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# Decision Criteria for the Development of Stormwater Management Systems in Poland

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**Abstract:** Progressing urbanisation is one of the key causes of environmental degradation. This problem also applies to stormwater management. For this reason, drainage infrastructures should be designed in harmony with nature and the decision for selecting a specific stormwater management system solution must not be taken on an ad-hoc or single-perspective basis. The purpose of this paper is to identify the criteria for selecting the best solution for a problem involving the selection of a stormwater management system, and to present a method that will enable all relevant criteria to be taken into account in the decision-making process. The developed decision problem structure takes into account all criteria related to the construction and operation of stormwater infrastructure, and its individual elements were identified based on the analysis and synthesis of information regarding the principles of stormwater management in Poland. The presented approach will allow for the taking into account of all, often mutually exclusive, criteria determining the choice of the stormwater management system option. This, in turn, will make it possible to significantly simplify the decision-making process. The indicated criteria can form the basis for choosing the most favorable stormwater management system for both large urban catchments and individual facilities. Thanks to the considerable flexibility of the developed decision problem structure, its widespread application can contribute to improving the efficiency of stormwater management systems. An example of the developed model's application in a decision-making process is presented, concerning the selection of a design variant of a single-family residential building's stormwater management system in Poland. Four design variants were included in the analysis, and the Analytic Hierarchy Process was used as the tool to select the most favorable option. This study shows that nature-based solutions are the most beneficial decision stormwater management options.

**Keywords:** Analytic Hierarchy Process; decision criteria; decision support; nature-based solutions; stormwater management; single-family house

## 1. Introduction

Progressing urbanisation is one of the key determinants of environmental degradation [1], which also facilitates the emergence of a range of problems that can be analysed from the perspective of stormwater management [2]. These problems are more severe due to the lack of a comprehensive approach to the issue of designing municipal infrastructure [3], including stormwater management systems. In Poland, the selection of a specific system solution is currently made ad-hoc or based on the financial resources available to realize the project, without assessing the possible consequences of the decisions taken that may arise in the years following the construction of the drainage infrastructure. As a consequence, the degree of implementation of nature-based solutions for stormwater management is low [4]. The problem of focusing on financial criteria concerns both the selection of a specific facility dedicated to stormwater management [5] and the selection of its dimensions [6]. This issue is present in many other countries [7]. It should also be noted that even scientific research on stormwater management systems is often based solely on financial criteria [8]. However, from the perspective of effective functioning of municipal stormwater infrastructure and users' convenience [9], it is necessary to take into account all criteria related to its construction and operation. A high level of public participation is also required in the planning, implementation and operation of stormwater management systems [10]. Only consideration of all the above aspects will limit the use of the conventional stormwater management systems. This is important because the use of the conventional systems provides no possibility of delaying the outflow or retaining the stormwater within the drainage area [11,12], and the negative consequences of this state of affairs are observed both in the catchment [13] and in the stormwater receiver [14].

Among the potential options, in addition to the conventional stormwater management systems, there are systems that have positive impacts on the surrounding environment, including facilities designed for periodic retention [15,16], infiltration of stormwater into the soil [17,18], and for harvesting rainwater [19,20]. The use of facilities classified as green infrastructure is particularly recommended. Their location in appropriate places is an important way of adapting urban catchments to expected climate changes [21]. Sustainable stormwater management systems [22] can be used both in existing and newly-constructed infrastructures, although the possibilities of applying individual devices, including nature-based solutions, are limited, and the effectiveness of operation is dependent on a range of factors [23–25]. Potential restrictions are mainly related to the characteristics of the drained catchment and the area within which the stormwater management system is to be located. An important aspect is also the issue of society's attitude to the implementation of individual solutions [26]. In addition, as noted by Zawilski et al. [27], all aspects of stormwater management are interrelated and affect each other, which can cause local conflicts. An important problem is also the need to make decisions in the face of weather uncertainty [28]. This results in a need to determine and analyse all criteria that could affect the legitimacy of utilising the possible stormwater management system solutions, including nature-based solutions, and to select a tool that can enable them to be compared objectively in light of these criteria. Only such an approach will allow for the elimination of potential conflicts of interest and allow for the improvement in the efficiency of stormwater management systems in urban catchments.

Taking into account the various aspects associated with the construction and operation of stormwater management systems is possible when using multi-criteria decision making (MCDM) methods. In some parts of the world, attempts at implementing a multi-criteria analysis in the stormwater management process have already been made. This primarily concerns areas affected by a water deficit [29–31] and countries where an intensive pro-ecology policy is enforced [32–34]. In the first case, it can be assumed that the interest in the possibility of using these methods was compelled by the situation arising from the need to find technically and economically justified alternative sources of water. Research conducted in India [35], Bangladesh [36], Botswana [37] and Nigeria [38], focuses mainly on rainwater harvesting systems, and both individual solutions for these systems and their possible locations are analysed. Similar research has also been conducted in Great Britain [39], which was a consequence of the need for unconventional water sources in some parts of the country.

Decision support methods find use when it is necessary to analyse in detail the investment variants in question, in relation to their effectiveness in removing individual types of pollutants present in stormwater. The need to take the quality aspect of stormwater into account was noted, for example, by Ellis et al. [40] and Cheng et al. [41], who investigated runoffs from highways. Stormwater drained from highways was also studied by Ki & Ray [42], although in this case the focus was on the potential locations of infiltration trenches. Specific devices were also discussed by other authors. For example, Jato-Espino et al. [43] studied three types of urban pervious pavements designed for managing stormwater, while Grant and Jones [44] analysed green roofs. Another example of using a multi-criteria analysis in stormwater management is its application in the process of managing the existing drainage infrastructure. Such a solution was applied, for example, in Algeria [45].

A separate scientific issue is the multi-level comprehensive approach to the problem of selecting the best system solution intended for managing stormwater in city drainage areas. Preliminary research on this subject was conducted using the drainage area located in the city of Blacksburg, Virginia (USA), as an example [46]. Attempts at using a multi-criteria analysis in the drainage infrastructure planning process were also made in China [47] and France [48], although in all these cases the possibility of implementing the obtained results was limited to the location of the specific drainage area, preventing them from being utilised under Polish conditions. This results primarily from the different climate, differences in current legal regulations as well as differing priorities. The presented examples demonstrate, however, that the use of a multi-criteria analysis in the field of stormwater management is justified, giving rise to the need for implementing it in Poland as well. The presented examples also prove that the use of MCDM methods allows for the inclusion of a number of criteria that are often contradictory and whose inclusion in the decision-making process is necessary to determine the best stormwater management system solution.

The objective of this paper is to identify the criteria for selecting the best solution for a problem involving the selection of a stormwater management system in Poland, and to present a method that will enable the described criteria to be taken into account in the decision-making process. The research took into account all aspects related to the construction and operation of stormwater infrastructure in Poland, with an example for the selection of a design variant of a single-family residential building's drainage system.

The remainder of this paper is structured as follows. The next section covers the description of the research method used and the case study. Then, the results are presented and discussed. Finally, the conclusions of the research and directions for future research areprovided.

