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RAINWATER HARVESTING SYSTEM IN A MULTI-FAMILY BUILDING LOCATED IN POLAND

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Abstract

Rainwater harvesting, storage, and utilization systems are widely used in many countries in order to reduce tap water usage. In Poland rainwater is utilized in very limited manner despite the fact that potable water resources per capita are one of the lowest in Europe. There are many different ways of using rainwater within a household, public or any other building. It might be used for watering gardens, flushing toilets and due to its softness for cars and windows washing, and in washing machines. In this paper authors described rainwater utilization system for flushing toilets in a multi-family building located in Poland. In this type of building rainwater commonly does not fully cover the demand and during dryer periods needs to be supported by tap water, nevertheless, it generates noticeable savings on potable water. This paper presents economic and environmental aspects of using rainwater harvesting system in a multi-family building under conditions of Polish climate. Calculations of cost, types of systems and designing methods, including tank sizing are presented and discussed.

Introduction

Rainwater utilization is an inherent problem, from the moment when first buildings were constructed. However, the aim of rainwater system typically was to drain the water as far as possible from the place of living. Different situation was in the countries with a very dry climate, where water is priceless and was always collected to the very last drop. Until the nineties of the 20th century it was considered that storm water problem solution in the cities was to quickly collect and remove it to a receiver, but

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progressive urbanization and replacing natural land cover with tight surfaces, e.g. concrete, led to approach change (WOJCIECHOWSKA et al. 2015). Nowadays people try to lower the impact on the environment by using renewables, but water unfortunately does not qualify as one of them. Water is a valuable and exhaustible resource, the demand on it is constantly growing and it is anticipated that this tendency will obtain (DÖLL et al. 2009).

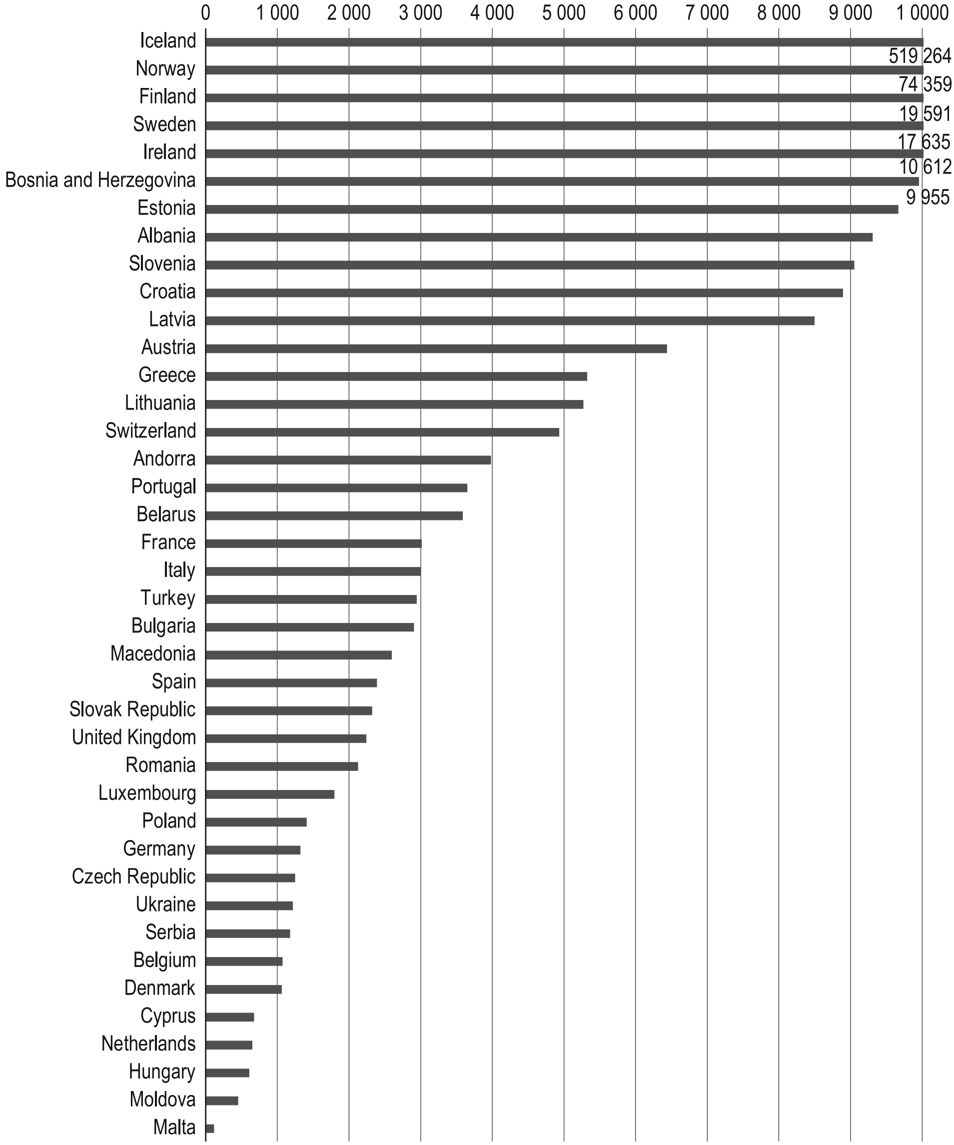

Fig. 1. Freshwater resources per inhabitant – long-term average [cubic meters] (FAO 2014)

