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Analysis of Alternatives for Sustainable Stormwater Management in Small Developments of Polish Urban Catchments

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Abstract: Sustainable stormwater management approaches in accordance with the EU Water Framework Directive (WFD) allow a source control to handle the quality and quantity of the runoff at local level or near the source. The most popular technologies applied in Europe are green roofs, porous pavements, retention basins and bioswales/raingardens. In this article, two of these solutions (retention tank with reuse, and rain garden, respectively), applied to single dwelling case studies in a suburban area in the Silesia Region (Poland), are illustrated and analyzed. The selected cases consider technical and economic aspects as the most important factors for decision on the selection of onsite stormwater management approach. Both systems have been operational for approximately two years. The retention tank proved a good solution, reducing stormwater overflows and allowing local water reuse for lawn irrigation; however, investment and maintenance costs in this case are relatively higher. The raingarden proved to work efficiently in this small scale implementation and implied much lower initial investment and costs. The economic sustainability of these interventions at single dwelling scale was analyzed, showing interesting returns, with outcome depending on the degree of possible water reuse (lower water bills) and availability of fiscal or fee incentives. Introduction of financial incentive schemes will encourage homeowners and developers to implement stormwater control solutions, allowing rapid amortization of investment costs with additional benefits to the community, such as reduced environmental impact of stormwater overflows and possible economies in the construction and management of stormwater systems.

Keywords: stormwater management; retention basin; rain garden; low impact development (LID); green infrastructure; cost analysis

1. Introduction

Sustainable stormwater management has been and still is a long-time issue in urban drainage systems. In addition to potentially causing adverse impacts on wastewater treatment operations in traditional combined systems [1], flooding during storm events has always been a common problem in urban areas: in fact, almost every city, regardless of the type of sewer network, is potentially vulnerable to this phenomenon, whose frequency has exacerbated due to the increased intensity and recurrence of extreme hydro-meteorological events linked to long term climate variability. Increases in impervious urban surfaces, poor resiliency of urban drainage system design and increased frequency of downpours in urban areas can increase peak storm runoff with corresponding impact on human life and health, property and water security. The Intergovernmental Panel on Climate Change (IPCC) reported that the number of heavy precipitation events has significantly increased in inland areas worldwide [2].

Climate indicators for the last decades show generalized statistical increase of event-specific maximum precipitation in many cities [3,4]. In addition, extreme hydro-meteorological events impact on the physical, chemical and biological parameters of water in urban water bodies, both through direct runoff, and separate or combined sewer overflows (CSOs) [5]. Pollutants conveyed by storm flows in addition to organic matter include pathogens (Fecal Indicator Bacteria, FIB), nutrients, metals and emerging contaminants [6,7], the latter often at low level concentrations, which are difficult to monitor by traditional means [8].

Safe urban stormwater management is becoming a major concern: the conventional approach based on piped drainage is currently criticized as poorly efficient as, only partly effective during meteorological extremes, it does not eliminate environmental problems [9]. In the 1980s, structurally intensive approaches were proposed such as the "deep tunnel" concept: large, underground collectors designed to relieve urban sewer systems from excess stormwater flow and curtail overflow frequency. These systems were built in large cities in the U.S. (e.g., Milwaukee, Chicago, Boston, Atlanta) and around the world (e.g., Hong Kong, Guangzhou, Singapore) [10,11]. In addition to the high cost involved (the deep tunnel project in Milwaukee, one of the first of this kind, required 14 years, at a cost in excess of US$2.3 billion, to complete [12]), the features of these systems may raise unexpected management challenges [13]. Furthermore, their operation requires high energy inputs for pumping and subsequent treatment of dilute sewage, increasing the already high greenhouse gases (GHG) emission footprint of water systems [14].

While these may have proven use in large urban areas, this approach may not be fully resolutive for the targeted impacts. Low-tech, more sustainable methods in accordance with the EU Water Framework Directive (WFD) [15] may be effective in many cases, especially in smaller urbanizations [16]. Sustainable storm water management should promote source control methods at, or nearby, the source. The most effective approach, which could successfully complement technologically-intensive approaches, consists of trapping stormwater and storing it into temporary impoundments for evaporation or ground infiltration. Rain and roof gardens, grassy swales or ditches (bioswales and bioretention basins) and permeable pavements could be highly beneficial [17]. Many mitigation measures are also being proposed to increase urban systems' resilience against floods [5,18]. These include discharge separation at source [19], local water reuse [20] and implementation of decentralized water management [21]. Modern stormwater management requires separation of rainwater from sewage, providing a higher level of service and benefits such as: elimination of CSOs, pollution prevention and possible use of stormwater as an alternative resource.

Sustainable storm water management is connected with so-called blue-green infrastructure (BGI). BGI foresees the implementation of either natural or man-provided solutions to enhance management of water resources and water infrastructure and services risk resilience. Innovative fiscal and non-fiscal tools, which may include payment for ecosystem services schemes [22], may be introduced to encourage their implementation on public and private property [23]. These practices are described in the literature under various labels, such as Low Impact Development (LID) [24], nature-based solutions (NBS) [25] or Sustainable Urban Drainage Systems (SUDS) [26]. All reduce the impact of constructed impervious surface areas (ISA) and of their hydrological and ecological disturbances. A generally accepted scale to assess ISA impact on urban watersheds indicates stress conditions, with ISA between 1% and 10%, impacted if between 10–25% and degraded if greater than 25% [27]. The global ISA average is estimated at 93 m^2 per person. As a comparison, ISA in Poland is about 110 m^2/person, similar to other European countries (Germany, Italy, the United Kingdom, the Czech Republic, Hungary, Austria, Switzerland, Bulgaria, Slovakia, and Denmark) with ISAs around 100-150 m^2/person. In France, Portugal, Belgium, Ireland, Sweden and Spain, ISA is between 150–220 m^2/person, in the USA, close to 300 m^2/person, and in China around 68 m^2/person [28].

This article presents two case studies of sustainable stormwater management practices in small urban developments in Polish catchments, respectively concerning: (1) on-site retention and reuse, and (2) rainwater infiltration gardens. The aim of the analysis of the two approaches is to highlight their application's sustainability, considering also related legal and economic aspects. With this objective, a simple cost-benefit analysis and a general discussion on urban stormwater management are also presented.