## 2. Materials and Methods

### *2.1. Analytic Hierarchy Process*

Rational investment decision making is supported by advanced methods divided into multi-objective and multi-attribute methods [49]. In the former case, decisions are made based on a set of objectives that the decision maker aims to achieve, and a set of accompanying limits, while the number of possible decision options is infinite. In the case of multi-attribute problems, decision options under consideration are clearly defined and their number is limited, while the decision is made on the basis of a set of criteria. These criteria can be assessed arbitrarily [49].

As part of the research described in this paper, one of the multi-attribute methods was used. The use of the Analytic Hierarchy Process (AHP) [50] enables rational investment decisions to be taken, concerning the selection of a stormwater management system. This method is one of the most commonly utilised multi-criteria decision making methods in the world, and numerous studies have been published on the subject of the possibilities of its application in various areas. A significant part of these papers addresses matters of sustainable environmental management and applications of modern pro-ecology technologies in technical engineering. For example, Ghimire and Kim [51] and Wang et al. [52] raised the issue of using unconventional energy sources, while Giner-Santonja et al. [53] studied pollution emissions to the air. The AHP method has also been used in studies concerning urban river systems [54], surface water quality assessment [55] and wastewater treatment plants [56].

The AHP method is not without its flaws, resulting mainly from the use of an arbitrary rating scale and the need to perform a large number of pairwise comparisons [57]. However, it is characterized by high flexibility and an intuitive approach to the assessment of individual elements of the decision model. Hadadian and Rasoulian [58] also pointed at the possibility of eliminating the problem of falsifying results. Some authors [59,60] have also pointed out that the chosen research method allows for the reflection on the natural tendency to segregate individual elements of the decision model at different levels. Thanks to this, its application enables a systematic approach to the decision problem under consideration.

The essence of the AHP method, created by Thomas L. Saaty of the University of Pittsburgh, is based on arranging individual decision process elements in a hierarchy. Level 1 of the hierarchy comprises the objective that the decision maker aims to accomplish. Subsequent levels are created by decision criteria, often referred to as attributes, while the lowest level in the hierarchy is occupied by decision options [61]. In the AHP method, all elements of the hierarchy present on a given level (except level 1) are compared in pairs with the subsequent elements of the level directly above. The comparison of elements difficult to quantify is performed using the nine-degree comparison scale created by T.L Saaty [50,61].

Based on the obtained comparisons, square matrices were created whose dimensions corresponded to the numbers of elements at the given level $n$. Subsequently, based on the obtained data, weight coefficients, i.e., local priorities, were calculated. For this purpose, appropriate computer programs can be applied that use, among others, methods such as [62]: eigenvector method, arithmetic mean method and geometric mean method. In this research the eigenvector method was used. The application of the indicated method allowed for the obtaining of results comparable with most commonly used techniques, and the correctness of calculations was not conditioned by the number of compared elements (as in the case of geometric mean, for example) [63].

Equation (1) presents the general evaluation matrix diagram and the matrix written using weight coefficients [61,64].

$$\boldsymbol{A} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} = \begin{bmatrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdots & w_2/w_n \\ \vdots & \vdots & \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n \end{bmatrix} \tag{1}$$

where: $\boldsymbol{A}$—matrix of pair comparisons, $a_{ij}$—result of comparing one element with another in the light of the adopted criterion, $w_i$—weight coefficients.

Later, global priorities were determined, enabling the best option to be selected. They were calculated as products of priorities of the given sub-criterion and its corresponding criterion [63]. However, before making the final decision, it is necessary to verify the correctness of the pair comparisons. For the purpose of verifying the consistency of matrices, the consistency coefficient $CR$ is determined, whose threshold value is assumed at 10% [65]. If results are inconsistent, the study must be repeated.

Individual elements of the developed decision support model must be compared in pairs with subsequent elements of the levels directly above them. Due to their varied nature, three different approaches may be used for evaluating individual elements, specifically: Life Cycle Cost (*LCC*) analysis [66] of the considered design variants, hydrodynamic modelling [67] and expert methods, primarily surveys [68]. Surveys are particularly useful in situations when it is necessary to compare elements that are difficult to quantify. This is the reason why they found application in the analysis described in this paper.

### *2.2. Case Study*

The analysis concerning the selection of the best investment variant of the stormwater management system was performed for a single-family building located in Rzeszow, Poland. The degree of surface sealing is relatively low there (approximately 35%). The administrator of the centralized stormwater management system is the municipal body, however, the owners of the premises are responsible for the decentralized systems. The operator of the conventional stormwater management system only determines the maximum amount of stormwater that can be discharged into this system. For this reason, it was assumed in the study that the decision on selecting a specific stormwater management system depended exclusively on the premises owner's preferences. In the analyzed case, the premises owner was also a person professionally involved in stormwater management, which made him an expert in this field. A survey was chosen as the tool for assessing individual decision model elements. In accordance with the decision maker's indication, only devices designed for infiltrating stormwater into the soil were included in this model. Additionally, a pre-selection of usable stormwater management system design variants was performed on the basis of the location criterion and characteristics of the analysed building. The following factors were taken into consideration: the size of the surface available for the infiltration system and the roof area, as well as the soil parameters.

As a result, the analysis includes four decision options, which are shown in Figure 1. Two of them (infiltration boxes and infiltration well) represent devices intended for underground infiltration. In turn, the next two (infiltration basin and infiltration trench) were nature-based solutions. The infiltration basin is a device in the form of a depression in the ground whose task is short-term retention and infiltration of stormwater into the ground. The surface of the infiltration basin is sown with grass, which stabilizes its slopes, intensifies the process of stormwater treatment and produces favorable aesthetic features. The infiltration trench is a device in the form of a longitudinal trapezoidal trough. Its slopes are sown with grass, and below the bottom there is porous material.

