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Financial Aspects of Sustainable Rainwater Management in Small-Scale Urban Housing Communities

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Abstract: Sustainable rainwater management may counteract the effects of climate change and significantly improve the distorted water balance in urbanized catchments. However, despite the hydrologic advantages of rainwater management, acceptance and willingness-to-pay in the local society are required. This paper presents an assessment of the financial aspects, i.e., the cost-efficiency and economic feasibility, of various designs of rainwater management for a small-scale urban housing community in Lublin, Poland. The research was performed for a housing community covering approx. 1.38 ha and five multi-family residential buildings. The proposed designs covered rainwater harvesting systems, supported with extensive green roofs, with rainwater retained in underground or above-ground reservoirs, used with variable demand for watering the green areas and for underground parking lot flushing. For each designed variant, the investment as well as operation and maintenance costs were estimated. The assessment of the cost-efficiency and profitability of the proposed rainwater management systems was based on three indicators: Dynamic Generation Costs, Payback Period and Benefits–Costs Ratio. The performed calculations showed that only two designs, utilizing above-ground rainwater reservoirs, could be assessed as economically profitable. Thus, local communities may be unable to financially sustain investments in sustainable rainwater management, so it seems that financial support is required.

Keywords: sustainable rainwater management; economic efficiency; LID; rainwater harvesting; urban catchment

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1. Introduction

1.1. Sustainable Water and Rainwater Management in Urban Catchments

Sustainable water management in urban areas should cover several important issues related to the altered hydrologic cycle and its consequences, the quality of the rainwater and snowmelt runoff, as well as the availability of freshwater and water service pricing.

In urbanized areas, the hydrologic cycle is significantly modified compared to in natural catchments due to the changed proportions of infiltration, evapotranspiration and surface runoff [1–3]. An increased fraction of impervious surfaces results in a higher risk of waterlogging and floods caused by enlarged runoff, shorter rainwater flow times and reduced evapotranspiration compared to natural catchments [4,5]. An increase in the area of sealed surfaces also causes a reduction in rainwater infiltration and, as result, may lead to groundwater shortage [6–8]. However, changed proportions between infiltration, evapotranspiration and surface runoff in urbanized areas, and the scale of the consequences resulting from unbalance water cycles, differ depending on the characteristic of a certain catchment [1]. The consequences of changed water balance may be additionally intensified by climate changes responsible for climate anomalies such as higher temperatures, prolonged dry periods and increased numbers of intense rainfall events [9,10].

The second important issue of sustainable water management is related to the quality of the runoff of rainwater or snowmelt that can be deteriorated in urban areas, causing

the contamination of water receivers [11,12]. As was underlined in several scientific papers, the major sources of pollution are atmospheric deposition and transportation and metallic materials used in construction. These are responsible for water contamination with pollutants identified as follows: biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total phosphorus (TP), NH_3 Cd, Cr, Cu, Pb, Ni, Hg or Zn [11,13,14] or even microplastics (MPs) [15].

The growing water demand and availability of water resources are further challenges of sustainable urban water management. Access to water is already limited in many places of the world [16–19]. Over the last century, water use has more than doubled compared to the rate of population growth [20]. About 20% of the world's groundwater resources, supplying drinking water to more than 50% the world's population, is already overexploited and this stress will intensify as water demand is expected to increase over the next 30 years [21], especially in developing countries where even an 80% increase can be expected [22]. The limited availability of water resources is additionally threatened by climate change related, among other factors, to increasing drought and water supply variability [16,23]. In the future, this situation could affect such important issues as food security on both a macro- and microscale [23,24].

Poland, one of the main suppliers of agricultural produce and foodstuffs in the European Union, is a country with low water resources. The total amount of surface water flow per capita is lower than 1600 m^3, while the average for Europe is approx. 4600 m^3/capita [25]. Moreover, drought threat analyses have shown that almost 56% of Poland is under serious threat of drought [26].

Additionally, tap water prices have been rising over the years. The average global price of combined traffic for water and wastewater services increased by 27% between 2011 and 2019 (from USD 1.70/m^3 in 2011 to USD 2.16/m^3), resulting in an approx. 3.4% increase in the annual combined tariff value [27]. In Lublin (Eastern Poland), the localization selected for the case study presented in this paper, the net increase in the water and sewage service increased by approx. 38% between the years 2010 and 2021 [28], resulting in an average annual growth of 3.5%. In some parts of the world, these changes may be even more dynamic. One example is Bangladesh, where between 2016 and 2020 the water tariff price nearly doubled [29].

It is important to underline the fact that, in the urban areas, the significant water demand covers activities in which non-potable water could be used, for example, the irrigation of green spaces, car washing, toilet flushing, cleaning, etc. [30]. The introduction of more sustainable methods of water management in cities can lead to a reduction in natural water reserve stress, creating, at the same time, potential for saving. Thus, in the face of climate change, manifested by changes in the intensity and frequency of rainfall, rainwater management, especially in urban areas, should be based on solutions aimed at retaining, managing and purifying rainwater in the catchment area [31–34].

1.2. Low-Impact Development in Urbanized Catchments

The application of low-impact solutions (LID) instead of traditional rainwater management methods, makes reversing unfavorable changes in rainwater runoff, as a result of the urbanization of urban catchments, possible [35]. Under LID, various types of devices are used to restore or maintain the hydrology of the area before development, by increasing evapotranspiration, infiltration and/or groundwater recharge. The most popular designs include green roofs, green walls, rain gardens, rain water harvesting (RWH) systems and water-permeable surfaces [36,37].

In developed urban areas, where roof surfaces account for 40–50% of all impervious surfaces, green roofs are a solution that has visible, positive effects in rainwater management and can reduce the risk of flooding. Thanks to their ability to retain water for a longer time (the retention of a green roof is in the range of 60–70%) [38,39], green roofs enable a reduction in the volume of rainwater discharged from the catchment area from 30% to 86%, a reduction from 22% to 93% and a delay from 0 to 30 min [40] in the peak flow, as well as

increase in evapotranspiration [41]. The retention capacity of green roofs depends on the type (extensive or intensive) and age of the green roof, the depth and type of the substrate layer, the roof slope, the type of vegetation and climatic conditions [36–38,40,42].

However, on a building scale, green roofs contribute to energy savings [43,44], influencing the building's thermal comfort by lowering the temperature in buildings in the summer (from 4 °C to 6 °C) and limiting heat loss in the winter. The use of green roofs increases the durability of partitions and extends the life of roofs [45,46], reduces the transmission of sound to buildings [47,48] and may also increase the efficiency of photovoltaic (PV) panels [49,50]. The large-scale implementation of green roofs, green walls and rain gardens, apart from their measurable benefits, also has a non-economic advantages in the form of increasing the aesthetics and recreational use of public spaces, increasing biodiversity and promoting the health and well-being of citizens [51,52]. The use of LID solutions is undoubtedly associated with numerous environmental, economic and social benefits. The main benefits primarily result from reducing the number of floods; reducing the consumption of drinking water; improving the quality of water transported into water reservoir; increasing water infiltration into the ground; increasing the attractiveness of the surroundings; reducing the green deficit in the city structure; increasing oxygen production; reducing carbon dioxide and other pollutants; improving the microclimate; reducing the urban heat island effect; and, in the case of buildings, saving energy for heating and cooling and noise suppression [36–38,40,42,53,54]. These benefits are consistent with the main United Nations' Sustainable Development Goals of clean water, sustainable cities and communities, responsible consumption and production and climate action [55].