2. An Overview of Sustainable Stormwater Management Practices

Sustainable urban stormwater management solutions face increasing complexity from conflicting demands resulting from increasing urbanization, influence of expected climate variability and financial and budgetary constraints of cities. To address these, the current approach has evolved to accommodate increasing use of LID techniques: these aim to restore urban watersheds functions to pre-development stage hydrology, increasing resilience to external stresses, without compromising the requirements of modern urbanization. Figure 1 summarizes the effects of urban development on flow volumes and frequency. LID can be optimally applied in new urbanization planning, but also as retrofit of existing infrastructure. In addition to purely hydrologic issues, recent stormwater quality regulations are a major factor in LID adoption. While traditional urban stormwater management relies on fast conveyance of excess water away from affected areas, LID relies mainly on infiltration, evapotranspiration and the incorporation of natural hydrologic features extending water retention and reducing runoff, peak flows and pollutant loads. A review of implementation and performance of low impact development approaches was recently published [29].

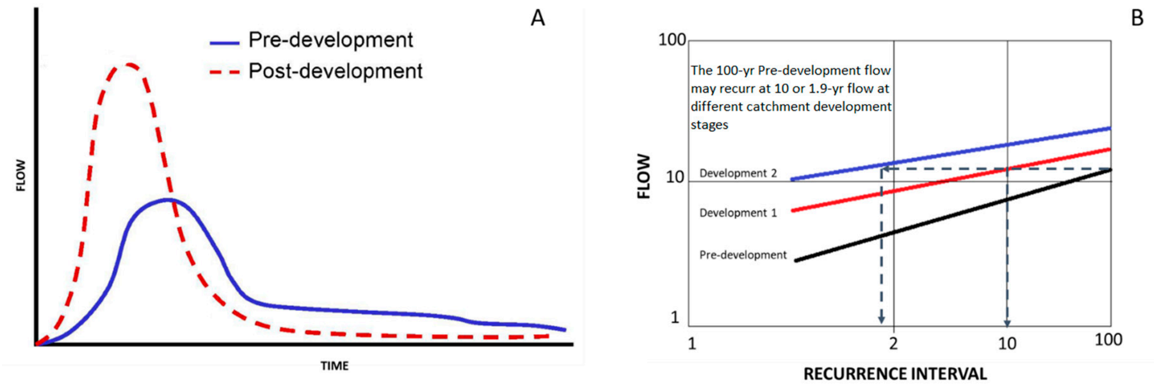

Figure 1. Effect of urban development on stormwater flow (**A**) and return frequency (**B**). With increasing urbanization, the recurrence interval of a 100-year flood can be reduced by one or more orders of magnitude, increasing the probability of risk to life and property.

LID stormwater management occurs mainly by means of two approaches: infiltration-based and retention-based. Both reduce an urban basin's effective impervious surface [30]; however, neither of the two individual approaches is generally sufficient to successfully restore a natural flow regime. Management of rainwater may also include installations for collection and reuse of precipitation [21], which can help decrease consumption of water, treated to drinking quality. Several combined solutions to limit runoff and promote use of collected rainwater were recommended by the European Commission [31]. Possible uses that do not require potable water are car washing, garden and lawn watering, laundry making, or toilet flushing. These have been already implemented around the world. Depending on climatic conditions, type of building and use, the reduction of demand for mains water may be as high as 60% [32].

Infiltration-based approaches assist in baseflow restoration by recharging subsurface and groundwater flow [31]. They include swales, infiltration trenches and basins, unlined bioretention systems (e.g., rain-gardens), and porous pavements. Their effectiveness is highly affected by site conditions, hence the wide reported range of performances.

Swale systems (open channels filled with vegetation) can be used to replace traditional curbs and for erosion control in peri-urban areas. They are designed to induce infiltration, sedimentation, and filtration during flow conveyance, resulting in some degree of water quality improvement. Infiltration trenches usually consist of gravel-filled channels covered with soil and vegetation. Bioretention ponds (also called rain gardens) are landscaped low areas where onsite reduction and treatment of runoff occurs. They are generally vegetated with shrubs, perennials, or trees, and covered with bark mulch. Finally, permeable pavements (including paving blocks, plastic grids, porous asphalts and concretes) allow slow runoff infiltration, promoting pollutant removal by entrapment, adsorption or biological degradation.

Retention-based approaches are designed to hold collected stormflow and reduce outflow from a catchment. They have substantial influences on local flow regime, reducing peak flow, but may result in increased outflow persistence. They include wetlands, ponds, green roofs, and decentralized rainwater harvesting; some have been used extensively for years. Although they can be quite effective for pollutant removal, they have limited effect in reducing overall runoff volumes, since this occurs mainly by evapotranspiration.

Green roofs have proven beneficial for stormwater control in many studies. It has been claimed that green roofs, in addition to runoff control, may induce other additional environmental benefits, such as air quality improvement, urban heat-island effect mitigation and urban aesthetics amelioration. According to existing experiences, there are few disadvantages to this solution, the cost of installation being the main one. In addition to the cost of the vegetated component, which may vary according to execution and aesthetic requirements, the added expense to install a green roof, compared to a traditional flat roof, consists mainly in higher structural costs, as the underlying structure may have to be strengthened to cope with the extra structural load. Green roofs show effectiveness in stormwater retention, with ability to attenuate runoff peaks from events with 2–100 years recurrence intervals, reducing the need for detention basins, with beneficial environmental impact. Green roofs can effectively retain 100% of rainfall in events with precipitation less than 12 mm, and significantly delay hydrologic responses, slowing onset of runoff by an average of 5.7 h, and peak runoff response by an average of 2 h. Annual runoff reduction between 38% to 54% and peak flow reductions up to 90%, were reported [33]. Green roofs have an effect on buildings' energy requirements, raising winter roof temperatures by up to 6 °C, and lowering it by up to 19 °C in the summer, with much narrower ranges of diurnal fluctuations [34]. Several municipalities in Europe provide economic incentives for this practice. Over the last 25 years, many such projects have been completed in the USA and Northern European countries, including Germany and Switzerland.

Decentralized stormwater harvesting may significantly improve water retention within a catchment, reducing annual runoff volumes. Stormwater harvesting is more efficient in terms of runoff reduction if designed to supply water on a daily (short-term), rather than seasonal, basis. Harvested water may be readily used onsite, e.g., for irrigation, or can be further treated for high-quality uses, becoming a significant component of urban hydrology. It is increasingly seen as a valuable resource, especially in water-scarce areas. The potential range of rainwater use as public water substitute is limited by quality and cost of any necessary treatment [20], but it can also imply significant energy requirements and emissions reductions for supply systems [14]. In some areas, due to particularly favorable environmental quality, rainwater could be directly used as a drinking water supply source [35].

In Poland, although the University of Warsaw Library is considered one of the most beautiful and the largest roof garden in Europe, with surface of 1 hectare [36], issues concerning sustainable, low impact stormwater management have largely remained outside the mainstream of research and application interest, with few significant examples.