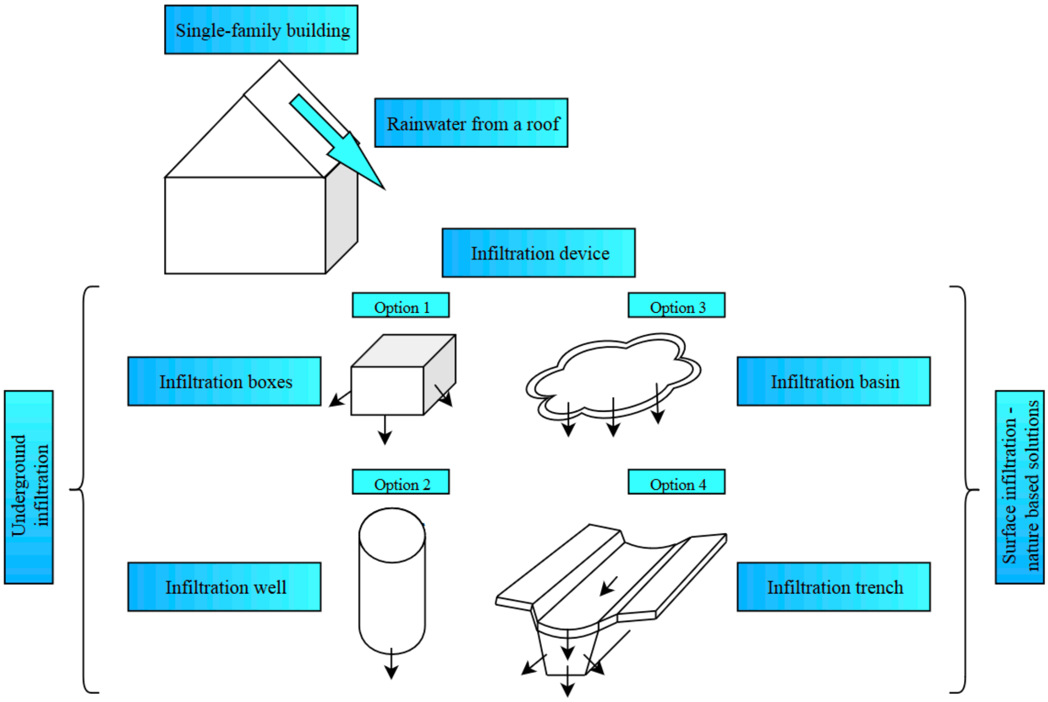


**Figure 1.** Case study.

In order to take into account the impact of changes in individual assessments on the final results of the analysis, a scenario analysis was also carried out. The following scenarios were included:

- Scenario 1—only the operating criterion was considered;
- Scenario 2—economic, operating, aesthetic and technical criteria were considered;
- Scenario 3—hydraulic, social and environmental criteria were considered;
- Scenario 4—all criteria were considered, but they were of equal weight.

Stormwater will be removed from the roof of the analysed building. The values of the input parameters are summarized in Table 1.

The inflow to the devices was determined for the region of Central Poland based on the Bogdanowicz–Stachy model [69]. Infiltration intensity $Q_{inf}$ was determined based on Equation (2) [70]. Calculations were performed assuming the probability $p = 50\%$, generally accepted for residential areas [71]. Rainfall with a duration of 10 to 200 min was analyzed. For such objects, as infiltration basin and infiltration trench, rainfall over the devices was also considered.

$$Q_{inf} = c_s \cdot k_f \cdot F_{inf} \quad (2)$$

where: $c_s$—safety factor ($c_s$ = 0.5), $k_f$ —filtration coefficient, m/s, $F_{inf}$—infiltration area, m$^2$.

**Table 1.** Input parameters.

| Parameters | Units | Values |
|---|---|---|
| Roof area | m$^2$ | 150 |
| Roof slope | ° | 30 |
| Ground slope | % | 0.3 |
| Soil filtration coefficient | m/s | $4 \times 10^{-5}$ |
| Water table location | mbgl | 3.2 |
| Maximum available area | m$^2$ | 16 |
| Roof depression storage | mm | 1.27 |
| Manning's coefficient for roof surface | - | 0.015 |
| Rainwater runoff coefficient (based on [72]) | % | 100 |

Devices whose use under the given conditions is technically and financially justified are listed in Table 2. Runoff from the roof of the analyzed building, calculated using the Storm Water Management Model (SWMM) software [73], is shown in Figure 2.

**Table 2.** Characteristics of the design variants under consideration.

| Option | Device | Characteristic |
|---|---|---|
| 1 | Infiltration boxes | width: 2 m, length: 4 m, height: 0.4 m, effective capacity: 0.95 |
| 2 | Infiltration well | diameter: 1.2 m, height: 2 m, infiltration through the bottom of a well |
| 3 | Infiltration basin | infiltration area: 16 m$^2$, height of stormwater: 0.14 m |
| 4 | Infiltration trench | width: 1 m, length: 7.6 m, height: 1.2 m, material porosity: 0.25 |

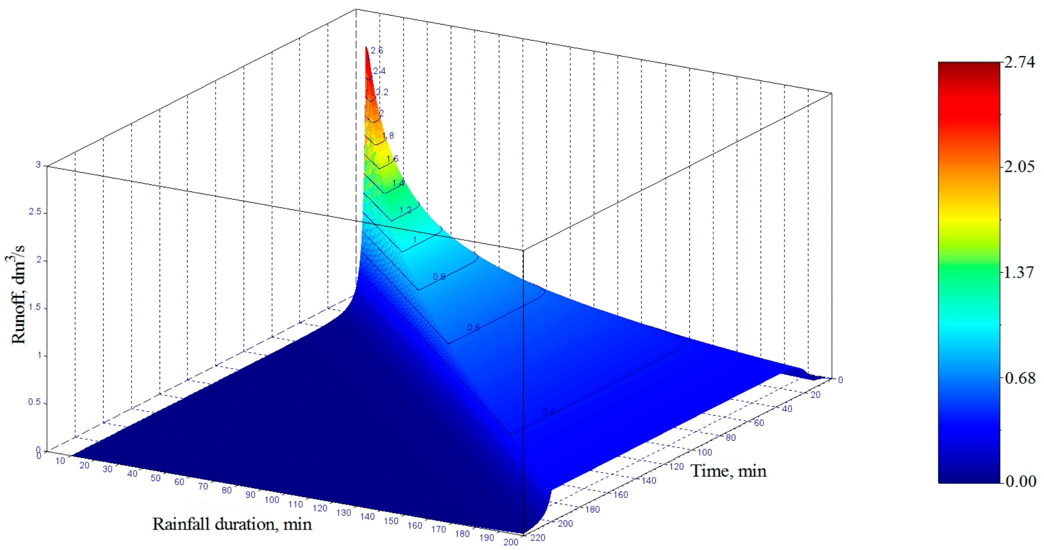


**Figure 2.** Runoff from the analysed roof (determined using SWMM 5.1 software).

## 3. Results and Discussion

### *3.1. Model of Decision Support in Stormwater Management*

According to the decision making procedure, one of its initial stages is defining the factors that determine the selection of the best problem solution. Traditionally, the design variant is selected based on the economic criterion. In this study, operating, aesthetic, hydraulic, locational, social, environmental and technical criteria were considered, and within them additional sub-criteria were designated. All these factors were determined on the basis of a detailed analysis and synthesis of the information on the principles of stormwater management in Poland. Both the data contained in the literature and the suggestions of people involved in water and sewage management in Poland were taken into account. The designated criteria of the decision process involving the selection of a design variant of a management system for stormwater forming within urban catchments are presented in Table 3.