Water resources are decreasing due to human negative impact on the environment (DUDKIEWICZ and LASKA 2019). These factors create necessity of more reasonable water usage and searching for alternative sources like rainwater. In addition, there is an economical factor – people always prefer to pay less for the bills if there exists such a possibility. Poland is a country with low level of water resources (STEC and SŁYŚ 2017) – Figure 1 comparing to other European Union countries (FAO 2014), it takes further than 20^{th} place (GUTRY-KORYCKA et al. 2014) which means that people should pay more attention to water usage. Utilizing rainwater also has another aspect, especially in big cities due to high surface sealing through which water cannot permeate, rainwater can cause floods especially so-called "flash floods". Urbanized area, which can be assumed as a tight surface, takes now ca. 5,4% of total surface in Poland (Figure 2)

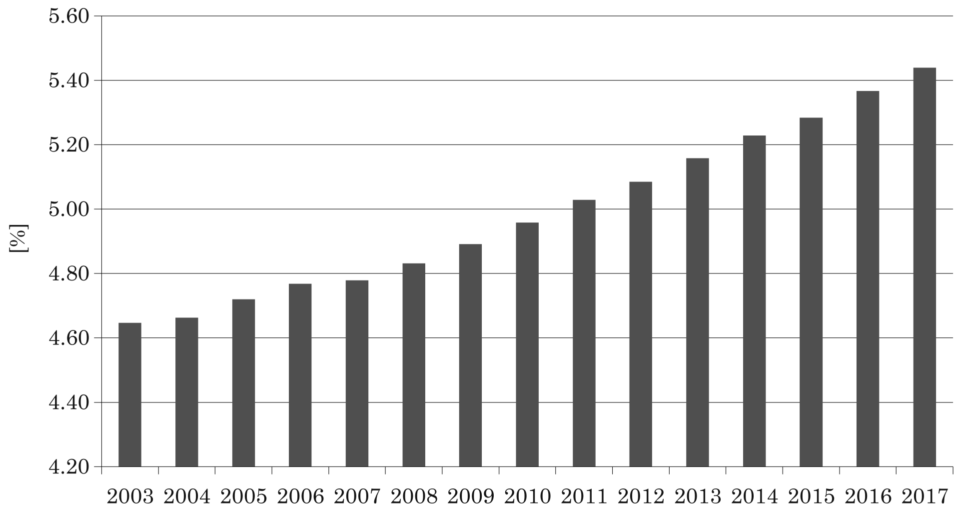

Fig. 2. Percentage quota of urbanized and built-up areas in Poland (GUS 2018)

and is constantly growing (GUS 2018). On the contrary this water, due to its softness, is a perfect cleaning agent for washing many different things, i.e. car washing, windows, and, which is the most useful in a household, laundry. It requires some minor treatment, like filtration and temporary disinfection. After filtering it can be used as well for flushing toilets, which in average covers 30% of total household water usage (Figure 3) and even 43% in public buildings (LUDWIŃSKA and PADUCHOWSKA 2017). Rainwater might be purified to the drinking water level, which can be useful in certain cases, but this process is very expensive and simply unprofitable from the economical point of view. People should therefore significantly change approach to dealing with rainwater and start treating it as a precious

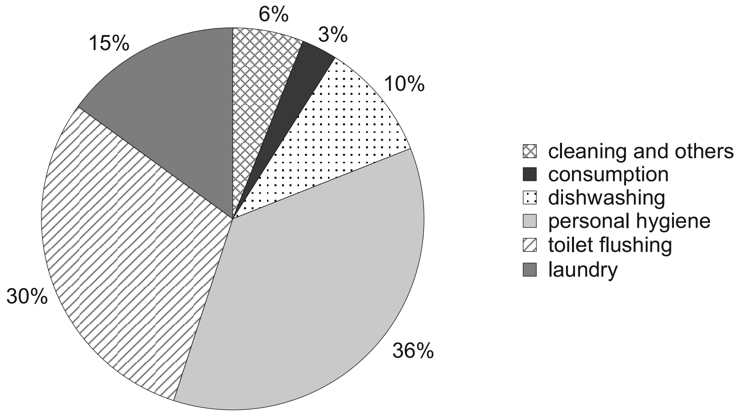

Fig. 3. Household typical water usage
Source: own study on the basis of LUDWIŃSKA and PADUCHOWSKA 2017

resource instead of a wastewater or sewage. In Poland there are regulations determining collecting and removing storm water to the sewage system or harvesting it and utilizing within the area around the building (Rozporządzenie Ministra Infrastruktury… DZ.U.2015.1422, 2018). Rainwater resources depend mainly on meteorological conditions, which may vary significantly in different regions and annual weather cycles. In Poland it varies from c.a. 500 to 1400 mm/year, in Olsztyn: 600–700 mm/year (IMGW 2018). It should also be mentioned that utilizing rainwater for household purpose lowers sewage volume introduced to wastewater collecting system thereby it decreases the whole sewerage system and treatment plants capacity. The objective of this paper is to present rainwater usage possibilities and their benefits based on a multi-family building example located in Poland.