Legal and Economic Aspects of Stormwater Management

The adoption of alternative approaches to storm-water management bears an implicit economic impact on land development scenarios and water resource protection. Studies have been carried out, showing that the impact of LID and similar practices on property value is quite complex and variable.

While this impact may be compensated by appropriate taxation policies, it reduces externalities due to avoided pollution [37].

Through the implementation of the Water Framework Directive into Polish law (Polish 'Water Law'), an obligation to manage stormwater runoff according to sustainable development rules came into existence [38]. Rainwater should be retained as much as possible at or near the location where precipitation occurred, through the use of surface or underground retention, and in-ground infiltration. Pursuant to the Polish Act, the "discharge of rainwater or meltwater into waters or into water facilities, contained in open or closed rainwater drainage systems for the discharge of atmospheric precipitation or into collective sewage systems within the administrative boundaries of cities" is part of "water services". Regardless of legal obligations related to discharge, financial obligations also exist. As provided for in Art. 389 IP, for this discharge it is necessary to obtain a suitable permit and abide by payment of fees to the service operator.

In the USA, a similar situation exists: The Water Quality Act of 1987 mandated the implementation of a comprehensive program to address stormwater runoff. Since no specific funding provision was established, municipalities introduced various fees in order to fund stormwater projects, effectively implementing a separate local taxation system. Other countries, like Canada, the United Kingdom, Germany, and Australia, have similarly introduced stormwater charges [39,40]. Communities currently use a combination of instruments: some introduced user fees to provide dedicated funding to "stormwater utilities" (separated from wastewater utilities), notwithstanding the complexity of identifying who pays and benefits for what, since drainage systems are often interconnected. Alternate funding methods include local bonds for infrastructural improvements, developer extension fees (capital costs shared among new developers), impact fees (based on mitigation costs of new developments' impact), special assessment fees, property taxes, and stormwater user (i.e., service) fees. User fee schemes could provide an equitable, dedicated source of funding, with charges commensurate with the cost of service, but they are not always applicable. Stormwater utility fees are considered more efficient and environmentally sustainable, allowing long-term planning and solutions, at the political cost of high visibility. Unlike other water cycle related fees, these could be reduced by stormwater credits for introducing best management practices (BMPs), such as those described.

In European countries, stormwater fees have been introduced for many years: in most German Lands, fees are calculated based on the impervious surface area. In Hamburg, for example, it is calculated according to the total costs attributed to the impervious area connected to the public sewer, and currently amounts to 0.73 €/m^2 impervious area [41]. In Italy there are no specific stormwater management fees so far. The cost of water services is covered under the formula of an "Integrated water tariff" paid to the local sewer operator, which takes care of all the aspects of water services from supply to collection and treatment, based on metered water consumption.

In Poland, the issue of stormwater fees foresees a water service fee, due for discharge of rainwater or snowmelt. The purpose is to encourage users to rationally manage water and limit pollution, as well as cover costs associated with drainage and facilities for its treatment. Fees consist of a fixed and a variable component: the former, sometimes referred to as "subscription" fee, depends on the maximum allowable rainwater discharge specified in the water permit. The base fee is PLN 0.75/m^3 (about 0.17 Euro) yearly, but if water retention devices with capacity >30% of annual runoff from the area are installed, it is reduced tenfold. In areas covered by combined sewer systems, the fee represents the cost of sewage collection. In areas with separate sewers, the fee is based on the volume of collected runoff or on the impervious area. The latter could range from 0.31–7.06 PLN/m^2 (about 0.07–1.63 Euro/m^2) [42].

In addition, Polish Water Law sets conditions for runoff drainage from industrial areas. In the case of areas greater than 3500 m^2, a variable fee is applied if more than 70% of the surface is excluded from biologically-active areas (Article 268.1) as shown in Table 1. The fee is also assessed on all real estate located in areas not served by sewers. This applies to all real estate meeting the cited criteria, including large-surface commercial sites (e.g., supermarkets, warehouses), residential estate, office buildings, and housing communes.

Table 1. Variable stormwater discharge fees for industrial areas in Poland.

Site Characteristics	Fee Amount [PLN (€)/m^2/yr)] *
Site without retention devices permanently connected	1.00 (0.23 €)
Site with retention devices with capacity of up to 10% of the annual runoff, permanently connected	0.60 (0.14 €)
Site with retention devices with capacity of 10–30% of the annual runoff, permanently connected	0.30 (0.07 €)
Site with retention devices with capacity of more than 30% of the annual runoff, permanently connected	0.10 (0.02 €)

* 1 PLN ≅ 0.2278 € (average between October 2019 and October 2020). This exchange rate will be used in all subsequent cost figures exposed in the paper.

In 2003, the city of Pila pioneered the introduction of a stormwater fee, quickly followed by other towns (Ostrow Wielkopolski, Nysa, Bielsko-Biala, Poznan, Biala Podlaska and Boleslawiec). Today, almost 95% of Polish town have implemented stormwater fee structures.

3. Case Studies of Stormwater Management Upgrade in Two Urban Developments in Silesia

Notwithstanding a clear global trend towards the increasing development and implementation of sustainable urban drainage systems, this issue is not addressed on a widespread scale at the moment in Poland, where a conventional stormwater management approach still remains the most common in urban management. In Poland, which has an unfavorable water balance, rainwater still constitutes an unappreciated contribution to the urban water cycle and is still mostly treated as a nuisance to be disposed of, and discharged as quickly as possible to a receiving water body. Only recently, following the momentum of predicted effects of climate change, and the problem of a lowered groundwater table across the country [43], is stormwater starting to be considered as a possible alternative resource. An analysis of national domestic water consumption trends showed that approximately 50% of public drinking-quality water consumption could be substituted by reused rainwater, with peak of about 65% in public buildings [44].

Two case studies of sustainable stormwater solutions implemented in small buildings in the Kobierzyce commune in the Silesia Region of south Poland are presented and analyzed herein. These concern on-site retention and subsequent water reuse, and a rainwater infiltration garden installation, respectively.

3.1. Case Study 1: Onsite Rainwater Retention and Subsequent Reuse

The first case examined concerns a community center building with playground and parking, built on the site of a demolished establishment, where a local rainwater retention system was implemented. The total plot area of 3300 m^2 consists of directly connected impervious areas (roof and parking) of about 700 m^2 (21% of the lot surface). Built area (including terrace) is 380 m^2, total paved surfaces 1500 m^2, playground 150 m^2, and biologically active area (lawns and trees) 1250 m^2 (37.88% of total) (Figure 2). The organic soil layer consists of low-permeability compacted sand, clay and sandy loams. Groundwater occurs at a depth of 1.5–1.8 m below surface, and therefore is poorly suitable for stormwater infiltration.