**Table 3.** The criteria for selecting the most favorable stormwater management variant.

| Criteria | Sub-Criteria (Objectives) |
|---|---|
| $A_1$: Economic | $A_{11}$: Providing a source of funding<br>$A_{12}$: Minimising the charges paid for stormwater discharge<br>$A_{13}$: Reducing the stormwater management system's life cycle costs |
| $A_2$: Operating | $A_{21}$: Reducing the stormwater management system's failure risk<br>$A_{22}$: Ensuring the stormwater management system's operation safety<br>$A_{23}$: Minimising the frequency of maintenance operations |
| $A_3$: Aesthetic | $A_{31}$: Adapting to the current area development plan<br>$A_{32}$: Creating a landscape design component<br>$A_{33}$: Fitting into current terrain features |
| $A_4$: Hydraulic | $A_{41}$: Adapting to the existing drainage infrastructure<br>$A_{42}$: Unloading existing sewerage pipelines and enabling new connections<br>$A_{43}$: Unloading facilities located on the sewerage system<br>$A_{44}$: Enabling control and delay of stormwater outflow from the catchment to the receiver<br>$A_{45}$: Reducing the amount of stormwater removed to the receiver |
| $A_5$: Social | $A_{51}$: Designing the stormwater management system in accord to current legal regulations<br>$A_{52}$: Adapting to the local communities lifestyle<br>$A_{53}$: Improvement of the environmental awareness of the local community<br>$A_{54}$: Enabling rainwater harvesting for greenery watering<br>$A_{55}$: Enabling rainwater harvesting for toilet flushing<br>$A_{56}$: Ensuring citizen safety<br>$A_{57}$: Reducing social losses resulting from incorrect stormwater management |
| $A_6$: Environmental | $A_{61}$: Protecting the stormwater receiver<br>$A_{62}$: Pre-treatment of stormwater<br>$A_{63}$: Improving the condition of urban greenery<br>$A_{64}$: Improving the biological diversity in cities<br>$A_{65}$: Creating an attractive microclimate<br>$A_{66}$: Groundwater recharging |
| $A_7$: Technical | $A_{71}$: Facilitating the design of the stormwater management system<br>$A_{72}$: Streamlining the construction of stormwater management system |
| $A_8$: Locational | $A_{81}$: Adapting to the characteristics of the stormwater management area<br>$A_{82}$: Adapting to the position of the groundwater table<br>$A_{83}$: Adapting to the size of the area available for the stormwater management system<br>$A_{84}$: Adapting to the size of the catchment<br>$A_{85}$: Adapting to the soil filtration coefficient |

In the case of stormwater management systems, consideration of various criteria determining the legitimacy of the application of specific solutions is necessary due to the relatively large number of potential design variants, differing not only in their characteristics, but also in possible restrictions on use. Therefore, the application of a comprehensive approach to the described problem, allowing the consideration of the drainage infrastructure lifetime, is necessary from the point of view of the efficient functioning of the stormwater management system and the comfort of its users.

Only this approach will meet the main goals of rational stormwater management. These include ensuring protection against flooding while maintaining high economic efficiency of investments and high social, environmental and cultural values [74].

Furthermore, it is advisable to take preferences of the various participants of the decision process considered in the analysis. When selecting a method of managing stormwater generated within urban drainage areas, the possible actors can be representatives of the local government and the water and sewerage company, designers or individual users. It is also sensible to consider the priorities of the people who may feel the consequences of executing the selected decision alternative. In the latter case, the opinion of residents and operators of the stormwater management system is of particular importance, although taking into account the positions of tourists or ecologists may also be necessary at times.

Due to the high complexity of the discussed decision issue and the significant number of its possible solutions, it is sensible for the drainage infrastructure planning process to only include those decision options whose application under the given conditions is technically and financially justified. Such an approach to the issue of designing stormwater management systems will enable the number of required pair comparisons of individual hierarchy elements to be limited and will significantly reduce the duration of the analysis. Preliminary selection of design variants can, for example, be based on the location criterion—i.e., the soil and water characteristics and the surface of the area where the drainage facility is to be located as well as the management method and the catchment area. This stems from the fact that every device that is utilised in water and sewerage management has unique characteristics and limits of application.

A fragment of a survey that could be utilised to compare the main criteria of a decision process from the perspective of the decision objective in such a case is presented in Appendix A. The expert's task here is to select the criteria that are the most important from the perspective of selecting a management system for stormwater generated within urban drainage areas, and determine the degree of the selected criterion's advantage over the compared element. The effect of this procedure is the creation of square matrices which are, in turn, used as a basis to determine weight coefficients. Weight coefficients can be determined thanks to the use of appropriate computer programs. These programs use, among others, methods such as: the eigenvector method, arithmetic mean method and geometric mean method [62].

Figure 3 presents values of weight coefficients determined by the eigenvector method using expert judgments for the example presented in Appendix A. They are an integral part of the studies conducted among eight specialists from the environmental engineering field concerning their preferences for stormwater management systems. The choice of experts for surveys was mainly determined by their competence. They were persons professionally involved in the design, construction and operation of stormwater management systems, with many years of experience in this matter. In turn, the scientific community was represented by recognized people in the field of stormwater management. The chart includes only those results that meet the matrix consistency condition ($CR \leq 10\%$). The value of the consistency ratio ($CR$) of each expert was determined based on the maximum eigenvalue of the pairwise comparison matrix ($\lambda_{max}$), the number of compared criteria ($n$), and the consistency ratio ($RI$) [75].

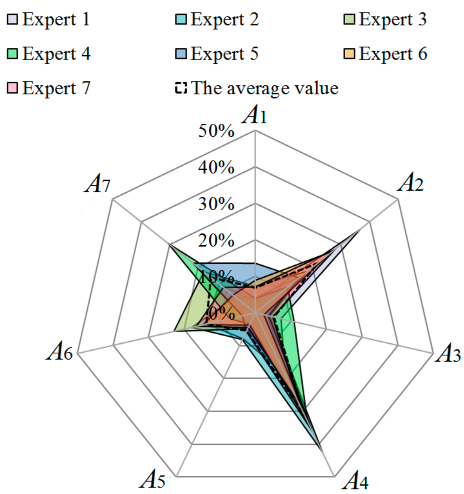


**Figure 3.** Weight coefficient values determined using the judgments of experts in the field of environmental engineering.

The presented data clearly indicates that experts consider operating and hydraulic factors as the most important, giving the least weight to aesthetic and social ones. However, it is to be expected that assessments of other participants of the decision process will differ drastically from these presented using the chart. For example, economic factors will play a major role for investors, while environmental criteria will play a major role for ecologists. In turn, from the perspective of local residents or tourists, the most important will be the decision process criteria related to aesthetics and quality of life. This gives rise to a need to take into account, during the stormwater management system's design stage, the preferences of all groups that may experience the results of executing such an undertaking as well as those of possible decision makers, as only this kind of approach enables finding a satisfactory solution to the analysed problem.

It is also worth emphasising that the prepared structure of the decision problem related to selecting a stormwater management system can be modified. Depending on the project's scale, investment conditions, origin of the stormwater and requirements towards it, individual sub-criteria of the analysed decision problem can be ignored, which will simplify the decision-making process, or divided, consequently isolating another level of the problem. For example, sub-criterion $A_{61}$ of the environmental criterion can be detailed in relation to phenomena occurring in the receiving body of water (Figure 4a). In the case of sub-criterion $A_{62}$, it can be the effectiveness of removing various types of pollution (Figure 4b).