Rainwater harvesting and usage systems

Rainwater can be collected from the rooftop and from other surfaces surrounding a building. Quality of water depends mainly on location, whether it is a polluted industrial region or place surrounded by forest and lakes, or by other environmental factors. In particular the type of collecting surface is crucial. Pollution that might occur in harvested water are: bird feces, leftovers of food carried by birds, organic matter e.g. leaves, street dirt and sand, chemical contaminant from industry, and other pollutions like oil or petrol. Rainwater harvesting systems are typically equipped with a tank, where water is collected after filtration. This process removes organic matter, partly dust and sand. In case of collecting water from pavements or streets grease separators and settlers must be utilized to remove oil and other floating particles before introducing water into collecting tank. From the tank water is next pumped to smaller tanks nearby the sanitary equipment or directly to the devices. Collecting tanks might be situated at the higher floors to enable gravity flow and omitting pump application. It is strongly advised to use disinfection, e.g. UV-rays to prevent *Legionella* in systems utilizing rainwater for other purposes than watering gardens and flushing toilets.

The simplest form of rainwater harvesting system is a tank, in which water is collected from the rooftop. Then it is used for garden watering or car cleaning without any treatment, besides a simple filter capturing leaves. More complicated systems, which deliver water to the building as well, can be divided according to the way of distributing it to the sanitary devices (LEGGETT 2001). Systems with indirect pumping (Figure 4) are based on two tanks, the smaller one is installed on the highest floor, above all the sanitary devices. Water is pumped from the main tank to the smaller one and subsequently it gravitationally flows to sanitary devices.

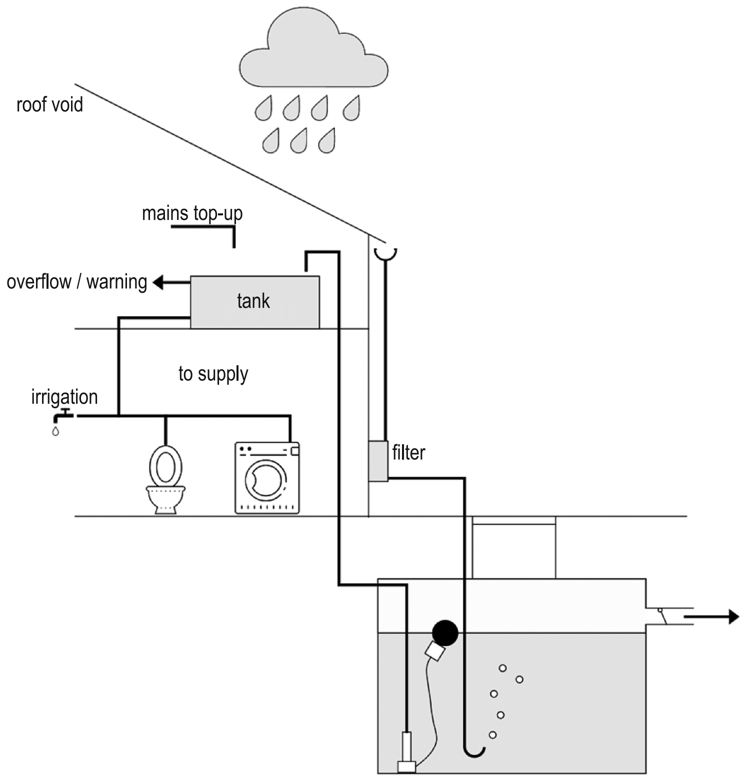

Fig. 4. Scheme of the indirect pumping system (LEGGETT 2001)

These tanks are additionally supplied with tap water in case of low rainfall during dryer periods. It is advised to mount them at least 1 meter above the sanitary devices level. Excess water should be discharged to sewage or drainage system. The advantage of this system type is lower pump expenditure due to less on/off turning. Notwithstanding the cost is higher comparing to the single-tank systems due to additional tank and, in certain cases, construction reinforcement necessity due to the tank weight. Alternative rainwater harvesting system type is direct pumping system (Figure 5), where water is collected in one tank and directly from it pumped to the sanitary devices. This system requires tap water supply in case of low rainfall and an overflow valve connected to sewage system.