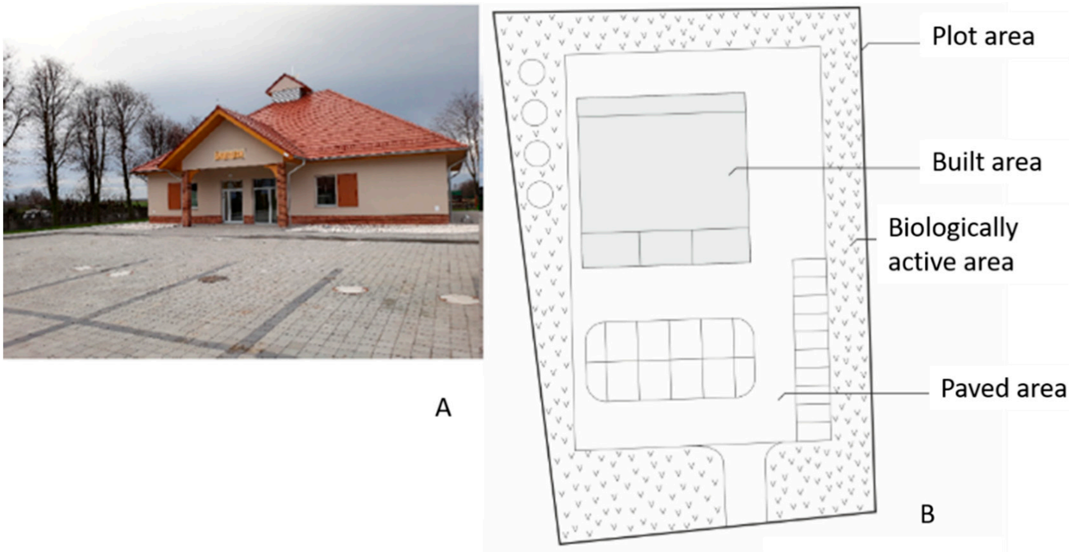

Figure 2. (**A**) New rural community center building, (**B**) plot area.

In the original site conditions, stormwater was discharged directly to a sewer network; with the increased impervious area (larger building and paved area), higher runoff and overflow events were expected. Aside from pure ecological considerations, the main factor suggesting the adoption of an alternative stormwater management solution was related to the increased fee for its discharge. During redevelopment, the site drainage was therefore re-designed with the implementation of a retention basin to reduce stormwater release into the sewer from the property area.

The design of the retention system is based on the estimate of the amount of rainwater and snowmelt on site: for small-scale solutions (e.g., single-family housing, service construction, single public facility building) as in the described case this does not require complex dynamic flow calculations, unlike the case of large catchments [45]. The site's 20-year average annual precipitation (rainwater plus snowmelt), obtained from records of a nearby meteorological station, was estimated at about 600 mm (Figure 3). In the last two years, values of 812 mm and 544 mm were observed, respectively.

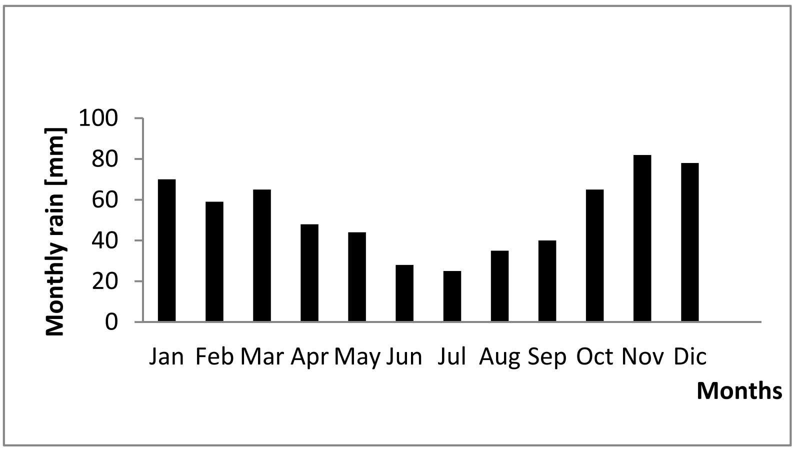

Figure 3. 20-year, monthly average rainfall for the case study site.

The widely used Polish standard (conforming to European standards) PN-EN 75 indicates the following formula for calculating the runoff rate for surfaces <10,000 m^2:

$$Q = \Psi \times I \times A \quad (1)$$

where Q is the maximum flow (L/s), Ψ the permeability coefficient, I the rainfall intensity (per ha), and A the area (ha) considered.

The maximum rainfall rate can be calculated using the Błaszczyk method, for 15-min events (Figure 4) and areas with annual rainfall H < 800mm:

$$q = \left(6631 \sqrt[3]{H^2C}\right)/t_3^2\Big) \tag{2}$$

where C is the return frequency during which rain occurs with duration t and intensity q, and H the average annual rainfall, in mm.

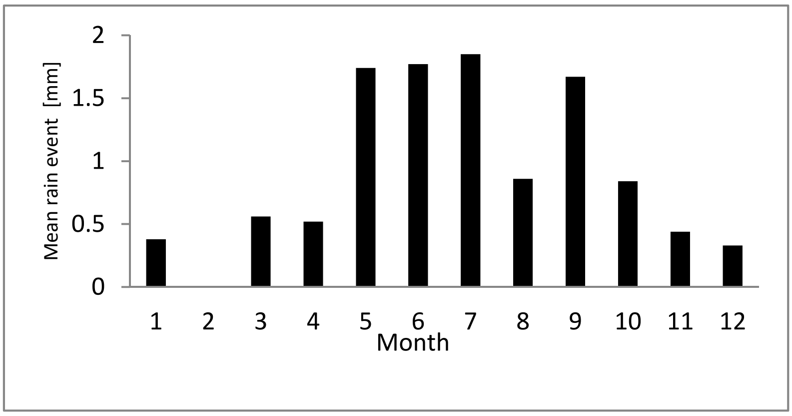

Figure 4. 20-year average values of rainfall on the Kobierzyce site for 15-min events.