In recent decades, many countries have been promoting the implementation of RWH systems in an effort to reduce drinking water consumption. Numerous studies indicate the possibility of significant savings in drinking water consumption when using systems for collecting, storing, distributing and using treated rainwater, instead of tap water, for various purposes (watering greenery, washing surfaces, washing or flushing toilets) [56]. Additionally, numerous researchers have confirmed the positive impact of RWH systems on the water balance of urbanized catchments [30,57–60].

In many countries around the world, RWH systems are treated as a possible alternative method of supplying water, which, additionally, can increase the security of the water supply and counteract and prevent the effects of urban floods [61–63]. It was reported that, in built-up areas, the use of RWH systems can reduce drinking water consumption by up to 60–80% [64,65]. The possibility of implementing RWH systems, and the water savings obtained in this respect, depend primarily on climatic conditions (amount and frequency of rainfall) and the demand for non-potable water (type of building, number of users and individual water consumption standards for a given purpose) [66]. These factors also affect the financial efficiency of using a rainwater collection system [67].

The degree of implementation of LID systems varies significantly between different countries all over the world [68–84]. The use of low-impact solutions very often requires additional investment and/or operating costs compared to conventional designs, which may be one of the factors affecting the limited application of these systems. Factors influencing limitations in the use of LID designs are mainly related to the economic, technological, regulatory, social and environmental aspects. The most common obstacles observed worldwide include high investment costs and the lack of appropriate state subsidies and investment support programs, engineers having insufficient knowledge of designing LID solutions, a lack of appropriate legal regulations, as well as a lack of appropriate ecological awareness and a reluctance to use green infrastructure by society [85–87]. Research conducted, among others, by Musz-Pomorska et al. [30], regarding the use of RWH solutions in Polish conditions, showed the limited profitability of the studied projects and the insufficient financial support from the state, which may translate into reluctance on the part of residents to implement the designed systems. The low economic profitability of selected LID designs for the decentralized management of rainwater discharged from the roofs of two different buildings located in Poland was demonstrated in research conducted by Iwanek and Suchorab [83]. The obtained

research results showed the profitability of using dual installations and infiltration tunnels, and the unprofitability of using infiltration boxes without additional sources of financing, for example, in the form of subsidies. Research on the economic effectiveness of a dual installation with a rainwater tank of various capacities, conducted by Stec and Zeleňáková [73], indicated that the economic profitability of this type of investment depends largely on the location of the building. The obtained results clearly showed that the implementation of RWH systems in the dormitory in Rzeszów was unprofitable for all tank capacities tested, and the payback period of the investment significantly exceeded the period of 30 years adopted for analysis. In the case of RWH systems in a student residence located in Kosice (Slovakia), the financial indicators NPV (Net Present Value) and PP (Payback Period) were very favorable. Model studies of the hydraulic and economic efficiency of using green roofs under Polish conditions, conducted, among others, by Widomski et al. [84] and Bus and Szelągowska [74], showed a clear environmental effect in the form of reduced stormwater runoff from the studied catchments. However, the economic profitability of this type of investment in Polish conditions may be noticeable only in the long term, in most cases, with additional external financial support for the investment. An additional problem in the implementation of LID solutions in Poland is the lack of information campaigns promoting this type of system, as well as guidelines for their implementation and operation and any analyses supporting investment decisions. The scale of public support and the availability of financial resources are also important [88–91].

Based on the experience of countries such as Canada, Germany, the USA, Switzerland, Singapore and Japan, it appears that the introduction of appropriate legal regulations at the state level directly translates into an increase in the development and installation of LID systems on a large scale [43,92,93]. In Stuttgart, Germany, a combination of regulation and subsidies has led to the development of green roofs covering an area of approximately 2 km^2 [94].

1.3. Scope of the Study

The performed literature review showed that, despite the numerous proven significant environmental and social benefits of various LID designs, including the green roofs and rainwater harvesting systems, their economic aspects are a possible barrier to their wide application by the residential building owners, stakeholders or small housing communities. Thus, in the described particular cases, the low economic viability of urban rainwater management based on LID designs may result in a low social acceptance and limited willingness-to-pay, without which their sustainability may be doubtful. However, according to the presented literature studies, the discussed determinants of economic feasibility of LID application are non-uniform and may vary among not only countries but also regions. There is still an unanswered question as to what extend the economic sustainability of rainwater management designs is related to the selection of technology and devices and the volume of reused rainwater.

This paper was focused on the financial aspects of several selected possible designs of sustainable rainwater management, utilizing rainwater harvesting systems and extensive green roofs, proposed for a typical small-scale multi-family housing community under climatic and economic conditions in Lublin, Poland. The determined results of the financial analyses allowed us to assess the possible economic attractiveness factors affecting the acceptance and willingness-to-pay of the local residents, as well as the co-owners of the housing community. This work may also contribute to the current state of knowledge considering the main determinants of the economic sustainability of small-scale rainwater management in urbanized catchments.

2. Materials and Methods

The main aim of this study was to determine the financial feasibility and to understand the economic profitability and cost-efficiency of eight variants of possible, technologically up-to-date sustainable rainwater management systems for a small-scale housing commu-

nity under the actual economic conditions in Poland. The presented studies were based on the carefully estimated investment as well as operation and maintenance (O&M) costs, which allowed us to determine values of selected economic indicators: Dynamic Generation Costs, Payback Period and Benefits–Costs Ratio. The research methodology assumed is presented in Figure 1.