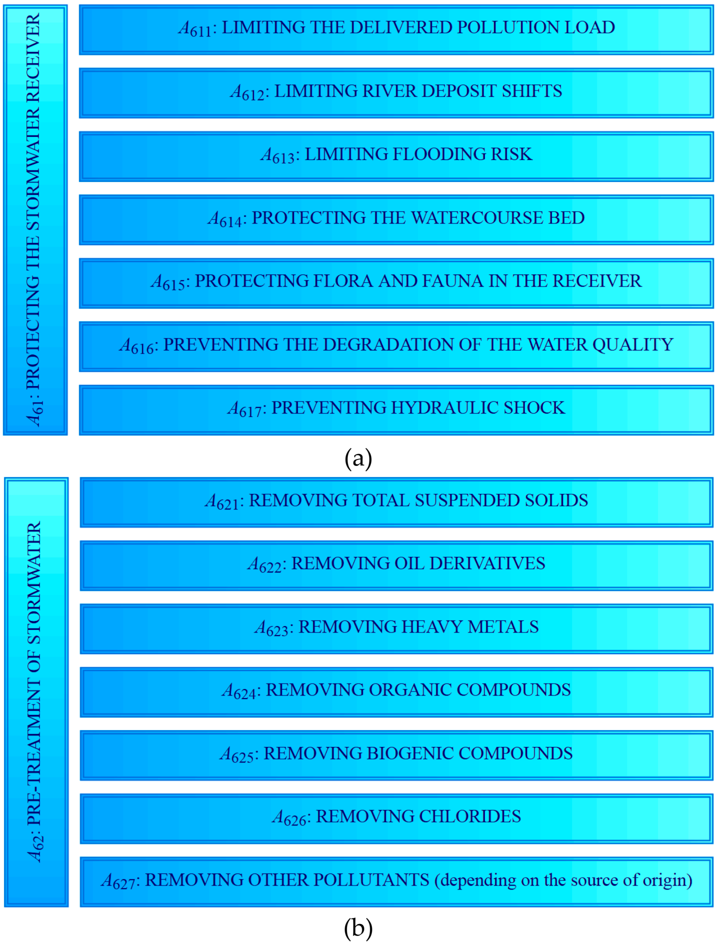


**Figure 4.** Sample division of selected sub-criteria of the analysed decision problem: (**a**) Protecting the stormwater receiver, (**b**) Pre-treatment of stormwater.

The presented hierarchic model of the problem can be simplified when a single-family building is analysed, and the decision is made only on the basis of the owner's preferences. In these situations, individual sub-criteria of the hydraulic or environmental criteria, extremely important from the perspective of other groups, may appear irrelevant to the decision maker, resulting in their elimination from the model. Additionally, if the building in question is located in a city where charges for rainwater drainage are not imposed the economic criterion can be reduced merely to lifecycle costs of the design variants under consideration.

### 3.2. Possible Design Variants of the Stormwater Management System

Implementation of the developed decision support model in the investment process will enable an unbiased comparison of a conventional stormwater management system with alternative solutions that include rainwater harvesting [76,77], underground and surface infiltration of stormwater into the soil [78,79] and its retention [80–82]. Due to the significant number of available devices (Figure 5) and their possible combinations, both with each other and with stormwater pre-treatment facilities, the decision process must only take into account the options that are technically justified under the given circumstances. It must be noted that the preliminary selection of considered investment variants can be made not only on the basis of the location criterion, as mentioned above, but also on the basis of the decision maker's preferences, who can reject individual variants even before commencing pair comparisons.

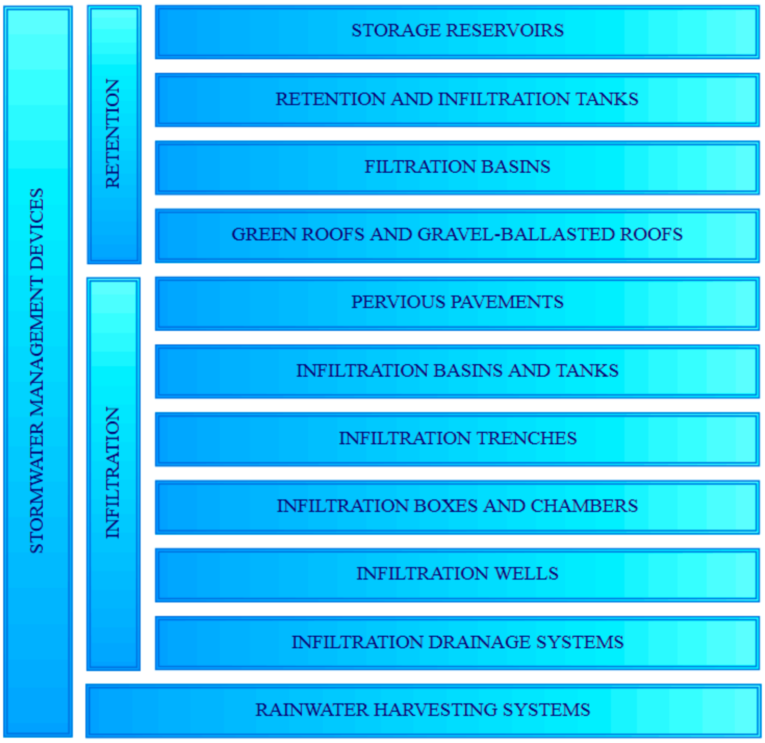


**Figure 5.** Stormwater management devices used in Poland.

### 3.3. Model Implementation

Due to the fact that in the Rzeszow area no charges are imposed for drainage of stormwater, and the investor in this case is the premises owner, the economic criterion $A_1$ is only related to the life cycle costs of individual decision options. On account of the small scale of the project, the other fragments of the hierarchy have been simplified as well. The decision support model, which takes into account the implemented changes, is presented in Figure 6. All decision criteria included in it are described in Appendix B. Additionally, the results of calculations performed using the eigenvector method and the decision maker's judgments are presented in Figure 6. The second level of the hierarchy describes the local priority values of the main decision process criteria, and level three—global priorities of individual sub-criteria that have been calculated as products of priorities of the given sub-criterion and its corresponding criterion. The lowest hierarchy level presents the summary grade of the analysed decision variants.