The observed behavior of monthly and burst precipitation time series has significant seasonal variability, with relatively dry summers of intense, short rainfall events. This makes local storage an issue of primary relevance in runoff management. Total average runoff of 1134 and 642 m^3/year were thus calculated for parking area and roof. Based on the maximum value of 1.85 mm intensity for the 20-year 15-min event, runoff volumes of 27.75 m^3 and 11 m^3 were calculated for the parking and roof areas, respectively, and targeted for temporary storage. Excess runoff during the more intense events would be diverted to the sewer. Storage tank volume was determined by the practical formula [46]:

$$V_u = V_j \times F_{zr} = 0.06\,[q_{max}(t) - q_{dl}] \times t_d \times f_a \times f_z \times F_{zr} \tag{3}$$

where: V_j indicates the unit retention volume (m^3), F_{zr} the reduced area (ha) of the contributing surface, $q_{max}(t)$ the maximum unit rainfall intensity (L/ha) with duration t_d [min], q_{dt} maximum specific outflow from storage (L/ha), f_a a reduction factor (≤1), depending on corrivation time in the network, t_p (min) and the frequency of rainfall C [years], and f_z a safety factor for volume exceedance (1.1–1.2).

Runoff management was thus reconfigured as follows: roof runoff directed immediately to underground storage (11 m^3 capacity); runoff from car parking, processed in a class I oil separator according to PN-EN 858:2005 standard, to reduce residual concentration of petroleum substances below 5 mg/L. Parking runoff is conveyed by the site's drainage network (137 m of DN400, 49 m of DN315, 54 m of DN200 and 30 m of DN160 pipes, for a total available free volume of 23.3 m^3, enough to hold approximately 85% of the maximum parking runoff volume during and after the design event), and ends in the underground tank from which the excess overflows to the storm sewer. The maximum 15-min runoff calculated from (2) amounts to 132 L/s; the maximum downstream conveyance capacity of the drainage network is 14.3 L/s. A prefabricated oil separator, with integrated settling tank, type OKSYDAN-P 15 (OKSYDAN Sp.z.o.o, Gliwice, Poland)) with nominal capacity of 15 L/s and integrated settling tank of 1.5 m^3 was installed upstream of the underground tank. Local prescriptions on maximum overflow into storm sewers prescribe a limit of 10 L/s, hence a flow regulator (AQUANTIS 330598, diam. 160 mm) was installed at the outlet of the tank.

Stored runoff is targeted for local non-potable reuse: green area watering, surface washing or car washing. According to locally adopted design criteria, the retention tank volume could be suitable to irrigate a green area close to 1000 m^2, as shown in Table 2.

Table 2. Storage tank sizing requirements.

Roof Area (m^2)	350	400
Max. green watered area (m^2)	830	950
Minimum retention tank volume (m^3)	10	11

The underground tank, the pivot element of the system, is fitted with a replaceable cartridge filter (sieve size 25 µm) to retain suspended solids prior to overflow into the municipal storm system. The filter operates with a limited head loss (1–3 cm, depending on fouling), and does not require additional energy inputs, but it must be periodically replaced. A recirculation pump is provided to feed lawn irrigation and other reuse options. This design is able:

1. to reduce and delay runoff drainage into the sewer system;
2. to retain rainwater at source;
3. to infiltrate irrigation water, enhancing evapotranspiration from biologically-active surfaces;
4. to reuse retained water for local uses and reduce water bills;
5. to optimize storm sewer network operation, reducing flood risk in the neighboring area and pollution of receiving waters.

In addition to the reduction of costs associated with lower volumes of stormwater discharged into the drainage system, collected runoff can be used, according to local regulations, for non-potable purposes, thereby reducing water bills at the site. Drawbacks include the need for periodic cleaning of filters and gutters from debris. From a cost-balance standpoint, if runoff from impervious surfaces were to be discharged in full to the sewage system, as in a conventional system, costs of discharge fess would be applicable. This amount can be determined based on existing regulation as 0.34 € per square meter-year of impervious area, at the amount of about 230 € per year. An additional fixed fee for discharge is assessed at about 46 € per year. With the designed system, the annual discharge fee amount is reduced to less than 90 €. Additional costs for the installation of the retention system (storage tank and flow regulator only as local drainage network, the oil separator being required by regulations in either case) amount to about 1600 €, system maintenance (periodic cleaning) and operation cost was assessed at 0.2 €/m^3 storage volume. These figures are summarized in Table 3.

Table 3. Economic balance of stormwater management in Case study 1.

	Without Runoff Retention System	**With Runoff Retention System**
Water reuse from collected runoff (est. average) [m^3/year]	0	640
Water consumption for irrigation (average) [m^3/year]	400	0
Construction costs of additional storage [€]	0	1600
Maintenance & operating costs [€/year]	20	75
Water tariff (1.25 €) /m^3 × 400 m^3) [€/year]	500	0
Stormwater fee [€/year]	276	137
Fee for discharge to sewer network [€/year]	256	<90
Total annual costs [€/year]	1052	302

Figures presented in Table 3 are based on “design” data and actual billing for municipal and water and stormwater services (2017, prior to retention system installation, and 2019, after). Figures include actual fees paid, including changes introduced in 2018 due to new local regulations. Considering an average initial interest rate of 1.5% per year (average historic Polish discount rate till February 2020; it is now 0.1%), and considering the annual cost difference, the additional investment for the retention system was recovered in the first 2.3 years. Considering a design lifespan of 20 years, water bills’ saving at year 20 would total about 13,200 €, assuming no tariff variations, over eight times the amount of the initial investment.

3.2. Case Study 2: Rainwater Infiltration Garden

The second case study concerns a rural community center building constructed near a residential area in the Kobierzyce commune. The community center plays an important role for the local community: it is the place for town meetings, public participation and other organized events. The roof area of the building is about 650 m^2, a small underpass and parking cover 500 m^2 of a total plot area of 2100 m^2, in which the biologically active area amounts to 950 m^2 (Figure 5). Rainwater was originally discharged into the sewer network, but due to the high discharge fees it was decided to seek alternative stormwater management practices. A solution contemplating the implementation of a rain garden was selected after consultation with the residents, as a perceived adequate approach for the local community, since is relatively simple to implement, may constitute an occasion for enhanced public involvement and participation, which is an important factor in all matters of sustainable management, and required minimal disruption to the existing site. Participation in the construction, planting and ongoing maintenance of the garden can in fact be treated as a form of integration within the local community.