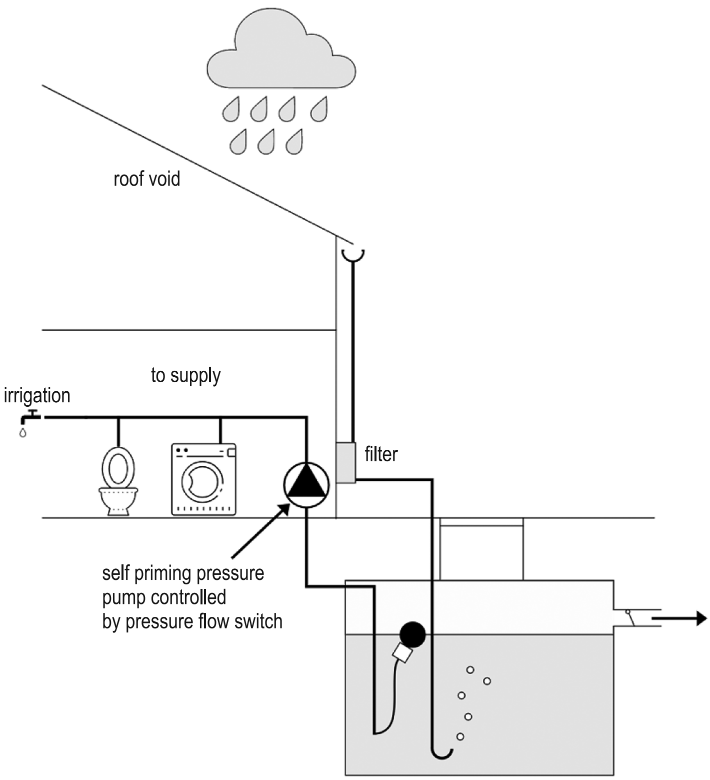

Fig. 5. Scheme of the direct pumping system (LEGGETT 2001)

One disadvantage of this system type is higher pump failure probability as a result of more frequent on and off turning. Secondary tank is not necessary. The third system is a gravity system (Figure 6) where the tank is placed on the highest floor or just under the rooftop (at least 1 m above sanitary devices) and the water flows gravitationally to sanitary devices.

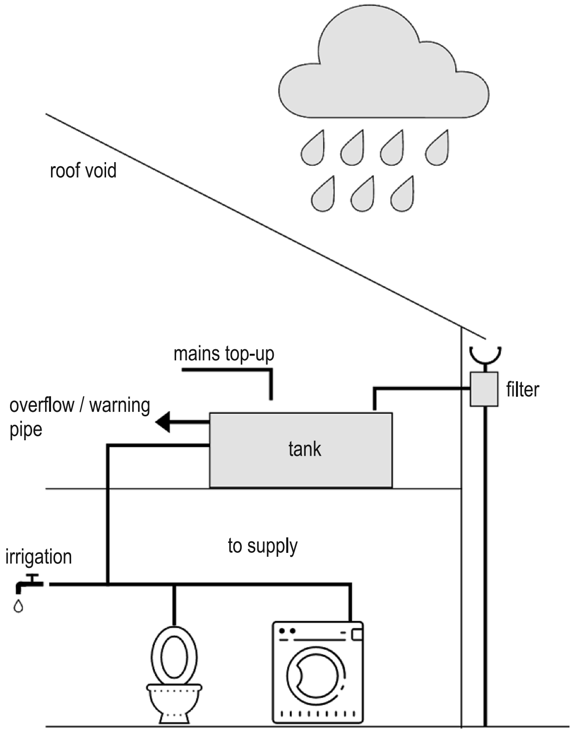

Fig. 6. Scheme of the gravity system (LEGGETT 2001)

The tank cannot be situated too high in terms of letting gravitational inflow of the water from the rooftop. It also requires adequate construction reinforcement on behalf of the very high tank weight, e.g. 10 tons. This system does not require any pump which results in reliability increase and cost effectiveness. Tap water and overflow valve should be installed as in the previous system types.

Design of rainwater utilization systems

One of the most important factors deciding on implementing installation with rainwater use is medium yearly rainfall in given region and the volume of water possible to collect from the rooftop or another collecting area. Design process of rainwater utilization systems is shown on Figure 7. Rainwater collecting surface is a total surface from which water can be collected, specified in m^2. Predominantly for this purpose a building roof is used, however, as it was already mentioned, water can be collected from pavements, streets and parking places. In case of collecting rainwater

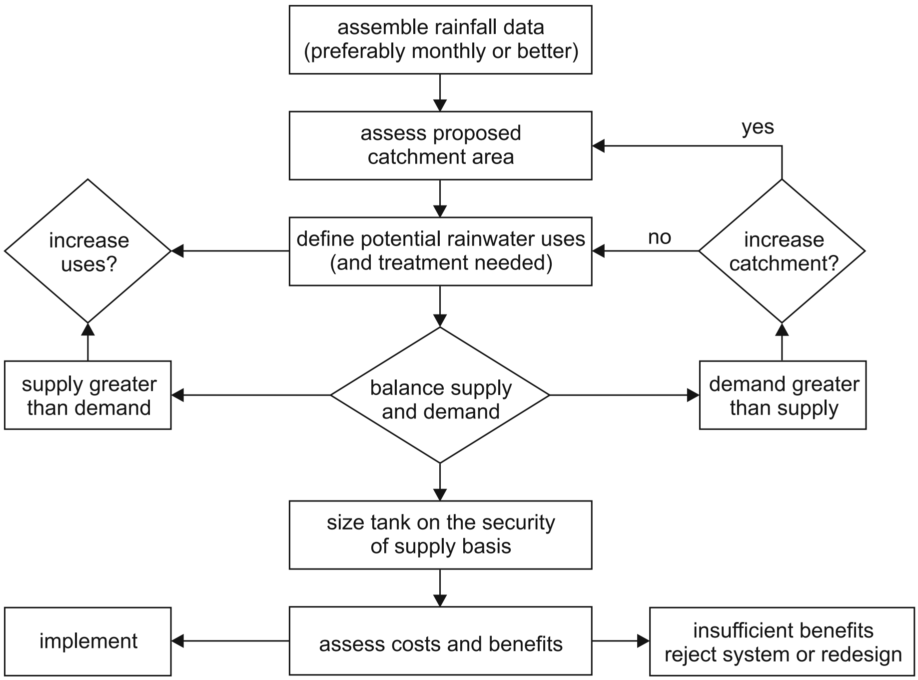

Fig. 7. Rainwater utilization system decision and design process (LEGGETT 2001)