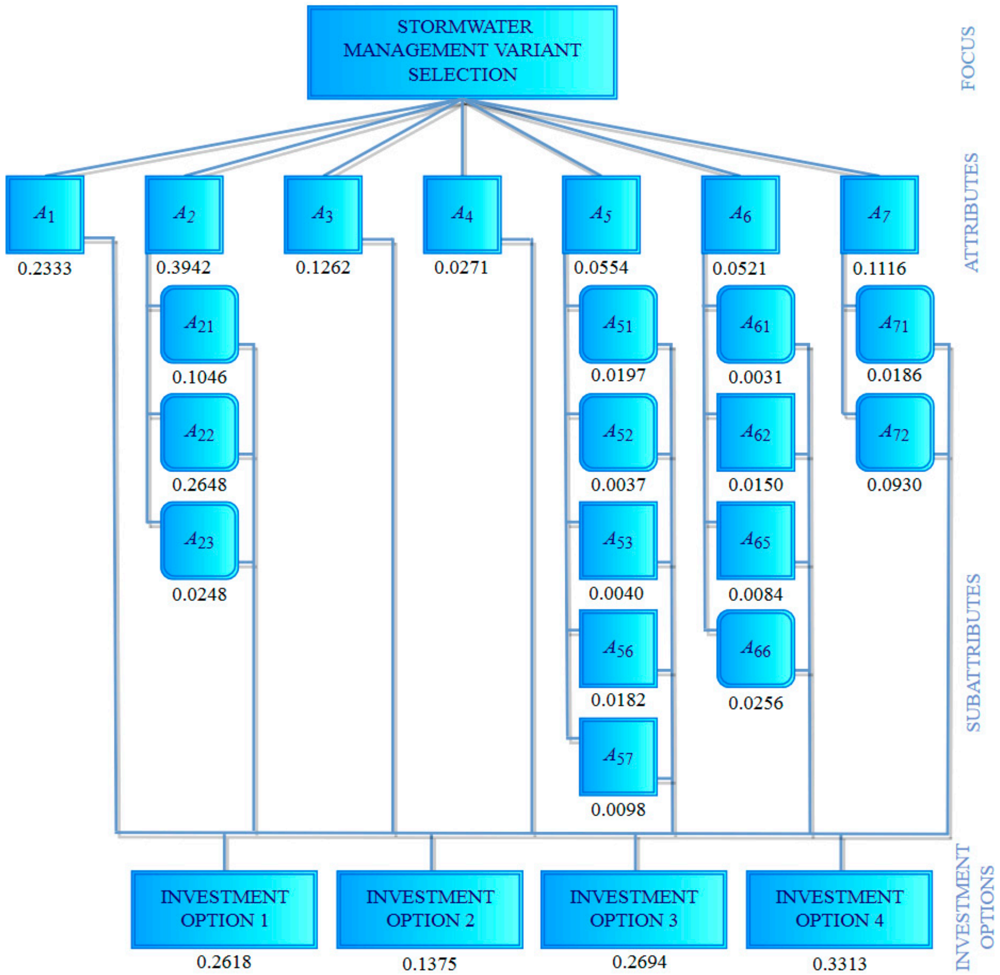


**Figure 6.** Modified model of decision support for selecting the best stormwater management system solution.

The decision maker, who in this case is the building's owner, considers the operation criterion as the most important, which has also received high grades in surveys held among environmental engineering experts (Figure 3). However, the priority values of other decision process criteria differ significantly. For example, the hydraulic criterion—highly important from the standpoint of experts—found itself in the last place of the ranking. On the other hand, the decision maker showed appreciation of the economic factor related to the scale of the life cycle costs of the analysed investment variants.

The values of priority of individual criteria and sub-criteria of the decision process were decisive for the final order of the decision options under consideration, according to which the most beneficial method of managing stormwater at the analysed premises was the construction of an infiltration trench. It is worth noting that infiltration trenches are not highly popular in Poland. At the same time, the conducted studies have demonstrated that they are characterised by better aesthetic properties and a lower risk related to their operation than other investment variants. In Appendix C, unlike Figure 6, the values of local priorities assigned to individual elements of the decision model were summarized. The least beneficial solution turned out to be the infiltration well, which is one of the most commonly utilised infiltration devices designed for managing stormwater drains from residential buildings in Poland. This confirms that stormwater management systems currently in use in Poland do not always meet the requirements placed on them. For this reason, it is necessary to perform an analysis of the decision participants' preferences in each individual case, as it is the only approach that enables selecting the investment variant consistent with the needs of the investor, operator and the system's users.

In order to take into account the impact of changes in individual assessments on the final results of the analysis, a scenario analysis was also carried out. The results obtained under the scenarios described in Section 2.2 are summarized in Table 4. In scenario 1, according to which only operational criteria were considered, an underground infiltration device (infiltration boxes) turned out to be the best solution. This is due to the fact that the infiltration boxes have been relatively highly rated in terms of the possibility of reducing the required maintenance and ensuring the safe operation of the system. It should be noted, however, that the next positions in the ranking included nature-based solutions, i.e., the infiltration trench and the infiltration basin. The infiltration well remained at the last position in the ranking.

**Table 4.** The sensitivity analysis results.

| Scenario | Investment Options Evaluation | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| 1 | 0.399 | 0.134 | 0.158 | 0.309 |
| 2 | 0.291 | 0.130 | 0.248 | 0.330 |
| 3 | 0.248 | 0.203 | 0.280 | 0.270 |
| 4 | 0.229 | 0.155 | 0.290 | 0.327 |

For scenarios 3 and 4, nature-based solutions were placed in the first two positions in the ranking, similar to the basic analysis. Additionally, in scenario 2, the first position in the ranking was taken by the infiltration trench. In all cases, the last place in the ranking was taken by the infiltration well. This confirms that the use of nature-based devices can bring multiple benefits to people and the surrounding environment, while being characterized by high landscape values. The use of the most popular solution in Poland, i.e., infiltration wells, does not have visual values and has low social and technical values.

## 4. Conclusions

The need for gathering and draining of stormwater flowing from the surface of urbanised drainage areas is one of the primary challenges of the 21st century. Many of the problems encountered by operators of stormwater management systems and people inhabiting drainage areas can be avoided by considering all aspects accompanying the construction and operation of such systems during the design stage. Such an approach to the issue of selecting the strategy of stormwater management will limit the negative impact of stormwater on the natural environment and the local community. As part of the research described in this paper, the criteria determining the selection of the best stormwater management system solution were identified. These included criteria directly related to the construction and operation of the stormwater management system (economic, operational, hydraulic, technical and locational), as well as factors regarding aesthetic values and social and environmental aspects.

The research described in the paper used the AHP method to indicate the most favorable way of managing rainwater discharged from the roof of a single-family house. Based on the identified decision criteria and the owner's preferences regarding potential investment options, a decision model was built and its individual elements were evaluated. As a result, the ranking of considered decision options were obtained, according to which the infiltration trench came first. The next positions were taken by the infiltration basin and infiltration boxes. The infiltration well came last, and received a rating of almost 60% lower than the infiltration trench. It is worth noting that the first two positions in the ranking included nature-based solutions, which in the case of Poland do not enjoy much interest. The infiltration well, which is currently frequently used, was assessed as the worst, mainly due to its low rating in relation to the environmental criteria of the decision-making process. It proves that the stormwater management system solutions commonly utilised in Poland do not always meet the needs. Meanwhile, numerous nature-based solutions are available that enable effective management of stormwater and additionally are characterised by aesthetic properties and positively affect the microclimate and the local community. As part of this study, sensitivity analysis was also carried out. Its results confirmed that the most favored option was the use of nature-based solutions.