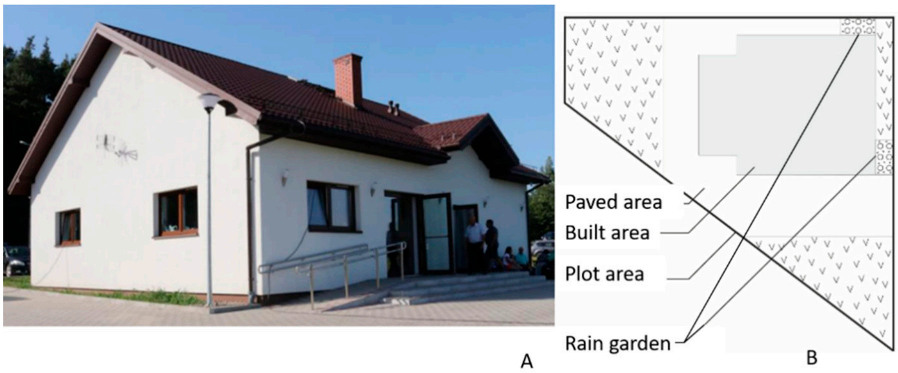

Figure 5. (**A**) Rural community center building, (**B**) surrounding area.

The rain garden system provides runoff infiltration, temporary retention and pre-treatment. A rain garden is built in a shallow depression of the terrain, receiving rainwater from the roof with a gutter and downpipes. The water may flood temporarily on the garden surface (immediately after precipitation), but for the most part of the year it functions as a dry (unirrigated) garden. Its construction implies a proper layering of the subsoil with substrates of good permeability and porosity, which ensure water penetration into buried drainage pipes connected to a storm sewer network or into the underlying aquifer. Coarse sand, limestone and volcanic rock are used for substrate layering.

A rain garden surface includes increased permeability soil (gravel) and vegetated areas with specially selected plants (usually species original to wetlands) that can play an important role in water purification from nutrients and heavy metals. An appropriate soil and vegetation choice can not only fulfill functions of water storage, but also those of biological pollutants removal. A rain garden is specifically designed to collect roof and paved surfaces runoff, store it temporarily, and infiltrate it to underground drainage pipes. Guidelines indicate that a suitable required garden area should be at least 2% of the effective drained area (total area multiplied by a runoff coefficient, depending on the type of surface). Based on the site's characteristics, the total calculated area, with runoff coefficient equal to 1, should be at least 13 m^2, therefore two raingarden plots, each of 8 m^2, located on opposite building corners, were planned, each receiving runoff from an opposite roof pitch.

The installation of the garden started with the excavation of a trench with a depth of about 1 m, with a bottom filled with two 10 cm layer of gravel aggregates (8–16 mm and 2–8 mm size) over which a perforated drainage pipe (diameter 90 mm), enveloped in coconut braid cloth, was laid. A vertical overflow pipe (also 90 mm in diameter) installed into the drainage pipe and protruding about 10 cm over the decorative surface gravel of the garden, allows rapid infiltration in case of high intensity events. The horizontal drainage pipe is covered by a 30 cm layer of fine gravel aggregate. The space between the drainage layer and the surface (45 cm) is filled with a mix of coarse sand, brick ore and dolomite aggregate. (Figure 6). The drainage pipe is connected to the public storm water drainage system to avoid overflow and local flooding in case of extreme events. The rain garden top layer consists of a 15–20 cm thick decorative gravel and stonecrop (*Sedum* spp.) vegetation, with a 2% slope from sides to center. Stonecrop is a succulent perennial plant ideal for dry areas, with easy maintenance and low culture requirements. The chosen plants are Jade and Echeveria.

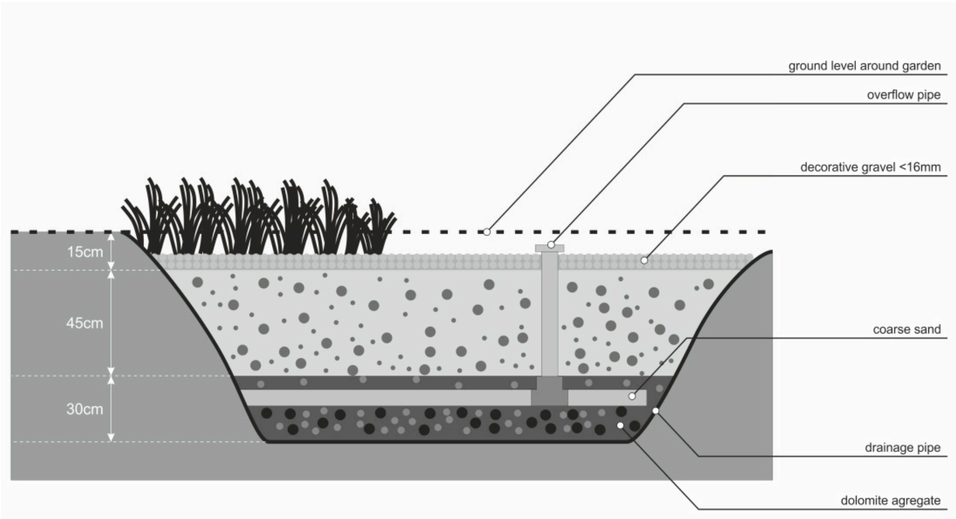

Figure 6. Cross-section of the rain garden layers.

Runoff volumes were calculated (using the same rainfall data of case 1) as: runoff from parking, 226 m^3/year, and from roof, 1047 m^3/year; the average volume of rainwater overflow to the sewage system after rain garden implementation was estimated at less than 10 m^3/yr. In this case, parking area runoff, representing a small fraction of overall runoff, was discharged directly to the storm sewer, at a cost estimated at 90 €/year.

Before construction of the raingarden, the cost of stormwater discharge into the sewer involved payment of a fee of 220 €/year. The rain garden construction cost was quite low (12.3 €/m^2, excluding vegetation), and on the grounds of analyses carried out during the first year of operation, annual maintenance and operating costs were estimated at about 0.5 €/m^2/year. The economic summary of the solution is presented in Table 4.

Figures in Table 4 are based on "design" rainfall volumes and actual billings received. With the same assumptions adopted in case 1, it can be seen that the entire investment for raingarden installation was recovered in less than one year. Assuming a useful project life of 8–10 years (after which some intervention to restore soil permeability would probably be necessary) accrued tariff savings between 2900 and 4100 € would have accumulated, or between 13 and 18 times the initial cost for raingarden operation.

Table 4. Economic balance of stormwater management in Case study 2.