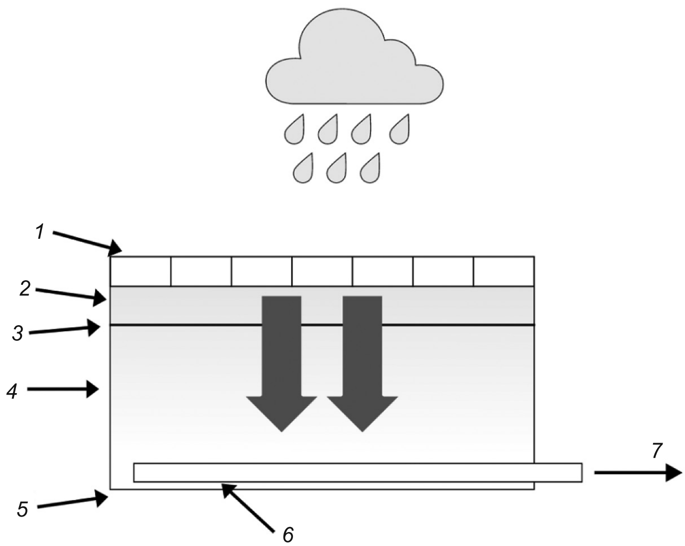

Fig. 8. Permeable pavement (LEGGETT 2001): *1* – permeable surface; *2* – bedding layer; *3* – permeable geotextile; *4* – permeable sub-base with storage voids; *5* – for attenuation: robust welded geo-membrane; *6* – collection pipe network; *7* – rainwater to further treatment, storage or directly to re-use

from other surfaces than rooftop much higher filtration and disinfection is required on account of the dust, sand, oil, petrol and other pollution that can be found on streets and pavements. An exception here can be so called *permeable pavements* (Figure 8) thanks to filtrating dust through utilizing proper layers absorbing pollution and causing proper conditions for biological oil degradation (SCHOLZ and GRABOWIECKI 2007). While designing rainwater harvesting system collecting area is taken as a flat surface which means that roof or pavement slope is not taken into account. It is normally necessary to divide area into smaller parts on behalf of different rooftop or pavement materials. The predominant wind directions should be taken into account as well as surrounding buildings and trees that can lower water volume reaching the planned area. Total volume of water does not run into the tank because of evaporation, absorption by materials, or its loss caused by bounce from the roof and falling on the lawn. Flat rooftops, covered with crushed stone, maintain huge amount of water, which slowly evaporates, while from the sloping roof made from tile or plate water flows down almost immediately. Roofs covered with straw or so-called *green roofs* covered with grass absorbs huge amount of water which slowly evaporates and only some small volume is drained to a tank or sewerage system. Run-off coefficients for different surface types are presented in Table 1.

Table 1

Rainwater run-off coefficient (ŚWIGOŃ 2008)

Surface type	ψ
Roofs covered with plate or slate	0.90–0.95
Asphalt and conrete roads	0.85–0.90
Roofs covered with tile	0.80–0.90
Paving surfaces	0.75–0.85
Flat roofs and wooden elements	0.50–0.70
Grass-concrete parkings (lawn grilles, loose row and stone cubes, broken stone surfaces)	0.25–0.60
Gravelroads	0.15–0.30
Cultivated lawns	0.10–0.20
Parks, gardens, fields, greens	0.05–0.10

Atmospheric conditions and surrounding area (possible industries and factories) have a big impact on rainwater quality before it reaches collecting surface. Chemicals such as sulphur dioxide, nitrogen oxides or carbon dioxide are absorbed by raindrops making rain sour. Next pollution stage occurs at the moment of water flow on the roof, street or pavement. Roofs are quite often covered with plate or other materials having some metal parts, e.g. steel, brass, copper etc. Therefore, water can contain higher metals concentration. In certain case it can result in lower bacteria development so in this context it can be taken as an advantage. Brittle materials on the roof lead to overgrowing with moss due to longer water keeping on the surface. This can cause increased bacteria development. Roofs made of steel or glass, as well as oblique roofs, especially these with high inclination angle, cause faster flow of the water, which cleans the surface and stops moss growth or bacteria development. Concrete roofs might to some extend improve the acid pH reaction, and "green roofs" result in lower water clarity, change of its colour to brown, which requires additional filtration. Roofs and gutters should be mechanically cleaned periodically in terms of eliminating as much pollution as possible. The best material for the pipework is polyethylene (PE). Pollution such as street dust, food leftovers, bird feces can cause occurrence of pathogens. Conditions caused by this pollution can be suitable for bacteria development such as *Legionella* or *Pseudomonas aeruginosa* (CHIDAMBA and KORSTEN 2015). The number of bacteria in the rainwater depends also on storage conditions. If the collecting tank is exposed to the daylight, an algae growth can occur which is perfect nourishment for bacteria and its further development. It is therefore recommended to situate tanks in shady places, preferably underground. The tank should not be oversized to prevent water stagnation. To obtain biological activity it is important to ensure proper oxygen conditions in the lower parts of the tank. This can be achieved by proper tank construction and way of introducing water. Oxygenation can be caused by introducing water to the lower part of the tank, bearing in mind not to put in motion matter which sedimented already before. Activity of the anaerobic bacteria is caused by too high amount of organic matter and other nutrients and can entail obnoxious smell of sulphuric acid. Tanks should therefore be ventilated.