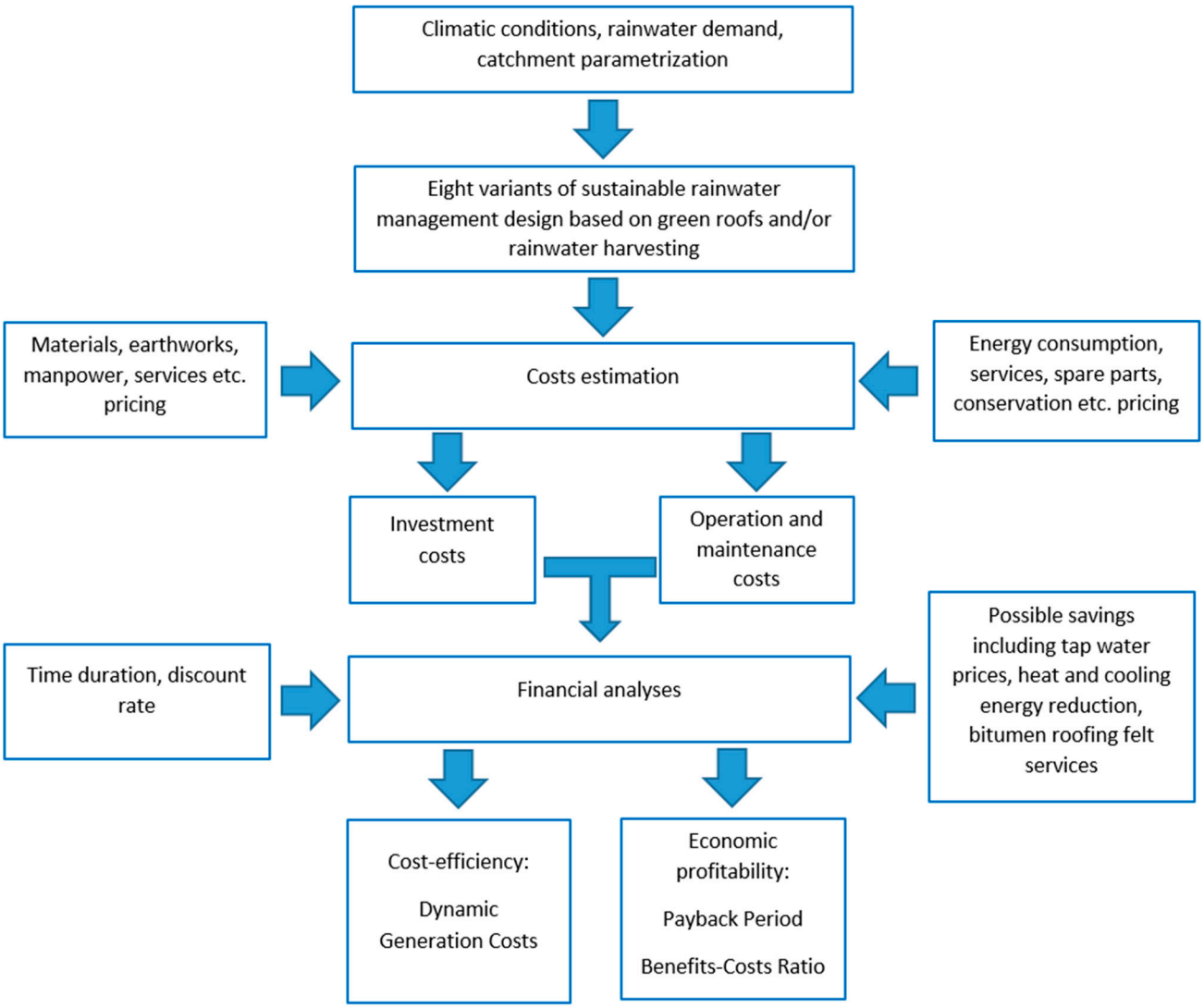


Figure 1. Block scheme of assumed methodology of research presenting all required input data and steps of research.

2.1. Object Description

A small-scale housing community, covering a total 13,842 m^2 (approx. 1.38 hectare) area covering five blocks of flats located in Lublin, Poland, was selected for this study. The selection of this area, built in approx. 2008–2010, as a typical multi-family housing in Lublin established in last two decades, was related to the area's lack of sustainable rainwater management, significant share of impermeable surfaces and risk of possible flooding, an example of which occurred in this area in May 2014, resulting in serious street and underground parking lot flooding [95,96]. The spatial arrangement of the studied urbanized catchment, together with the roof areas of all included buildings, is presented in Figure 2. The following components constituted the studied area: buildings roofs—3078.74 m^2, grass—3901 m^2, roads and pavements—3499 m^2 and 3364 m^2—high vegetation. All the studied buildings have the same construction, i.e., concrete frame structures that

are flat, have an inclination that is lower than 5 degrees and have roofs covered with bituminous roofing felt. There are two underground parking lots, of a total area of 6118 m^2, available for the residents.

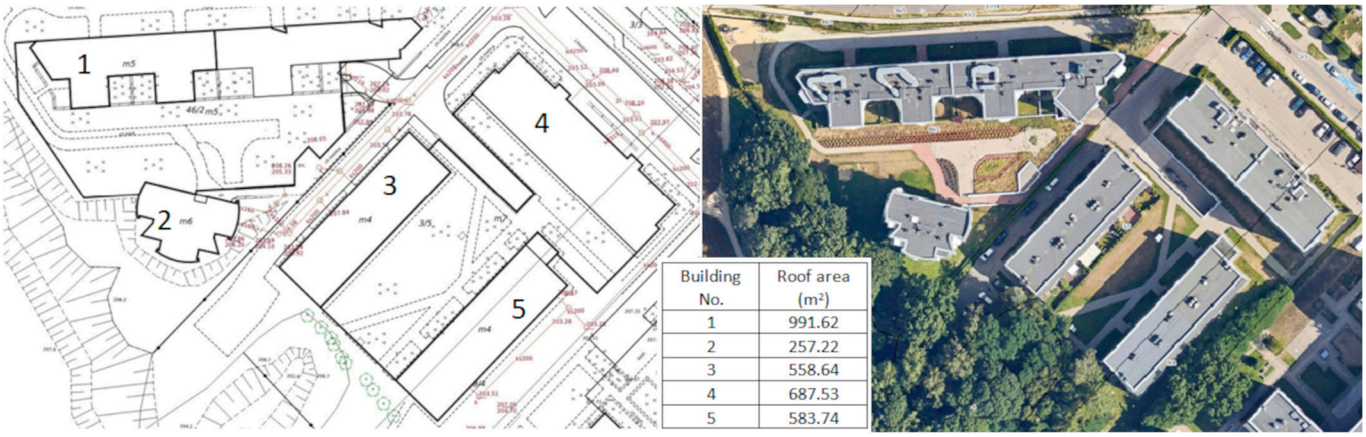


Figure 2. Map and ortophotomap of studied catchment with 5 residential buildings (1–5—numbers of buildings).

The climatic conditions of the site's location are characterized by 600 mm of annual precipitation, a mean temperature of 7.3 °C degrees and 200–210 days of vegetation period.

2.2. Assumed Variants of Rainwater Management

The developed variants of possible rainwater management in the studied urban catchment, utilizing the rainwater harvesting (RWH) and/or green roofs considered in this study, are presented in Table 1 and in Figure 3. Calculations of the available rainfall runoff volume collected from roofs were based on the assumed mean annual rainfall depth of 600 mm [97], a runoff coefficient for flat roofs covered with bituminous roofing felt of $\psi = 0.8$ and a runoff coefficient for extensive green roofs of $\psi = 0.5$ [98,99]. The proposed methods of sustainable rainwater management for housing communities were assumed to be operational only during the warm part of year.

Table 1. Description of proposed variants of sustainable rainwater management.

Variant	Description	Total Volume of Reservoirs (m^3)	Extensive Green Roof Area (m^2)	Annual Rainwater Demand (m^3/year)
1	RWH system, rainwater retained in underground storage reservoirs used for green area watering	24 (13 m^3, 9 m^3, 2 m^3)	-	390.01
2	Combined extensive green roof and RWH system, rainwater retained in underground storage reservoirs used for green area watering	24 (13 m^3, 9 m^3, 2 m^3)	2616.93	390.01
3	RWH system, rainwater retained in underground storage reservoirs used for green area watering and washing the floors of underground parking lots	48 (12 m^3, 15 m^3, 10 m^3, 8 m^3, 3 m^3)	-	830.60
4	Combined extensive green roof and RWH system, rainwater retained in underground storage reservoirs used for green area watering and washing the floors of underground parking lots	48 (12 m^3, 15 m^3, 10 m^3, 8 m^3, 3 m^3)	2616.93	830.60
5	RWH system, rainwater retained in above-ground storage reservoirs used for green area watering	24 (18 × 1 m^3, 2 × 2 m^3, 4 × 0.5 m^3)	-	390.01