	Without Raingarden	With Raingarden
Construction costs [€]	0	227 (199 + 28 for plants)
Maintenance & operating costs [€/year]	0	7.40
Water services fee [€/year]	60	0
Stormwater fee [€/year]	250	0
Fee for discharge to sewer network [€/year]	220	90 (parking area only)
Total annual costs	530	97.40

4. Discussion

In both case studies presented, benefits of an alternative stormwater management approach result from two factors, runoff delivery reduction, and reduction of discharge fees due to implementation of mitigation measures. Introduction of such solutions brings environmental benefits in addition to economic ones: the possibility of using water for irrigation (case 1) allows improved maintenance of green areas, even during long intervals between rainfall events; in addition, lower water consumption from the public supply network reduces not only water bills but also energy consumption and related emissions. Improved maintenance of green areas will reduce surface soil erosion during intense storms, decreasing the load of directly mobilized sediments (and associated pollutants). The use of storage to relieve the flow load on rainwater drainage during heavy rainfall can prevent network overload and local flooding. Both systems have been operated now for two years. The retention tank proved a good solution, notwithstanding its relatively higher cost, and the rain garden also proved to work efficiently. In the first two years of operation (one of which with 35% higher than average cumulative precipitation), no direct local overflows to the Ślęza river were observed from either site's outfall, even during the most intense events. Prior to the introduction of these systems, overflows of various intensity occurred approximately 10 times per year, as per qualitative records of the sewer operator. While it is early to assess the long-term performance of these systems, they have shown a positive effect in their operation so far. In case 1, the implemented solution showed direct positive effects on receiving water visual quality near the outfall, preventing pollutants from impervious areas being discharged into the stream, and reducing hydrocarbon residues and suspended solids compared to previous conditions (control analyses carried out twice per year for compliance purposes showed no detectable traces of these pollutants).

The cost analysis carried out for the two rainwater management solutions allows the following conclusions:

- the lowest investment costs were obtained for the rain garden solution. In that case, construction cost amounted to 0.22 €/m^3 of estimated captured annual runoff. In case 1, the investment cost amounted to 0.9 €/m^3.
- operating and maintenance costs (excluding investment amortization) of the two solutions are respectively 0.17 €/m^3/year (case 1) and 0.09 €/m^3/year (case 2). This includes systems' maintenance and municipal fees. Without any intervention, cost of the operation and maintenance would be respectively 0.60 €/m^3 and 0.50 €/m^3, for the most part due to municipal fees.

According to the analyzed figures, the rain garden solution appears to be the most appropriate from the cost point-of view; however, site subsoil conditions must be conductive to rapid infiltration. Furthermore, this solution excludes any subsequent local water reuse. Application of a rain garden solution in Case 1 (although subsoil conditions were not ideal) would yield a scenario summarized in Table 5.

Table 5. Comparison of rain garden vs. local storage solution in Case study 1 site.

	With Rain Garden (Estimated)	With Existing Runoff Retention System
Water reuse from collected runoff (est. average) [m^3/year]	0	640
Water consumption for irrigation (average) [m^3/year]	400	0
Construction costs [€]	570	1600
Maintenance & operating costs [€/year]	18.20	77.50
Water tariff (1.25 €/m^3 × 400 m^3) [€/year]	500	0
Stormwater fee [€/year]	137	137
Fee for discharge to sewer network [€/year]	<90	<90
Total annual costs [€/year]	745	304.50

As illustrated, the lower cost of rain garden installation would be quickly offset by the remaining cost of water supply (as in the case of no intervention), since this solution does not allow water reuse. On the other hand, it can be seen that in the absence of discharge fees (and related incentives) the economic analysis of the two cases would be completely different, as shown in Table 6.

Table 6. Economic analysis in the case of no discharge fees.

	Case 1 (Retention and Reuse)	Case 2 (Rain Garden)
Construction costs [€]	1600	227
Maintenance & operating costs [€/year]	304.50	7.40
Water tariff saved (1.25 €/m^3 × 400 m^3) [€/year]	500	0
Annual net cost [€/year]	−195.50	7.40

In case 1, in fact, investment costs would be recovered in less than four years, with a subsequent accrued gain of 16,950 € due to water bill savings until project year 20, i.e., over 10 times the amount of the initial investment. This contradicts the conclusions of a previous review of rainwater collection and usage systems for single-family houses in Poland, conducted in 2009 and based on the offer from manufacturers' catalogues, with costs estimated at 265–1225 €/m^3_{stored} (1050–5000 PLN/m^3), much higher than in the case study presented. It is clear that under these assumptions, investments would show recovery after a period of 59–100 years, depending on water demand and capacity, and thus hardly be justifiable [44].

In case 2, no economic advantage would exist, and initial cost would never be recovered. This analysis confirms that a financial incentives policy are paramount to the achievement of sustainable stormwater management at the local level.

Reducing, on average, by 89% and 81.5% the runoff volumes from local site discharges in the two cases, considerable savings on sewer network construction could be achieved by the city, offsetting the missed income from discharge fees. An estimate of the overall cost/benefit balance of such citywide policies requires, however, a complex approach that goes beyond the purpose of this paper.

While non-potable reuse of rainwater may provide significant conservation of potable water supplies, the possible relationship between reuse and microbiological risks should be carefully considered. Very few studies are available to date on pathogen risk related to such onsite reuse, and clearly the contamination potential is highly dependent on the specific site. Generally, studies showed that a large percentage of roof runoff samples were non-detects with reference to pathogens (95%–90%, depending on microorganism), while stormwater samples from residential and commercial/light industrial areas showed most probable number (MPN) lognormal organisms distributions in the range of 1.3 ± (1.3–2.5) MPN 10 L^{-1} [47]. While some studies indicated that ingestion of untreated, onsite-collected roof rainwater and stormwater may result in gastrointestinal infection risks occasionally greater than that traditionally acceptable (10^{-3} ppy), they also determined that conventionally collected and treated wastewater pathogen log-reductions may be too restrictive when applied to stormwater, with conflicting evidence about the level of treatment (if any) required for health protection [48]. Decentralized treatment for stormwater may eventually be necessary in specific cases, in the direction of what has already been proposed for greywater reuse: applied technologies may include membranes and microbial fuel cell applications, both showing a compatible degree of pathogenic organism reduction [49,50]. Pathogen cells commonly range from about 1 to 10 microns in length, hence higher degrees of filtration than the one already used in Case 1 (25 μm) may be required.

4.1. General Considerations on Stormwater Control Practices

Although the effectiveness of LIDs on storm flow control has been demonstrated in a number of cases, barriers still exist to their broader implementation in new urban developments, due in part to the additional upfront costs for their implementation and long-term maintenance. Costing tools have been developed to allow designers to assess life-cycle costing of different LID practices and evaluate their efficiency [51,52]. These provide a framework to facilitate for capital, operation and maintenance costs estimation, and assess present life-cycle value. Their use, however, is limited by the availability of actual system components costs for specific areas, which sometimes cannot be easily estimated due to lack of previous installations.

