbiornika bezodpływowego. System ten okazał się najkorzystniejszy z uwagi na możliwość ponownego wykorzystania wody, niskie koszty budowy oraz łatwość eksploatacji.

Słowa kluczowe:
zagospodarowanie wody opadowej, metoda wielokryterialnego wspomagania decyzji, AHP, zielone dachy, skrzynki rozsączające, podziemny zbiornik bezodpływowy, zbiornik infiltracyjny