The limitations of the research described in this paper include the lack of consideration of objects intended for the retention of stormwater and their harvesting. An increase in the number of potential decision options may change the final ranking of decision options. It should also be taken into account that in the case of small plots, the application of nature-based solutions may not be possible due to the larger demand for space for the development of such facilities. In extreme cases, it may even turn out that the only rational way to manage stormwater is its intake and direct discharge to a conventional stormwater management system, especially for existing buildings.

It is also worth stressing that depending on the case, the decision maker's preferences may differ, resulting in the need for an independent analysis of possible gains and losses resulting from the considered investment variants to be performed in each individual instance. In the case of larger-scale projects, it is also important to analyse the sensitivity of the obtained results to changes of individualscores, which will enable the investment risk to be reduced.

Previous research on the use of multi-criteria decision-making methods in the field of stormwater management rarely concerned individual residential buildings. They rather focused on larger urban catchments, where the decision to choose a specific decision option was not usually consulted with building owners. Research related to the discharge of rainwater from individual properties focused on assessing the possibility of using them as an alternative source of water. This shows the need for further research aimed at assessing the possibility of using multi-criteria decision-making methods in the field of stormwater management. These studies should include the application of the developed decision problem structure for catchments of various characteristics. It is also necessary to develop models dedicated to optimizing specific design variants of the stormwater management system. This process may, for example, be aimed at selecting optimal dimensions of objects, including nature-based devices, or minimizing their life cycle costs.

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## Appendix A. Determination of Local Priorities Values

Individual elements of the decision model were assessed by means of surveys, by comparing them in pairs with respect to subsequent elements of the level immediately above. Figure A1 presents an example of a questionnaire (translated from Polish) created to compare the main criteria of the decision-making process from the point of view of the main purpose of the analysis, which was the selection of the centralized stormwater management system. Based on the assessments assigned by one of the experts (Figure A2), a square matrix of pairwise comparisons was created (Figure A3). Then, based on the eigenvector method, the values of local priorities were determined, which were:

- economic criteria $w_{A1} = 0.071$,
- operating criteria $w_{A2} = 0.279$,
- aesthetic criteria $w_{A3} = 0.048$,
- hydraulic criteria $w_{A4} = 0.279$,

- social criteria $w_{A5}$ = 0.045,
- environmental criteria $w_{A6}$ = 0.166,
- technical criteria $w_{A7}$ = 0.112.

The consistency ratio was $CR$ = 2%.

Please compare in pairs the main decision criteria listed in the table below in terms of their importance from the point of view of choosing the most favorable stormwater management system solution in the urban catchment.
The survey uses the 9-point fundamental Saaty's scale, according to which:
- „1" – determines the equivalence of the compared items,
- „3" – indicates a moderate preference for one element over another,
- „5" – indicates a strong preference for one element over another,
- „7" – defines a very strong preference for one element over another,
- „9" – means the absolute preference of one element over another,
- „2", „4", „6" and „8" – describe the intermediate preferences between those described above.

Please put exactly one „X" next to each pair of the main decision criteria being compared.

| Criteria | Intensity of Importance | | | | | | | | | | | | | | | | | Criteria |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Extreme importance | | Very strong importance | | Strong importance | | Moderate importance | | Equal importance | | Moderate importance | | Strong importance | | Very strong importance | | Extreme importance | |
| | 9 | | 7 | | 5 | | 3 | | 1 | | 3 | | 5 | | 7 | | 9 | |
| $A_1$: Economic | | | | | | | | | | | | | | | | | | $A_2$: Operating |
| | | | | | | | | | | | | | | | | | | $A_3$: Aesthetic |
| | | | | | | | | | | | | | | | | | | $A_4$: Hydraulic |
| | | | | | | | | | | | | | | | | | | $A_5$: Social |
| | | | | | | | | | | | | | | | | | | $A_6$: Environmental |
| | | | | | | | | | | | | | | | | | | $A_7$: Technical |
| $A_2$: Operating | | | | | | | | | | | | | | | | | | $A_3$: Aesthetic |
| | | | | | | | | | | | | | | | | | | $A_4$: Hydraulic |
| | | | | | | | | | | | | | | | | | | $A_5$: Social |
| | | | | | | | | | | | | | | | | | | $A_6$: Environmental |
| | | | | | | | | | | | | | | | | | | $A_7$: Technical |
| $A_3$: Aesthetic | | | | | | | | | | | | | | | | | | $A_4$: Hydraulic |
| | | | | | | | | | | | | | | | | | | $A_5$: Social |
| | | | | | | | | | | | | | | | | | | $A_6$: Environmental |
| | | | | | | | | | | | | | | | | | | $A_7$: Technical |
| $A_4$: Hydraulic | | | | | | | | | | | | | | | | | | $A_5$: Social |
| | | | | | | | | | | | | | | | | | | $A_6$: Environmental |
| | | | | | | | | | | | | | | | | | | $A_7$: Technical |
| $A_5$: Social | | | | | | | | | | | | | | | | | | $A_6$: Environmental |
| | | | | | | | | | | | | | | | | | | $A_7$: Technical |
| $A_6$: Environmental | | | | | | | | | | | | | | | | | | $A_7$: Technical |

**Figure A1.** Questionnaire created to compare the main criteria of a decision process from the perspective of the decision objective, i.e., selection of a stormwater management system.

| **Criteria** | **Intensity of Importance** | | | | | | | | | | | | | | | | | **Criteria** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Extreme importance | | Very strong importance | | Strong importance | | Moderate importance | | Equal importance | | Moderate importance | | Strong importance | | Very strong importance | | Extreme importance | |
| | 9 | | 7 | | 5 | | 3 | | 1 | | 3 | | 5 | | 7 | | 9 | |
| *A*1: Economic | | | | | | | | | | | | | X | | | | | *A*2: Operating |
| | | | | | | | | X | | | | | | | | | | *A*3: Aesthetic |
| | | | | | | | | | | | | | X | | | | | *A*4: Hydraulic |
| | | | | | | | | X | | | | | | | | | | *A*5: Social |
| | | | | | | | | | | X | | | | | | | | *A*6: Environmental |
| | | | | | | | | | | X | | | | | | | | *A*7: Technical |
| *A*2: Operating | | | | | | X | | | | | | | | | | | | *A*3: Aesthetic |
| | | | | | | | | | X | | | | | | | | | *A*4: Hydraulic |
| | | | | | X | | | | | | | | | | | | | *A*5: Social |
| | | | | | | | | X | | | | | | | | | | *A*6: Environmental |
| | | | | | | | X | | | | | | | | | | | *A*7: Technical |
| *A*3: Aesthetic | | | | | | | | | | | | X | | | | | | *A*4: Hydraulic |
| | | | | | | | | | X | | | | | | | | | *A*5: Social |
| | | | | | | | | | | | | X | | | | | | *A*6: Environmental |
| | | | | | | | | | | | X | | | | | | | *A*7: Technical |
| *A*4: Hydraulic | | | | | X | | | | | | | | | | | | | *A*5: Social |
| | | | | | | | | X | | | | | | | | | | *A*6: Environmental |
| | | | | | | | X | | | | | | | | | | | *A*7: Technical |
| *A*5: Social | | | | | | | | | | | | | X | | | | | *A*6: Environmental |
| | | | | | | | | | | | | X | | | | | | *A*7: Technical |
| *A*6: Environmental | | | | | | | | X | | | | | | | | | | *A*7: Technical |