The effect of LID practices should not be underestimated even in areas traditionally subject to high volume storms, since these practices successfully trap and filter a considerable portion of runoff, alleviating pressure on existing conveyance systems and reducing runoff side-effects such as downstream erosion, pollutant loadings, and damage to stream and riparian area habitats. Even in high-density urbanization areas, such as the center of the city of Athens (Greece), simulated introduction of LID practices showed potential peak flow reduction in the range of 13.4%–28.2%, and total runoff volume reduction in the range of 24.5%–29% [53]. A U.S. EPA review of 17 LID application case studies in the country showed that capital cost savings in infrastructure development following LID methods application ranged from 15% to 80% [54]. A model-based study concerning the selection of cost-effective LID strategies in Graz (Austria) considering the entire water balance and life-cycle-cost (including land costs) issues showed that there is not one specific optimal LID strategy, but that application of LID treatment trains, consisting of multiple interventions, shows high potential for cost-effective runoff reduction and control [55]. Cost-benefit analysis of LID for stormwater management in an urban catchment in Norway showed that these methods reduce combined sewer overflow (CSO) and that basin-wide optimized solutions in terms of maximum effects and minimum cost can be identified through the use of hydrological modelling [56]. Although no published studies have so far quantified the generalized impact of basin-wide LID practices in urban settings on storm sewers sizing requirements, it can be assumed that their wide-scale adoption could provide long-term benefits in terms of infrastructure design and investment costs.

A key factor in selecting the appropriate LID practice for a specific site lies in the understanding of the site specifics. For example, vegetated filter strips or rain gardens may be an ideal solution for small developments as in case 2 presented herein, but not for sites with large drainage areas. Some other limitations on potential LID installations include requirement of local codes' approval, possible increased pavement failures at LID/curb interfaces, liability and safety concerns, and reduced performance over time.

As interest in rainwater harvesting increases even in humid regions with well-developed water supply infrastructures, it is important to understand the functions and quantify the impacts of these systems. The most popular rainwater harvesting option for homeowners, the so-called "rain barrel" (or small buried storage, less than 1 m^3), often provides inadequate storage even for small irrigation demands in dry periods, and overflows frequently in response to intense storm events. Rain barrels, while providing a valuable demonstration and awareness function, do little to limit runoff, except in particular cases. Studies indicate that only larger rainwater harvesting systems, such as that described in case 1, may have substantial impact on both runoff volume capture and replacement of typical household irrigation demands [32].

In urban settings, regulations in most countries do not allow the use of harvested rainwater for domestic applications other than toilet flushing at the moment, but water utilities are increasingly confronted with customers aiming to decrease their household water footprint by treating rainwater onsite for drinking uses. According to literature, rainwater quality may be better than some surface waters, especially when these are mixed with treatment plant effluents that could still contain pharmaceutical residues or microbial contamination [57]. However, depending on local conditions, rainwater might also be susceptible to microbiological contamination from local pests or wildlife (e.g., avian or rodent species, and even large animals, such as dogs, boars or deer), hence precautionary methods or treatments should be adopted in such cases. A study of a new development district in the Amsterdam area, with total impervious area of about 93,600 m^2, estimated that 64,000 m^3 of water could be harvested adopting current practices, covering about 51% of the drinking water demand of future residents [58]. A combined supply scheme (rainwater harvesting plus central drinking water production) was proposed; however, in order to maintain sufficient supply capacity to deliver drinking water at any time (including dry periods), treatment process and network design would be identical to a traditional system. Site specific economic and energy simulation would be needed in these cases to ascertain any advantage of such solutions. Several studies concluded that cost-efficiency of rainwater harvesting strategies for drinking water provision is strictly linked to local water prices, and that such systems should be preferably installed at the neighborhood level in new construction areas to be cost-effective [59–61].

In addition to cost factors, green infrastructure projects should include early community involvement and communication, and clear evaluation based on project motivation and outcomes. Public perception may be one of the greatest hurdles to overcome, since studies suggest that industrial and commercial users often choose to use municipal water over harvested rainwater, despite its availability [62]. Case study 2, where residents were actually involved in the planning and in the management of the rain garden, is a good example of such practices.

4.2. Potential for Rainwater Reuse in Poland

It was estimated that, at current costs, under Polish conditions rainwater provision for non-potable uses is nearly twenty times cheaper than purchase from public supply, considering only energy consumption for the harvesting system, but excluding initial investment [44]. Climatic conditions in Poland would generally enable effective functioning of such systems, as confirmed by the results of simulation studies [63]. Although it was shown that under the current conditions investment costs are much lower than they had been assessed a few years ago, the financial sustainability of such choices should be evaluated on a case-by-case basis. The introduction of local incentives and fee reduction is without doubt a strong boost to the adoption of these systems in new developments, improving the economic aspects.

In Poland, approximately 85% of potable water comes from surface waters, and requires subsequent purification processes [64]; water supply infrastructure was designed in the 1970s and 1980s to meet the increasing water demand of intensively developing, water-absorbing industries, as well as the high water consumption in the residential sector, and still has considerable reserve capacity. Limiting flow in these networks could require measures to detect and counteract possible secondary contamination during longer in-pipe residence, if this and other water savings solutions were to be adopted on a large scale. Improved systems for in-line detection of waterborne pollutants, such as the application of drinking water contaminant warning systems that are currently being developed may be of use [65].

From this point of view, drastically reducing consumption of water from existing municipal systems may not always be desirable, however, as the price of tap water will become higher; due to the need to modernize the existing treatment and distribution systems, the introduction of mixed supply schemes may become appealing.

5. Conclusions

At the moment, the scale of rainwater reuse is still small in Poland, therefore the issue of sustainable rainwater management is highly relevant and an object of active technical debate. The most popular, relatively simple, solution is to adopt small retention/infiltration devices for single development units, allowing increased use/infiltration of rainwater. As shown, this could bring significant environmental and financial advantages to the community and property owners. The economic sustainability of these measures is strictly correlated to the existence of fiscal/fee incentives, although those solutions that contemplate local reuse also benefit from lower public water purchase costs.

Alternative rainwater management solutions aim primarily at relief and possible replacement of traditional sewage systems: as shown, raingarden is a cost-effective and resilient approach, that provide a number of advantages for facility managers interested in sustainability, but its financial viability is limited by the lack of reuse options. Onsite rainwater storage (harvesting) for reuse implies direct financial savings on water supply costs that could make the solution appealing for individual users even in the short term.

Although the generalized use of these systems would add resiliency to stressed water supply networks, additional aspects such as longer flow residence times in distribution systems and resulting quality issues that may arise should be evaluated and addressed.

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