Table 1. *Cont.*

Variant	Description	Total Volume of Reservoirs (m^3)	Extensive Green Roof Area (m^2)	Annual Rainwater Demand (m^3/year)
6	Combined extensive green roof and RWH system, rainwater retained in above-ground storage reservoirs used for green area watering	24 (18 × 1 m^3, 2 × 2 m^3, 4 × 0.5 m^3)	2616.93	390.01
7	RWH system, rainwater retained in above-ground storage reservoirs used for green area watering and washing the floors of underground parking lots	48 (10 × 2 m^3, 7 × 1 m^3, 8 × 2 m^3, 2 × 1 m^3, 6 × 0.5 m^3)	-	830.60
8	Combined extensive green roof and RWH system, rainwater retained in above-ground storage reservoirs used for green area watering and washing the floors of underground parking lots	48 (10 × 2 m^3, 7 × 1 m^3, 8 × 2 m^3, 2 × 1 m^3, 6 × 0.5 m^3)	2616.93	830.60

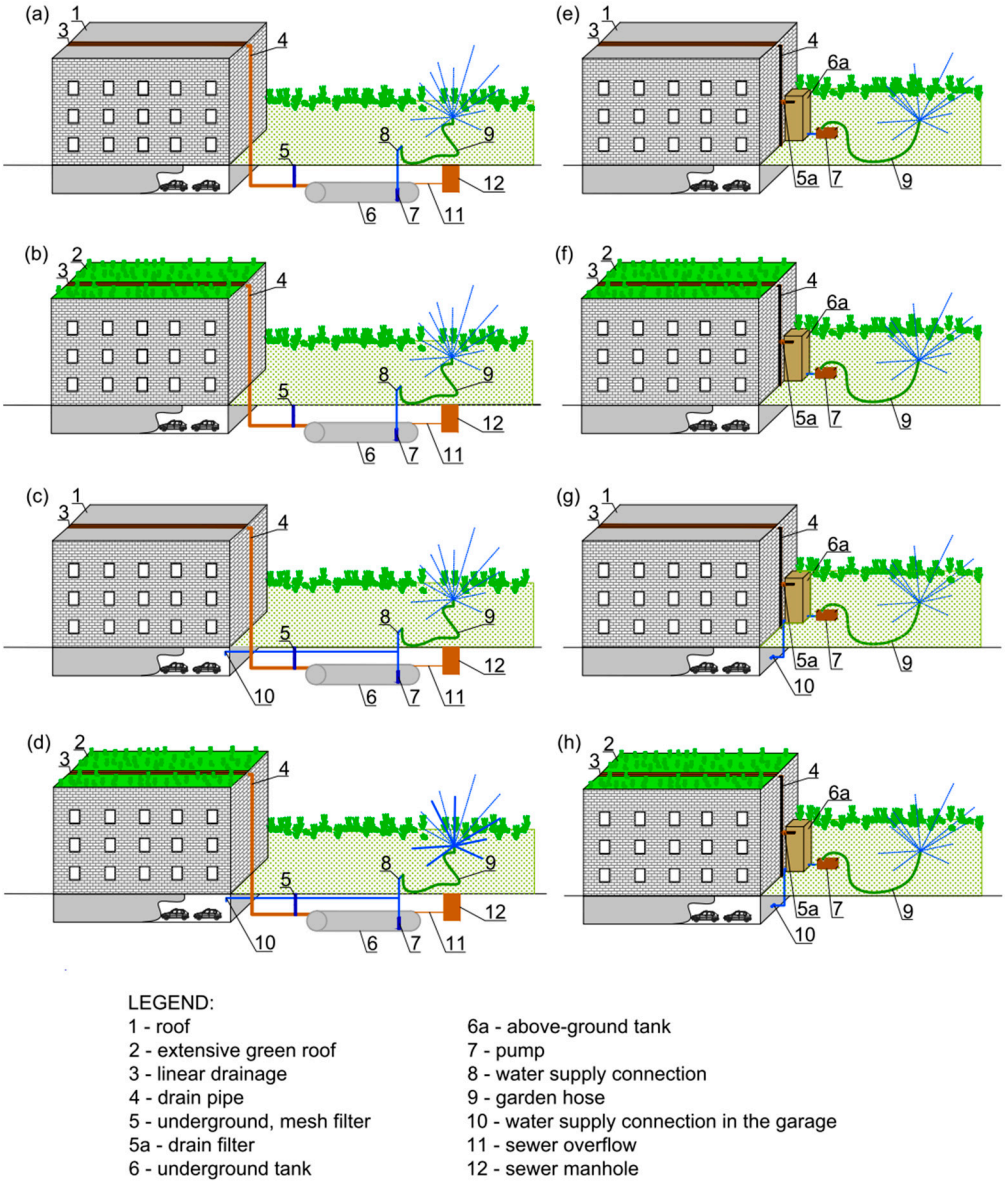


Figure 3. Schematic diagrams of developed designs for sustainable rainwater management for small-scale urban housing communities: (**a**) Variant 1, (**b**) Variant 2, (**c**) Variant 3, (**d**) Variant 4, (**e**) Variant 5, (**f**) Variant 6, (**g**) Variant 7, (**h**) Variant 8.

According to the assumed variants, rainwater demand covered water for green area watering and underground parking lot washing. The unit demands for the above purposes were assumed, according to reference [100], to be 2.5 $dm^3/(d \cdot m^2)$ (watering 40 times during the vegetation period) and 1.5 $dm^3/(d \cdot m^2)$ (parking lots washing 4 times per month in the warm part of the hydrologic year), respectively. Rainwater retention time in storage tanks was assumed, according to references [98,101–103], to be 21 days.

Variants 1–4 required the installation of 3 booster sets and submersible pumps; HYDROFOR 50L sets and SKM 100 OMNIGENA pumps, Q_{max} = 45 dm^3/min, H_{max} = 60 m, P = 0.75 kW, were selected to the study. Variants 5–8, based on the above-ground rainwater reservoirs, required only a portable pump installation in the above-ground reservoirs; the Garden com 82M, Q_{max} = 3.6 m^3/h, H_{max} = 47 m, P = 0.85 kW was selected.

All rainwater reservoirs assumed in the proposed designs, both underground and above-ground, were made of HDPE (high-density polyethylene). The above-ground tanks in Variants 5–8 are already equipped with the required mechanical filters. In the other variants, i.e., Variants from 1 to 4, underground, outside, unidirectional, polyethylene rainwater harvesting filters with metal racks baskets were installed.

As is visible in Table 1, four assumed variants of sustainable rainwater management, i.e., Variants 2, 4, 6 and 8, covered the application of extensive green roofs of a total area 2616.93 m^2. Extensive green roofs of the following typical construction (see, also, Figure 4) were assumed in this study [84]: (i) perennial vegetation layer, (ii) 8 cm of commercially available light bulk density, 0.83 kg/dm^3 density, extensive substrate, in agreement with German FLL and GRO UK green roof guidelines [104–106], (iii) polypropylene geotextile filtration layer, (iv) high-density polyethylene drainage mat drainage layer, (v) polypropylene/polyethersulfone geotextile protective layer, (vi) reinforced polyvinyl chlorine membrane insulation layer and (vii) low-density polyethylene mat root protection barrier.