**Figure A2.** The assessments assigned by one of the experts.

| | *A*1 | *A*2 | *A*3 | *A*4 | *A*5 | *A*6 | *A*7 |
|---|---|---|---|---|---|---|---|
| *A*1 | 1 | 0.20 | 2 | 0.20 | 2 | 0.50 | 0.50 |
| *A*2 | 5 | 1 | 4 | 1 | 5 | 2 | 3 |
| *A*3 | 0.50 | 0.25 | 1 | 0.25 | 1 | 0.25 | 0.33 |
| *A*4 | 5 | 1 | 4 | 1 | 5 | 2 | 3 |
| *A*5 | 0.50 | 0.20 | 1 | 0.20 | 1 | 0.25 | 0.33 |
| *A*6 | 2 | 0.5 | 4 | 0.50 | 4 | 1 | 2 |
| *A*7 | 2 | 0.33 | 3 | 0.33 | 3 | 0.50 | 1 |

**Figure A3.** A square matrix of pairwise comparisons (based on the assessments from Figure A2).

## Appendix B. Description of Criteria

Table A1 presents the characteristics of criteria taken into account in the research on the selection of a system dedicated to rainwater drainage from a single-family house.

**Table A1.** List of criteria with a short description.

| | | |
|---|---|---|
| Economic criterion $A_1$ | - | In the analyzed case, this criterion is mainly related to the amount of life cycle costs of individual infiltration facilities, which result from the amount of investment outlays and the expected operating costs of the system. |
| Operating criteria $A_2$ | $A_{21}$ | This sub-criterion concerns the failure rate of the decision options considered. Solutions whose use ensures long-term, trouble-free operation of the stormwater management system should be used. |
| | $A_{22}$ | This sub-criterion is related to the need to use solutions that are adaptable to changing environmental conditions, including forecast climate change. |
| | $A_{23}$ | This sub-criterion refers to the frequency of required maintenance, including, for example, maintaining an adequate level of stormwater infiltration. It is necessary to use solutions that will have minimum operational requirements. |
| Aesthetic criterion $A_3$ | - | In the case under consideration, this criterion mainly refers to the need to create an element of small architecture, the implementation of which will improve the quality of the landscape and living conditions of the residents, without losing its original purpose. |
| Hydraulic criterion $A_4$ | - | In the case under consideration, this criterion mainly refers to the need to adapt the designed system to the existing drainage infrastructure and to limit the amount of stormwater directed to the receiving body of water. |
| Social criteria $A_5$ | $A_{51}$ | This sub-criterion includes the need to design a stormwater management system in accordance with the applicable legal regulations. |
| | $A_{52}$ | This sub-criterion concerns the need to design a system whose functioning will be adapted to the lifestyle of residents. Communing with nature is one of the most desirable aspects of spending free time. |
| | $A_{53}$ | This sub-criterion concerns the improvement of ecological awareness of individual system users. Even they should be aware of the importance of the problem arising from the need to manage stormwater and the need to solve it in harmony with nature. |
| | $A_{56}$ | This sub-criterion is related to the need to ensure the safety of residents, including the elimination of threats to their health and life. |
| | $A_{57}$ | This sub-criterion concerns the need to limit social losses resulting from improperly managed stormwater, including infrastructure damage. |
| Environmental criteria $A_6$ | $A_{61}$ | This sub-criterion refers to the need to protect the stormwater receiver. This can applies to the protection of rivers as a result of limiting the amount of stormwater discharge, as well as groundwater in the case of stormwater infiltration into the ground. |
| | $A_{62}$ | This sub-criterion relates to the possibility of treating stormwater flowing through the device, for example during filtration through layers of soil. |
| | $A_{65}$ | This sub-criterion includes the possibility of improving the local microclimate through the use of nature-based solutions. |
| | $A_{66}$ | This sub-criterion concerns the possibility of supplying groundwater resources as a result of infiltrating stormwater into the ground. |
| Technical criteria $A_7$ | $A_{71}$ | This sub-criterion concerns the possibility of supporting the stormwater management system design process by using appropriate computer programs or design materials. |
| | $A_{72}$ | This sub-criterion is related to the need to use solutions that are relatively simple and quick to implement. |

## Appendix C. Local Priority Values

Table A2 presents the values of local priorities obtained from individual square matrices of pair comparisons in studies on the selection of a system dedicated to draining stormwater from a single-family house. The studies were based on the criteria described in Appendix B.

**Table A2.** The local priority values of individual elements.

| Criteria | Sub-Criteria | Local Priority Values | Local Priority Values of Investment Options | | | |
|---|---|---|---|---|---|---|
| | | | Investment Option 1 | Investment Option 2 | Investment Option 3 | Investment Option 4 |
| $A_1$ | - | - | 0.0681 | 0.1669 | 0.4849 | 0.2800 |
| $A_2$ | $A_{21}$ | 0.2654 | 0.1999 | 0.0815 | 0.3593 | 0.3593 |
| | $A_{22}$ | 0.6716 | 0.4829 | 0.1570 | 0.0882 | 0.2720 |
| | $A_{23}$ | 0.0629 | 0.3444 | 0.1165 | 0.0509 | 0.4881 |
| $A_3$ | - | - | 0.0790 | 0.0483 | 0.3304 | 0.5423 |
| $A_4$ | - | - | 0.2500 | 0.2500 | 0.2500 | 0.2500 |
| $A_5$ | $A_{51}$ | 0.3557 | 0.2500 | 0.2500 | 0.2500 | 0.2500 |
| | $A_{52}$ | 0.0671 | 0.4488 | 0.2346 | 0.0819 | 0.2346 |
| | $A_{53}$ | 0.0714 | 0.0809 | 0.1539 | 0.4773 | 0.2880 |
| | $A_{56}$ | 0.3285 | 0.4489 | 0.2109 | 0.0572 | 0.2830 |
| | $A_{57}$ | 0.1774 | 0.2500 | 0.2500 | 0.2500 | 0.2500 |
| $A_6$ | $A_{61}$ | 0.0601 | 0.1055 | 0.0609 | 0.5693 | 0.2643 |
| | $A_{62}$ | 0.2878 | 0.1055 | 0.0609 | 0.5693 | 0.2643 |
| | $A_{65}$ | 0.1615 | 0.0500 | 0.0500 | 0.4500 | 0.4500 |
| | $A_{66}$ | 0.4905 | 0.2500 | 0.2500 | 0.2500 | 0.2500 |
| $A_7$ | $A_{71}$ | 0.1667 | 0.4829 | 0.2720 | 0.0882 | 0.1570 |
| | $A_{72}$ | 0.8333 | 0.3936 | 0.0753 | 0.1375 | 0.3936 |

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