Rainwater storage

Storage tanks can be made of different materials, such as plastic or concrete and have different shapes. One of the basic issues is the tank volume which has impact on whole system cost and savings that installation may bring. Then it is necessary to properly balance water demand and the available rainwater volume (MROWIEC 2008). The tank size depends on harvesting surface, medium rainfall, water demand, retention time (storage period), cost of the tank and its accessories. Potential rainwater volume collected from the given surface can be calculated as below (LEGGETT 2001):

mean rainwater supply [dm^3/year] = mean annual rainfall [mm] · surface area of catchment [m^2] · run-off coefficient · filter coefficient

The result is approximate and there are many elements that can disturb the real collected water volume and potential money savings, first of all unpredictability of weather. There are three typical situations of dimensioning the tank. The first is when given data and calculations indicate that possible rainwater collection would never satisfy the needs. This situation is typical for high multi-family buildings or office buildings with a large number of users and here the tank size depends only on rainwater available to collect. The second situation takes place when possible to collect water significantly exceeds the needs of the building. This is typical for factories or other buildings with low users' density. In that case tank size estimating is based only on the needs and water surplus is poured to sewerage system. The tank should not be oversized since water stagnation favours bacteria development. The third case is when possible to collect rainwater thereabout responds to the needs. The tank should be then dimensioned upon all the available factors, it should not be too small to prevent too often overflows to wastewater collecting system, nor to large, which could be conducive to bacteria growth and needlessly enlarge installation cost. A project conducted in Great Britain called "Buildings That Safe Water" *(*BTSW*)* (LEGGETT 2001) indicated that in most of cases storage tanks were oversized on account of too optimistic assumptions of designers. There are many different methods to calculate tank size used currently by producers and designers. Some of them are greatly complicated, based on different type of data, but there also exist simplified methods based on tables or charts. One of them indicates dimensioning of garden watering (Table 2) and household (Table 3) tanks (PIASNY 2013).

Table 2

Rainwater tanks for garden watering dimensioning (PIASNY 2013)

Garden area for watering [m^2]	Minimal roof area [m^2]	Tank volume [dm^3]
100	20	1 000–1 500
300	40	2 500–3 500
500	70	3 000–5 000
800	90	5 000–7 500
1000	100	7 500–10 000
1500	120	10 000–15 000

Table 3

Rainwater tanks for household dimensioning (PIASNY 2013)

Number of residents	Minimal roof area [m^2]	Tank volume [dm^3]
1–2	35	2 500–3 000
3	65	2 500–5 000
4–5	80	5 000–7 500
6–9	100	7 500–10 000

Catalogues of different brands such as *Kingspan* suggest calculating tank size according to an average from yield of rainwater and water demand, assuming 21-day retention period. *Roth* company suggests estimating 1 m^3 of tank for each 25 m^2 of the collecting surface. There is also analytical method with the formulas given:

$$E = NA\eta \qquad V = E \cdot 6\%$$

where:
N – mean annual rainfall [mm]
A – surface area of catchment [m^2]
η – run-off coefficient
E – mean rainwater supply [dm^3]
V – required tank volume [dm^3]

All the accessories, pipes, tanks, filters, pumps etc. require regular service to ensure faultless and long-lasting system operation. In the previously mentioned project BTSW the most common system malfunction was pump fault caused by filter soiling, not having them cleaned on time (LEGGETT 2001).

Rainwater treatment

To clean rainwater three basic methods are used: filtration, biological purification and disinfection. The purpose of filtration is to remove mechanical contamination before introducing water into the tank and after water storage in it. Biological purification is used in terms of removing nutritional substances for bacteria and preventing bacteria reproduction. Disinfection eliminates microorganisms. Gutter filters can be both internal and external. It is also recommended to use floating filters inside the tank which capture floating pollution from the water. These filters should be also connected directly to the pump with a pipe to ensure suction of the clearest water located just under the water surface (LEGGETT 2001).