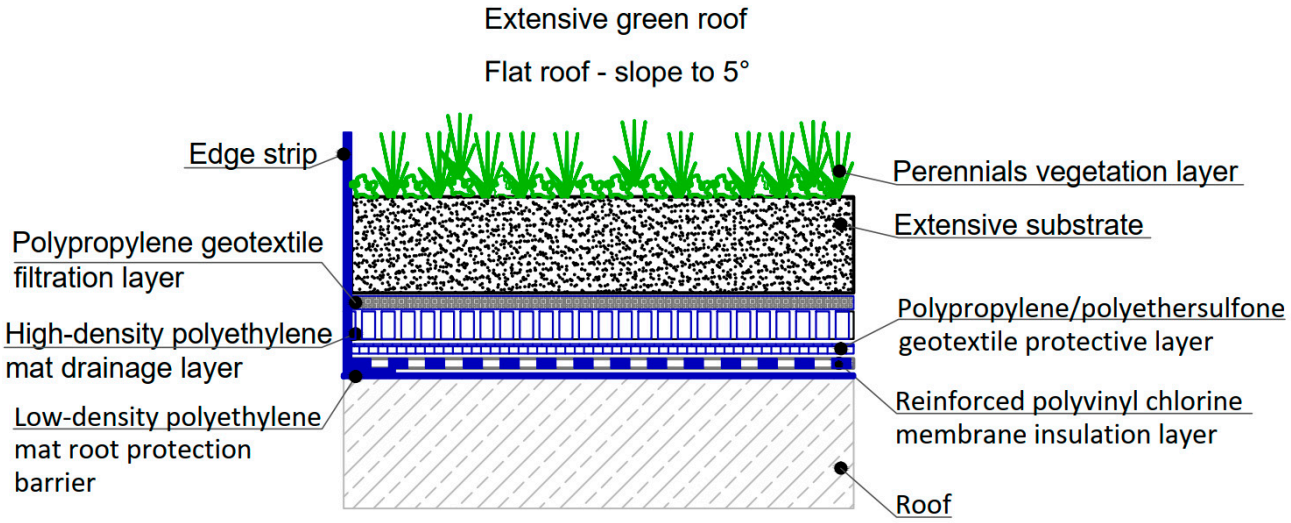


Figure 4. Assumed construction of extensive green roof applied to designed rainwater management system, consisting of vegetation, substrate, filtration, drainage, protective, root barrier and insulation layers.

2.3. Economic Analysis Assumptions

For each of the developed variants of sustainable rainwater management, the preliminary investment as well as operation and maintenance (O&M) costs were estimated. The investment costs covered materials (rainwater reservoirs, pumps, pipelines, filters, manholes, green roof substrate, geotextiles and mats, fittings, valves, etc.) and workload and services (earthwork, tanks, pumps, filters and pipelines, as well as extensive green roofs layers installation). The determined O&M costs covered inter alia energy, services (pumps, valves and filters servicing and exchange, green roofs conservation, rainwater reservoirs

cleaning, garden hose purchase, etc.). All the pricing included in the cost estimations were based on the actual (available via the Internet) pricings in Poland (PLN), particular to the project location, and were recalculated to EUR using the mean currency EUR 1 = PLN 4.5. The determined investment as well as operation and maintenance costs for all developed variants are presented in Table 2.

Table 2. Determined investment and mean annual operation and maintenance costs for proposed variants of sustainable rainwater management.

Variant No.	Investment Costs	Mean Annual O&M Costs
	(EUR)	(EUR)
1	18,445.93	1115.16
2	131,264.65	1696.70
3	23,869.85	1324.25
4	136,688.57	1905.79
5	8228.94	94.20
6	121,047.66	675.74
7	17,736.47	112.34
8	130,555.18	693.88

The analysis of the financial aspects of the proposed designs, including their cost-efficiency and economic profitability, was based on a selected set of popular, sound and clear indicators. The cost-efficiency of possible investments was assessed according to the determined vales of the Dynamic Generation Cost (DGC) indicator, which allows us to present the price of ecological effect [107–109]. The DGC is a very popular and easy to understand indicator, which allows an assessment of the averaged costs of the product unit during the assumed life cycle of the design, and which was successfully adopted in numerous technical analyses, including not only into various water, wastewater and rainwater systems but also into providing heat energy and materials (fuels plastics, zeolites, etc.) production [109–114]. This indicator, in the case of our studies, allows for the comparison of several designs and for the obtaining of the same effect, i.e., 1 cubic meter of retained and reused rainwater [115]. The economic profitability of the proposed designs was determined by two popular indicators involving the costs and benefits of each studied design, the simple Payback Period (PP) and the dynamic Benefits–Costs Ratio (BCR), which allowed us to introduce the time-related variable of value for money to the analysis [116–120]. Payback Period is a simple indicator of investment economic viability, based on annual cash flows and applicable in numerous aspects of economic, civil engineering, energy and agricultural applications, that allows for the determination of the time after which the benefits obtained from a tested investment, design or technology exceed the investment and operational costs [121–125]. The main commonly recognized disadvantage of the Payback Period is in its not taking into account the discounted value of cash flows during the assumed duration of the investment operational life [126]. A comparison of different possible designs using the Payback Period is based on the shortest time of investment returns. The Benefits–Costs Ratio indicator belongs to a group of more sophisticated methods of profitability assessment in a Costs–Benefits Analysis (CBA) and presents the discounted benefits of a design related to its discounted investment, as well as the operation and maintenance costs [127–130]. The application of the BCR indicator is relatively simple; a positively assessed profitable design should present a value of BCR > 1.0. The proposed indicators were calculated according to Formulas (1)–(3) presented below:

$$DGC = p_{EE} = \frac{\sum_0^{t=n} \frac{IC_t + EC_t}{(1+i)^t}}{\sum_0^{t=n} \frac{EE_t}{(1+i)^t}} \quad (1)$$

where IC_t—annual investment costs (EUR), EC_t—annual operation and maintenance costs (EUR), t—year of investment time duration, from 0 to n (year), i—discount rate (%), p_{EE}—price of the ecological unit effect of the investment (EUR/m^3) and EE_t—annual ecological unit (m^3).

$$PP = \frac{IC}{NCF} \tag{2}$$

where IC—initial investment costs (EUR) and NCF—net cash flow (EUR/year).

$$BCR = \frac{PV_b}{PV_c} = \frac{\sum_{t=0}^{n} \frac{CF_{bt}}{(1+i)^t}}{\sum_{t=0}^{n} \frac{CT_{ct}}{(1+i)^t}} \tag{3}$$

where PV_b—present value of investment benefits (EUR), PV_c—present value of investment costs (EUR), CF_{bt}—benefits cash flow for a t period (EUR) and CF_{ct}—costs cash flow for a t period (EUR).

The following necessary assumptions for economic calculations were taken: (i) time duration of the investment—30 years [115] and (ii) the discount rate, i = 5%, as a typical value for water management [115,131–134].

The determination of the Benefits–Costs Ratio indicator requires an assumption of the possible annual financial benefits of each studied design (see Equation (3)). None of the proposed methods of sustainable rainwater management bring direct profits (understood as financial incomes) to the investors, but several possible savings are possible and were introduced to the presented analysis: (i) tap water and sanitation services payment reduction due to decreased tap water consumption as measured by watermeters [30,46,56,63,64,67], (ii) reduced heating and cooling costs due to additional isolation related to green roofs installation [43,44,94,135] and (iii) reduced frequency of bitumen roofing felt cover services and exchange, possible due to green roofs installation [85,135]. Thus, the following benefit indicators were assumed with VAT included: (i) tap water and sanitation price in Lublin 2.18 EUR/m^3 (9.82 PLN/m^3) [136], (ii) annual energy saving due to heating and cooling [74,84,132,135,137,138], 8.14 kWh/m^2 and 0.59 kWh/m^2, respectively, combined with the local heat (0.444 PLN/kWh) and (0.972 PLN/kWh) energy prices, allowed for the determination of financial savings due to heating and cooling (3.62 PLN/m^2) and (0.57 PLN/m^2) and (iii) the cost of roofing mat purchase and exchange (21.66 EUR/m^2 (97.5 PLN/m^2)) [139]; one exchange per 30 years was assumed instead of two without the green roofs [85]. As can be seen, the presented research was based on measurable and quantitative microeconomic financial benefits, which are clear and easy to understand for possible investors. Thus, the benefits related to carbon reduction, mitigation the heat island effect, habitat creation and nitrogen oxide uptake were not introduced to this study, as they do not bring clear and direct savings to the owners of the studied buildings under the local legal and economic conditions.

3. Results

The determined cost-efficiencies of the proposed possible systems of sustainable rainwater management, based on rainwater harvesting and extensive green roofs application and characterized by Dynamic Generation Cost indicator values, are presented in Figure 5. It can be seen that the investments' cost-efficiencies, measured by the price of the ecological effect, i.e., 1 cubic meter of retained and reused rainwater, are extremely different, from 1.44 EUR/m^3 to 24.90 EUR/m^3. Thus, the cost-efficiency of the proposed designs of sustainable urban rainwater management is highly dependent on the assumed technologies of rainwater collection, retention, reuse and the assumed demand for non-potable rainwater. Only two variants, Variant 5 and 7, assuming an application of the RWH system equipped with above-ground rainwater reservoirs and using rainwater for watering green areas and flushing the floors of underground parking lots, achieved a satisfactory cost effectiveness, allowing for unit costs lower than the usage of tap water (as was mentioned above, the actual price of tap water in the region reaches a level of 2.18 EUR/m^3, with

sanitary sewage included). The highest cost-efficiency, determined by the lowest value of the calculated DGC indicator, was observed for the technically simplest variants in which minimal investment and O&M costs were possible. In the other cases, the proposed designs generate costs higher than the usage of tap water for watering grass and washing parking lots. The low cost-efficiencies in these cases are related, in our opinion, to (i) higher investment costs covering required earthworks for underground rainwater reservoirs and green roofs installation, together with the required equipment and (ii) higher operation and maintenance costs related to services and energy consumption. It is worth noting that the costs are very high for the assumed ecological effect for Variants 2 and 6, assuming a combined application of extensive green roofs and a rainwater harvesting system and the use of retained water only for watering green areas.

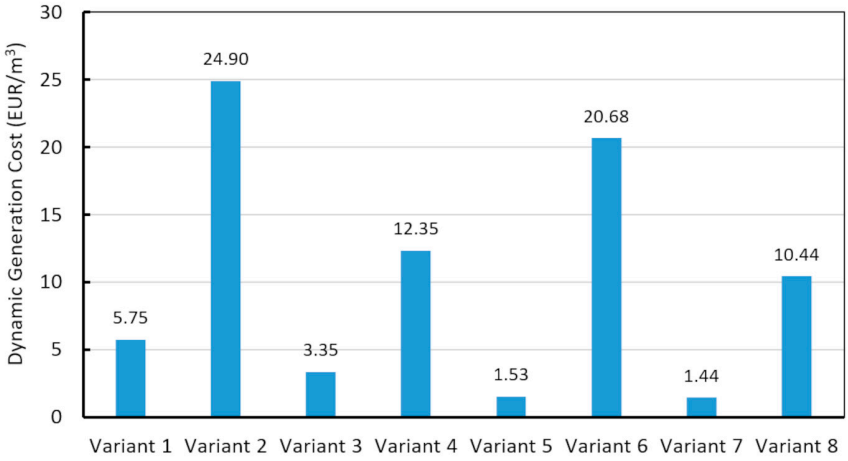


Figure 5. Calculated values of Dynamic Generation Cost indicators for all the proposed systems of sustainable rainwater management; the lower DGC value, the more cost-effective the design.

Figure 6 presents the determined values of Payback Period indicators, allowing for the simplified assessment of the profitability of the proposed designs of sustainable rainwater management for the selected group of blocks of flats. As may be expected, the economic profitability, defined by the Payback Period, of the studied designs is non-uniform and is related to their investment and O&M costs. The higher investment and O&M costs, the longer duration of the Payback Period, and, thus, the lower profitability of the design. According to the results presented in Figure 6, two variants, i.e., Variant 5 and 7, of RWH utilizing above-ground rainwater reservoirs and using rainwater for watering as well as for parking lot washing, present satisfactorily short Payback Periods, 10.87 and 10.43 years, respectively. Another two variants, Variants 6 and 8, also present promising PP values, shorter than the assumed time duration of the expected life of the designed systems. In one case, i.e., Variant 1, determining the PP value was impossible, no matter the value of the investment costs, because the annual operation and maintenance costs were higher than the determined possible financial benefits due to tap water savings.

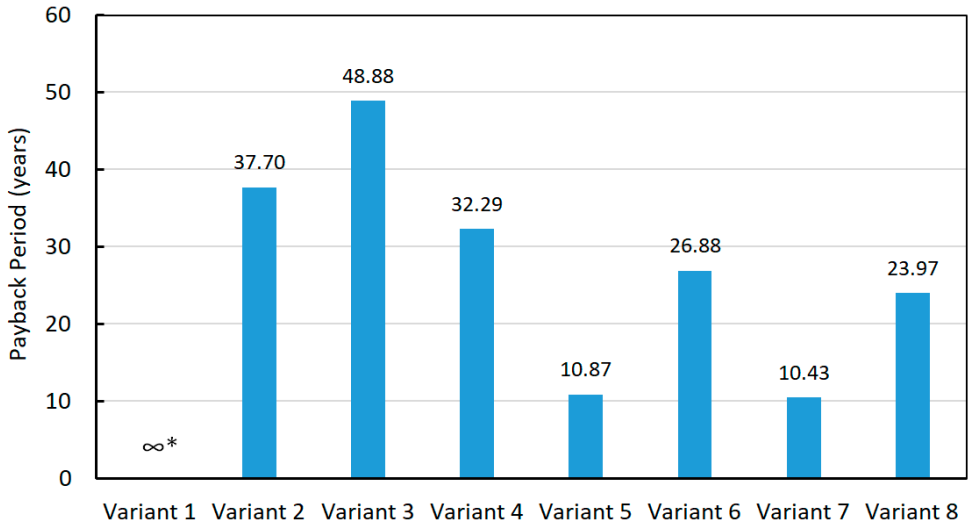


Figure 6. Calculated values of Payback Period duration (*—PP unable to be determined, mean annual O&M costs greater than possible benefits from the investment).

Figure 7 shows the values of Benefits–Costs Ratio dynamic indicators determined for all studied variants of sustainable rainwater management proposed for the selected small-scale urban catchment. Again, the determined economic feasibility of the proposed rainwater collection and reuse designs is non-uniform; in many cases, the possible benefits are lower than the required discounted investment and O&M costs, which, in turn, are related to the selected technologies of rainwater retention and reuse. This issue is discussed in more detail in the following section. As was observed above, only two of proposed variants, Variant 5 and 7, were profitable, as characterized by BCR $\geq$ 1.0. The most financially efficient Variant 7 assumed an application of a rainwater harvesting system with above-ground water reservoirs, with this water used for green area watering and for washing the floors of underground parking lots. The second positive value of BCR was determined for Variant 5, which differed from Variant 7 only in the value of rainwater demand. In this case, retained rainwater was used only for green area watering. The remaining proposed variants of sustainable rainwater management showed unsatisfactory values of BCR < 1.0. Thus, these designs of rainwater management would only bring potential investors financial losses rather than benefits.