In Germany, based on many years observation of utilizing internal gutter filters and floating filters, the water quality was sufficient for flushing toilets without any further purification. Biological purification is typically used as one of the purification stages in larger installations, where water is collected not only from the roof but also from pavements or streets. This process is carried out after collecting water in the tank. Bacteria that occur in water are used to remove such pollution as oils, organic matter, phosphates, nitrates and ammonia. Phenomenon of biological purification occurs also in previously mentioned permeable pavements. After filtration and eventual biological treatment disinfection might be required in terms of removing bacteria and other living organisms. Most of rainwater harvesting systems, which typically use water for flushing toilets and watering garden do not require disinfection at all, on condition that the primary pollution was not very significant. Nevertheless, if necessary, disinfection can be carried out in a physical manner as UV-rays, but adequate water transparency is required. This type of disinfection is typically used to remove bacteria such as *Legionella* or *E. coli*, which can have negative impact on the users' health. UV lamps consumes some amount of energy, ca. 120–140 kWh per year, which increases the whole system usage cost. This type of disinfection becomes more economical when the water is used more often on account of the fact, that UV-rays are equally effective for every water flow, if proper transparency is provided. Chemical disinfection is not recommended for rainwater harvesting system because of typically small amount of pollution. This process is more valuable when utilizing greywater but this is another topic.

Rainwater harvesting system usage in multi-family building

For the purposes of this article an elaboration of conceptional project has been made for a multi-family 4-storey building localised in Olsztyn. On each floor there are 6 flats, 2 persons for each flat in average. There is no terrain slope around the building. The rainwater is supposed to be used for flushing toilets, which induces savings on tap water. According to the calculations the rainwater does not fully cover the needs, thus replenishment from the water supply is provided. Tap water inflow is regulated automatically through a water level sensor, controller and valve to maintain minimal water volume in the tank during dryer periods. The system is designed as direct pumping system, which means that water supply is held from the main tank directly to the sanitary devices. The pump is enabled upon signal from the pressure sensor mounted on the pipe providing water to the toilets. Tank, made of plastic, is situated outside the building underground, below the frost level. It is equipped with a spillway to drain water excess to the sewerage network during heavy rainfalls. Pipes used are made of polyethylene on account of their resistance to corrosive nature of rainwater. For water purification an internal gutter filter has been selected – WISY, type WFF 150 – Vortex filter DN150. The filter is adopted on the final gutter length to remove such impurities like leaves, roof dirt, bird feces, insects and others.

Water demand has been calculated as below:

6 flats · 2 persons · 4 storeys · 4 times a day toilet flushing · 6 dm^3 of water for each flush =

$$= 6 \cdot 2 \cdot 4 \cdot 4 \cdot 6 = 1152\ dm^3/day$$

$$1152 \cdot 365\ days = 420\ 480\ dm^3/year$$

Rainwater possible to use:

Rooftop area:	$41.0 \cdot 12.6 = 516.6\ m^2$
Mean rainfall in Olsztyn:	700 mm/year
Run-off coefficient:	0.90 (oblique roof covered with plate)
Filter efficiency:	0.90

mean rainwater supply [dm^3/year] = mean annual rainfall [mm] ·

· surface area of catchment [m^2] · run-off coefficient · filter coefficient (LEGGETT 2001)

$$V = 700 \cdot 516.6 \cdot 0.90 \cdot 0.90 = 292\ 912\ dm^3/year$$

The tank volume calculation is based on *Kingspan* recommendations, with the reservation that retention time taken into account is 10 days, which has been calculated upon a book *Frequency of days with precipitation in Poland* (OLECHNOWICZ-BOBROWSKA 1970), where it was given that periods without any rainfall longer than 10 days occurs very rare. According to the German experience (SAYERS 1999) it is recommended to select tank size in a manner enabling periodical overflows of the water and removing ipso facto floating pollution (suspended solids). Tank size was calculated with the formula given (KINGSPAN 2011):

$$\frac{\text{yield} + \text{demand}}{2} \cdot \frac{10\ \text{days}}{365} = \frac{292\ 912 + 420\ 480}{2} \cdot \frac{10}{365} = 9772\ dm^3$$

A rainwater plastic tank chosen is *Rewatec* type *BlueLine II*, 10 000 dm^3 volume. Installation scheme is shown on Figure 9. All the pipework diameters, materials, pumps, valves, filters, etc., for both rainwater and tap water installation, have been calculated according to all currently applicable standards and regulations in Poland. Rainwater is collected from the rooftop through roof gutters Ø 150 mm and directed to the tank through the pipework.