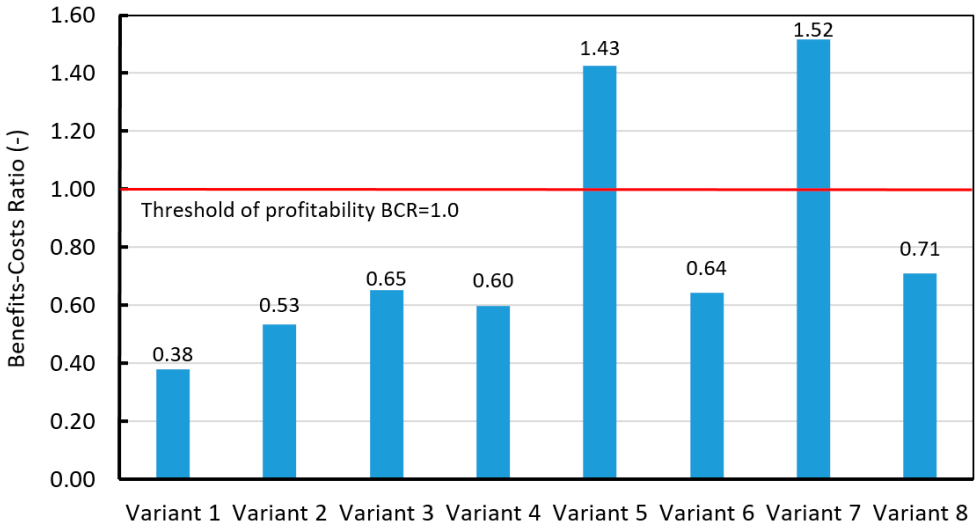


Figure 7. Calculated values of Benefits–Costs ratio for all proposed variants of rainwater management.

4. Discussion

The results of cost-efficiency and economic profitability presented in Figures 5–7 show that most of the proposed variants of sustainable rainwater management are not effective and unprofitable. Thus, our research is in agreement with reports in the literature suggesting the possible low economic feasibility of the studied designs. The components of the investment as well as the operation and maintenance costs for all variants, presented in Figures 8 and 9, allow for a better understanding of the obtained results.

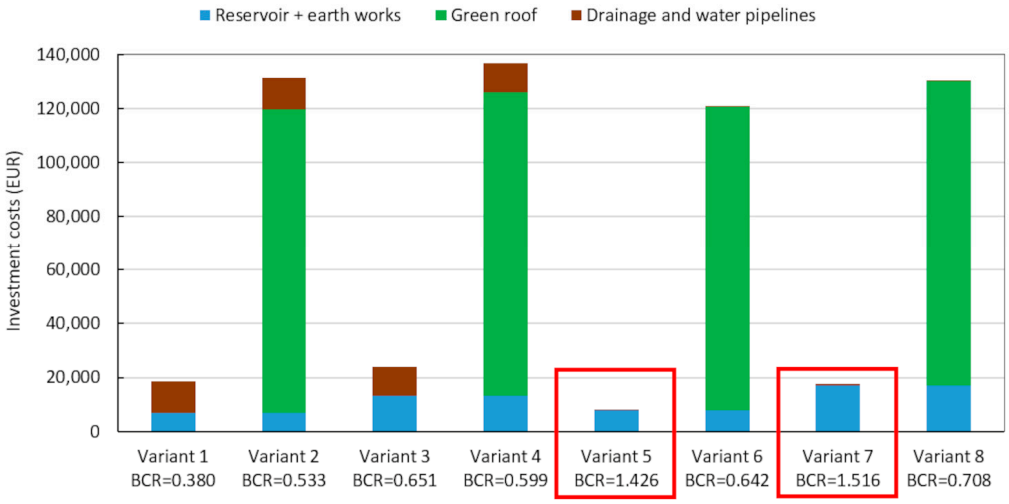


Figure 8. Components of investment costs of proposed variants affecting their economic feasibility; red squares indicate profitable variants.

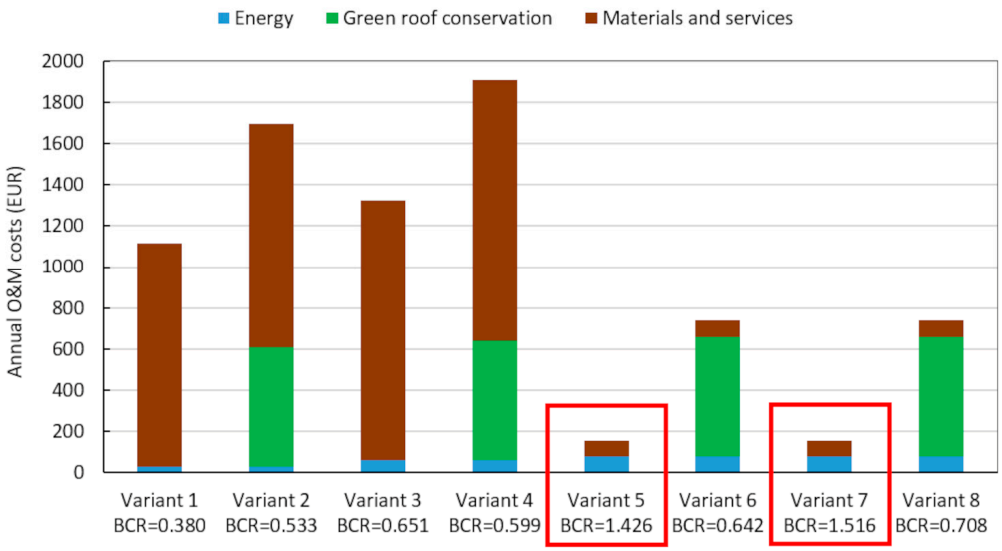


Figure 9. Components of operation and maintenance costs of proposed variants affecting their economic feasibility; red squares indicate profitable variants.

Figures 8 and 9 indicate that the economic profitability was determined for variants for which the combined investment and O&M costs were the lowest. Considering the investment costs of the studied variants, with the comparable costs of rainwater reservoirs and the required earth and installation works, the decisive factors were the cost of green roofs (see Figure 8). For example, the investment costs of Variants 5 and 6, covering the same volume of above-ground rainwater reservoir and assuming the usage of stored rainwater for green area watering, differ only in the cost of extensive green roofs, but this difference results in a significantly different assessment of their profitability. The same situation was

observed for Variants 7 and 8. The analysis of O&M cost components presented in Figure 9 shows that the highest economic efficiency was obtained by designs without green roofs and with above-ground rainwater reservoirs for which different equipment, spare parts and services are required. Variants 1–4, based on underground rainwater reservoirs, booster sets, submersible pumps and water filters, required significantly higher servicing costs to sustain their operation during the assumed time duration of the investment.

According to the literature, the profitability of sustainable rainwater management may be improved by increasing [30,43,92,93] rainwater demand (related to the reduced consumption of tap water), local government support or governmental or/and commonwealth co-founding. In the case of the proposed designs, the increase in rainwater demand, allowing greater financial savings due to limited tap water consumption, would be possible only by introducing rainwater to dual water installations, allowing for the use of non-potable water in toilet flushing and laundry. However, such an enlargement of rainwater harvesting system in already occupied residential buildings would result in significantly increased investment and O&M costs, including rainwater reservoirs of greater volume, additional filters, pipelines and fittings of rainwater installation, rainwater control stations, greater energy consumption, and required services and spare parts. Unfortunately, no satisfactory institutional local governmental support for rainwater harvesting systems and green roofs installation allowing, e.g., property tax reduction or exemption, is available. There is currently one available governmental financial support programme for rainwater harvesting in the Lublin Voivodeship "Moja Woda" ("My water" in Polish) [140] that allows co-founding and covers up to 80% of the eligible investment costs, but only to the value of PLN 6000 (approx. EUR 1333). However, this programme is dedicated only to the owners or co-owners of single-family buildings. The performed additional calculations showed that, in order to assure the economic profitability of the proposed designs, understood as BCR $\geq$ 1.0, outside co-founding should account for 67–32% of the total investment costs. Thus, in most cases, the only reasonable possibility of reaching the threshold for economic feasibility using a small-scale rainwater harvesting system could be related to the European Funds [141,142].

The similar observations for the economic feasibility of 13 designs of rainwater harvesting systems in single-family buildings located in the same area, Lublin, Poland, and under similar economic conditions were reported in 2020 in [30]. According to the considered pricing scenario of the possible benefits, only one to six of the designs could be identified as profitable. An increase in profitability was reported as a possible result of increased rainwater use instead of tap water. Moreover, the locally available refund programs were assessed as being unsatisfactory, not allowing for reaching of the profitability threshold or gaining the interest of possible investors. Similar results regarding the limited profitability of various LID applications in sustainable rainwater management in different regions in Poland were also reported in [73,83].

Generally, the observations presented in this paper considering the economic feasibility of rainwater management in multi-family buildings, based on rainwater harvesting and green roofs application, under the climatic and economic conditions of the selected region of Poland, are in agreement with scientific reports for different regions in the world with different local environmental, legal and economic conditions. As an example, the studies performed for a university campus building in Portugal [75] showed that rainwater harvesting for providing water for non-potable uses, such as toilet flushing and garden watering, is economically viable, allowing for an investment return in, according to the assumed scenario, approx. 9–12 years (Payback Period). Another study [76] performed on an industrial building in Portugal showed comparable results in relation to the duration of the Payback Period. The investment in the proposed rainwater harvesting system was assessed as feasible and the determined PP was 11.29 years. However, for the same location, investment in green roofs to control rainwater management was assessed as being unprofitable and the determined duration of the Payback Period was longer than the commonly accepted life-time operation of a green roof (over 100 years). The extensive

use of green roofs acting as a sole measure of rainwater control was also reported as being unprofitable for investors in selected locations in Poland, under local climatic conditions and an assumed 5% discount rate [74]. The research performed by Farreny et al. [77] for dense urban Mediterranean regions suggested that the profitability of rainwater harvesting systems is highly related to the scale and range of their application; not all studied systems were economically feasible. The mixed results of the costs–benefits analysis for potential rainwater harvesting systems in Sicily, Italy, under local conditions and for variable rainwater reservoir sizes, were also reported [78].

On the other hand, there are known studies reporting completely failed economic assessments of sustainable rainwater management. For instance, the authors of reference [79] showed that, for standard multi-family buildings with 500 residents each, in four different locations in China and under different climatic conditions, in all cases, the designed rainwater harvestings systems were unable to reach BCR values greater than 1.0; they were thus assessed as being unprofitable, bringing only financial losses to the potential investors. It was also underlined that the unfeasibility of RWH systems in large multi-family buildings could be decreased by the availability of governmental co-founding. The same findings were reported for residential rainwater harvesting systems in Austin, Texas, USA, where studied RWH systems would be not profitable without financial support [80]. A recent paper by Jin et al. [81] underlines that national and financial policies promoting rainwater harvesting systems should be available to ensure the economic profitability of these systems and to increase the acceptance of the potential investors and their users' willingness-to-pay. The required community acceptance for rainwater harvesting designs, highly related to the economic issues of such systems, was also underlined as a social aspect of sustainable rainwater management [82]. Thus, in our opinion, a detailed cost-efficiency and benefits–costs analysis, based on the measurable financial expenditures and benefits, should be introduced for each single design, under the precisely identified and qualified local economic and climatic conditions and in order to ensure the mentioned social acceptance. Otherwise, the limited economic viability of untested and unverified LIDs application in residential buildings may negatively influence the potential investors in other locations and significantly decrease the public acceptance of sustainable rainwater management. In our opinion, the proposed methodology of assessing cost-efficiency and economic profitability is sound and clear, and may be successfully implemented into the decision-making process and selection of the most suitable manner for sustainable urban rainwater management.

5. Conclusions

The performed analysis of financial feasibility for several proposed methods of sustainable rainwater management in selected small-scale urbanized catchments allowed us to draw the following conclusions:

- Only two of the eight proposed designs for sustainable rainwater management based on rainwater harvesting systems and extensive green roofs, under the specific local conditions, were determined as financially viable, bringing profits to potential investors;
- The variants of determined positive economic feasibility covered the rainwater harvesting system, rainwater storage in above-ground water reservoirs and variable rainwater demand, for green area watering, for watering plants and for washing underground parking lot floors;
- The profitability of rainwater management designs in all proposed variants was highly related to their investment and O&M costs, e.g., the application of cheaper—both in construction and operation—above-ground rainwater reservoirs positively influenced the economic feasibility of the designs and reduced the price of their ecological effect;
- An improvement in cost-efficiency and economic profitability was also possible in the tested catchment as a result of the increased use of non-potable rainwater, allowing for greater financial savings due to the reduction in tap water consumption;

- The extensive application of green roofs, in most of the studied cases, decreased the cost-efficiency and economic profitability of the proposed designs, increased the financial benefits due to energy saving in heating and cooling and prolonged the life span of bitumen roof cover; these were eclipsed by the significant installation and maintenance costs;
- In most of the proposed cases, despite the obvious ecologic and environmental advantages of the proposed rainwater management designs, the local urban housing community would not be able to single-handedly sustain them without outside financial support, on the scale of local government or national policies;
- It must be underlined that the determined financial viability of the proposed designs of sustainable urban rainwater management should be treated as appropriate and suitable only under the specific local conditions;
- The obtained results confirm that the economic feasibility of sustainable rainwater management in the studied small-scale urban catchment is strongly related to the selected technologies, the local microeconomic conditions and the possible benefits;
- In our opinion, to ensure acceptance and willingness-to-pay, the decision-making process of rainwater management design should always be firmly supported by a reasonable cost-efficiency assessment and benefits–costs analysis, already allowing for identifying the economic feasibility of the proposed systems on a design level;
- Such an assessment should be always based on clear, measurable and quantifiable values of the possible microeconomic financial benefits for potential investors;
- The proposed methodology of assessing the cost-efficiency and economic feasibility, based on easily available data, is sound, clear and easy-to-understand; thus, it should be commonly adopted in the designing and decision-making processes of sustainable urban rainwater management systems.

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