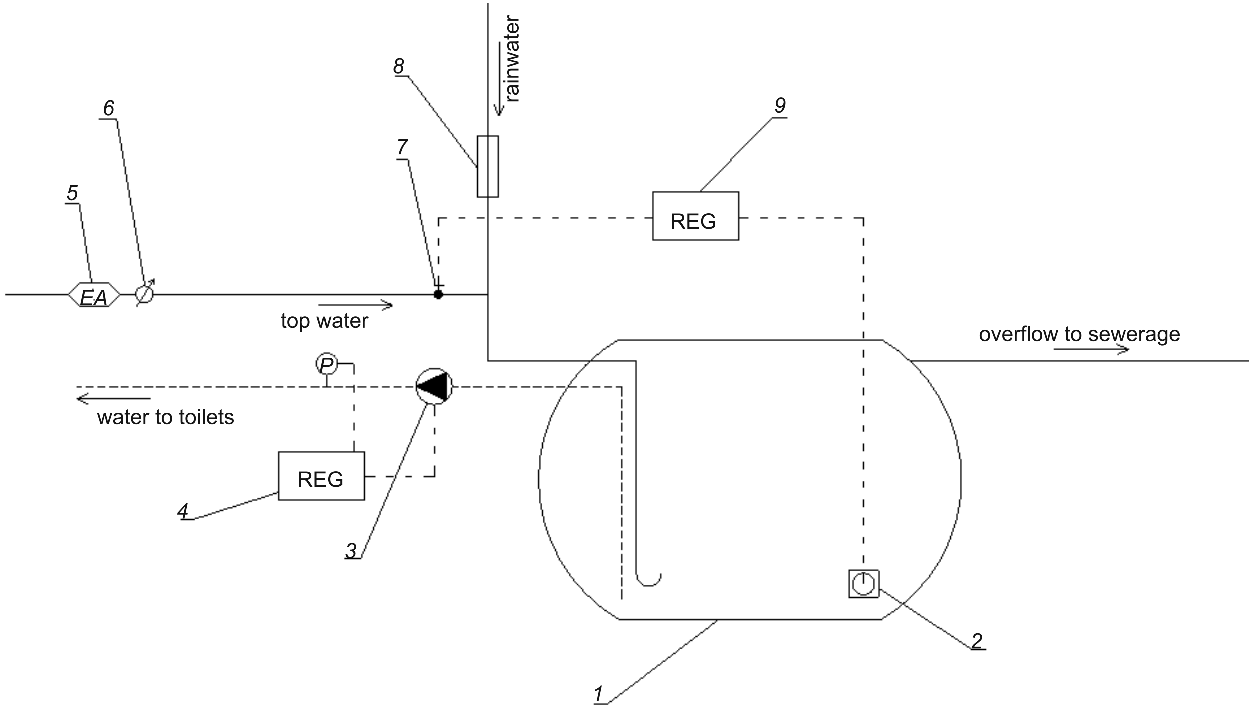

Fig. 9. Rainwater harvesting system example installation scheme: *1* – rainwater collecting tank Blue Line II 1000 dm^3 PE; *2* – water level sensor; *3* – pump activated on basis of pressure sensor; *4* – controller; *5* – anti-contamination filter; *6* – water meter of tap water; *7* – valve with actuator activated on basis of rainwater level sensor; *8* – inner gutter filter; *9* – controller

Rainwater harvesting system economics

The rainwater harvesting system in the multi-family building described above is supposed to bring the savings of 292 912 tap water litres per year, which covers almost 70% of the total demand for flushing toilets in the building.

$$\frac{\text{mean rainwater supply}}{\text{water demand for flushing toilets}} \cdot 100\% = \frac{292\,912}{420\,480} \cdot 100\% = 69.7\%$$

Total water demand savings:

$$69.7\% \cdot 30\% \text{ (household toilet flushing)} = 69.7\% \cdot 30\% = 20.1\%$$

Taking into account current water and wastewater prices in Olsztyn (PWIK 2017) the financial savings presented below seem to be optimistic as well. Taxes for storm water have not been introduced in Olsztyn yet, nevertheless, it seems to be probable in the nearest future.

Water price for households: 4.32 PLN/m^3

Wastewater price: 6.44 PLN/m^3

$$\text{water cost savings} = (\text{water price} + \text{wastewater price}) \cdot \frac{\text{water volume savings}}{1000}$$

$$(4.32 + 6.44) \cdot \frac{292\,912}{1000} = 3152 \text{ PLN/year}$$

The prices vary significantly in different regions of Poland, and in comparison the highest price in Poland is 12.05 PLN for water and 17.25 PLN for wastewater cubic meter in Szklarska Poręba (KSWIK 2018), which almost triples the potential savings. In addition, the environmental aspect should be considered, regarding lower potable water consumption. Whole installation and project costs depend on many factors, mostly on complexity of the installation, designer brand and his prices. Occasionally calculations are held by unqualified house owner and potential user of the installation, which can at glance lower whole cost, but at last expenses may grow due to incorrect long-term system operation. The costs are much lower when new building is constructed since all the machinery, e.g. excavators are present anyway at the construction site thus digging additional hole for the tank is not a problem. When the rainwater utilization system is mounted to an existing building in certain cases it might encounter such difficulties as terrain development with small architecture, which does not allow excavators to easily enter the area. Having the system installed the only maintenance costs seems to be pump work, UV lamps, filter cleaning and some repairs. In the multi-family building described above the system is simplified, without disinfection lamps or biological purification, and with one pump only which lowers whole operating cost.

Conclusions

Rainwater harvesting system in a multi-family building can be successfully used for flushing toilets purpose and bring significant environmental and financial savings, regarding constantly rising water and wastewater prices and upcoming rainwater taxes. In the example building described in this paper it occurred that almost 70% of water demand for flushing toilets can be covered by rainwater, which gives 20% savings on total water demand. One of the most important issues is to properly dimension the rainwater tank bearing in mind periodic overflows. During evaluating of the conceptual system in a multi-family building some problems have been encountered. One of them was the method of accounting for tap water consumption during dry season. This water can be counted by a water meter but it is impossible to divide the consumption into individual flats. The most favourable solution seems to be equal division to each flat. In certain case this might cause dissatisfaction of a group of people. Rainwater harvesting systems should be considered in every new-constructed building as well as in the existing ones especially in Poland where the water resources are quite limited.

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